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Impact of Cruise Speed on Productivity of Supersonic Transports

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A comparison of airplane productivity and utilization levels derived from commercial airplane type schedules based upon 1995 passenger demand forecasts was made between two subsonic and four supersonic cruise speed aircraft. The cruise speed component is the only difference between the schedules. Productivity-to-speed relationships were determined for three discrete route systems: North Atlantic, transpacific, and North-South America. All three route systems show airplane productivity practically doubling between cruise speeds of Mach 0.82 and 2.0. Above Mach 2.0, further productivity gains are a function of the particular route systems. The route systems with longer cruise distances are able to take advantage of cruise speeds higher than Mach 2.0. A weighted average of all three route systems shows only an additional 10% increase in productivity of the Mach 2.7 aircraft over the Mach 2.0 aircraft.

Introduction

IT would seem that a fast aircraft is inherently more productive than a slow aircraft since shorter trip time offers the possibility of more trips for a given period of time. However, within the context of an airline system, increasing speed alone does not necessarily provide an improvement in productivity, particularly for supersonic speeds. For example, an aircraft cruising at Mach 2.0 reduces transatlantic trip time by more than 3 h over today's jets; cruising at Mach 2.7 saves only an additional 25 min; and at Mach 3.0 saves only an additional 11 min over Mach 2.7. For a fixed distance, the potential for improving productivity decreases as speed increases simply because the ability to generate significant time savings diminishes. The distances of the most frequently travelled intercontinental routes, therefore, are a limitation to the potential for improving airplane productivity with increased speed. This limitation is even more pronounced when all of the restrictions and constraints of commercial airline operations are included. Factors such as airport curfews, time-zone differences, and market types, as well as block-time allowances not affected by cruise speed, must be considered in a realistic assessment of a productivity-to-speed relationship.

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One effective method for making productivity assessments incorporating airline operational and market considerations is by comparing the productivity potential of different cruise speed aircraft using airline-type schedules. This method was used in a NASA sponsored study conducted jointly by Trans World Airlines, Inc., Braniff International, and the Lockheed-California Co.[1] Airline-type routing schedules to meet projected passenger demands were developed by TWA for North Atlantic and transpacific route systems, and by Braniff for a North-South America route system. The objective in developing these schedules is to meet the projected passenger demands with a minimum number of aircraft.

Each route system was scheduled independently for six different cruise speed aircraft. This paper describes some of the results of this work, especially with regard to the productivity-to-speed relationships resulting for each of the route systems.

Study Aircraft

Most of the aircraft concepts selected for the study were adopted from NASA sponsored Supersonic Cruise Research (SCR) study programs. The six study aircraft identified by their cruise speed are listed in Table 1.

These aircraft are preliminary design concepts except for the Mach 0.82 aircraft. All are large commercial-type transports in the 500,000-600,000 lb class for the subsonics, and the 600,000 lb class for the supersonics.

Scheduling Requirements

The scheduling requirements include city-pair selections for each route system, projected levels of service based upon forecast passenger demand, and the constraints and restrictions usually followed in aircraft routing schedule development including determination of the block-time requirements for the different speed aircraft.

Table 1 Study vehicles (4800 n. mile design range, 290 seats)

Cruise Mach no.	Vehicle	Average cruise altitude, ft
0.70	Low energy transport	35,000
0.82	Current wide-body	35,000
1.4	SST concept	47,000
2.0	SST concept	55,000
2.2	SST concept	57,000
2.7	SST concept	62,000

Table 2 Selected city-pairs, 1995 forecast passenger demand and flight frequencies—290 seats

City-Pairs	Airports		Passengers per week each direction	Flts. per week	Load factor, %
North Atlantic					
New York					
—Frankfurt	JFK	—FRA	3710	21	61
—London		—LHR	7840	42	64
—Madrid		—MAD	3850	21	63
—Milan		—MXP	1890	12	54
—Paris		—CDG	3850	21	63
—Rome		—FCO	3850	21	63
Boston					
—London	BOS	—LHR	2100	14	52
—Paris		—CDG	1330	7	66
Chicago					
—London	ORD	—LHR	2800	14	69
Philadelphia					
—London	PHL	—LHR	1400	7	69
Washington					
—London	IAD	—LHR	2100	14	52
Transpacific					
Los Angeles					
—Honolulu	LAX	—HNL	5019	28	62
San Francisco					
—Honolulu	SFO	—HNL	4907	28	60
—Tokyo		—TYO	3045	18	58
Honolulu					
—Guam	HNL	—GUM	3276	21	54
—Hong Kong		—HKG	1064	7	52
—Sydney		—SYD	4032	21	66
—Tokyo		—TYO	6461	35	64
Guam					
—Hong Kong	GUM	—HKG	644	4	56
North-South America					
New York					
—Panama City	JFK	—TUM	3150	17	64
—Bogata		—BOG	5600	30	64
—Guayaquil		—GYE	2100	11	66
—Lima		—LIM	2350	12	68
—Santiago		—SCL	800	5	55
—Buenos Aires		—EZE	3360	18	64
Miami					
—Guayaquil	MIA	—GYE	3150	17	64
—Lima		—LIM	3500	18	67
—Santiago		—SCL	1190	6	68
—Buenos Aires		—EZE	2450	12	70
Los Angeles					
—Bogata	LAX	—BOG	1050	6	60
—Lima		—LIM	1680	9	64

City-Pair Selections

Major U.S. and foreign cities currently being served by U.S. airlines were selected for schedule development. A sufficient number of city-pairs was chosen for each market so that the route structure would be approximately the size of a single airline's international market.

The city-pairs listed in Table 2, including their respective airport designations, are generally within the range capability of a 4800-n. mile design-range aircraft. Some of the transpacific westbound flights require a slightly longer range capability due to wind conditions. The additional range requirement is less than 200 n. miles for the supersonic aircraft, which is assumed to be within their fuel payload tradeoff capability.

