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THE OPERATION AND ECONOMICS OF THE SUPERSONIC TRANSPORT

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Abstract

The United States SST will have the most advanced flight deck instrumentation and cockpit displays of any manned flight article when it is introduced into airline service in 1978. This paper will briefly describe these displays and their use during a commercial flight. The economics of the supersonic transport have been widely questioned. An economic analysis of the operation of this advanced aircraft will be presented. Comparisons to the economics of the introduction of the turbojet transport into the piston engine transport will be made. The results will show that the SST will be very attractive in the passenger market of the 1980's.

I. Introduction

The supersonic transport era started on December 31, 1968 with the flight of the USSR's Tupolev 144. The British-French Concorde flew in March of 1969, and the United States SST is expected to fly in the last quarter of 1972.

There has been a great amount of controversy surrounding these airplanes. Can they operate from today's airports and in the airway system, will large ground equipment expenditures be necessary, will they break windows, walls, old buildings, cause climate changes, and lastly, be economic liabilities? Each of these questions has a logical, factual, unemotional answer.

This paper will treat the operation of an SST and describe the economics of the SST in an airline environment. In the process, some of the other questions will also be answered.

II. Operational Aspects

In order to properly design and equip the U.S. SST which will be flying in the late 1970's and on, it is necessary to look ahead and attempt to visualize the operational situations likely to be encountered in that time period. The expanded flight regime of the SST places new requirements on the airplane and flight crew. The development of new instruments, displays, and automatic flight modes is a consequence of these requirements. An insight into the piloting problems associated with the SST flight regime provides the basis for an understanding of the instruments and displays which are under development.

Generally speaking, piloting considerations can be categorized into two basic flight operational areas; subsonic and supersonic. The problems in the subsonic area are identical to those being encountered by the subsonic jets today. Supersonic flight operations, however, present unique problems to the airline pilot. The supersonic mode will be treated first.

Supersonic Operations

The operational envelope for the SST is presented in Figure 1 where the flight limits have been defined as a function of Mach number, weight, temperature, and altitude. The data indicate the corridors within which the climb, cruise, and descent phases of flight can be conducted. The dive speeds on the aircraft have been established by the application of an upset-dive recovery requirement, as defined in the United States Tentative Airworthiness Standards for Supersonic Transports. Minimum operating speeds were determined by buffet-free maneuvering up to 1.3 g with normal operating and handling qualities.

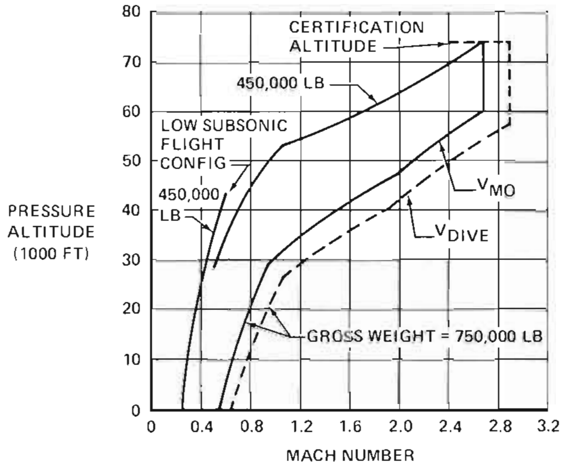

Fig. 1. Operational Envelope

Performance optimization studies on the SST have shown that the most efficient operational procedure to obtain cruise altitude and speed is to climb and accelerate along the maximum operating speed (V_{MO}) placard. To avoid exceeding placards or off optimum climb schedule requires improved climb-speed and altitude control. Since the standard flight parameters of airspeed, Mach number, climb rate, and pitch attitude are continually varying along the V_{MO} placard, the crew workload would be increased during manual flight using conventional aircraft instruments (even the monitoring of automatic flight becomes more difficult). A suitable autopilot mode and/or an adequate computed display is required. Further, Mach number-altitude rate information is desired as well as other energy management displays.

Temperature, wind, and or pressure gradients encountered during cruise tend to disturb the aircraft. With the time lag which exists in today's instrumentation these effects may result in poor manual control of its attitude in pitch and therefore its altitude. Improved instrumentation and displays to overcome this problem include: an order-of-magnitude increase in the pitch scale sensitivity, an autopilot and flight director display, and a sensitive rate-of-climb or flight path display. Note: The capability to hold altitude is partly a sensor problem in the measurement of altitude but recent air data systems have been improved by an order of magnitude.

Speed control during supersonic cruise is required on the SST since the structure has a design stagnation temperature of 500°F. Thus, the supersonic cruise speed limit is a function of both Mach number and temperature as shown in Figure 2. Pitch control of speed is unsatisfactory in that it results in altitude excursions. Therefore, variation in thrust is required to control speed. To prevent an increase in manual work load, autothrottles are desired and have been incorporated in the U.S. SST design. Additionally, limit indicators for V_{MO}, maximum operating temperature (T_{MO}), and maximum operating Mach number (M_{MO}) have been installed on the airspeed display as well as an aural warning of each.

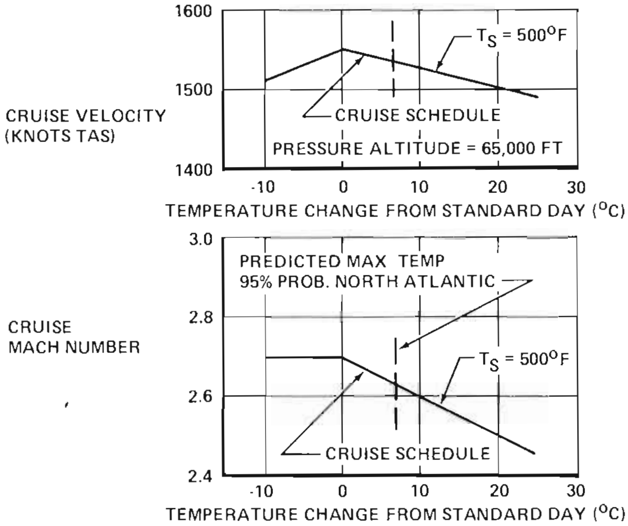

Fig. 2. Cruise Speed and Mach Number

The expanded flight regime of the SST results in an increased movement of the aerodynamic center (a.c.). Since the allowable center-of-gravity (c.g.) is dependent on this a.c. location, it may be inferred that the allowable c.g. position range is also a function of Mach number. The balance and loading characteristics of the SST are such that a standard fuel usage sequence ensures that the airplane c.g. never exceeds the structural or aerodynamic limits during normal operation. The c.g. in the zero-fuel-weight condition (operating empty weight plus payload plus ballast if required) must fall within the landing limits. Similarly, the c.g., in the takeoff-weight condition, must fall within the takeoff limits. Weight and c.g. location are determined prior to takeoff and allows fuel transfer to optimize takeoff c.g. location. Fuel transfer is not visualized as being a dispatch item. During flight, current and accurate weight and c.g. control information is desired for fuel management. Additionally, fuel remaining and range information are desired. Monitoring and control of the fuel remaining will ensure that the optimum economical flight profile is followed.

A final operational consideration and one which takes on greater significance with increased flight speed is navigational accuracy. The introduction of inertial navigation systems (INS) has relieved the flight crew of many difficult navigation tasks. However, new procedures in air traffic control will require increased capabilities of the aircraft and its crew in performing the required guidance and navigation functions. Precise enroute and terminal area positioning is desired. This is discussed more fully in the next section.

Subsonic or Terminal Operations

Flight in the terminal area results in the area of most concern in the subsonic flight regime. Safety, environment, and economics are all involved and are, to a great extent, interrelated. The most necessary improvements are:

(1) Improved Automatic Approach and Landing Systems for Safety
(2) Visibility Enhancement for All Weather Operations
(3) Air Traffic Management Techniques for Congestion Relief
(4) Pilot Aids for Safe Noise Abatement Procedures

Improved Autoland - The SST will have the benefit of an extensive research and development program to improve the safety, reliability and utility of the Automatic Flight Control System in the approach and landing mode. Redundant flight control equipment and use of combined inertial and radio data to provide smooth "fail operative" autoland capability with maximum immunity from ground system failures and beam anomalies is being developed and has already been test flown in the 707 prototype. This is one of the essential elements for all weather operation and improves operating safety, particularly in heavy gust or wind shear conditions and when the ILS beam quality is below that desired.

Visibility Enhancement - The second problem associated with the approach and landing phase is the lack of visual information available during low visibility landings. Achievement of air travel's full potential, with safety and reliability, requires that the existing dependency on weather conditions be reduced if not eliminated. In the case of poor visibility, "real world" information is needed during the last stages of the landing. Boeing has an active research program for visibility enhancement, in which both sensitive TV and microwave perspective radar are candidate sensors. When combined with appropriate flight data symbology the system is called an "ILM" or Independent Landing Monitor. The same techniques may be useful for taxi guidance.

Air Traffic Management and Noise Reduction - Since the U.S. SST will be flying in the late 1970's and on, it was necessary to take a look ahead and attempt to visualize the operational situations and problems likely to be encountered in that time period. Knowledge of the current problems along with traffic growth predictions and introduction of V/STOL and VTOL aircraft rapidly leads one to the conclusion that air traffic management is high on the current list of U.S. national priorities. The Federal Aviation Agency (FAA) states in its "R&D Plan to Increase Airport and Airway System Capacity" (May, 1970) as follows: "A critical imbalance exists between the forecast demand for air transportation service and the system capacity. The result is increasing congestion, delay, inconvenience, and a potentially unacceptable level of safety. Immediate R&D action is required to reverse this trend. This has been recognized by many, including recent Congressional reports, the Air Transport Association Air Traffic Control Systems Planning Group report, and the Secretary of Transportation, Air Traffic Control Advisory Committee (ATCAC) recommendations."

"The system to be improved must be considered in the broadest sense, including not only airways and airports but extending beyond airport and airspace boundaries into financial, legal, community, international and other aspects. The goal of increasing capacity to levels forecasted for the 1980 to 1995 period requires a carefully planned and aggressive development program to assure timely completion and adequate performance levels of the end product. The nature of this plan, therefore, is to develop hardware under a total system management concept which will preplan the total program and continually assess adequacy, making necessary adjustments until completion."

