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Summary

Advanced air traffic control (ATC) systems are being developed which contain time-based (four-dimensional) trajectory predictions of aircraft. Airborne flight management systems (FMS) exist or are being developed with similar 4D trajectory-generation capabilities. Differences between the ATC-generated profiles and those generated by the airborne 4D FMS may introduce system problems. Significant design challenges must be addressed to ensure compatibility between future airborne and ground-based systems.

A simulation experiment was conducted to explore integration of a 4D-equipped aircraft into a 4D ATC system. The NASA Langley Transport Systems Research Vehicle (TSRV) cockpit simulator was linked in real time to the NASA Ames Descent Advisor (DA) ATC simulation for this effort. Approximately 30 hours of simulation were conducted with three active airline pilots participating as test subjects at Langley and six active air traffic controllers and one research controller as test subjects at Ames. Candidate procedures for handling 4D-equipped aircraft were devised and traffic scenarios established which required time delays absorbed through speed control alone or in combination with path stretching. Dissimilarities in 4D speed strategies between airborne and ATC-generated trajectories were tested in these scenarios.

The 4D procedures and FMS operation were well received by the airline pilots, who achieved an arrival accuracy at the metering fix indicated by a time error with standard deviation of 2.9 seconds and negligible mean. Further clarity in the time clearance procedures and integration of the time guidance into the airline cockpit were cited as future needs. In addition, the amount and nature of the information transmitted during a time clearance were found to be somewhat of a problem using the voice radio communication channel. In particular, an error in required arrival time entered by the pilot would not be obvious to the controller. Application of a digital data link for transmission of time clearances and restrictions may be required for successful and efficient system operation.

Dissimilarities between airborne and ATC-generated speed strategies were found to be a problem under moderate traffic conditions when most of the traffic remained on established routes. The different cruise speeds of the TSRV (flying FMS-generated speeds) and the other traffic (flying ATC-generated speeds) produced potential in-trail conflicts that required controller intervention. The controller vectoring of aircraft to prevent the in-trail separation violations resulted in significant fuel penalties. An offset route scenario, designed to permit 4D-equipped aircraft to fly dissimilar speeds without being in the trail of other aircraft, also produced greater fuel usage than in-trail scenarios with similar speeds. It therefore appears more efficient for 4D-equipped aircraft to fly trajectories with similar, though less fuel-efficient, speeds which conform to the ATC strategy when traffic conditions require speed control by ATC.

Heavy traffic conditions, where time delays forced off-route path stretching, were found to produce a potential operational benefit of the airborne 4D FMS. For the scenarios tested, the pilots were able to consistently fly controller vectors to absorb time delays using their FMS to decide when to turn back on course. This procedure showed potential for relieving controller work load while improving efficiency. The pilot could minimize the delay range by closely monitoring his own delay situation and determining the earliest opportunity for turning back.

Introduction

Airborne flight management systems have become an integral part of the commercial aircraft cockpit. Flight planning capabilities that include horizontal and vertical path definition for cost efficient operation have become standard on new production aircraft. Some of the newest systems are capable of computing flight profiles with prespecified arrival times at the destination airport, (that is, four-dimensional (4D) navigation). These advanced flight management systems can be retrofitted to several older aircraft as well. Perhaps the major factor inhibiting further growth and acceptance of advanced flight management systems, especially 4D navigation, has been the air traffic control (ATC) restrictions incurred during the critical en route arrival and departure phases of flight (within approximately 100 nautical miles of the airport). Interruptions of programmed flight plans by ATC have prevented full utilization of the flight management system capabilities on current generation aircraft.

The NASA Langley Research Center has been conducting and sponsoring research on flight operations of advanced transport airplanes for a number of years. During the course of this research, operational issues have been a primary concern. One of the areas of this research has been the practical implementation of 4D flight management concepts to permit fuel efficient operations in an en route time-based ATC environment.

The NASA Ames Research Center has recently developed advanced ATC automation concepts that incorporate time-based trajectory predictions of arrival traffic in a graphical display for controller interaction. This research has addressed the trajectory prediction algorithms, automation requirements, and graphical controller interface issues of future time-based ATC operations. One of the major design challenges of this research has been to permit efficient handling of aircraft that are not equipped with flight management systems. Such aircraft must be given heading vectors, speed constraints, and descent instructions computed by the automation algorithms to achieve arrival sequencing and separation.

Aircraft with advanced flight management capabilities present the opportunity to enhance the operation of time-based ATC systems by assisting in the time-sequencing process and relieving the controller of additional speed and descent clearances needed for unequipped aircraft. From the airborne side, the presence of a time-based ATC system provides the opportunity for full utilization of an advanced flight management system to optimize operations within the constraints imposed by the traffic sequencing of ATC. Significant design challenges must be addressed to ensure the compatibility of future airborne and ground-based systems.

The purpose of this experiment was to introduce an airborne flight management system, capable of computing and tracking 4D trajectories, into a 4D ATC system and to explore the issues related to integration and effective operation of the two systems. Of particular interest were the procedural issues of pilot and controller clearances and the technical issue of dissimilarity between the 4D speed strategies from the airborne and ground trajectory-generation techniques. Also addressed were the guidance and display requirements for successful 4D operations in congested en route arrival airspace. This report describes the experiment and results from an airborne perspective. ATC issues and controller-related aspects of the experiment are not discussed in great detail in this report.

Research System

This study was conducted by using a piloted cockpit simulation in conjunction with an air traffic control simulation. The research system was designed to provide a realistic environment for pilot and controller interaction with 4D automation aids. A block diagram of the research system is shown in figure 1. The key components of the system being evaluated were the Transport Systems Research Vehicle (TSRV) cockpit simulator and the Descent Advisor (DA). The icons in the center column represent the system components that create the simulation environment and control the air traffic scenarios. The ovals in the figure represent manned positions with bold ovals referring to test subjects.

The cockpit simulator at NASA Langley Research Center was connected via voice and data lines to the air traffic control (ATC) automation laboratory at NASA Ames Research Center through the NASA Program Support Communications Network (PSCN). The PSCN is a digital network employing both terrestrial and satellite transmission facilities which interconnect NASA Centers. The data link, a dedicated asynchronous 9600-baud data line, provided one-way transmission of the Langley TSRV position information for real-time display on the Ames controller displays. A voice link between the Langley TSRV cockpit and the Ames controller stations permitted ATC voice communication. A second voice link between Langley and Ames research personnel was provided for coordination of the two simulations.

Cockpit Simulator

The cockpit simulator utilized for this study was the fixed-base replica of the research cockpit in the NASA TSRV airplane (ref. 1). This simulation included six-degree-of-freedom equations of motion with nonlinear mathematical models of the Boeing 737-100 airplane aerodynamics and engine performance. The equations were processed by a Control Data Corporation (CDC) CYBER 175 digital computer. Standard day atmospheric effects were included in the simulation with no winds.

The configuration of the TSRV cockpit simulator is shown in figure 2. Electronic primary and navigation displays were provided in an over-and-under arrangement. A control display unit (CDU) was located in front of the pilot just below the navigation display. Two center-mounted electronic displays provided vertical situation and engine information. Manual flight control was handled by a two-axis sidestick controller located to the left of the pilot's seat. A mode control panel on the center glareshield was used for selection of autopilot control modes.

Air Traffic Control Simulation

The ATC simulation is comprised of both the ATC automation aids (controller stations) and the air traffic simulation. The communications manager, center block of figure 1, is the software connection between the ATC controller stations and the various sources of air traffic (simulated radar) data including the TSRV piloted cab and the Ames air traffic simulation. Sun Microsystems, Inc., workstations were used for each controller and pseudo-pilot station. A description of the air traffic simulation and pseudopilot system may be found in reference 2.