Passenger Traffic Projections

Passenger traffic projections for the year 1995 were made by TWA for the North Atlantic and transpacific route systems, and by Braniff for the North-South America routes. These projections are primarily for the purpose of establishing the level of passenger demand during the time period when a second-generation supersonic aircraft might be introduced. The accuracy of the projections was determined not to be critical to the study conclusions. The projected greater level of passenger traffic allows including more cities and flights than would be practical with present day traffic.

The projected passenger traffic shown in Table 2 was obtained by applying average annual growth rates to 1975 base-year market data for a single airline. For the North Atlantic, a 5% projected average annual growth rate in scheduled passenger traffic is used. For the transpacific, the rates among the city-pairs range from 2.5% for Los Angeles-Honolulu to 7% for San Francisco-Tokyo and Honolulu-Sydney. The overall average annual growth rate used in the North-South America projections is approximately 8%, reflecting the higher growth rates expected in less developed markets.

Scheduled Flight Frequencies

Scheduled flight frequencies shown in Table 2 were established to provide a load factor between 52 and 70% for the North Atlantic and transpacific routes, and to provide load factors between 60 and 70% for the North-South America route system.

Flight Segment Distances

A summary of the flight segment distances is shown in Table 3. A general rule applicable to the selected flight paths was that no supersonic flight was allowed over inhabited areas. This results in segment distances for some of the city-pairs being considerably longer for supersonic aircraft than for subsonic aircraft.

Segment distances for the subsonic cruise aircraft for the North Atlantic are great circle distances between the city-pair airports plus 1% for possible operational variations.

North Atlantic segment distances for the supersonic aircraft are great circle distances between waypoints selected to preclude supersonic cruise over land masses, plus the distance from the waypoint to origin or destination airport. One percent was added for possible operational variations to obtain the total distance.

Where supersonic cruise aircraft require subsonic departure or arrival legs, this portion of the flight was determined as the distance from the departure airport to the coastline or from the coastline to the destination. The paths selected minimize subsonic flight. For example, the Chicago-London flight overheads New York and then proceeds to London on the same path as a New York-London flight.

Transpacific segment distances for both subsonic and supersonic cruise aircraft are great circle distances between the city-pair airports plus 1% for possible operational variations. There are no subsonic cruise leg requirements for supersonic cruise aircraft on the transpacific.

North-South America segment distances for the subsonic aircraft are the same as those currently in use. The corresponding data for the supersonic aircraft are based on flight paths that avoid supersonic flight over inhabited land

Table 3 Segment flight distances

Segment	Subsonic aircraft Total n. miles	Supersonic aircraft Total n. miles	Supersonic aircraft Subsonic n. miles[a]
North Atlantic			
JFK-FRA	3373	3440	0/268
JFK-LHR	3020	3119	0/70
JFK-MAD	3141	3165	0/241
JFK-MXP	3495	3515	0/486
JFK-CDG	3177	3206	0/183
JFK-FCO	3756	3762	0/628
BOS-LHR	2856	3005	0/70
BOS-CDG	3016	3095	0/183
ORD-LHR	3457	3765	681/70
PHL-LHR	3101	3223	100/70
LAD-LHR	3217	3333	151/70
Transpacific			
LAX-HNL	2239	2239	0/0
SFO-HNL	2102	2102	0/0
SFO-TYO	4516	4516	0/0
HNL-GUM	3320	3320	0/0
HNL-HKG	4860	4860	0/0
HNL-SYD	4452	4452	0/0
HNL-TYO	3374	3374	0/0
GUM-HKG	1844	1844	0/0
North-South America			
JFK-TUM	1971	2015	0/0
JFK-BOG	2216	2238	0/175
JFK-GYE	2659	2689	0/184
JFK-LIM	3245	3395	0/0
JFK-SCL	4550	4727	0/135
JFK-EZE	4714	4800	0/507
MIA-GYE	1728	1934	0/184
MIA-LIM	2340	2640	0/0
MIA-SCL	3681	3972	0/135
MIA-EZE	3935	4342	0/507
LAX-BOG	3098	3360	0/200
LAX-LIM	3695	3695	0/0

[a]Subsonic departure/arrival.

areas assuming a sonic boom path width of 50 miles. For purposes of the study, uninhabited areas are defined as areas having less than three inhabitants per square mile. Some of the supersonic tracks pass over such sparsely populated areas.

Block Times

The scheduled block times are based on the flight profiles shown in Fig. 1 for the subsonic aircraft and Fig. 2 for the supersonic aircraft. Block time is defined as the time required for the aircraft to travel from the passenger gate at its departure point to the passenger gate of its destination.

The block times for the three route systems are listed in Tables 4-6. This information includes wind corrections based on 75% annual winds for the average cruise altitudes of each aircraft design.

The block-time data include a minimum of 10 min gate-taxi time allowance for departure and 5 min for arrival. These time allowances are increased where necessary to match the longer time allowances from the Airline Block-Time Conference (ABC) statistical data shown in Table 7.

Scheduling Constraints

While many airports prohibit takeoffs and landings from 2400 to 0600 local time, passenger preferences for most U.S. and European airports for no departures before 0900 and no arrivals after 2300 are more restrictive and are therefore included in the schedules. The following ground rules are generally applicable to each route system:

1) No arrivals between 2300 and 0600 and no departures between 2300 and 0900 local time.
2) Minimum turn time of 1.5 h.
3) Allowance for aircraft maintenance requirements.
4) No subsonic tag-end flights.
5) Passenger preferential departure/arrival times observed.