Obviously the SST must fit in the air traffic system of the 1980's and on. In order to predict the requirements of that time period, studies of the various possible improvements have been conducted. The studies result in at least one general conclusion, i.e., the aircraft must be able to be accurately and precisely controlled, positionally, in the airspace throughout the entire flight and especially in the terminal area. Again to borrow from the FAA R&D Plan - "The proposed use of closer-spaced parallel runways, closer-spaced buildings to the runways, multi-taxiways, higher density of aircraft, and the flexible and/or curved approach and departure paths has indicated that the performance of the present (approach system) will be inadequate under these more restrictive environmental conditions. A new approach and landing system is necessary to achieve the more accurate guidance required and to minimize the site sensitivity at the larger and higher density airports."

Another general conclusion that appears valid is that the basic concept of how we operate, the ground rules, that are at the heart of the air traffic management problem must be re-examined. We have in the past operated with the "first come, first served" concept. "First come" means arrival into the area under the jurisdiction of the enroute or terminal traffic controller. Consequently, 80 or more airplanes can individually plan to land on a given runway in one hour whereas the runway's known saturation rate may be 40-50 airplanes per hour. This results in uneconomical and irritating delays. "First come, first served" should mean that the first to request or plan a landing (or takeoff) is served and operations beyond the capacity of the airport are not permitted. This would allow airplanes to operate efficiently (and safely) and also clearly point up the need for more facilities, runways, etc. The reservation concept is used in many other walks of life and actually improves freedom and efficiency of participants. Of course, in order to make the above concept work the aircraft must operate with more predictability and precision than in the past, i.e., must demonstrate capability to make good on their reservations. This capability defines the airborne and ground system equipment requirements.

Next, we observe that the ground controller has gradually taken over the task of navigating the airliners so that he can manage their arrival sequencing, a necessary function. His instructions are verbal to the pilot in relation to track during enroute, and a flight planned air speed is agreed upon. However, in the terminal area where the runway acceptance rate is controlled and affected, the instructions to the many aircraft and their compliance produce an input-output system with considerably poorer response characteristics than desirable from an air traffic management viewpoint. The runway use efficiency suffers as a consequence. It is possible to improve the present system considerably by making it possible for the ground controller to instruct the pilot to follow a specific track and flight path angle with a waypoint arrival time and let the pilot manage his navigation and speed control to accomplish the desired result. The control loop is much tighter if the airliner captain can see the position and speed error relative to a ground controllers desired situation and then take immediate and appropriate action. Again, to borrow from the FAA R&D Plan, - "One goal identified by ATCAC is to increase the capacity of air traffic control sectors by three times."

Capacity in the present air traffic control capability is constrained by the inherent capabilities of human controllers within the active air traffic control loop. Consequently, the sensitivity and capacity limitations imposed on air traffic services must be reduced by minimizing dependence on the controllers in the loop. To achieve the needed increase in capacity and lower sensitivity to the human element, many manual control functions must be automated, such as conflict prediction and resolution, and sequencing and spacing of arrivals. The role of the controller thus should change to that of monitoring the air situation and inserting supervisory system control inputs. The use of presently available navigation systems and computer aided monitoring and prediction techniques both on the ground and in the airplane can result in a much more precise air traffic control with much less ground controller workload. The possibility of backing this up with an effective proximity warning airborne system seems worth considering as a fail-safe feature.

Just as solutions to runway capacity needs require that both the ground and airborne systems be considered as part of a total system, the noise requirements can best be met by a total system approach also. Again to borrow from the FAA R&D Plan, - "Noise and air pollution are a growing problem in all types of community activities, including the airport. Reduction of this problem from the aviation standpoint requires improvements in land use, the aircraft engines and in the airspace and ground control systems. Some reductions in noise and pollution appear feasible with the use of improved aircraft power plants. Use of more flexible navigation and ATC systems for approach, landing and departure is necessary to reduce the noise and pollution effects on populated ground areas around the airport."

One of the most fruitful areas for reducing noise over populated ground areas around the airport is the use of appropriate information displays and automatic equipment to aid the pilot in flying other than the "standard" approach and departure profiles. Most of the emphasis, to date, has been on engine suppressors and aerodynamic improvements and these will certainly continue. However, it is possible for the airplane to be safely flown with considerably less noise than the standard methods produce if the pilot is given the necessary tools. The use of steeper approach paths, decelerating approaches, and curved approach and departure paths would be much more acceptable to the pilot if he had the necessary displays and automatic modes. Obviously the ground controller must have a compatible display to adequately monitor the particular approach path being used. Boeing has performed flight tests using closed circuit T.V., control wheel steering, direct lift systems, flight path angle, and ground track auto-pilot modes. Out of these tests considerable knowledge was gained as to which elements were significant as aids to help the pilot do a safe and precise airplane management job, while reducing the noise level.

The flight management system in the U.S. SST, which could apply to any future transport airplane, draws heavily on this experience and is designed to be compatible with the expected improvements in air traffic management and noise reduction techniques. The displays and automatic flight control systems are being tested in Boeing simulators and in the -80 prototype 707 research airplane. Basically, the equipment is designed to make it possible for the pilot without ground aids other than current VOR's, DME, etc., to very accurately position the airplane and control its speed and flight path angle according to either an advance plan or current instructions. It should then be possible as traffic density increases to resolve most of the conflicts and traffic problems, hopefully, even before takeoff. This is a logical computer application also, since it is "looking" into an organized, planned operation. This could lead to all aircraft being on hard flight plans (IFR) in congested terminal corridor areas. The airplanes equipped with such sophisticated guidance and control systems would use less airspace making more available for the unequipped.

The flight management system to be provided in the U.S. SST is described on the following pages. Extensive use is made of CRT technology because of the flexibility and adaptability of the electronic displays to the information requirements.

We have suggested some ways in which this equipment may be used to benefit air traffic management. It is important to note, however, that this equipment is justified by its on-board utility in any traffic environment and will not depend on any particular ATC technique for its hardware development. Adaptation for additional functions is made primarily by computer software modifications.

III. Advanced Instruments and Displays

Increased complexity of flight operations was inferred in the previous discussion on piloting problems. Solutions were indicated which will relieve the problems with proper implementation. The primary functional role of the crew is undergoing a metamorphosis from one of direct control actuation to the more "passive" one of system management. Thus, the development of new controls, instruments, displays, and cockpit procedures must be based on the integration of man and the aircraft's systems. The interface between man and machine must be such that the optimum utilization of man's capability as a decision maker is achieved.

In the past, the manual control of the aircraft required that the pilot be able to predict the reaction of the aircraft to any control wheel input. This involves considerable mental prediction and, with more complex aircraft, increases the mental "processing" time required to implement and verify the proper control response. The application of predictive displays will provide the level of anticipation required to reduce the mental processing time and the possibility of errors. In addition, it will increase the overall aircraft flexibility from an operational viewpoint (with its inherent improvement in economics).

The instruments, displays, and controls which are under current development for the U.S. SST are presented in the following paragraphs. Their basic concepts have been verified in a special facility devoted primarily to SST studies. Included in this facility are a complex of computers and simulator cabs. Figure 3 is an interior view of the U.S. SST Developmental Simulator Cab showing the three major new displays and the new panel mounted controller.

Since this simulator is used primarily for concept development, the arrangement of the instrument panel is quite flexible at this time. However, every attempt is made to maintain the most up to date arrangement to enable both company and airline pilots to fly the simulator. This assures that pilot comments, desires, and requirements are integrated into the basic engineering design at the earliest time. Figure 4 is a schematic of the proposed flight deck as it has evolved to date, and Figure 5 is a schematic of the pilot's main panel.

Electronic Attitude Director Indicator (EADI)

The EADI consists of a cathode-ray-tube indicator, an electronic symbol generator, a mode control panel, and a forward/downward-looking television camera mounted on the underside of the fuselage. The symbol generator receives signals from several sensors, computers, and the television camera, processes these signals, and generates a composite of the video scene and the symbology on the indicator. The symbology is in register with the pictorial scene (i.e.,

Fig. 3. SST Developmental Simulator Cab

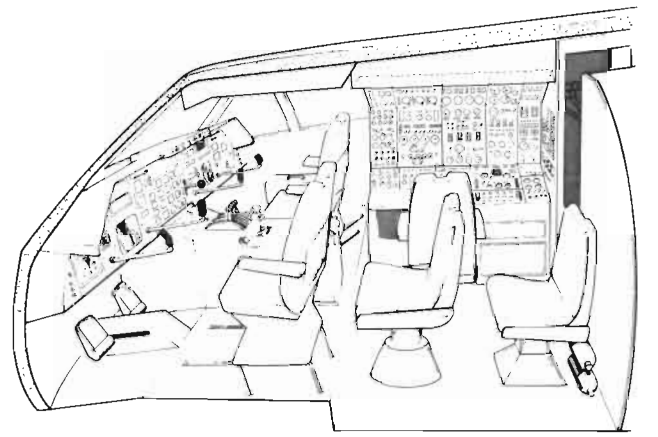

Fig. 4. Flight Deck Arrangement

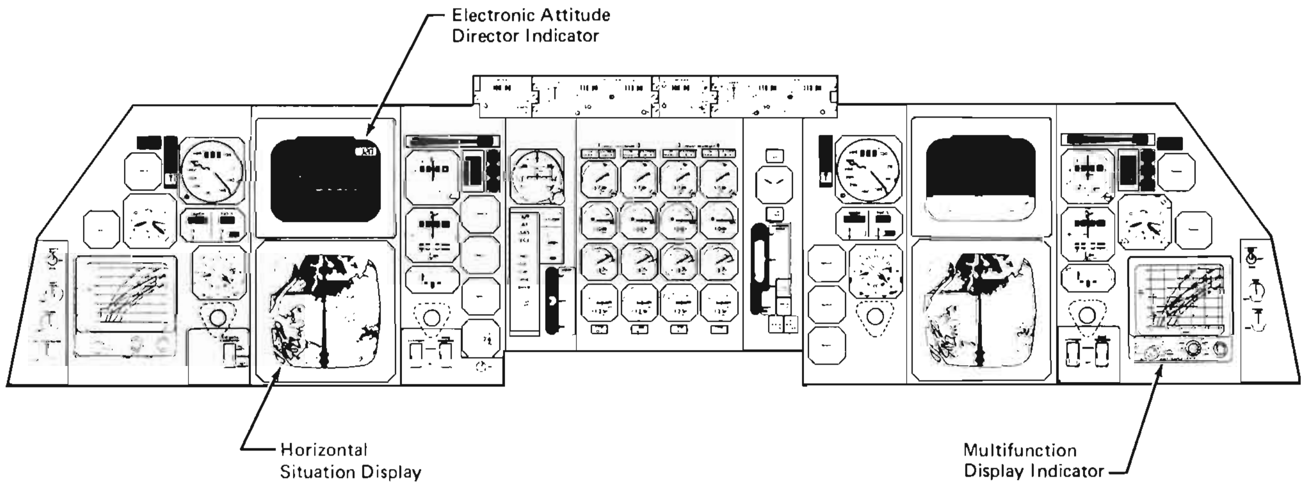

Fig. 5. Pilot's Main Panel

the artificial horizon overlays the real televised horizon.) The EADI format is shown in Figure 6. The display functions are described below:

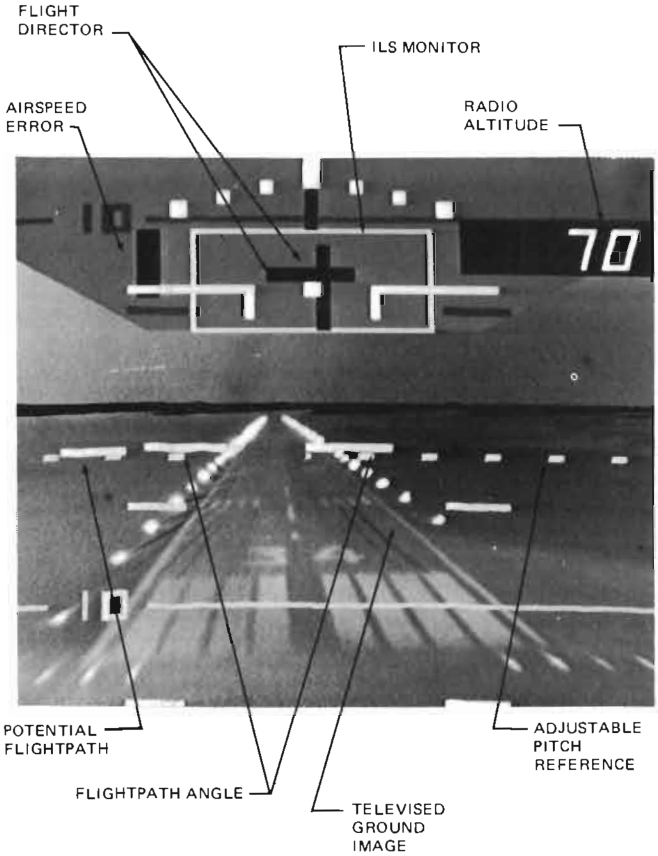

Fig. 6. Electronic Attitude Director Indicator Format

- Attitude–The artificial horizon is a line dividing the dark (ground) and light (sky) shadings of the display. Pitch reference lines move in coordination with the artificial horizon, with major divisions every 10 degrees and minor divisions every 2 degrees. A roll pointer at the top of the display face indicates the roll angle by its alignment with the indices immediately above the screen. These indices denote 0, ±10, ±20, and ±30 degrees of the roll angle.

- Flight director–The flight director command bars are also similar to those found on conventional ADI's. The bars are read against the center dot of the airplane symbol, so that if the pitch director bar is above, fly-up is commanded, and if the roll director bar is to the right, bank-right is commanded.

- Airspeed error–Deviation from a desired or reference airspeed is indicated by a bar that grows out of the left wing of the airplane on the display. If the bar is above the wing, the actual airspeed is higher than desired; conversely, if the bar is below the wing, the actual airspeed is lower than desired.

- Radio altitude--Digits in the upper right-hand corner indicate landing gear height above the surface in 10-foot increments above 100 feet up to 2,000 feet and in 2-foot increments below 100 feet.

- Flightpath angle–A long horizontal bar is used to indicate the velocity vector of the aircraft, relative to the horizon. This is in a sense more important than pitch angle due to the wide variation in angle of attack. This symbol and the flight path acceleration symbol are the most unique and productive features to be incorporated in the EADI.

- Potential flightpath–To the left of the flightpath-angle bar is a short horizontal bar that responds to acceleration of the aircraft along the flightpath as influenced by changes in thrust or drag.

  To better understand the utilization of this symbol and that of the flight path angle, consider the approximate equation for the flight path, as defined in Figure 7.

$$\frac{T-D}{W} = \gamma + \frac{\dot{V}}{g}$$

where

T	=	thrust
D	=	drag
W	=	weight
γ	=	flight path angle
V	=	speed
g	=	32.2 feet/sec^2

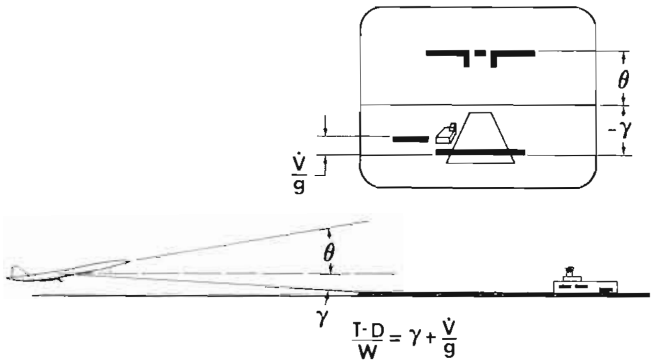

Fig. 7. Flight Path Acceleration and Angle Symbols

The first term on the right hand side drives the flight path angle symbol relative to the horizon, and the second term drives the acceleration symbol relative to the angle symbol. Thus, if there is a positive acceleration, the location of that symbol on the EADI indicates the approximate flight path angle that can be maintained if the thrust is held constant and the acceleration reduced to zero. The combined use of these two symbols relative to the horizon line in noise abatement climbs, level-off maneuvers, and approaches represents how the proper choice of display information in a specific format can materially ease the pilot's tasks.

- Instrument landing system (ILS) symbol–An open rectangular symbol is provided for the ILS and is driven by glide slope and localizer data. If the airplane is on the glide slope, the airplane symbol is centered vertically in the rectangular symbol. Lateral motion of the ILS symbol corresponds to deviations from the localizer beam.

Under instrument landing conditions, the televised ground image signal is replaced by signals from an all-weather sensor system (such as radar or runway beacon signals). The combining of the horizon symbol and pitch reference lines with the visual scene results in a format similar to that of a heads-up display.

This instrument has been under development for several years at Boeing and is near operational status. Two commercial companies have built prototypes and these are under test. Development was undertaken to solve a number of the piloting problems previously mentioned: pitch display sensitivity, low visibility landing capability, accurate vertical path guidance during visual approach and landing conditions, noise abatement procedures, and finally, taxi guidance.

Pictorial Navigation Display (PND)

Area navigation systems are now being introduced on subsonic jets. The digital computers of these systems determine present position from the best available sensor data such as: visual omni range (VOR), distance measuring equipment (DME), inertial sensor system (ISS) or the INS, air data, compass system, or Doppler and other navigation systems. Their primary function is to compute range and bearing to selected points which, in turn, permits flying direct routes by removing the constraints of airway operations. The installation of area navigation systems reduces the computer requirements of the critical Automatic Flight Control System (AFCS) by: providing the required data rates for the AFCS; removing non-essential data conditioning functions from the AFCS; and providing Mach number-altitude display capability, thus reducing computer requirements of multifunction displays. Additional benefits of the area navigation systems include the provisions for: world wide magnetic heading; vertical navigation capability, wind velocity and direction data, and pictorial navigation display capabilities.

The latter display is under development to allow the flight crew to perform the primary navigation function in a manual mode or to serve a monitoring and control function during automatic guidance. The desired display will provide a fully integrated display of all navigational data and of information pertinent to the total navigation task. It will decrease the crew workload while enhancing their capability to both plan and fly optimum routes. The present concept is based on a moving map type of presentation with three basic candidates for the map display. These are: film projection which provides complex chart capability and color; cathode-ray tube (CRT) which offers flexibility and greater variety of dynamic symbology; and a combination of the two into a rear-projection CRT. The PND shown in Figure 3 is of the latter type, though it can simulate any of the three. Regardless of which map display is utilized, when used in conjunction with an Area Navigation System, the display will present the planned route and the aircraft position relative to that route. In those geographical areas without Area Navigation aids, the display would present the aircraft position relative to radio facilities and airport structure.

An all-cathode-ray tube PND concept is shown in Figure 8. This instrument is presently in use at Boeing in developmental activity to determine PND information requirements, display formats,

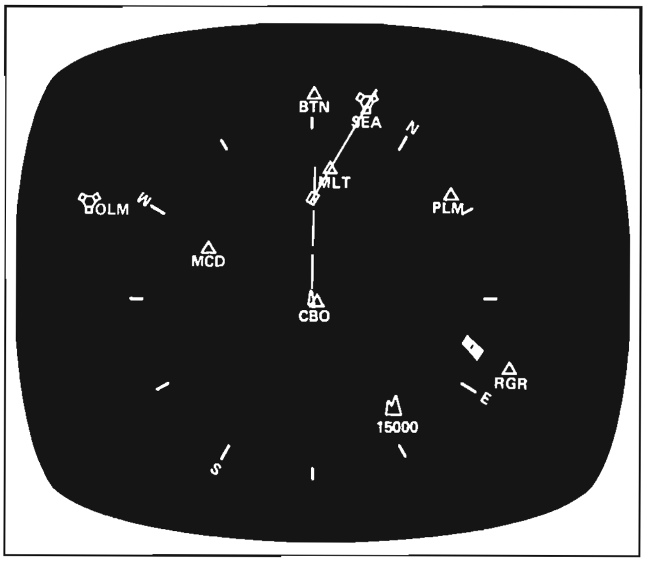

Fig. 8. Pictorial Navigation Display

and hardware techniques. Experiments to date have utilized the Multi-Function Display (MFD) CRT, shown in Figure 3, with all the symbology stored in the programmable digital display generator system. The format shown in Figure 8 is in an aircraft centered/track-up mode. The features of this concept include the depiction of terrain information of importance to the flight (the mountain symbol with its height is Mt. Rainier in this figure) and the indication of the navigation facilities which are available and are in use. The desired ground track is shown by the solid line, which in this case is an extension of the centerline of runway 34 at Seattle-Tacoma International Airport, Seattle, Washington, USA. The predicted ground track is indicated by the dashed lines, the length of which vary with ground speed. The predicted ground track in this figure is shown for a time period of three minutes, each dash being equivalent to one minute of flight time. The rectangle on the desired ground track is a moving time block, representing the desired position of the aircraft as a function of time. This time feature will be discussed in a later paragraph.