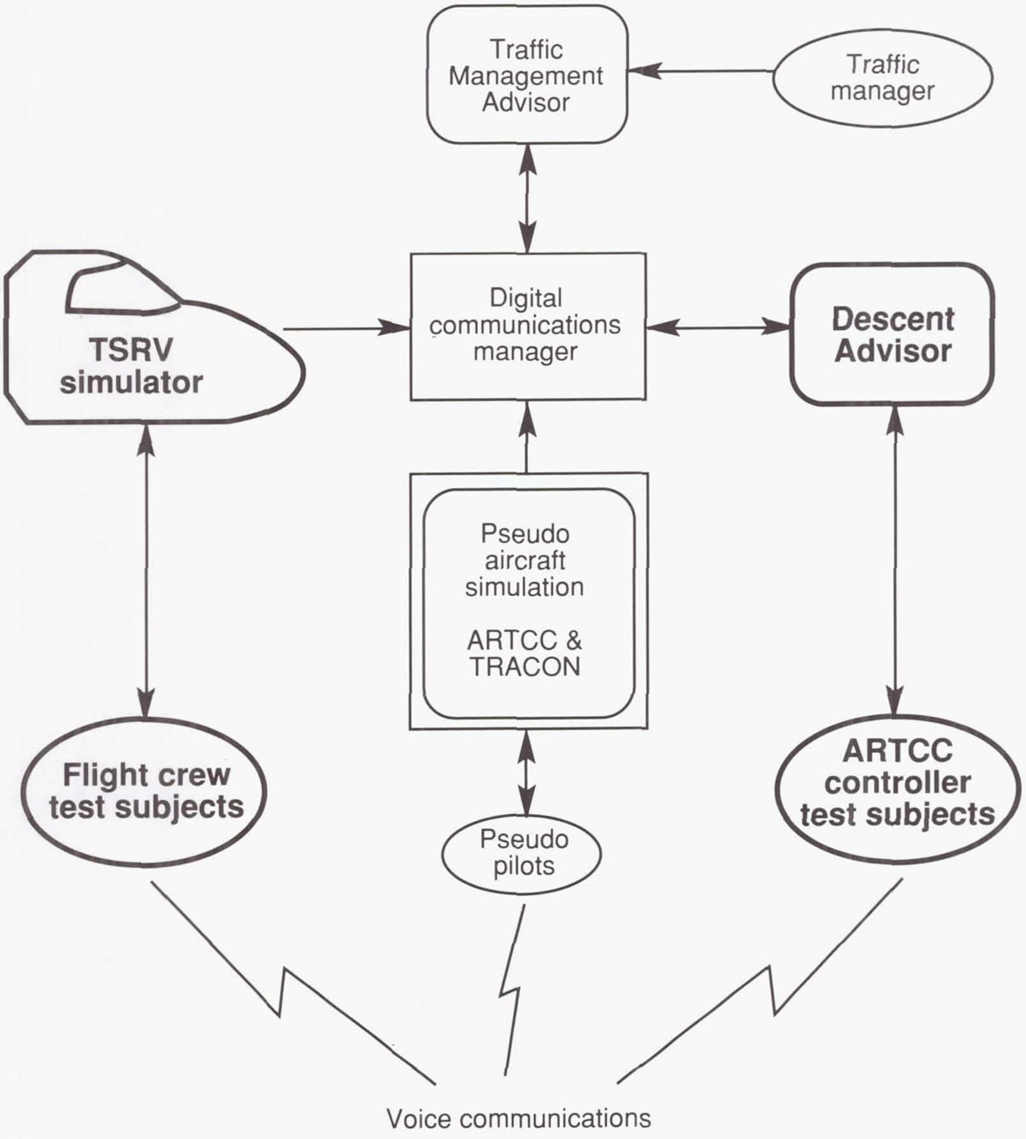

Figure 1. Block diagram of research system.

The configuration of the controller stations is flexible and may include any combination and number of air route traffic control center (ARTCC) or terminal radar approach control (TRACON) sectors. This experiment concentrated on ARTCC arrival operations with the primary ATC automation aid being the DA along with its associated planview display and graphical interface (fig. 3). The Traffic Management Advisor (TMA) was used in a secondary role to assist in the creation and control of the traffic scenarios. These automation aids are described in detail in reference 3.

Experiment Design

Flight Management System

The Langley Transport Systems Research Vehicle (TSRV) simulator was equipped with a fully capable 4D navigation and guidance system during the mid-1970's in support of the Terminal Configured Vehicle (TCV) Program (ref. 1). A schematic diagram of this system is shown in figure 4. The elements of this system consist of (1) the central flight management computer (FMC), (2) airplane system inputs of air data, inertial reference, and engine sensor parameters, (3) flight and thrust control systems, and (4) pilot interface consisting of electronic flight displays, mode control panel, and control display unit (CDU).

While this baseline system was capable of precise 4D navigation and guidance, it did not incorporate performance management features necessary for computation of vertical trajectories. Ground speeds and altitudes were required inputs to each way point in the guidance buffer of the FMC. The baseline system further lacked the flexibility of flight plan generation and modification found in current commercial flight management systems. For this study, the baseline TSRV flight management system was modified to incorporate flexible flight plan generation as well as vertical trajectory computation.

Flight plan definition. The control display units in the TSRV were replaced with the commercially available units currently used in the latest generation of Boeing 737 airplanes. As shown in figure 5, each CDU consisted of a display area with line select keys along the sides of the display, function and mode select keys below, and a complete alphanumeric keypad. A flight plan could be entered by selecting a prestored company route or by individually specifying jet routes and way points. Altitudes and speeds at each way point were not required as inputs to the flight plan. Departure and arrival way points had prespecified airspeed and altitude constraints as part of the navigation data base. Crossing speeds, altitudes, and times for en route way points were computed by the vertical-path-generation program based on a selected cruise altitude and cost index (a pilot-selectable quantity representing a ratio of time and fuel costs). Constraint values of airspeed and altitude could be entered at any way point to override the computed values and force the vertical profile to be recomputed using the constraint values. Further, for one way point an arrival time could be entered to force computation of a 4D vertical profile that satisfied the arrival time constraint. This way point was referred to as the "metering fix," or required time of arrival (RTA), way point.

Vertical path generation. A vertical-profile-generation computer program (PGA4D) was interfaced with the TSRV simulator navigation and guidance routines for this study. The program was designed as a stand-alone utility for developing and analyzing vertical-trajectory-generation techniques. A complete description of this computer program is provided in appendix A.

The horizontal path defined by the flight plan was constructed using the baseline TSRV path definition routines. Vertical profiles were computed for the defined provisional horizontal profile when (1) the pilot pressed the EXECUTE button on the CDU to accept a provisional flight plan, (2) the pilot selected DIRECT TO a way point, enabling the automatic provisional profile update mode, or (3) a special COMPUTE VERTICAL function was selected from the CDU. The computed altitudes, speeds, and times for the way points in the flight plan were then inserted into the provisional guidance buffer of the TSRV simulator upon successful return from the PGA4D program. In addition, a special vertical trajectory array consisting of time, altitude, calibrated airspeed, ground speed, and segment identifier as functions of flight plan range was returned to provide vertical guidance information. This vertical trajectory array provided all necessary discontinuity points in the vertical trajectory, such as top of descent and bottom of descent, which were needed for vertical guidance. The provisional guidance buffer and vertical trajectory array became the active guidance information only when the pilot pressed the EXECUTE button on the CDU.