The above rules were not applied absolutely to all route systems or flights. For North-South America routes, late-

Table 4 North Atlantic schedule block times (h: min)

Segment	Mach 0.70		Mach 0.82		Mach 1.4		Mach 2.0		Mach 2.2		Mach 2.7	
	Direct	Return	Direct	Return	Direct	Return	Direct	Return	Direct	Return	Direct	Return
JFK-FRA	8:28	9:54	7:23	8:09	4:58	5:10	3:56	3:56	3:42	3:41	3:18	3:18
-LHR	7:37	9:04	6:38	7:29	4:28	4:44	3:28	3:33	3:15	3:18	2:52	2:52
-MAD	7:52	9:12	6:52	7:41	4:37	4:51	3:40	3:44	3:28	3:31	3:06	3:05
-MXP	8:41	10:13	7:34	8:23	5:11	5:23	4:12	4:13	3:59	3:59	3:36	3:33
-CDG	8:02	9:29	7:01	7:50	4:44	4:54	3:45	3:45	3:32	3:31	3:09	3:05
-FCO	9:17	10:58	8:05	9:03	5:36	5:55	4:35	4:42	4:21	4:28	3:58	4:01
BOS-LHR	7:06	8:32	6:11	7:04	4:12	4:33	3:15	3:23	3:02	3:10	2:40	2:47
-CDG	7:34	8:59	6:35	7:25	4:31	4:44	3:32	3:35	3:19	3:22	2:57	2:58
ORD-LHR	8:38	10:11	7:29	8:26	5:31	6:05	4:32	4:54	4:19	4:40	3:55	4:16
PHL-LHR	7:40	9:15	6:39	7:40	4:29	4:53	3:29	3:41	3:16	3:26	2:50	3:02
IAD-LHR	7:50	9:34	6:48	7:53	4:35	5:02	3:33	3:48	3:19	3:33	2:54	3:08

Table 5 Transpacific schedule block times (h: min)

Segment	Mach 0.70		Mach 0.82		Mach 1.4		Mach 2.0		Mach 2.2		Mach 2.7	
	Direct	Return	Direct	Return	Direct	Return	Direct	Return	Direct	Return	Direct	Return
LAX-HNL	6:27	5:52	5:23	5:04	3:22	3:18	2:33	2:36	2:23	2:26	2:06	2:10
HNL-HKG	(1)	11:50	(1)	10:11	*6:56	6:24	*4:57	4:46	*4:34	*4:25	*3:54	*3:48
HNL-GUM	9:11	8:38	7:41	7:20	4:46	4:38	3:32	3:30	3:17	3:16	2:51	2:51
HNL-SYD	12:09	11:07	10:07	9:32	6:12	5:57	4:33	4:27	4:13	4:08	3:36	3:33
HNL-TYO	10:14	8:11	8:21	7:10	5:01	4:36	3:40	3:32	3:23	3:17	2:56	2:53
GUM-HKG	5:05	5:07	4:21	4:23	2:51	2:52	2:13	2:12	2:05	1:57	1:52	1:49
SFO-HNL	6:10	5:33	5:10	4:47	3:15	3:08	2:30	2:28	2:21	2:19	2:04	2:04
SFO-TYO	VIA ANC	10:40	VIA ANC	9:21	6:28	5:58	4:40	4:31	4:19	4:11	3:42	3:37
SFO-ANC	5:30	–	4:35	–								
ANC-TYO	8:15	–	7:08	–								

(1) Beyond range capability. *Restricted pax payload on this segment.

Table 6 North-South America schedule block times (h: min)

	Mach 0.70		Mach 0.82		Mach 1.4		Mach 2.0		Mach 2.2		Mach 2.7	
Segment	Direct	Return	Direct	Return	Direct	Return	Direct	Return	Direct	Return	Direct	Return
JFK-TUM	5:32	5:25	4:45	4:40	3:04	3:03	2:24	2:23	2:15	2:15	2:00	2:00
-BOG	6:07	6:04	5:13	5:11	3:25	3:26	2:42	2:44	2:34	2:35	2:18	2:19
-GYE	7:14	7:08	6:07	6:04	4:00	3:59	3:07	3:08	2:56	2:57	2:36	2:37
-LIM	8:38	8:36	7:20	7:19	4:47	4:47	3:36	3:36	3:21	3:21	2:54	2:54
-SCL	11:49	11:59	10:01	10:07	6:28	6:30	4:50	4:51	4:30	4:31	3:53	3:54
-EZE	12:04	12:25	10:05	10:17	6:46	6:48	5:16	5:18	4:57	4:58	4:23	4:24
MIA-GYE	4:50	4:50	4:11	4:11	3:02	3:03	2:27	2:28	2:19	2:21	2:06	2:08
-LIM	6:18	6:22	5:25	5:26	3:50	3:51	2:56	2:56	2:45	2:45	2:24	2:24
-SCL	9:35	9:49	8:10	8:13	5:30	5:35	4:10	4:12	3:53	3:55	3:23	3:24
-EZE	10:08	10:32	8:38	8:52	6:11	6:17	4:51	4:54	4:34	4:37	4:04	4:06
LAX-BOG	8:08	8:37	6:56	7:12	4:48	4:55	3:42	3:46	3:29	3:31	3:04	3:05
-LIM	9:36	9:55	8:10	8:22	5:07	5:12	3:51	3:52	3:35	3:36	3:06	3:06

Table 7 Taxi times

	Time, min	
	Out	In
Boston (BOS)	15	5
Chicago (ORD)	19	11
Frankfurt (FRA)	12	5
Guam (GUM)	13	5
Hong Kong (HKG)	11	6
Honolulu (HNL)	15	6
London (LHR)	18	6
Los Angeles (LAX)	11	7
Madrid (MAD)	16	6
Milan (MXP)	10	5
New York (JFK)	23	9
Paris (CDG)	18	11
Philadelphia (PHL)	15	8
Rome (FCO)	18	7
San Francisco (SFO)	15	6
Sydney (SYC)	12	6
Tokyo (TYO)	14	6
Washington (IAD)	10	6

night departures for North American destinations are usually preferred because of morning arrival. For the transpacific schedules, curfew restrictions were not applied to Guam or Honolulu and terminating flights up to 2400 h were allowed at other transpacific stations. No flight curfews are currently in force at Guam and Honolulu, and if such restrictions were imposed, they would severely restrict transpacific airline service.