Multi-Function Display (MFD)

The Multi-Function Display is a general-purpose, time-shared, electro-optical (CRT) instrument capable of presenting various types of flight operations and systems information. The display will be driven by an onboard general purpose digital computer and is capable of presenting graphic, symbolic, and alpha-numeric data. A mode control panel allows the flight crew to select the desired functional mode. Thus the MFD provides an add-on capability to perform data handling and display functions which are not provided by conventional aircraft instruments. The result is improved crew monitoring and management of subsystem operation. That the MFD is truly multi-functional, consider the following partial list:

- Mach number/Altitude–This mode presents in a graphical format the climb and descent placards as a function of altitude, Mach number, and gross weight. The optimum climb and descent speed schedules are also presented together with the instantaneous aircraft situation. Predictive information is shown for the immediate future by means of a trend vector. An example of

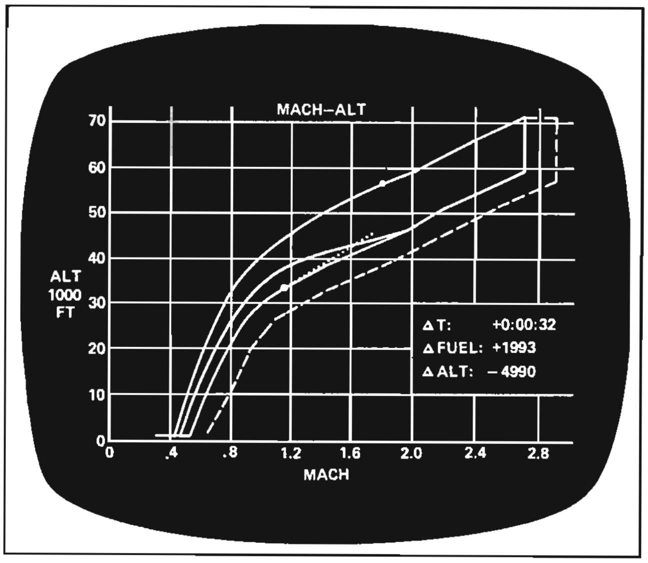

Fig. 9. Multi-Function Display in the Mach- Altitude Mode

this mode is shown on Figure 9 where the dashed line is the V_{DIVE} placard, the lower and middle solid lines are the V_{MO} placards for different gross weights, and the upper solid line is a normal descent profile for the planned descent gross weight. The instantaneous aircraft situation is depicted by the circle while the trend is the series of dots. In this example, the trend vector represents a time period of three minutes (15 second spacing of the dots) and indicates to the pilot the aircraft's situation during this time period if there is no control, thrust, or configuration changes. The near term effects of a change would indicate to the pilot the exceedance of limits or deviation from the desired profile prior to occurrence, thus providing time for corrective action. In non-accelerating level flight, the trend vector reduces to a single dot in the center of the circle. The digital data in the lower right-hand corner are the deviations from the stored flight plan. Expanded scale factors, with their greater accuracy, are a feature of the MFD. Figure 10 illustrates this using a magnification of five times that shown in Figure 9. Note: The data in Figure 10 are representative of a time subsequent to that shown in Figure 9. To avoid losing the airplane symbol during scale changes, the display has been developed with the symbol fixed in the center of the screen and providing for grid and profile movement as altitude and Mach number vary during the flight.

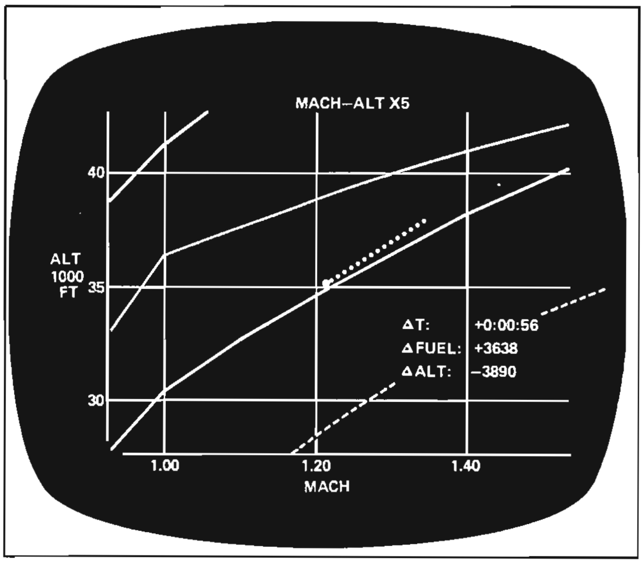

Fig. 10. Expanded Scale of the Mach-Altitude Mode

- Fuel Management Mode–Economic and safety considerations require that information regarding the fuel situation be available to the crew. Since this information is of the type normally required only at finite intervals during the flight, its'display is a logical candidate for the MFD on a time-shared basis. A typical display of this mode could be as shown in Figure 11. It presents a fuel versus range curve with the aircraft situation and trend information relative to the fuel schedule. Sub-modes could be provided for enroute phases, planning of alternate routes, and holding. An example of the latter is shown in Figure 12, where the aircraft is in a holding position 65 miles out and has 17 minutes of holding capability left. This particular situation requires that the aricraft arrive at its destination with 18,000 pounds of fuel remaining.

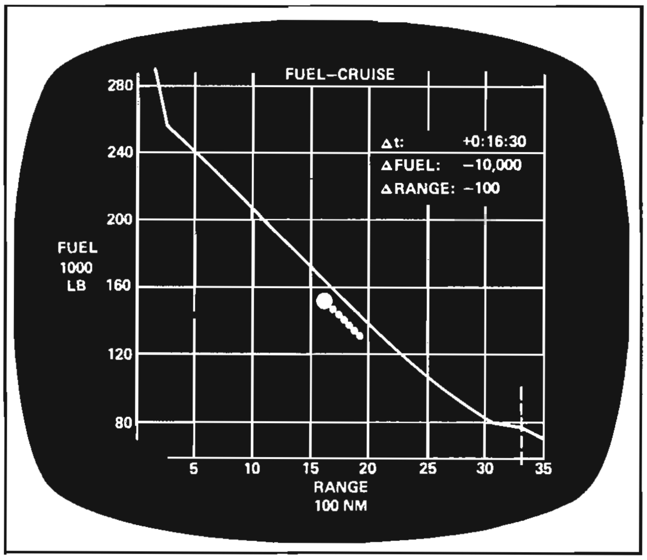

Fig. 11. Multi-Function Display in the Fuel Management Mode

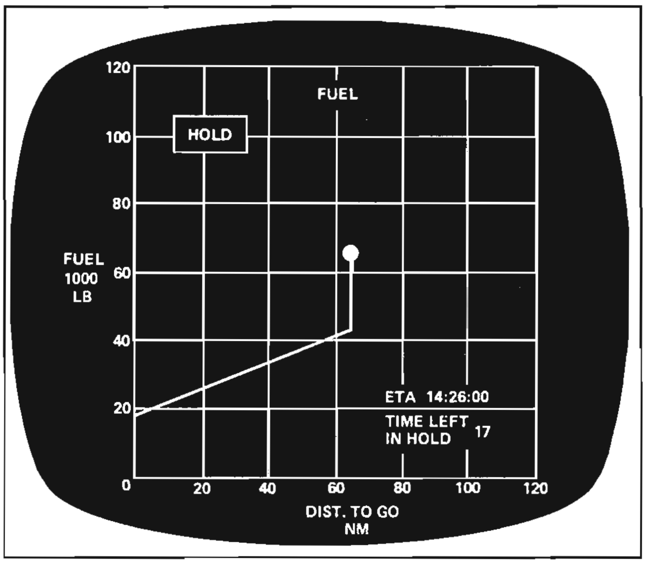

Fig. 12. Multi-Function Display in the Holding Sub-Mode

- Center-of-Gravity–This display mode, shown in Figure 13, presents current C.G. location and the corresponding forward and aft limits as they vary with Mach number. This time-shared display mode would be utilized as an aid in determining the requirement for fuel transfer for optimum trimmed flight and as a monitoring and control function.

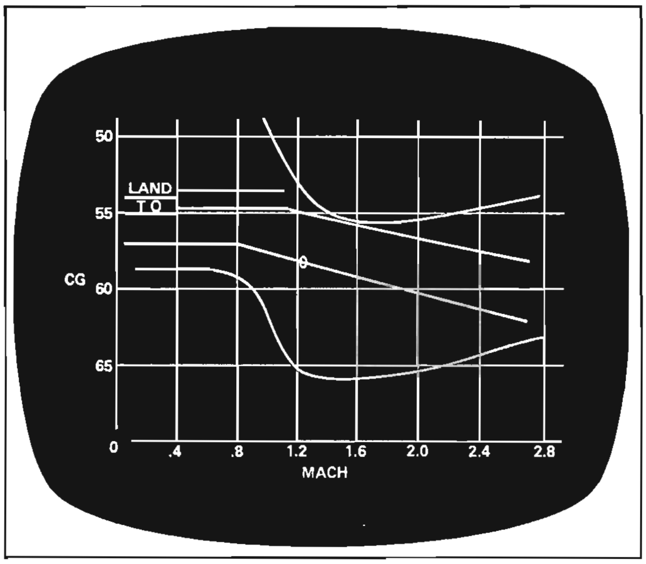

Fig. 13. Multi-Function Display in the Center-of-Gravity Position Mode

- Vertical navigation–In this mode, the MFD would depict the required profiles in graphical form, with aircraft situation (current) and trend information shown relative to the desired path and/or constraints.

- Checklist data–An alpha-numeric format with automatic checklist data, combined with failure detector systems. Display would indicate the fault and available courses for corrective action.

- Emergency procedures–An alpha-numeric format with checklists for emergency procedures. Under emergency conditions, this mode would be activated automatically and override other modes.

- Flight plan data–A format which would display waypoint lists and other flight plan data as stored for the guidance and navigation system.

- Special sensors--A display of special sensor output data; such as television and radar.

- Data link--An alpha-numeric format for data link messages with recall from storage provisions.

- Special data functions--A display for the Flight Engineer depicting time histories and trends of certain key system parameters.

- Mode control and system status data--A display, utilized during automatic Flight management, showing the various combinations of system operations available to the crew.