The way points in the flight plan were categorized as departure, en route, or arrival. Departure and arrival way points were required to have crossing altitudes and airspeeds already defined prior to calling the PGA4D program. The first arrival way point was referred to as the metering fix, for which arrival time could also be specified. These predefined

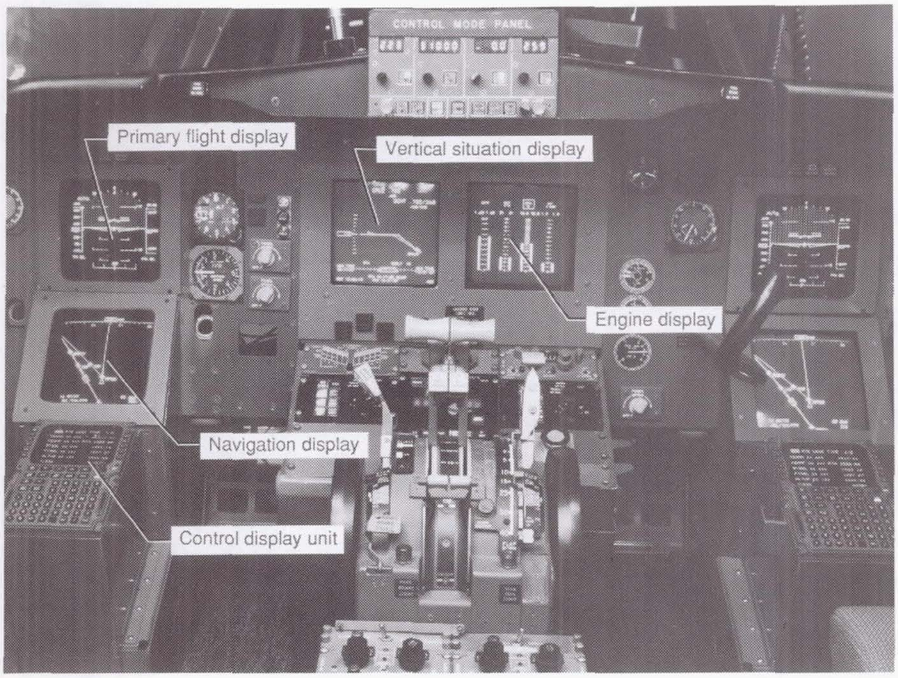

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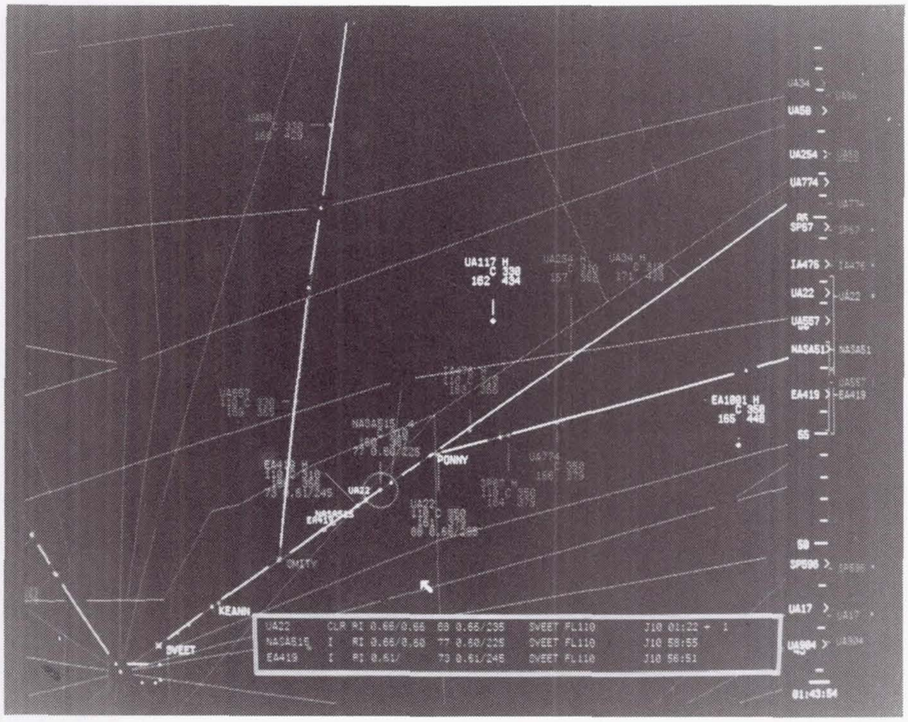
Figure 2. TSRV cockpit simulator.



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UA22      CLR RI 0.66/0.66  80 0.66/235   SWEET FL110      J10 01:22 + 1
NASA515   I   RI 0.66/0.60  77 0.60/225   SWEET FL110      J10 58:55
EA419     I   RI 0.61/      73 0.61/245   SWEET FL110      J10 56:51
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Figure 3. ATC display.

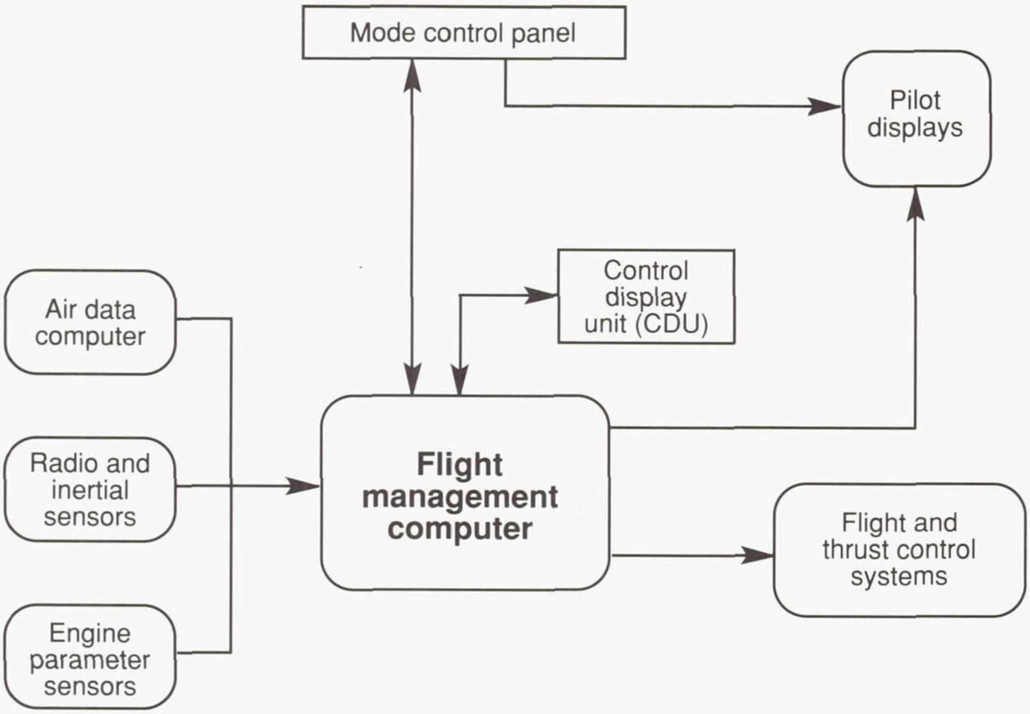


Figure 4. Schematic diagram of TSRV 4D flight management system.

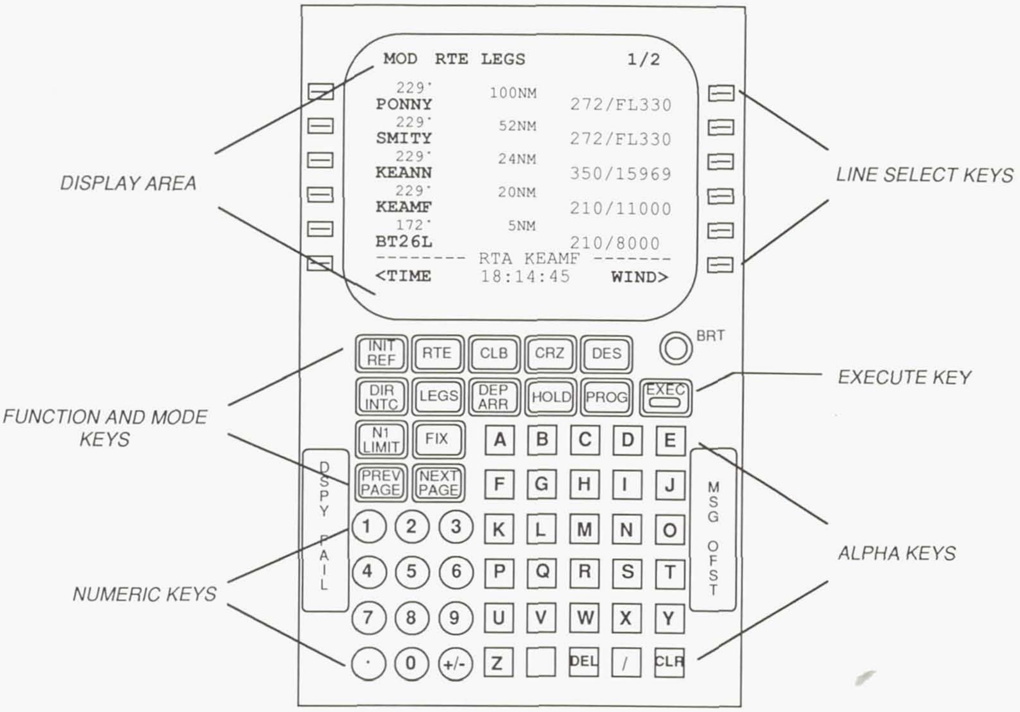


Figure 5. Control display unit (CDU) format in TSRV simulator.

values of crossing altitude, airspeed, and time were passed to the PGA4D program as constraints.