A standard turn time of 90 min has been selected for scheduling all aircraft. This is the approximate minimum time required to turn present day wide-body transports, provided the airplane remains at the gate. A breakdown of the turn time requirements is shown in Fig. 3. A modest reduction in turn time is generally possible to meet schedules, and in a limited number of instances, the 90 min requirement was reduced to 60 min to allow arrival at the destination prior to 2400.

Aircraft maintenance requirements refer to routing a fleet of aircraft so that each aircraft periodically spends extra time at airports designated as maintenance stations. The aircraft routing schedules include these maintenance layovers at intervals recommended by each airline's maintenance personnel. For example, the supersonic aircraft for the North Atlantic schedules were limited to seven roundtrips per routing cycle, at which time an overnight maintenance at JFK was scheduled.

Scheduling Results

A summary of the passenger scheduling demands, including totals and averages for each route system and for the overall system, is shown in Table 8. Aircraft routing schedules such

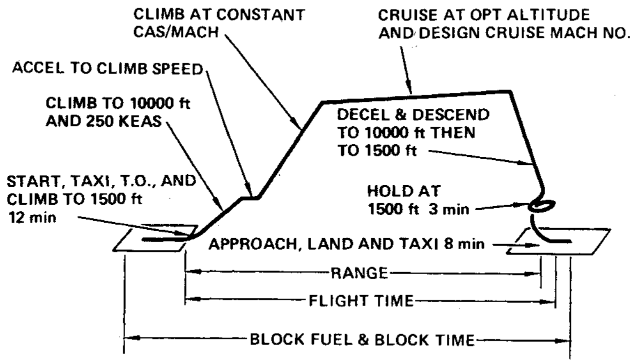

Fig. 1 Subsonic vehicle flight profile.

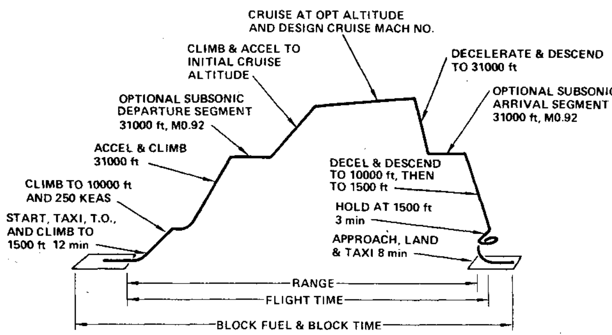

Fig. 2 Supersonic vehicle flight profile.

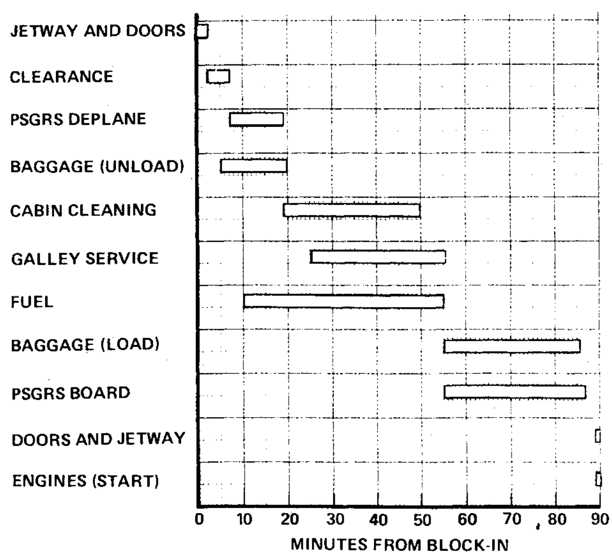

Fig. 3 On-gate servicing turn-time components.

Table 8 Summary of scheduling requirements—passengers, distances, and block hours

	North Atlantic	Transpacific	North-South America	Overall totals or average
No. of city pairs	11	8	12	31 (total)
1995 weekly pax each way—single airline	34,720	28,448	30,380	93,548 (total)
Required round trips per week (flights)	194 (388)	162 (324)	161 (322)	517 (total) (1034)
Average load factor per flight	62%	61%	65%	62% (avg)
Weekly route distance—subsonics, n. miles	1,250,524	1,050,408	936,846	3,237,630 (total)
Weekly route distance—supersonics, n. miles	1,287,770	1,050,408	983,066	3,321,244 (total)
Average segment distance—subsonics, n. miles	3,223	3,242	2,909	3,131 (avg)
Average segment distance—supersonics, n. miles	3,319	3,242	3,052	3,212 (avg)
Average SST subsonic cruise distance, n. miles	224	0	150	128 (avg)
Weekly revenue distance, statute miles	1,433,488	1,198,260	1,047,704	3,679,452 (total)

Cruise Mach no.	Total daily block hours	Avg. block hours/flight	Total daily block hours	Avg. block hours/flight	Total daily block hours	Avg. block hours/flight	Overall total daily block hours	Overall avg. block hours/flight
0.70	439.4	8.83	409.7	8.85	358.3	7.79	1,257.4	8.51
0.82	412.4	7.44	343.4	7.42	304.1	6.61	1,059.9	7.17
1.4	274.4	4.95	213.4	4.61	204.3	4.44	699.2	4.68
2.0	213.9	3.86	160.1	3.46	158.5	3.44	532.5	3.59
2.2	201.2	3.63	149.0	3.22	149.0	3.24	499.2	3.38
2.7	180.1	3.22	129.1	2.79	131.6	2.86	441.5	2.97