The above operational modes are but a few of the many which could be displayed on the MFD. Which ones will be incorporated on the SST, in what format, and even the consideration of separate MFD for each crew member are the items under development at Boeing.

Panel Mounted Controllers

Incorporation of the large format displays, discussed above, in the SST flight deck has required the development of a new primary controller. Advanced, primary displays presented a challenge to the instrument panel designer in their requirements for location and visibility. From the human factors viewpoint, these displays exhibit little flexibility in location. Removal of the control wheel and column, used in the current commercial jet transports, offered the potential of increased prime visibility area on the instrument panel. This potential has been realized with the development of the Panel Mounted Controllers shown in Figure 3.

The dual shafts are mechanically connected behind the panel to rotate together for roll control. Pitch control is produced by fore-and-aft movements of the shafts which slide through the panel. Two other features of this controller are the similarity in feel to the standard wheel and retaining of the conventional electro-mechanical control system (as opposed to a totally electronic system).

Integrated Mode Control and Data Entry

This input system permits logical selection of both display and automatic system modes. It insures that mode selection is compatible with the display formats, thus minimizing the time required to determine desired modes and their implementation. Data entry in this system is accomplished using a keyboard system below the Pictorial Navigation Display, as shown in Figure 3. This system is under study at this time to determine the required design features.

IV. Evolutionary Considerations

Air traffic volume has increased to the point of saturation at several of the major hub areas of the world. The predicted increase in the air travel market and its subsequent traffic requirements will cause this situation to spread to other terminals unless positive steps are undertaken to improve the efficiency of the total air transportation system. This includes airports, airways, airplanes, and the ground transportation segment. While the latter is certainly equal in importance from the passenger's viewpoint, its inclusion is beyond the intent of this paper.

Improvements have and are being made in each of the three other segments. Automation of air traffic control, expansion of existing terminals and facilities, and construction of new airports are areas covered by the United States "Aviation Facilities and Improvement Bill of 1969." Advances in airplane automatic flight controls and displays, such as have been discussed for the SST, are also undergoing continous and rapid development. These developments represent significant improvements in safety and operational efficiency. A systems approach, which considers the interaction between the various segments, must be synthesized for the optimum development of the total system. Knowledge of the functional (if not the hardware) features of the desired system is required from two standpoints; to insure that the final hardware will be useful for extended periods of time and to provide a building-block approach for system development. In this manner, the system may be developed in various segments which will be phased-in as they become operational.

Since the aim of air transportation is to provide economical and safe travel between two points in a scheduled minimum amount of time, it follows that the final system must provide the aircraft with the capability to fly between two points in the shortest and quickest time, regardless of weather conditions. This implies both precision navigation and all-weather landing capabilities. Precision navigation is here considered to be the continuous position measurement of the aircraft in longitude, latitude, altitude, and time.

The introduction of area navigation systems are the first step towards a precision navigation system. It has removed the requirement to fly over the normal airways and greatly reduced the dependency on the operational status of the ground based navigational aids. Improved navigation accuracy will be achieved, during the second step, by combining inertial and radio navigation sensor data using the Kolman filtering technique. The on-board digital computer will provide the data and filtering process required. This method provides a position estimate several times better than that obtained from Visual Omni Range/Distance Measuring Equipment (VOR/DME) navigation aids. The third, and possible final, step will introduce navigation sensor data obtained from satellite communications and navigation systems. In the final system, horizontal position (longitude and latitude) should be known, at all times, to an accuracy of less than ± 300 feet. In a similar manner, the altitude must be determined to an accuracy of less than ± 500 feet.

The benefits of increased navigation precision are reduced en-route separation and off airways operation. The resulting increase in air traffic capacity is obvious. Less obvious are the improvements in the terminal area of flight and airport utilization. By positioning landing aircraft precisely in time, space, and speed on final approach, a higher landing rate can be achieved and the holding pattern reduced or eliminated. The final goal should be to increase the landing rate, under Instrument Flight Rules (IFR), to the point where wake turbulence or evasion space requirements become the restricting factors.

Initial experiments of a time-synchronized approach control concept (1, 2) have utilized the MFD equipment (under development for the SST) as a PND. Figures 14 through 16 are sequential photographs taken during a piloted simulated approach to the Seattle-Tacoma International airport. In Figure 14, the airplane is situated south and east of Seattle towards Mt. Rainier (depicted at the bottom of the screen and showing its height). The display is in the aircraft-centered track-up mode with the predicted ground track shown via the dashed lines (which vary with ground speed). Each dash in the predicted track line represents one minute of flight. Other data shown are various way points, compass information, and a solid line representing the extension of the centerline of runway 34. The rectangle, on the extended centerline, is a moving time block representing the required position of the aircraft as a function of time. Under the concept of references 1 and 2, it would cross the

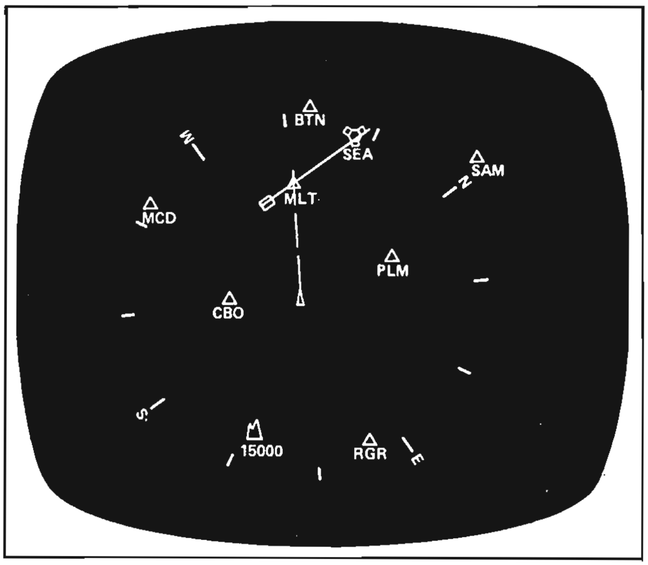

Fig. 14. Pictorial Navigation Display - Prior to Capture Maneuver

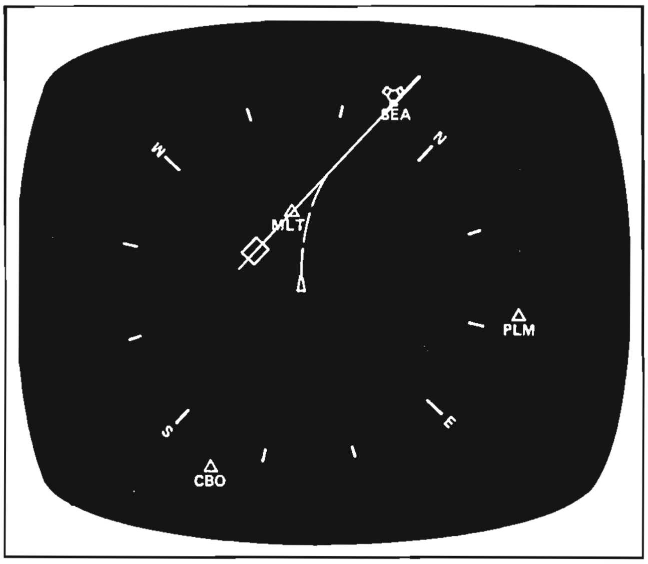

Fig. 15. Pictorial Navigation Display - During Capture Maneuver

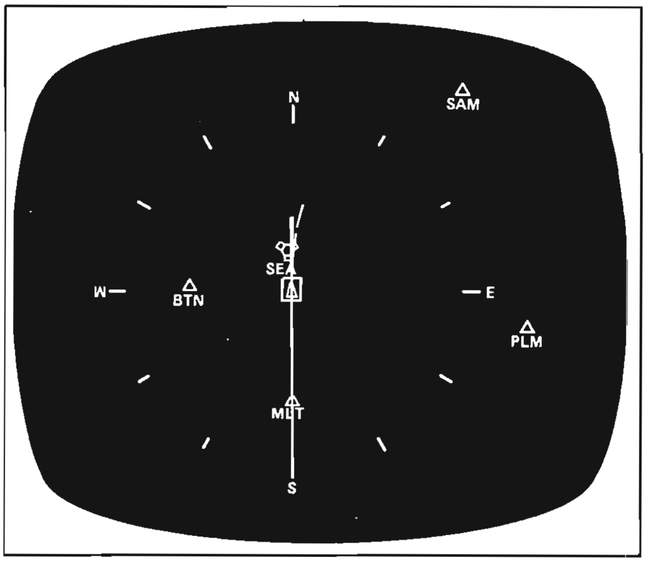

Fig. 16. Pictorial Navigation Display- After Capture Maneuver

threshold at the pre-determined landing time. Figures 15 and 16, using expanded scales for more precise maneuvering, indicate how the pilot utilizes the predicted path to insure that the existing bank angle is correct to capture the desired path and time block. Once the pilot has obtained the desired path and is in the time block and is close to the runway, the approach would be completed using the EADI, as discussed earlier.

The flexibility of the PND and its digital computer is indicated in Figure 17. In this format, the airplane symbol moves while the north direction is held fixed at the top center of the display. This figure shows the aircraft currently on a downward leg, in a right turn, and with the appropriate bank for capture. This type of format might prove to be more useful to the pilot for planning purposes.

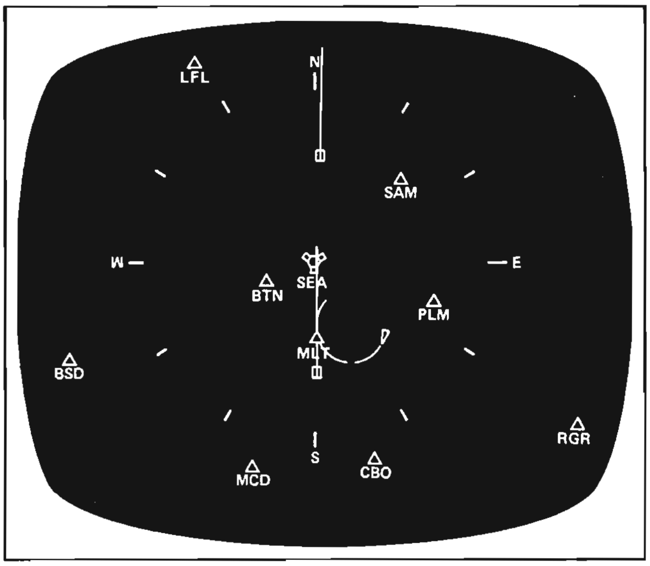

Fig. 17. Pictorial Navigation Display - North-Up Mode

For those desiring further or more detailed information on some of these displays and concepts, the reference list provides a cross section of papers prepared at Boeing.