Constraints on the vertical profile were either predefined or entered into the flight plan using the CDU. Typically, a flight plan consisted of a departure airport with a series of way points defined by a standard instrument departure (SID), an arrival airport with a series of standard terminal arrival route (STAR) way points, and a number of en route way points needed for navigation. The SID and STAR way points had predefined constraints on crossing altitudes and calibrated airspeeds, which were included in the navigation data base. The predefined constraint values could by modified by the pilot through CDU inputs. En route way points were unconstrained unless specific altitude or airspeed values were entered by the pilot.

The PGA4D program would compute a climb, cruise, and descent trajectory from the last departure way point (or current range, altitude, and speed if the aircraft had flown past the last departure way point) to the first arrival way point in the flight plan. For the scenarios in this study, the aircraft was already in cruise and did not require a climb segment.

Speed strategy. The vertical trajectories were computed using an empirical performance model of the TSRV airplane. Climbs were computed with a transition from constant calibrated airspeed (CAS) to constant Mach number speed schedules assuming maximum climb thrust. Cruise segments were at constant Mach number and altitude. Descents were programmed with a transition from constant Mach number to constant CAS using idle thrust. For the time-constrained profiles in this study, only the cruise and descent segments were computed. Two techniques for speed schedule selection were utilized. With the first method, speeds that minimized fuel consumption were chosen in a manner similar to commercial flight management systems, while with the second method, speeds were chosen in a manner similar to the ATC Descent Advisor program.

The minimum-fuel 4D speed strategy is an extension of standard 3D vertical trajectory generation. Flight costs are represented by a cost index which is a ratio of time cost and fuel cost. For a given cost index a unique cruise Mach number can be computed which minimizes total flight cost. Similarly, a unique descent speed schedule exists for the chosen cruise Mach number and altitude. A direct relation therefore exists between cost index and flight time. The minimum-cost trajectory that satisfies a specified flight time can be obtained by iterating on cost index. This technique produces a 4D flight trajectory that requires the least amount of fuel to fly.

The speed strategy used by the ATC Descent Advisor is designed to provide consistent final conditions for aircraft delivered to the metering fix. The descent CAS for all aircraft is initially chosen to be 280 knots. Time control is achieved by varying the cruise Mach number of the individual airplanes in order to satisfy the arrival time constraint. Only after the cruise speed has reached a prespecified limit for the particular aircraft type will the descent CAS be varied. This method allows a variety of aircraft types to be merged on final en route descent at a common airspeed for handoff to the terminal area controllers.

Both the minimum-fuel and the ATC Descent Advisor speed strategies were programmed into the TSRV simulation. The strategy to be used was set at the start of a simulation run and could not be changed by the pilot.

Flight Displays

The display system of the TSRV simulator consisted of a primary flight display (PFD), a navigation display (ND), an engine display, and a vertical situation display (VSD). The arrangement of these displays is shown in figure 2. The flight displays were developed for use with the velocity-vector control-wheel steering (VCWS) mode of the simulator. References 4 and 5 describe the design and development of the primary flight display.

Primary displays. The primary flight display and navigation display provided airspeed, altitude, and horizontal guidance information to the pilot. Figures 6 and 7 show the formats of these displays used in this experiment. The guidance philosophy of these displays was to present situation and trend information to the pilot. Corrective actions necessary to null trajectory errors, such as might be provided by a flight director system, were not included as display information.

Altitude, airspeed, and flight-path angle reference values were obtained by range interpolation of the vertical trajectory profile computed by the PGA4D program. These values were displayed on the PFD. The horizontal path of the programmed flight plan was drawn on the ND. In addition, a RANGE/ALTITUDE mode could be selected which would draw an arc on the ND indicating the horizontal range where a selected altitude would be achieved at the current flight-path angle. This mode effectively provided altitude guidance on the map display.

Vertical situation display. Vertical trajectory and time guidance information was presented to the pilot on the VSD in the left center-panel display location (fig. 2). This display was a modification to the VSD developed for the study reported in reference 6.

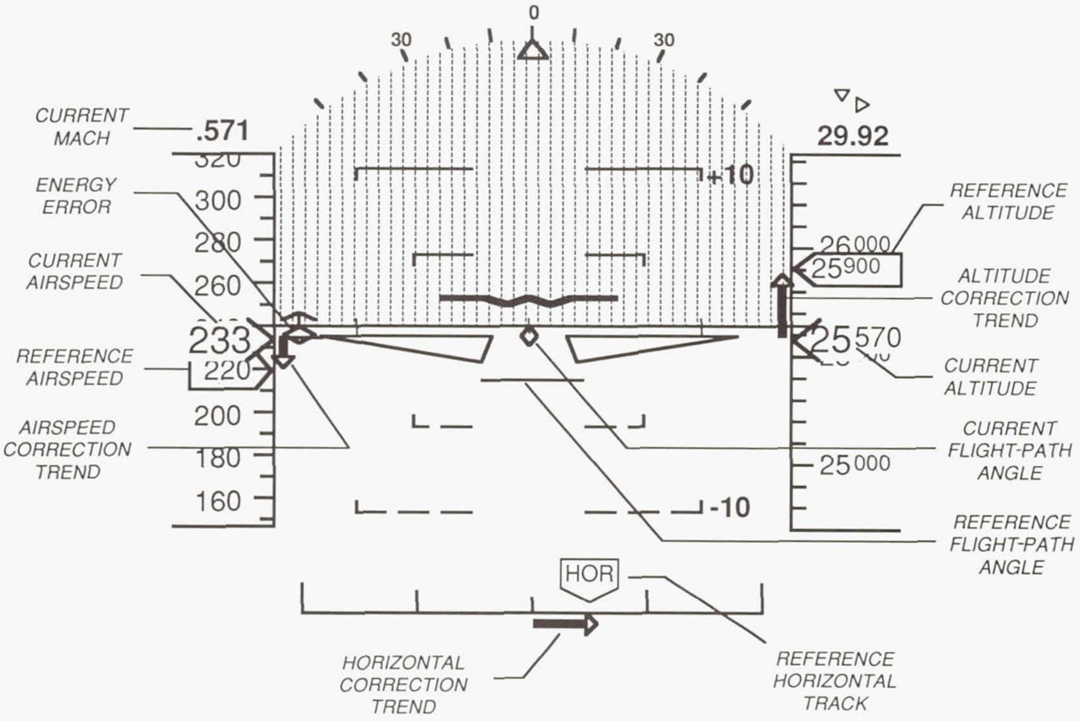


Figure 6. Primary flight display (PFD) format in TSRV simulator.