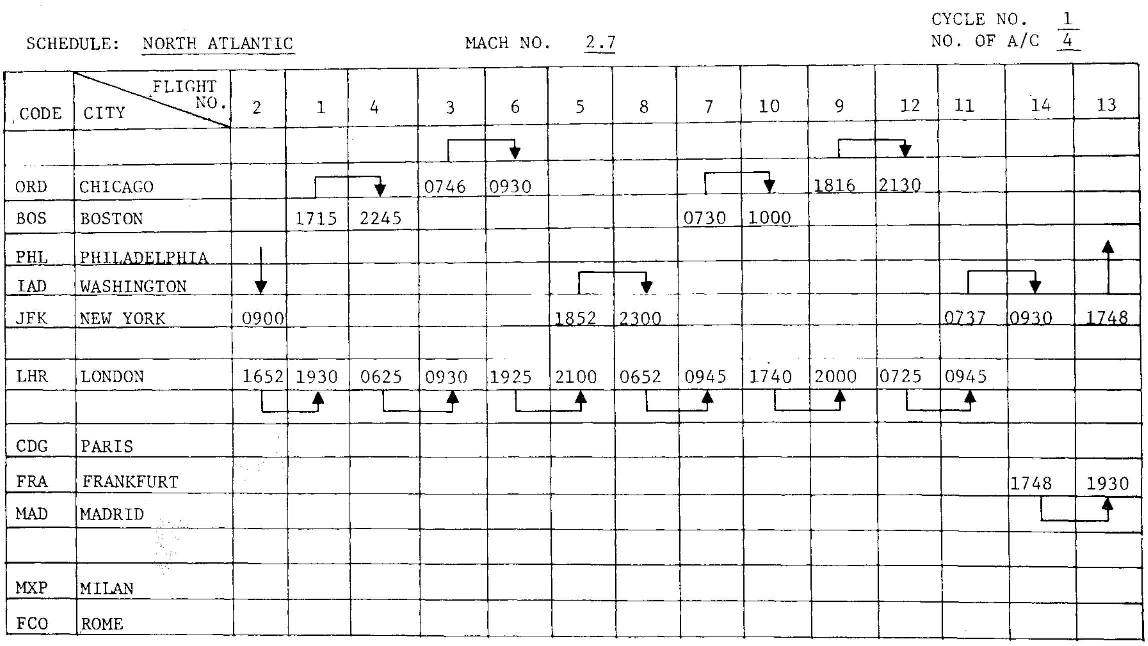

Fig. 4 Typical aircraft routing schedule.

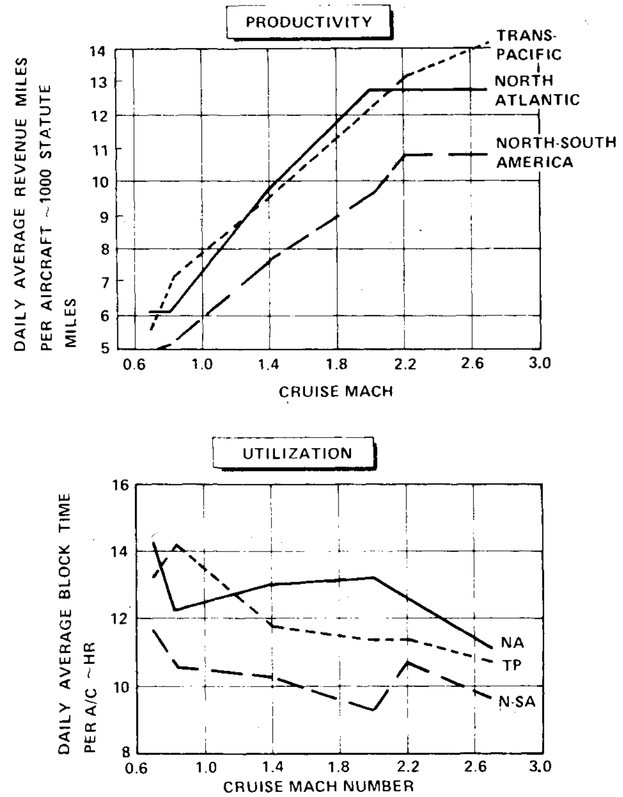

Fig. 5 Individual routes study results (290 seats).

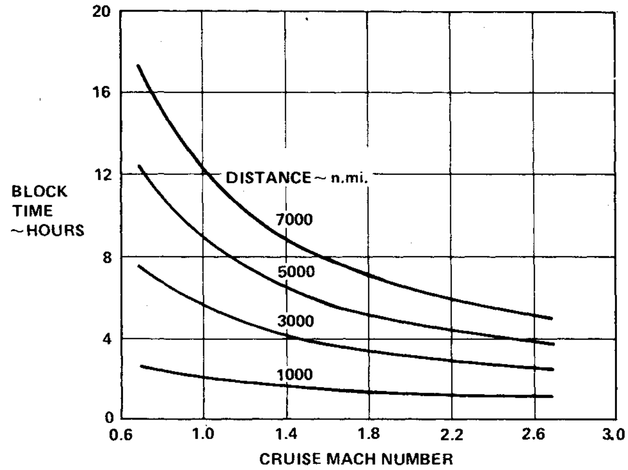

Fig. 6 Effect of cruise speed on block time for range of distances.

as the one shown in Fig. 4 were developed for each aircraft. These schedules govern the movement of individual aircraft to meet the projected passenger demands.

Table 9 presents a summary of the scheduling results for the three route systems. The most important parameter is fleet size since the object in developing routing schedules is to meet the projected passenger demands with a minimum number of aircraft. Aircraft utilization levels are relatively high, indicating efficient use of the aircraft. Aircraft productivity is expressed with statute miles to be consistent with air transport industry conventions.

All three route systems show airplane productivity practically doubling between cruise speeds of Mach 0.82 and Mach 2.0. Above Mach 2.0, as illustrated in Fig. 5, further productivity gains are made to Mach 2.2 for the North-South America route system and to Mach 2.7 for the transpacific routes. The possibility for further improving Mach 2.7 transpacific productivities with a Mach 3.0 cruise speed was investigated and the results showed no gain. All three route systems, therefore, exhibit a flattening out of the productivity-to-speed relationship. This occurs at approximately Mach 2.7 for the transpacific, at Mach 2.2 for the North-South America, and at Mach 2.0 for the North Atlantic.