V. Economical Aspects

The development of the advanced instrumentation displays, the automated equipment, and improved traffic control coupled with all-weather landing capability will assure the U.S. SST of operational capability leading to economical operation. The economics of and indeed all aspects of the United States SST program have been subjected to continual assessment by the government administration, by the Congress, and in the public press. A detailed economic analysis was presented in the April 1970 issue of Aeronautics and Astronautics. (3)

The assessment program utilized at that time for the SST is reproduced in Figure 18. Two basic assumptions which were employed in the earlier evaluations have since been subjected to more comprehensive analyses. They are the route structure and load factor preference values. The former was assumed to be the same as today's route structure for the 26 airlines holding delivery positions for the U.S. SST (this route structure incorporated some 150 city pairs), and did not allow for potential growth. The second assumption was that the SST's would exhibit a load factor preference, over the wide-body subsonics, similar to that enjoyed by the first generation jets over the piston aircraft. Another factor in the original assessment was that the aircraft's maximum payload was 298 passengers and had a maximum range of 3540 n.mi. The latest (current study in progress) evaluation incorporates data developed on a dynamic route structure and new load factor values. The results will allow a reassessment of the operations and economics of the SST to verify, or if required, modify the desired payload-range capability of the U.S. SST.

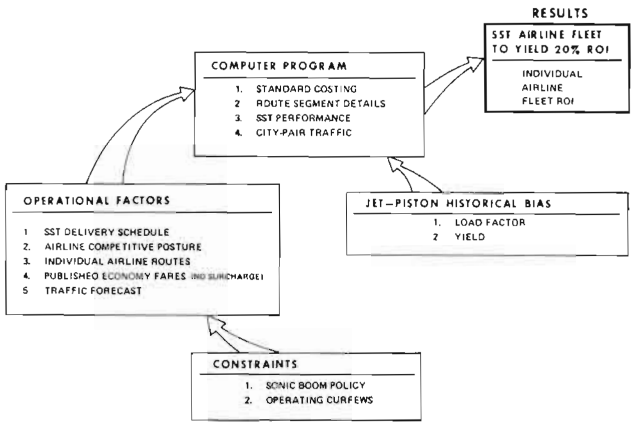

Fig. 18. SST Operational Assessment Program

Route Structure

The current route structure has resulted in a funneling of passengers through a limited number of international gateways. Feeder flights are required to carry passengers to and from these gateways resulting in the current heavy air traffic congestion and multi-stop routing for the passenger between his actual origin and destination points. The inevitable increase in air traffic will compound these problems unless new routes segments are introduced into the existing network. This is exactly what is occurring (in the United States domestic travel) with the introduction of the new satellite airport concept. Similar evolutionary trends are expected to occur in the intercontinental route structure. Since the SST will be flown (starting in 1978) on this evolving network, a study was undertaken to determine the dynamic characteristics of the network. The growth in air traffic, coupled with the demands for origin-to-destination (O-D) travel, were the basic factors used in determining when and where a new segment was required in the network. As traffic between any two centers (cities) reached a value of 1,000 passengers a week, it was assumed that an airline might profitably provide direct non-stop service between these centers. This service then constituted a new segment in the point-to-point airline route structure.

The initial step in this study was to forecast the "non-communist bloc" intercontinental air traffic, on a year-by-year basis through 1990, utilizing recent historical traffic trends, environmental, and economic factors. The results are shown in Figure 19 in terms of revenue passenger miles (RPMs). The data were developed using a declining growth rate (characteristic of a maturing industry) which approaches the predicted level of the "non-communist bloc" real Gross National Product (GNP) growth rate toward the end of the century.

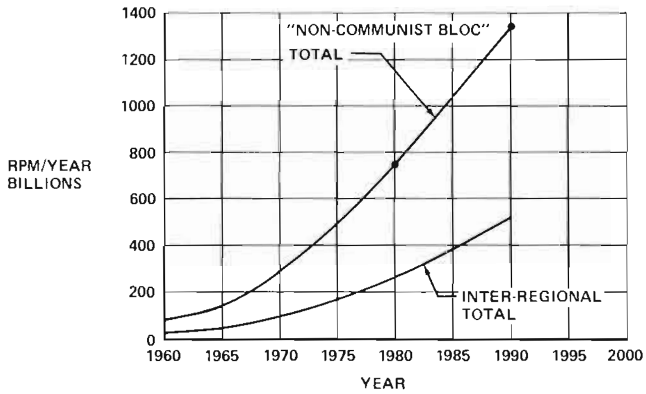

Fig. 19. Air Traffic Forecast

The data in Figure 19 represent the total market and as such do not provide an insight into specific O-D travel demands. This requires that the total traffic be distributed, in some manner, to the lowest possible level. The first distribution was based on a natural division of the world into fourteen basic geographical regions, as shown in Table I. Twelve of these are "non-communist bloc" regions and encompass the forecasted intercontinental air traffic. Interconnection of these regions in all possible combinations results in 66 regional pairs between which travel may occur.

Table I. World Regions

REGION	COUNTRIES
A	NORTH ASIA (EAST RUSSIA AND CHINA)
B	HAWAII
C	CANADA
D	UNITED STATES (INCLUDING ALASKA)
E	CENTRAL AMERICA
F	SOUTH AMERICA
G	WESTERN EUROPE
H	AFRICA (EXCLUDING U.A.R.)
I	SOUTH ASIA (INDIA, PAKISTAN, BURMA, AND THAILAND)
J	MIDDLE EAST (INCLUDING U.A.R.)
K	OCEANIA
L	EASTERN EUROPE
M	SOUTHEAST ASIA
O	FAR EAST

The distribution of air traffic between the regional pairs (inter-regional traffic movement) was based on a prediction technique which considers historical traffic data and regional GNP forecasts. The traffic data were obtained from the Official Airline Guide, Quick Reference Edition. The results of this first distribution show that of the 66 possible regional pairs, 39 account for substantially all (99+%) of the forecasted traffic in 1990. Figure 20 presents the traffic growth of the top ten regional pairs. Note that just these ten pairs account for 75% of the total inter-regional RPMs in 1990.

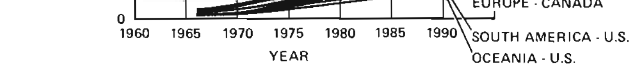

Fig. 20. Inter-Regional Traffic Forecasts - Top Ten Regional Pairs

The distribution of the traffic within each region was then accomplished by dividing the major regions into sub-regions and allocating to each of these a number of passengers based on one or more of the following: passport data, Immigration and Naturalization Service statistics, or to the volume of import-export reported between regions. The final distribution was to select cities, within these sub-regions, as representative centers and allocate traffic based on the population each center represents. The U.S. was divided into ten regions with 43 representative centers. The remainder of the "non-communist bloc" was divided by countries with a total of 80 representative centers. These 123 representative centers (or major hubs) may be combined into some 5,000 possible route segments.

The output of the study is the traffic flow, in passengers per week, for each of these possible route segments for each year

Table II. Origin to Destination Air Travel Demand In 1985
(United States to Europe)

	NEW YORK	PHILADELPHIA	BOSTON	PITTSBURGH	NEWARK	BUFFALO	CHICAGO	ROCHESTER	HARTFORD	PROVIDENCE
LONOON	10,858	4,463	3,047	2,260	1,772	1,259	5,058	781	741	697
MANCHESTER	12,313	5,061	3,455	2,563	2,009	1,428	5,735	886	840	791
GLASGOW	2,603	1,070	730	542	425	302	1,121	187	178	167
DUBLIN	2,211	909	620	460	361	256	1,030	159	151	142
PARIS	4,801	1,974	1,347	999	783	557	2,236	346	328	308
ROME	4,008	1,647	1,125	834	654	465	1,867	288	273	257
FRANKFURT	6,877	2,827	1,930	1,431	1,122	797	3,203	495	469	442
HAMBURG	2,909	1,196	816	606	475	337	1,355	209	198	187
MUNICH	2,386	981	669	497	389	277	1,111	172	163	153
AMSTERDAM	4,200	1,726	1,179	874	685	487	1,956	302	286	270

(EXAMPLE)

NOTE: NUMBERS ARE PASSENGERS PER WEEK

through 1990. A typical output for some representative city pairs (between the U.S. and Europe) is shown in Table II for the year 1985. The numbers in the matrix are the passengers per week between the given city-pair. Once this number reaches 1,000 passengers per week, the corresponding city-pair is added to the network. An example of how this dynamic network evolves is presented in Figures 21 and 22. Traffic from eight cities in the U.S. is destined for Europe. Since in the first year (1978) the traffic allocation reveals less than 1,000 passengers per week between any of these particular cities and Europe, the traffic is routed to New York on feeder flights for reboarding to Europe. This circuitous routing increases the passenger's travel time and adds to the air traffic congestion at New York. (To simplify the figure, the feeder flights from London to other points in Europe have been omitted, except for the one to Frankfurt). In 1985, as shown in Figure 22, the traffic has increased between these cities and Europe to a level which allows direct flights from five of these cities instead of just one. In development of these data, traffic was always routed through the nearest regional center offering non-stop flight.