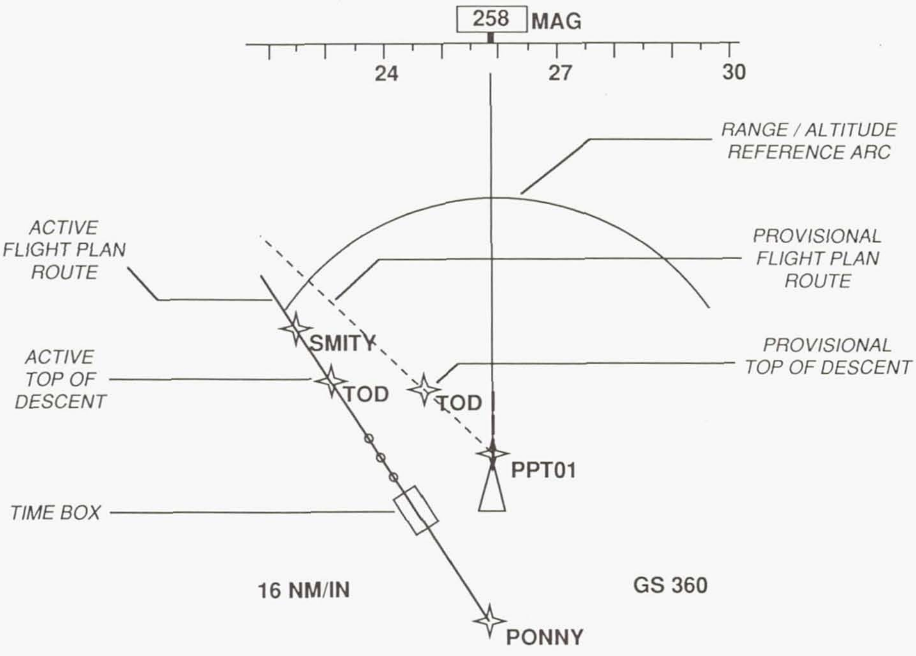


Figure 7. Navigation display (ND) format in TSRV simulator.

Featured on the display was a pictorial side view of the desired vertical flight path and the airplane's relative position. Also provided was information on the current altitude and energy errors, the planned speed schedule, and a window of possible arrival times at the CDU-specified RTA way point. Examples of this display are shown in figure 8. In both parts of the figure the aircraft is at the same time and distance from the metering fix. Figure 8(a) shows the display in active guidance mode with an assigned metering fix arrival time. Figure 8(b) shows the display when a provisional profile to a new metering fix time has been generated but not accepted by the pilot.

The top of the display provided a textual readout of the planned speed schedule for the programmed flight plan. The speeds were divided into climb (CLMB) Mach/CAS on the left, cruise (CRUZ) Mach number in the center, and descent (DCNT) Mach/CAS on the right. The active speed schedule was displayed in large letters to the right of the corresponding label. The color of the labels and active speed schedule was light cyan. If a modification to the flight plan had been made in the CDU and a provisional vertical profile had been computed, the speeds associated with the provisional path were displayed in small amber numbers immediately below the corresponding active speeds, as shown in figure 8(b). Once a flight phase had been completed, the flight phase label and associated speed schedule were deleted.

The vertical profile was an altitude versus distance plot of the desired flight profile. The distance scale (horizontal) corresponded to the map scale on the navigation display. The altitude-to-distance scaling ratio was 500 feet per nautical mile. As a result, the display did not present a true geometric representation of the vertical flight path. One degree of actual flight-path angle would appear as approximately 12 degrees of displayed flight-path angle.

The vertical profile associated with the active flight plan was displayed in white as a solid line. If a provisional flight path had been computed, the provisional vertical profile was displayed as an amber dashed line. The profile(s) moved on the display from right to left relative to the fixed aircraft symbol.

The bottom portion of the display provided arrival time information at the selected RTA way point. This information consisted of a time line with required and estimated arrival times at the selected way point as well as a window of possible arrival times shown both digitally and graphically.

The time line consisted of a blue horizontal line with vertical tick marks spaced 1 minute apart. The length of the time line and number of tick marks remained constant for this study. Superimposed on the time line was a white box (also called time window) indicating the range of possible arrival times from current aircraft position along the programmed flight plan to the RTA way point. The ends of this box corresponded to maximum and minimum arrival times, which were provided digitally to the right and left of the time line.

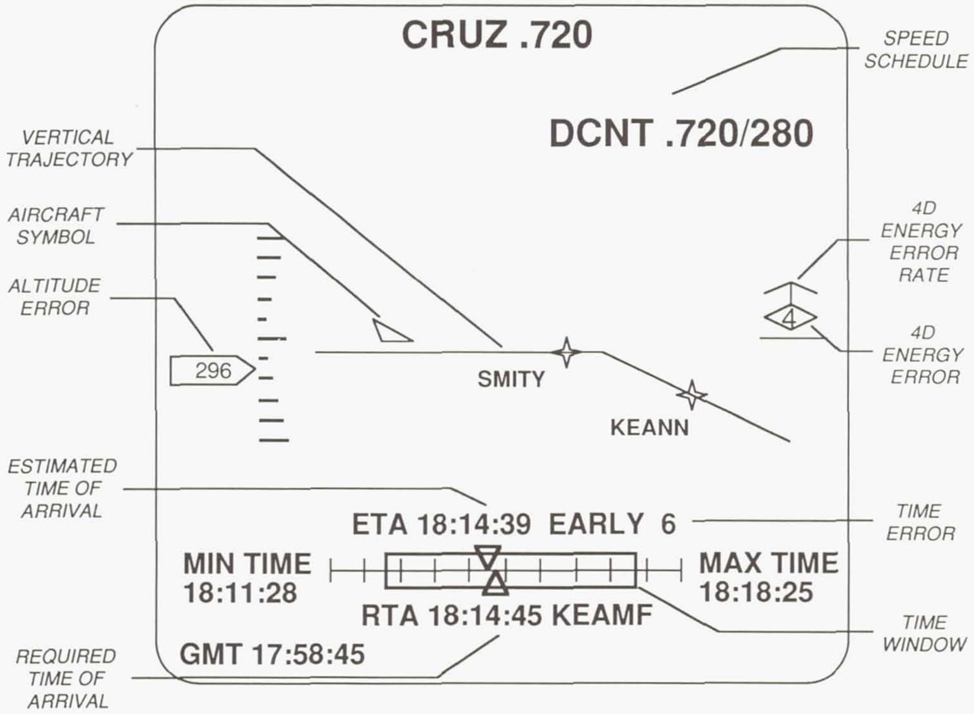
The RTA at the selected way point and the name of the way point were provided immediately below the time line. The location of the RTA on the time line was shown as a triangular wedge with the apex touching the time line at the appropriate position relative to the maximum and minimum times. The RTA text and graphical wedge were color-coded green for RTA time within the time window. RTA time more than 5 seconds outside the time window resulted in a color coding of yellow.

The estimated time of arrival (ETA) was provided immediately above the time line in the same manner as the RTA. In addition to the digital ETA time and graphical wedge, a digital time error (in seconds) was provided. During active guidance (fig. 8(a)) the time error was computed based on the current 4D energy error and the distance to the RTA way point. With provisional information displayed (fig. 8(b)), the time error was referenced to the time window. The provisional time error would indicate (1) ON TIME for RTA selected within the time window, (2) EARLY by the number of seconds that the RTA was greater than the maximum arrival time, or (3) LATE by the number of seconds that the RTA was less than the minimum arrival time. Details of the time error calculations for both active and provisional guidance modes are provided in appendix B.