Increasing cruise speed has only limited capacity for effecting block time savings. A graphic illustration of this is shown in Fig. 6. It will be noted that for speeds above Mach 2.0, relatively large speed increases are required to generate significant time savings for the shorter distances shown, but the amount of time savings increases rapidly as distance increases. This speed-distance effect is exhibited to some degree by the three route systems. This, as well as limits on aircraft use and the effect of various scheduling considerations, is presented in the following discussion.

Table 9 Summary of scheduling results—fleet size, utilizations, productivities, and other data—290 seats

	North Atlantic			Transpacific			North-South America			Overall totals or average		
Cruise Mach no.	Fleet size	Daily utilization per A/C hours	Daily revenue distance per A/C statute miles	Fleet size	Daily utilization per A&C hours	Daily revenue distance per A/C statute miles	Fleet size	Daily utilization per A/C hours	Daily revenue distance per A/C statute miles	Total fleet size	Daily utilization per A/C hours	Daily revenue distance per A/C statute miles
0.70	34	14.34	6,023	29	14.12	5,903	31	11.56	4,828	94	13.40	5,592
0.82	34	12.13	6,023	24	14.31	7,133	30	10.14	4,989	88	12.04	5,973
1.4	21	13.06	9,752	18	11.85	9,511	20	10.21	7,483	59	11.73	9,909
2.0	16	13.36	12,799	14	11.44	12,228	16	9.91	9,354	46	11.58	11,427
2.2	16	12.57	12,799	13	11.46	13,169	14	10.64	10,691	43	11.61	12,224
2.7	16	11.17	12,799	12	10.76	14,266	14	9.40	10,691	42	10.51	12,515

Cruise Mach no.	Flights per day per A/C	Average available turn-time hours	Flights per day per A/C	Average available turn-time hours	Flights per day per A/C	Average available turn-time hours	Flights per day per A/C	Overall average available turn-time hours
0.70	1.63	3.33	1.59	2.43	1.48	–	1.57	–
0.82	1.63	4.59	1.93	2.54	1.53	–	1.68	–
1.4	2.64	2.23	2.57	2.22	2.30	2.5	2.50	2.31
2.0	3.46	2.12	3.31	2.21	2.88	1.7	3.21	2.02
2.2	3.46	2.35	3.56	2.02	3.29	2.0	3.43	2.14
2.7	3.46	2.70	3.86	2.25	3.29	2.3	3.52	2.43

Table 10 Block time comparison between Mach 2.0 and Mach 2.7 aircraft for longest segments of each route system

	North Atlantic	Trans-pacific	No.-So. America
Percent of route system	38	39	45
Range of distances, n. miles	3440-3765	4452-4860	3695-4800
Range of supersonic cruise distances, n. miles	2800-3000	4300-4600	3500-4400
Avg. block time, h: min			
Mach 2.0	4:22	4:35	4:45
Mach 2.7	3:47	3:39	3:55
Δ time, Mach 2.0 to Mach 2.7	:35	:56	:50

Impact of Route Segment Distances

The most significant difference between the three route systems is their route segment distances. Both the transpacific and North-South America route systems include segments that are substantially longer and shorter than those of the North Atlantic, although the weighted averages as listed in Table 8 are approximately the same. However, the long distance city-pairs of the transpacific and North-South America route systems, coupled with their lower subsonic cruise requirements, result in supersonic cruise distances that average nearly 1000 n. miles longer than the longest North Atlantic distances. These longer supersonic cruise distances allow the Mach 2.7 aircraft to generate significantly greater time savings over a Mach 2.0 aircraft as shown in Table 10.

After completing three flights, the total time savings for Mach 2.7 over Mach 2.0 is 1 h 45 min for the North Atlantic compared to 2 h 48 min for the transpacific. The additional time saving places the Mach 2.7 transpacific aircraft in a much better position to accommodate a fourth flight than its North Atlantic counterpart. It is primarily this difference in time saving that accounts for the Mach 2.7 aircraft achieving greater productivity over the Mach 2.0 aircraft on the transpacific route systems.

Although long distance segments favor the productivity improvement potential of higher cruise speeds, there are limits to the length and number of such segments that are normally part of a route system. There is no other market containing as many long distance segments as the transpacific. Approximately 85% of the passenger demand for the three route systems studied are for city-pairs having segment distances less than 4000 n. miles, as shown in Fig. 7. Generally, the bulk of the scheduling requirements for most route systems is for the shorter distance flights as indicated by the 1975 world distributions of flight frequency versus segment distances shown in Fig. 8. It will be noted that the distribution for the three study route systems tends to follow the world trend. Figures 7 and 8 indicate that the vast majority of long distance segments are in the 2500-5000 n. mile range with supersonic cruise distances in the order of 2000-4500 n. miles. The fact that there are relatively few flights with supersonic cruise distance longer than 4500 n. miles, leaves little prospect for improving productivity with speed for speeds higher than Mach 2.7.

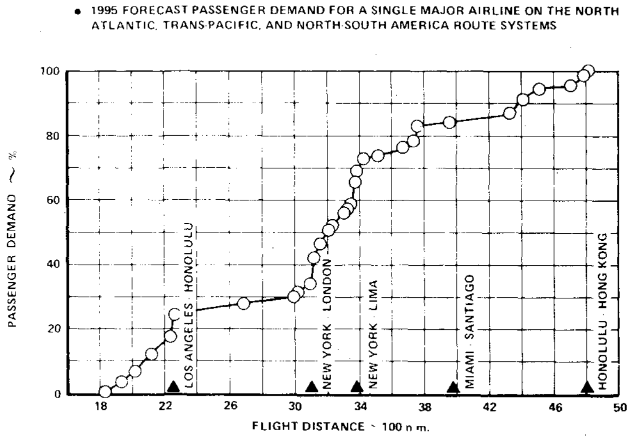

Fig. 7 Zero wind range requirements as function of passenger demand.