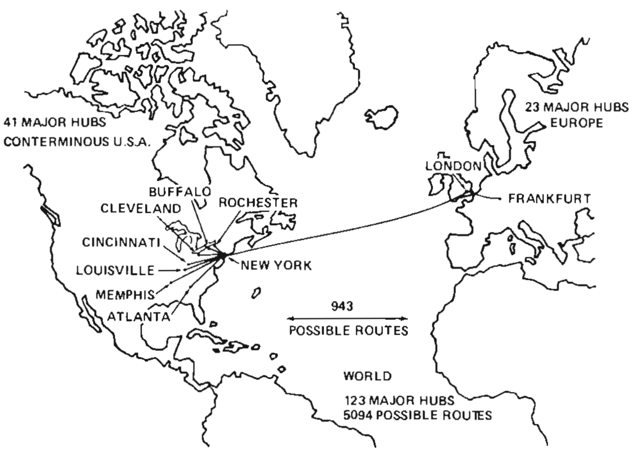

Fig. 21. Example - U.S. to Europe Traffic Flow - 1978

The result of this point-to-point study is the definition of a dynamic intercontinental route structure in terms of city-pairs and the corresponding traffic flow in passengers per week on a year-by-year basis. In 1978, it encompasses some 550 city pairs compared to the approximately 150 city pairs which were used to simulate today's route structure. (3)

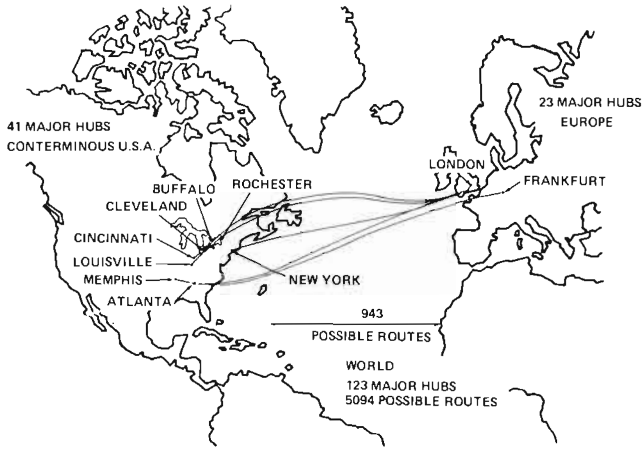

Fig. 22. Example - U.S. to Europe Traffic Flow - 1985

Load Factor

As stated earlier, the previous economic evaluations were based on an assumed load factor advantage for the U.S. SST. Attempts to verify this assumtion have resulted in a better understanding of the various factors which contributed to that advantage. This, in turn, has resulted in the development of an analytical technique for estimating the average load factor for a new airplane type throughout its competitive life cycle. This technique requires, as inputs, a knowledge of the following:

- A total international air traffic forecast
- An airplane replacement schedule
- The number of seats available for each airplane type in the world fleet
- The passengers' preference for a particular airplane type
- The number of passengers that are "turned away" as a function of the average load factor

Passenger response is a quantitative measure of preference in that it is determined by the number of passengers expressing their preference by actual travel on a specific airplane. Passenger preference, on the other hand, is a qualitative measure of how much the average passenger prefers one airplane over another and would like to travel on the preferred aircraft if it were available at a given time, etc. This preference may be obtained, prior to or during introductory operations of a new airplane, via surveys, etc.. However, the response can be obtained only after the airplane has been in service for some period of time. A method is therefore required which relates passenger preference to response. Considerable historical data are available regarding airplane load factors (passenger response) during the era when jet aircraft were being introduced and replacing piston airplanes. These data have been utilized in developing a method which relates passenger preference to passenger response.

Equations have been developed by which load factors may be determined. Figure 23 illustrates the approach used in this development. A simplified airline system of four piston aircraft is to be replaced by four jet aircraft, each having a 100-seat capacity (seats available). A constant market of 200 passengers is assumed to provide an average load factor of 50% on each of the four pistons prior to jet introduction. The question then is how do the load factors vary during the transition period between piston and jet service? Consider Case I, as shown in Figure 23, where the first jet has replaced the first piston airplane, and a passenger response value of 30% has been assumed. From a random distribution consideration each airplane should have 50 passengers. However, the 30% response factor means that 45 piston passengers (30% of 150) would transfer over to the single jet. This would increase the jet load factor to a potential value of 95% and reduce the piston load factors to 35%. However, a subtle factor becomes involved at this point. Airline data reveal that when a high de-

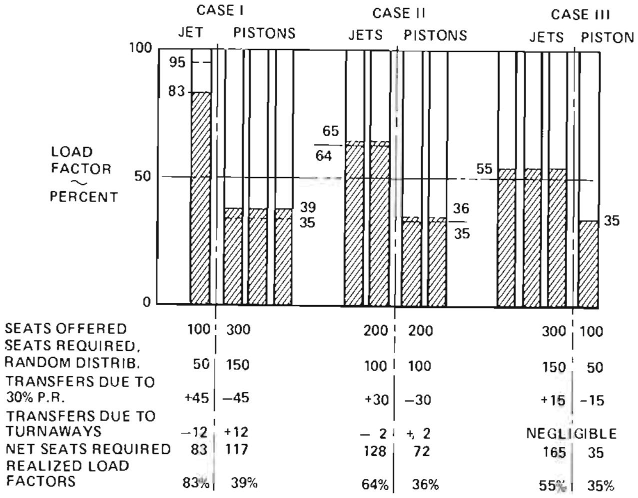

Fig. 23. Example - Loading Distribution with 30% Passenger Response

mand load factor exists, there is a certain number of turnaways associated with it. Thus, in the example of Case I, the 95% potential load factor causes a turnaway of 12 of the 45 passengers trying to board the jet. Therefore, the net transfer of piston passengers over to the jet is 33 and the jet realizes an actual load factor of 83%. The remaining passengers board the piston airplanes to provide an average 39% load factor for the pistons. As the jets continue to replace the piston airplanes, as illustrated in Cases II and III of Figure 23, the transfer of passengers is treated in the same manner considering the same 30% response and the turnaway factors.

Application of the derived load factor equations to historical data resulted in the measurement of an average passenger response factor of 30% for the jets over the piston airplanes. To verify the derived equations and the determined response factor, jet and piston load factors were calculated utilizing only that portion of the historical data which defined the seats offered by the jets and pistons and the total seats required. A typical result is shown in Figure 24. The computed load factors agree with the historical load factor data within an average error of $\pm 2\%$ for that period of time when the piston airplane's market share was being reduced from 80% to only 10%. The same remarkable correlation is also shown in Figure 25 where the abscissa has been changed from calendar year to a jet market penetration index (as measured in terms of the jet seats offered to total seats required ratio.)

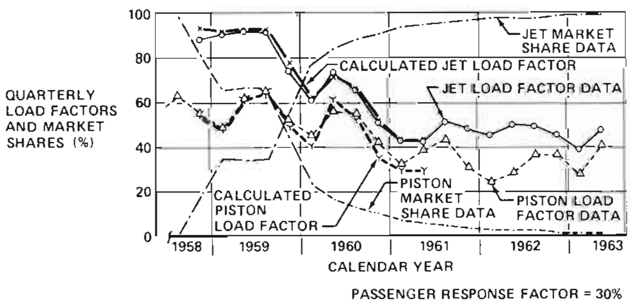

Fig. 24. Load Factor Correlation

The importance of the market penetration index (when used to compute load factors) is that it can provide the replacement schedule required to hold the average load factor, of the airplane fleet being replaced, above the break even value. In fact, a review of the historical load factor data indicates that the airlines achieved very nearly the optimum replacement schedule for the piston aircraft.

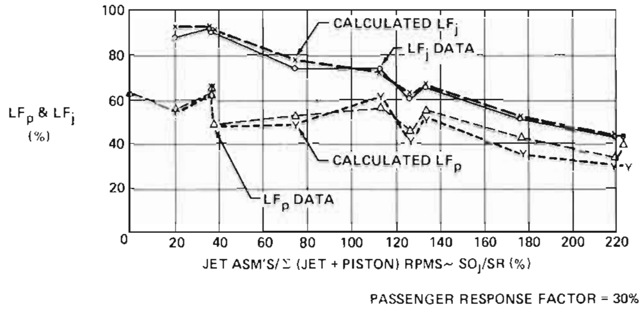

Fig. 25. Market Penetration Effects On Load Factors - North Atlantic

The correlation with historical data has encouraged the projection of passenger response into the future. A calibration of response versus preference was obtained from a rather large personnel survey. Consequently, a survey from was prepared and response curves for subsonic jets, wide-body subsonic jets, and the small and large supersonics determined. These projected passenger responses were used in the competitive economy studies which form the balance of this paper.

Competitive Economics

The economic assessment of the SST which was presented in Reference 3 was based on 1968 dollars and the previously mentioned load factor advantage. Further, the section on escalation considerations was based on an assumed constant load factor of 55% and the data were developed for an assumed average route range of 2500 statute miles. The results of that study, shown here for reference (Figure 26), indicate that the economics of

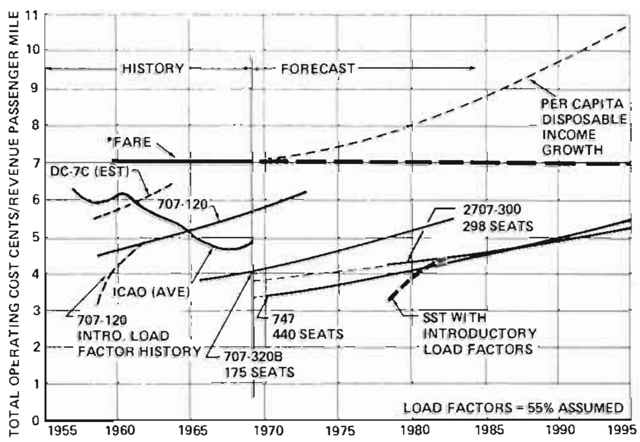

Fig. 26. Total-Operating-Cost Comparison : 1968 Dollars and All-Economy Payloads

the subsonic jet coupled with its high load factors in the early years caused the piston airplanes to be removed from the competition. The study also showed that the U.S. SST, because of its high productivity (available seat miles per hour) and its assumed attractiveness, would compete very successfully with the wide-body jets of the 1980 time period. The latest dynamic economic study was conducted to determine the effects of direct competition between the wide-body subsonic jets (exemplified by the 747), Concorde, and the U.S. SST as each is introduced into airline service. This study incorporates the results of the passenger preference/response effort but does not include the point-to-point route structure inasmuch as that analysis has not been completed at this time. Table III lists the other basic assumptions used in this study.

A delivery schedule and production rate were assumed for each type aircraft. The airplanes were then introduced into the ex-

Table III. Assumptions

PASSENGER RESPONSE	
SST/747	20%
SST/CONCORDE	15%
CONCORDE/747	10%
INTRODUCTION TO AIRLINE SERVICE	
747	1970 @ 8/MONTH (INTERNATIONAL)
CONCORDE	1973 @ 3/MONTH
SST	1978 @ 5/MONTH
SHORT TERM INFLATION	
CURRENT UNION CONTRACTS 1968 - 1971	
LONG TERM INFLATION	
AT 1955 - 1968 AVERAGE RATES	
INTERNATIONAL FUEL PRICES	
ONE HALF PERCENT/YEAR INFLATION	

isting (today's)route structure of each individual airline according to the delivery schedule. The annual intercontinental RPM forecast which was presented in Figure 19 was distributed into monthly route segment traffic which reflects both the seasonal variation of each region and its growth rate. The scheduling of each airline's airplanes was based upon considerations of the inter-airline's competitive positions.