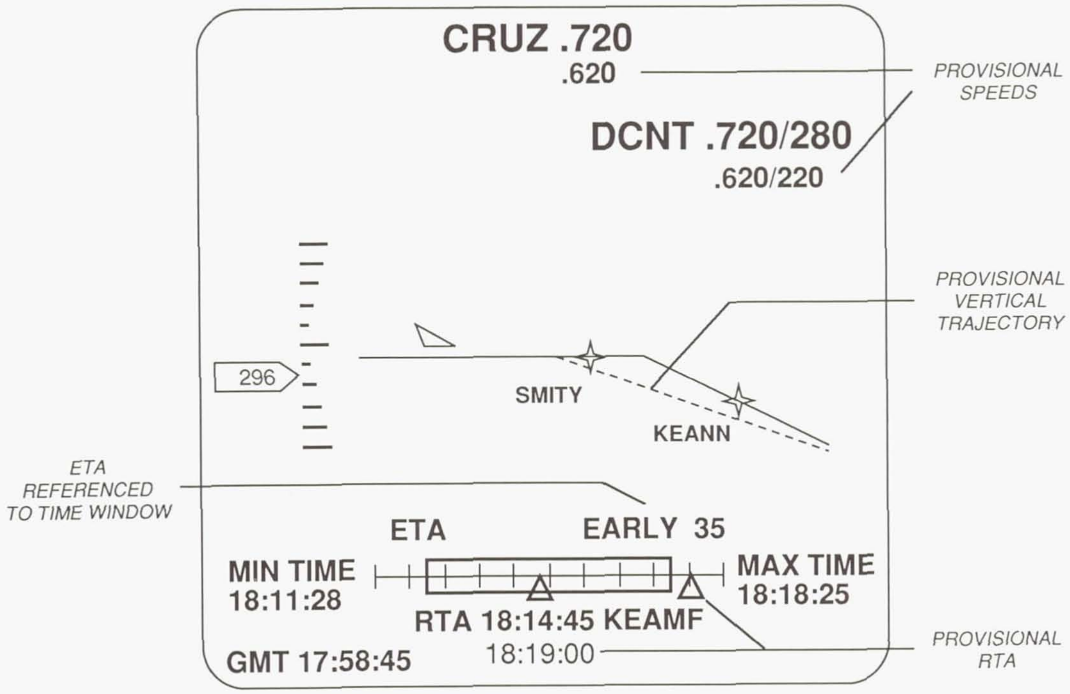
Air Traffic Scenario

The airspace used for this study was based on the Denver Air Route Traffic Control Center (ARTCC) northeast arrival sectors. Figure 9 illustrates the major arrival routes. All arrival traffic in this sector was merged and controlled to cross the metering fix at a specified time. The arrival schedule was determined during the simulation, in real time, by the Traffic Management Advisor (TMA). The sequence was based on a first come first served (FCFS) rule applied at a constant time horizon from the airport.

Although the simulated air traffic entered the airspace at a variety of altitudes and speeds, the TSRV was initialized on the same route and at the same altitude and speed for each flight. The initial conditions for the 4D-equipped aircraft were handled in this way to facilitate the controlled insertion of the aircraft into a particular traffic scenario. Each TSRV flight was injected into an arrival "rush"



(a) Active guidance mode.



(b) Provisional guidance mode.

Figure 8. Vertical situation display (VSD) format in TSRV simulator.

with an average traffic load of 32 aircraft per hour (80% of single active runway capacity).

The most important characteristic of the traffic flow, for this experiment, was the delay. Delay was defined here as the difference between the aircraft's original estimated time of arrival (OETA) and scheduled time of arrival (STA). Two levels of delay were studied: moderate and heavy. Moderate delay was defined to be a delay that was absorbable with speed reduction alone, whereas heavy delay required path stretching (off-route vectoring or holding) in addition to any speed or altitude changes. For the conditions of this experiment, the moderate delay was chosen to be 3 minutes and the heavy delay was chosen to be 8 minutes. The maximum delay absorbable with speed control alone, for the TSRV's test conditions, was approximately 6 minutes.

The FCFS rule allowed for the control of delay during a real-time simulation, even though the traffic flow in an ATC environment is chaotic. This allowed for the generation of traffic lists (initial conditions) that appeared random to the controller subjects yet maintained the significant test conditions. From the pilot's perspective, however, the only known characteristic of the surrounding traffic was the delay which the pilot could determine from his clearance. Although the traffic was designed to result in the same delay for each TSRV flight (moderate or heavy), the time at which the ATC clearance (delay) was transmitted to the aircraft varied depending on the controller's response to the traffic situation. The random time of delivery of ATC clearances resulted in variations in the 4D trajectory solutions (speed profiles and path stretching) for the same delay. The determination and characteristics of the traffic flow for this experiment are not described in detail in this report.

Airborne Procedures

ATC clearances were developed to handle the time-based traffic scenarios in this experiment. The pilots and controllers who participated in the study were provided with the purpose, context, usage, and phraseology associated with each clearance. Appendix C contains a complete description of these clearances, as well as the specific instructions provided to the pilot test subjects.

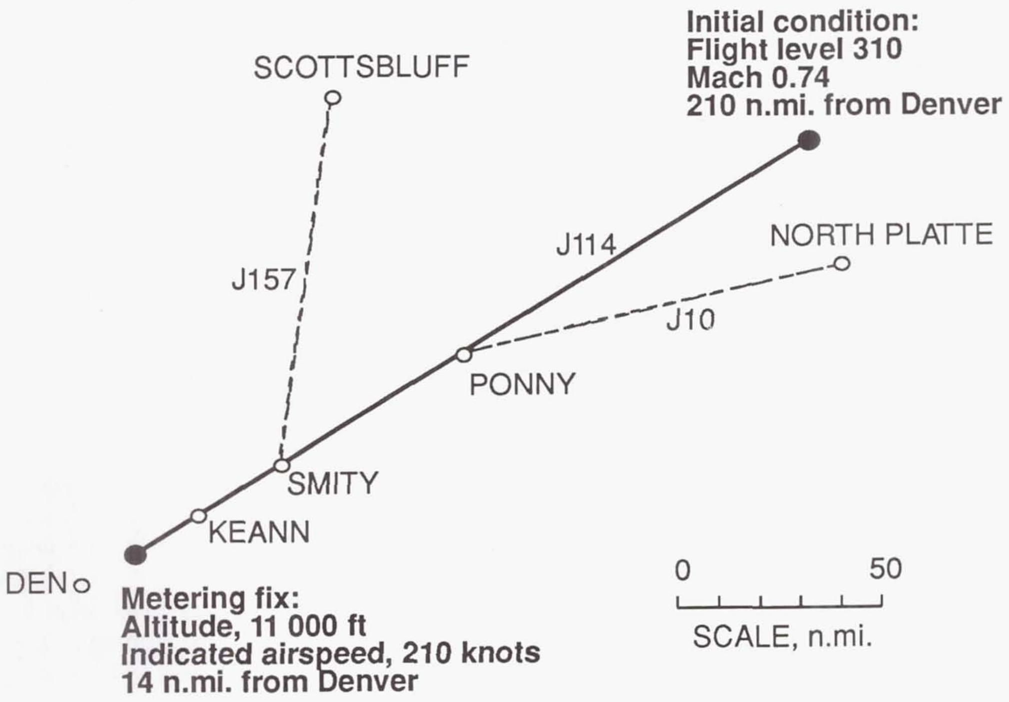


Figure 9. Simulation scenario showing the arrival route of the TSRV simulator.

The cockpit procedures utilized in this experiment were designed to allow a single pilot to both interact with ATC and fly the airborne 4D trajectory. A research engineer, who was not a test subject, occupied the right seat in the cockpit. Duties of the research engineer were to handle manual entries into the CDU and to select autopilot navigation modes at the direction of the pilot test subject. The pilot was required to handle all ATC communications and make all decisions regarding the operation of the aircraft.

The functions of the 4D flight management system (FMS) were explained and demonstrated to the pilot during a training session. The pilot was permitted to utilize the FMS and autopilot in any manner he desired to achieve the objectives of the ATC clearances during the cruise portion of the flight. During descent, the pilot was requested to manually fly the aircraft in the velocity-vector control-wheel steering (VCWS) mode to provide a consistent basis for comparing arrival performance.