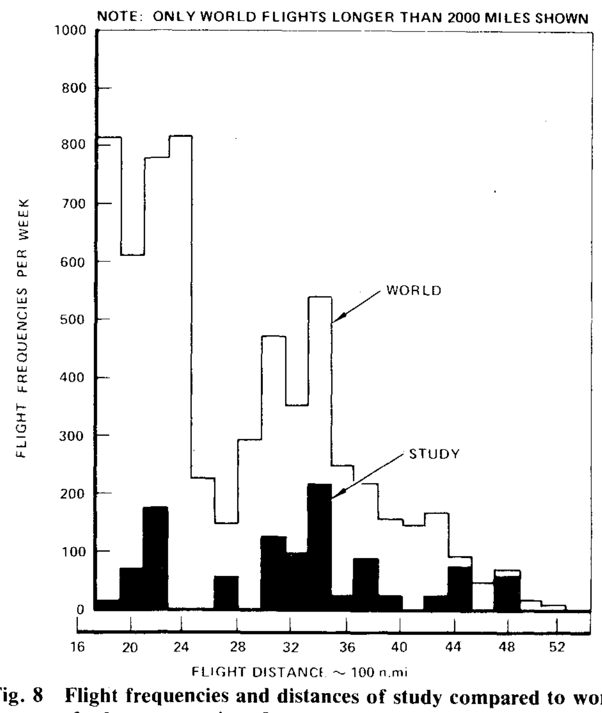

Fig. 8 Flight frequencies and distances of study compared to world averages for long-range aircraft.

Aircraft Utilizations and Flight Cycles

Daily aircraft utilization of 10-13 h, as shown in Fig. 5, is considered high by present day standards. A subsonic long-haul transport may attain such levels averaging one to two daily flights, but a supersonic transport must attain daily averages of three to four flights to even approach such levels. In this regard supersonic aircraft operations would be similar to current medium-range domestic transport operations which are also based on relatively high flight frequencies. For high flight frequency operations, a considerable amount of time is spent turning the aircraft, e.g., loading and unloading passengers. Consequently, domestic-service transports are not expected to have as high utilization levels as long-haul transports and supersonic transports likewise should not be expected to attain the same levels of utilization as subsonic long-haul transports.

Operational time is the sum of total block hours (utilization) and total turn time. An increasing fleet average operational time indicates an increasingly committed fleet, meaning there are fewer possibilities for greater aircraft use. Figure 9 illustrates the relationship between flight cycles and

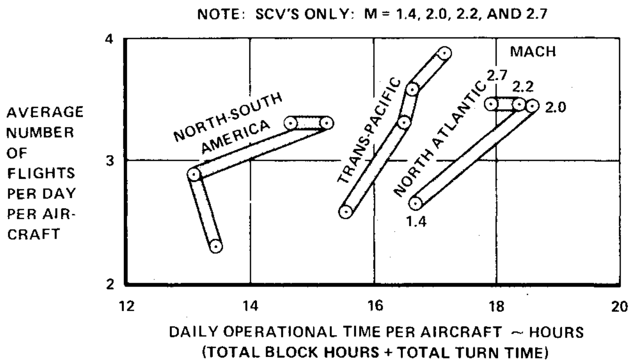

Fig. 9 Comparison of operational time and flight frequencies for three route systems.

daily operational time for the three route systems and shows that an increase in the number of flights usually increases operational time. Time savings generated by increased speed alone are usually not sufficient to cover the time needed for another flight. A faster, more productive aircraft generally has higher average operational time; however, faster aircraft operating at the same productivity level as a slower aircraft, such as the Mach 2.2 and Mach 2.7 aircraft on the North Atlantic, will have lower operational time and therefore be more flexible to schedule changes and less vulnerable to delays.

Effect of Minimum Turn Time

To quantify the effect of turn time on productivity, additional schedules were developed for the four supersonic aircraft on the North Atlantic and transpacific routes. Turn times 30 min shorter and longer than the study standard of 90 min minimum allowable were investigated.

Results of this investigation indicate that a 2-h minimum turn time would decrease productivity 4-10% with the higher penalties applicable to the slower speed aircraft. Reducing minimum turn time to 1 h caused a 5% productivity improvement for the Mach 1.4 aircraft and no productivity change for the higher speed aircraft; however, reducing turn time offers advantages in the form of improved scheduling flexibility for the higher speed aircraft.

One of the reasons a change in minimum turn time does not have a greater impact is that the scheduled turn time is often much longer than the minimum. In fact, the average scheduled turn time for the three route systems is 2.2 h. Turn time longer than the minimum usually occurs as a result of delaying a departure to remain within an arrival time limit.

Impact of Departure and Arrival Time Limitations

Passenger preferential departure and arrival time limitations, as mentioned previously, are more restrictive than airport curfews. These limitations coupled with time zone differences were not major obstacles to achieving full utilization of the aircraft. Among the three route systems, the most stringent of such constraints exists for the North Atlantic route system, and yet utilization levels for that system are the highest. In fact, North Atlantic aircraft are so fully used that abolishing the existing constraints would probably not make any difference.

Departure and arrival time constraints do not favor significantly either slower or faster aircraft. Departure time limitations required to remain within arrival time limits are as restrictive against slower aircraft going one direction as for faster aircraft traveling in the opposite direction.

Productivity Improvement Potential of Combined Routes

One type of scheduling constraint is lack of market, i.e., low passenger demand. Aircraft which can make three or four flights per day have no chance of being more productive if the market requires only one or two flights. This type of constraint was investigated by combining three individual route systems into a single system in an attempt to increase productivity further for the four supersonic aircraft. Aircraft were routed among North Atlantic, North-South America, and transpacific city-pairs under the assumption that a greater number of scheduling opportunities would increase opportunities for productivity improvement. The results of this investigation showed that a small improvement was gained over the averages of the three individual route systems. The improvement was only for the three lower speed supersonics and was achieved by improved aircraft use for the North-South America market. The productivities for the combined routes were lower than those achieved for the North Atlantic and transpacific individually. It was clear before the routes were combined that certain North-South American aircraft had insufficient use due to lack of passenger demand. There were instances when an aircraft was available for another flight but none was required. At the same time, it was equally obvious that it would be very difficult to route the North Atlantic and transpacific aircraft more efficiently. While the results were not unexpected, the investigation demonstrated that combining routes would be an effective method of taking advantage of the high productivity potential of supersonic aircraft in low passenger demand markets.