Operating costs were estimated using standard methods of computation. Direct costs were based on the 1967 ATA method while the indirect costs were based on a method developed by Boeing and Lockheed. For this study these costs were adjusted to reflect the yearly inflation rates shown in Table IV. As indicated, the short term rates apply for the years 1968-1971 and reflect the current high values. The longer term rates, for the years 1971-1990, are based on the rate of inflation which has occurred during the last two decades. The load factors were calculated (using the results of the passenger preference/responses study) as a function of the ratio of seats offered to the total seats required.

Table IV. Yearly Inflation Rates

	SHORT TERM (1968 - 1971)	LONG TERM (1971 - 1990)
AIRPLANE PRICE	5%	3%
MATERIAL (SPARES)	5%	0.5%
LABOR	10%	4.5%
FLIGHT CREW	15%	7.5%
CABIN CREW	10%	4.5%
FOOD	12%	4%
FUEL	–	0.5%

Yield is tha actual revenue received per passenger seat mile. Historical data indicate that the initial yield on jet airplanes was approximately equal to the fare, but that as the jets penetrated further into the passenger market, the yields were reduced (through incentive fares such as family fare plans, excursion rates, etc.). To duplicate the historical evidence, current fare levels on each route were used. To determine the future fare structure, a 747 fleet was flown over the route system and the study was iterated to determine a fare structure required to give a suitable Return on Investment while maintaining load factors similar to those required today. The results of this side study are presented in Figure 27. Note that the data shows that holding the current yield values requires an increase in load factor. To reduce these load factors back to the level of to-

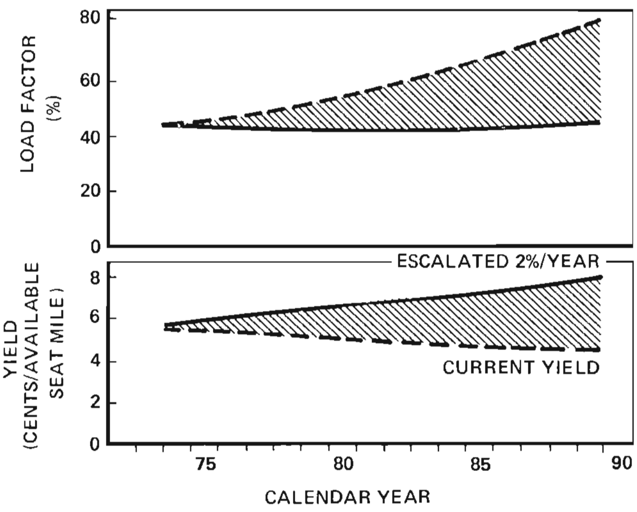

Fig. 27. Projected Yield Trend (Based on 747 ROI = 20%)

day requires about a 2% per year fare increase starting after 1971. In an inflationary cost period it requires a fare increase to hold a constant return on investment, consequently this 2% per year increase was incorporated in the basic study.

The number of aircraft in service on the sonic boom restricted SST routes, as a function of time, is shown in Figure 28. As the U.S. SST is introduced starting in 1978, the Concorde and the wide-body subsonic jets begin to be removed from the system.

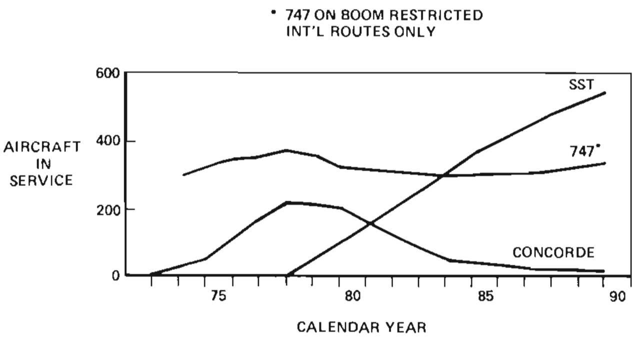

Fig. 28. Competitive Aircraft in Service

As traffic continues to increase over the years, the numbers of U.S. SST's increase substantially, the number of Concordes are reduced while the 747 fleet remains fairly constant.

The competitive load factors of the three airplanes are presented in Figure 29. The Concorde load factor reduces at the beginning

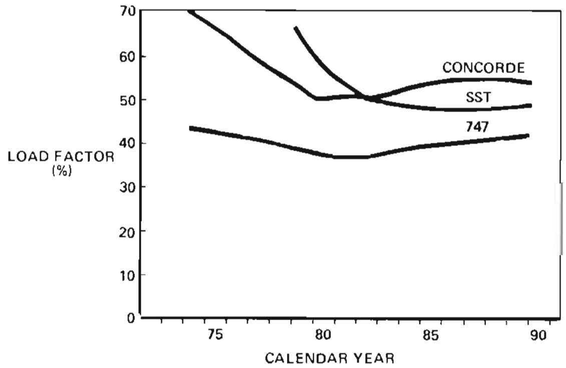

Fig. 29. Competitive Load Factor

due to its increased market penetration. As it approaches its maximum fleet size, its load factor flattens out at around 50% and then exhibits an increase which is attributable to the withdrawal of Concordes as the U.S. SST penetrates the market. The 747 exhibits the expected load factor corresponding to a fixed fleet size. The U.S. SST exhibits the characteristic decline in load factor as it takes over more of the market.

The total operating costs per revenue passenger mile are presented in Figure 30 for the three airplanes. Here again the U.S. SST exhibits a similar advantage over the two competitors to that which was indicated in reference 3. The U.S. SST is simply less sensitive to inflationary pressures because of the high productivity. The ultimate comparison must, as always, be made on a ROI basis. The competitive economic study is finalized by the presentation, in Figure 31, of the ROI's for each airplane.

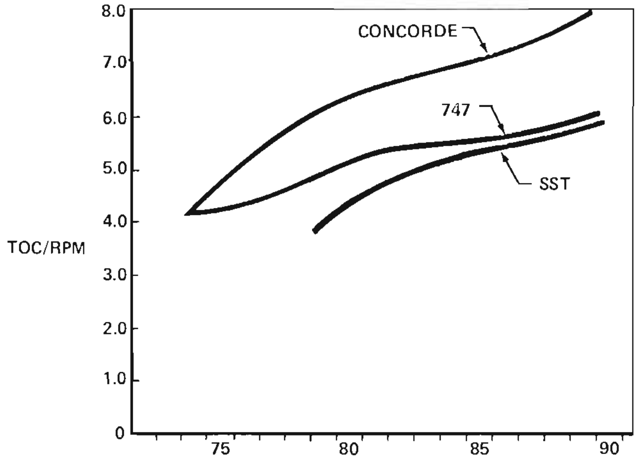

Fig. 30. Competitive Total Operating Cost Per Revenue Passenger Mile

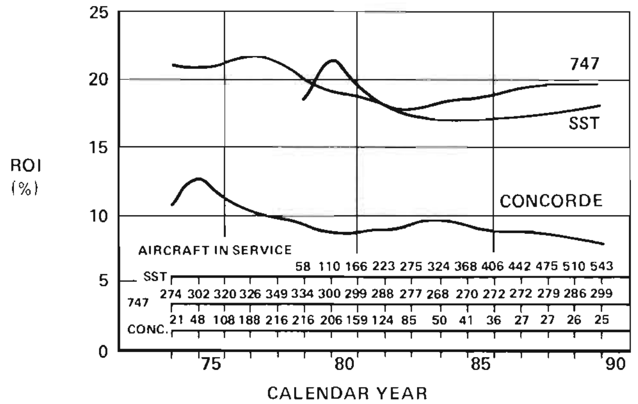

Fig. 31. Competitive Return on Investment

It should be noted that the U.S. SST and the 747 appear very competitive in this dynamic analysis on the sonic boom restricted routes. The reasons for this are that the size of the 747 fleet is being controlled in much the same manner as the piston fleet was being controlled to return a specified amount to the airlines. A review of Figure 19 will show that the passenger market available away from the boom restricted routes is very large and if one adds in the cargo capacity of the 747, there is substantial market available for these very efficient aircraft through the 1980's.

VI. Conclusions

1. The United States SST will have pilot's instrumentation that will enable him to operate with more safety and with a lower workload than is available in today's air transports. These modern instruments will allow an increase in air traffic system capacity.

2. Analysis of the U.S. SST operation on today's route structure has indicated a need to expand the city pairs for the future system. A preliminary look indicates that several new city pairs should have non-stop service in the 1980's. Completion of the analysis should indicate the desired range and payload size for the U.S. SST.

3. There was a substantial passenger preference for the subsonic jet as compared to the piston engine transport. The factors present then, such as one half the flight time, will be available again when the SST's enter the market. These factors are expected to cause a substantial load factor advantage to accrue to the SST when it is introduced into the wide-body subsonic jet system.

4. A dynamic competitive analysis shows that the U.S. SST will take over the market on the sonic boom restricted routes. It will operate at a lower total operating cost in cents per revenue passenger mile than the competition and it will return to the airlines a substantial percentage on their investment.

5. The U.S. SST will be a truly economical product and as a stable-mate to the 747 will offer the airlines and their passengers the finest possible modes of transportation. It will be a part of a world-wide rapid transit system.

References

1. Cook, W. H. and Clifford, D. R., "Evolution of Automatic Flight Control," AIAA Paper No. 68-208, February 1968.

2. Gannett, J. R., "Flight Management Concept," presented at the ALPA Air Safety Forum, Seattle, Washington, July 9-11, 1968.

3. Swihart, J. M., "Our SST and Its Economics," Astronautics and Aeronautics, April 1970, Vol. 8, No. 4, pp 30-51.

4. Price, H. E.; Honsberger, W. D.; Ereneta, W. J., "A Study of Potential Roles of Supersonic Transport Crews and Some Implications for the Flight Deck," NASA CR-561, August 1966.

5. Warner, J. D., "A Fundamental Study of Predictive Display Systems," NASA CR-1274, February 1969.

6. Annin, G. D., "Electronic Attitude Director Indicator Development for the Supersonic Transport," presented at the ISA 16th National Aerospace Instrumentation Symposium, Seattle, Washington, May 11-13, 1970.

7. Warner, J. D., "Advanced Controls and Displays for Future Commercial Aircraft Operations," AIAA Paper No. 70-938, July 1970.