Test Conditions

A series of test conditions was devised to exercise the 4D airborne and ground automation, as well as the ATC procedures developed for this study. Table I shows the specific combinations of test parameters. The first three test conditions were designed to investigate the effects of dissimilar speed strategies when traffic conditions forced ATC to exercise speed control on the arrival traffic. Condition 1 was considered the baseline reference where both the ATC and the 4D airplane were using similar speed strategies (Descent Advisor). Condition 2 introduced dissimilar speed strategies with the airplane using minimum-fuel speeds and ATC using Descent Advisor. Condition 3 again used dissimilar speeds; however, the airplane flew a parallel route offset 8 nautical miles during cruise to avoid in-trail conflicts. The last two conditions employed heavy delay levels which forced off-route vectoring by the controllers to accommodate the time delays. Similar speed strategies were utilized in condition 4 and dissimilar speed strategies in condition 5. Typically, a condition 4 or 5 heavy delay scenario would immediately follow a moderate delay scenario, to allow the traffic level to build, as described previously.

Results and Discussion

Approximately 30 hours of simulation were conducted with three active airline pilots participating as test subjects at Langley and six active air traffic controllers and one research controller at Ames. A total of 28 data runs were completed, with each pilot flying the first four test conditions at least one time. Test condition 5 was flown twice by the same pilot.

Table I. Experiment Test Conditions

Condition number	Delay level	Aircraft speed strategy	Horizontal route
1	Moderate	Descent Advisor	Normal
2	Moderate	Minimum fuel	Normal
3	Moderate	Minimum fuel	Offset
4	Heavy	Descent Advisor	Normal
5	Heavy	Minimum fuel	Normal

Results from this study were obtained in the form of pilot opinions from questionnaires and debriefing sessions, quantitative measures of airplane state variables and fuel usage, and researcher observations of pilot and controller performance. The pilot questionnaires and rating scales used in this study may be found in appendix D. The pilot rating was used primarily as a tool to prompt pilot thinking and discussion of the research issues, in particular regarding air traffic control (ATC) procedures and 4D guidance. The limited number of test subjects and lack of repeatable test conditions prevented any rigorous statistical analysis. The quantitative data were used in the analysis of the speed strategy dissimilarities between the airborne and ground 4D trajectory-generation techniques.

ATC Procedures

At the conclusion of each simulation, the pilots were asked to rate the acceptability, clarity, and work load of the ATC clearances and procedures which had been used during the flight. Figure 10 summarizes these ratings for all the simulation runs. As seen in the figure, the pilots rated the acceptability of the clearances as well as their clarity to be high. Work load was rated as essentially the same as normal 3D operations.

Despite the high ratings for acceptability and clarity of the ATC clearances, the pilots felt that the 4D clearances required further refinement before they would be acceptable for routine airline operations. In particular, they generally felt that clearances did not fully define the pilot's actions for all situations that could arise. For example, when a time clearance was interrupted by ATC with a vector, speed constraint, or altitude change, the pilot was sometimes uncertain what to do. The time clearance had given the pilot permission to initiate descent, but now ATC had given some additional constraint to observe. Unless the controller explicitly canceled the

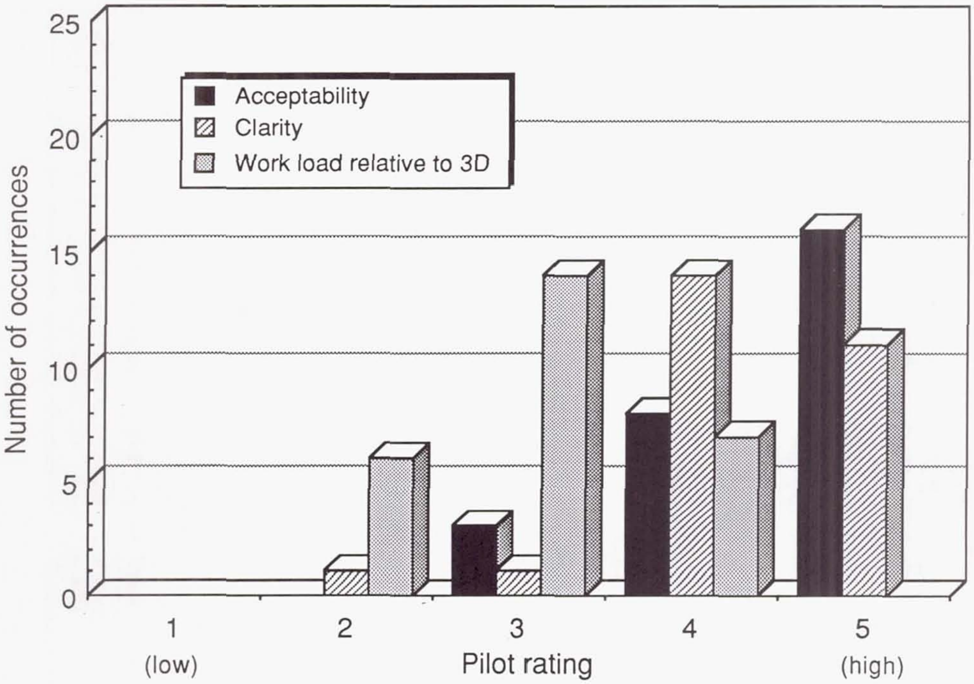


Figure 10. Summary of pilot ratings on 4D clearances and procedures.

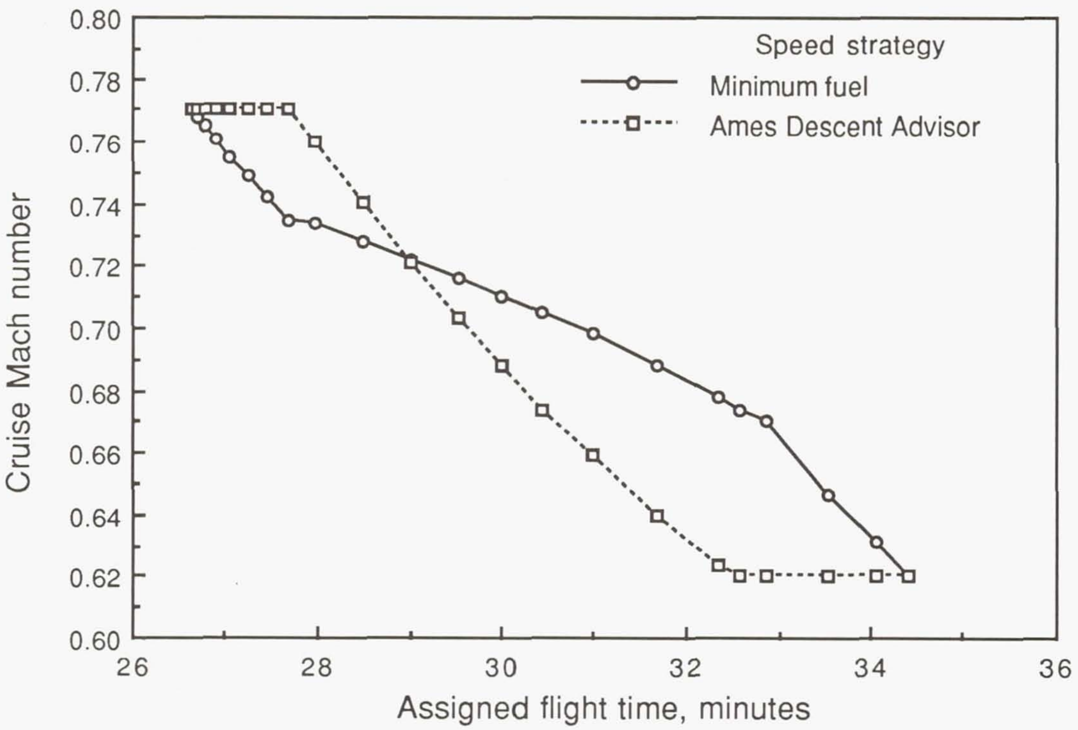
time clearance, the pilot was still expected to initiate descent and achieve the specified time objective while also adhering to any additional constraints that had been imposed. This additional complexity to normal clearance procedures was cited by one of the pilots as being a safety concern. The possibility for missed or misinterpreted clearances was greatly increased during these situations. The use of an air-to-ground data link for transmittal of time clearance and additional constraint information was cited as a possible necessity to handle these overlapping ATC clearances. This would provide the pilot (and controller) with a hard record of exactly what the pilot was cleared to do and avoid possible confusion.