Impact of Subsonic Cruise Requirements on Supersonic Aircraft

The transpacific is the only route system that does not require the supersonic aircraft to fly in subsonic cruise to avoid sonic boom on populated areas. For the North Atlantic, the average supersonic transport subsonic cruise distance is 224 n. miles and for the North-South American routes it is 150 n. miles. Elimination of the longest subsonic cruise segment of the study, the Chicago U.S. east coast segment which is 681 n. miles, reduces the Mach 2.0 aircraft block time by almost as much as that for Mach 2.7, i.e., 38 min compared to 47 min. All supersonic flight would benefit the Mach 2.0 and Mach 2.2 aircraft to almost the same extent as the Mach 2.7 aircraft and therefore would have little impact on productivity differences between these speeds.

A significant impact of the subsonic cruise requirement is that it increases block time. The average North Atlantic flight is 25 min longer because of the subsonic cruise requirements. This, in fact, accounts for much of the difference in utilization levels between the North Atlantic and the other route systems. The higher use and possibly less efficient fuel mileage for a supersonic transport in subsonic cruise indicate important economic implications for subsonic cruise requirements. Subsonic cruise requirements in the order of 100-200 n. miles will undoubtedly be a part of routine supersonic aircraft operations.

Overall System Comparisons

Many of the discontinuities that are characteristic of the individual route systems disappear when averaged for the overall system. The overall productivity-to-speed relationship shown in Fig. 10 reflects the fleet size requirements, passenger demands, and total route distances of the individual routes in proportion to the totals for the overall system. Because the North Atlantic is the largest of the route systems, it has the greatest impact on the overall averages. Since neither the North Atlantic nor the North-South American route systems show productivity improvement potential for the Mach 2.7 aircraft, the productivity-to-speed relationship for the overall system likewise shows little productivity improvement potential for this aircraft. A true weighted average based upon total market differences between the three route systems would probably increase the impact of the North Atlantic route system. This is because the route systems of this study are for single airlines and the singular North-Atlantic airline represents a smaller proportion of its total market than do the others in their markets. In any event, the three individual

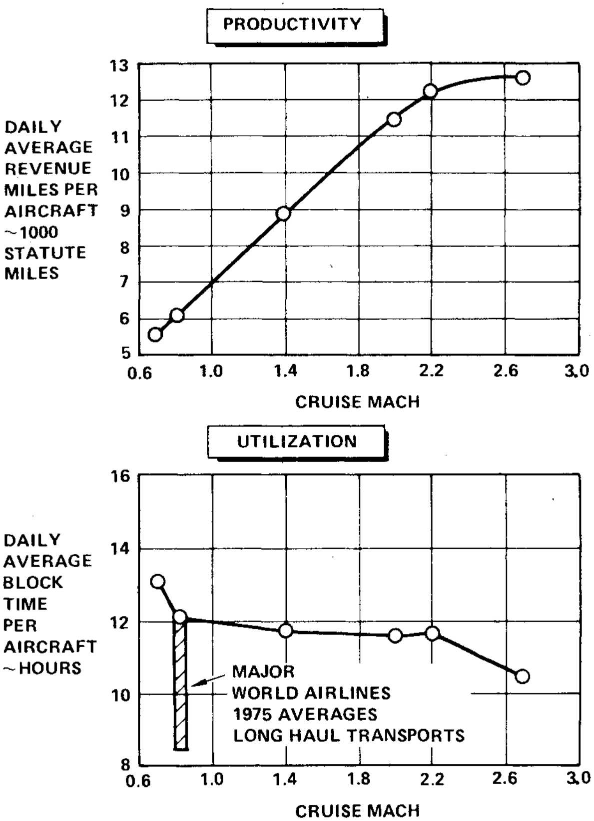

Fig. 10 Overall study results (290 seats).

route systems possess sufficient market diversity to conclude that the overall productivity-to-speed relationship shown is representative of the productivity improvement potential for cruise speed for most international route systems.

Conclusions

1) Increasing cruise speed is an effective means of improving aircraft productivity, but the maximum speed for which significant productivity gains are possible is primarily a function of the route system cruise distances. Productivity improvement is achieved up to a speed of Mach 2.0 for route systems comprised substantially of cruise distances of 2500-3000 n. miles. Further productivity gains by increasing speed higher than Mach 2.0 requires that an increasing proportion of the route system have cruise distances longer than 3000 n. miles, but the relatively small number of such routes available severely limits this prospect.

2) High daily aircraft utilization was achieved for supersonic aircraft under real-world-type scheduling limitations. Generally, aircraft were so fully utilized that attempts to increase use further by relaxing scheduling constraints were not successful.

3) Investigations directed at further increasing supersonic aircraft productivity by reducing minimum turn time by 30 min from the study standard of 90 min produced a small improvement for the Mach 1.4 aircraft only. A 30 min increase caused a 4-10% reduction in productivity with the two slower speed supersonics most sensitive to the change.

4) Departure and arrival time constraints arising from curfews and time zone differences were found in balance to be equally limiting to all speeds and usually have negligible effect on productivity.

5) Combining routes among two or more low passenger demand airlines would be an effective means for taking full advantage of the high productivity potential of supersonic aircraft.

6) Subsonic cruise requirements in the order of 100-200 n. miles will undoubtedly be part of routine supersonic aircraft operations. Elimination of these requirements would not have a significant effect on productivity differences between the different speed aircraft.

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