Another potential problem with the time clearance procedure was lack of a consistent cross-check that the pilot was actually flying to the correct assigned time. Unlike a vector, speed change, or altitude change, where the controller can directly monitor the pilot's compliance with the clearance, the time clearance can only be assumed to be correct if the controller hears a correct readback of the time. An error in the assigned time, in the readback by the pilot, or in manual entry of the time into the airplane flight management computer (FMC), may go undetected for a substantial period of time. During this experiment, several errors in the entry of the assigned arrival time were made by either the pilot or the research engineer copilot. On all occasions the errors were large enough to be detected by the pilots and corrected. This potential for errors, however, further supports the use of data link exchange of time clearance information. This exchange should include the actual information used by the airplane FMC and ATC automation software.

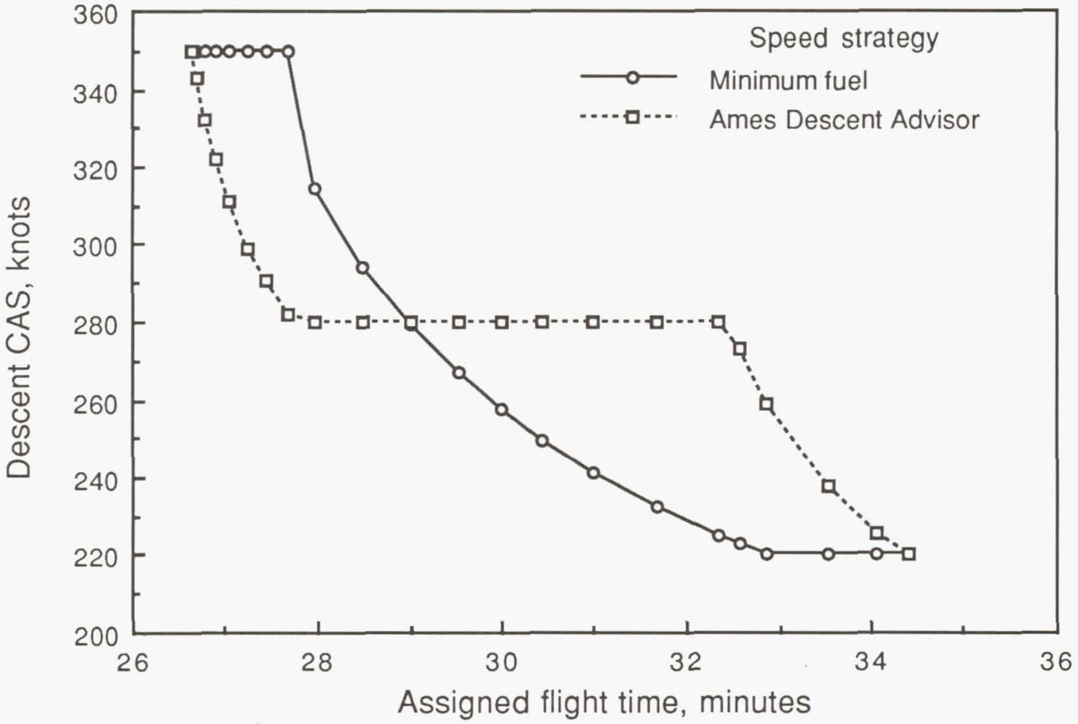
Speed Strategy

An example of the differences in speed schedules computed using the two speed strategies is illustrated in figure 11. The figure shows the cruise Mach number and descent calibrated airspeed (CAS) as a function of assigned flight time for the two strategies. As seen in the figure, between the extremes there is only one flight time for which the two strategies produce the same speed schedule. For earlier arrival times, the minimum-fuel strategy computes slower cruise speeds and faster descent speeds. Conversely, for later arrival times, the minimum-fuel strategy requires faster cruise speeds and slower descent speeds. The differences in speed schedules can be quite severe for a wide range of potential flight times.

Traffic conflicts. The major problem associated with the different speed strategies is the potential for traffic conflicts between pairs of aircraft flying different speeds for the same time objective along the same horizontal route. This situation is illustrated in figure 12 for two hypothetical 737 airplane pairs flying the moderate traffic scenario used in this



(a) Cruise Mach number.



(b) Descent calibrated airspeed.

Figure 11. 4D speed schedules versus assigned flight time for the simulation scenario.

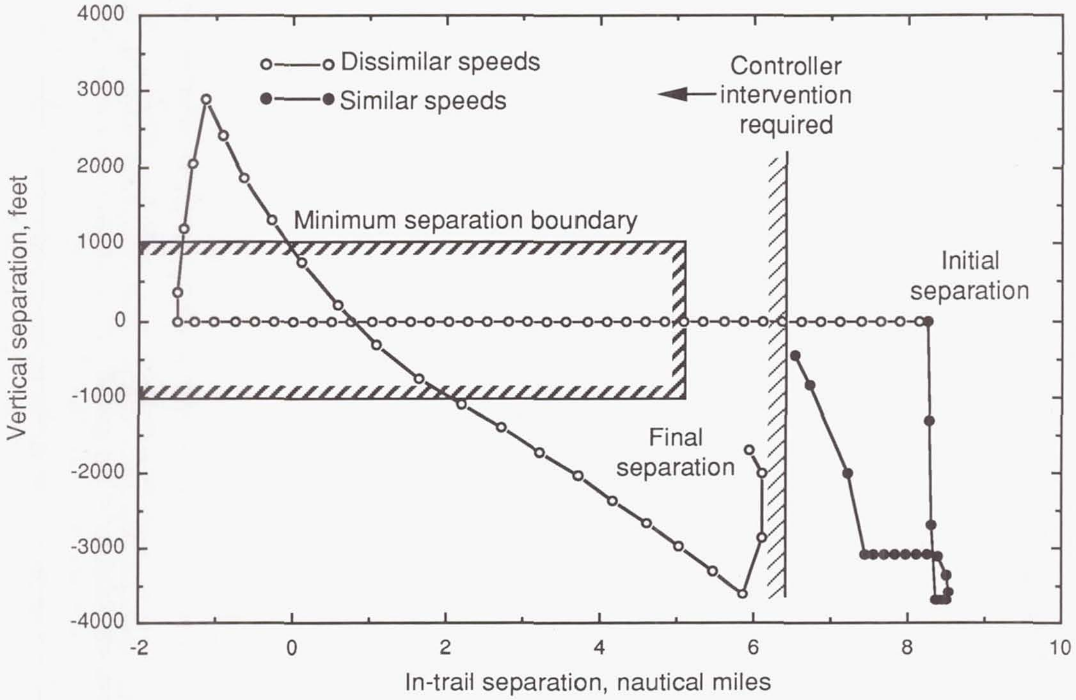


Figure 12. Hypothetical separation conflict induced by dissimilar speed strategies (32-minute assigned flight time). Note that data points are plotted every 30 seconds.

experiment. The figure shows vertical separation between airplane pairs plotted against horizontal in-trail separation for a 32-minute assigned flight time. One aircraft pair used ATC Descent Advisor speeds for both the leading and the trailing aircraft. With a time spacing of 80 seconds selected for initial and final separation, the aircraft pair can be seen to maintain an adequate separation throughout the flight. The other aircraft pair, however, has the leading aircraft flying ATC Descent Advisor speeds while the trailing aircraft flies minimum-fuel speeds. As seen in figure 11, for a 32-minute flight time, the trailing aircraft flies a significantly faster cruise speed and slower descent speed than the leading aircraft. As a result, the in-trail separation of the aircraft pair decreases to the point where, without controller intervention, the trailing aircraft would actually pass the leading aircraft prior to starting the descent. Separation would then increase again as the trailing aircraft flies the slower descent speeds.

Fuel efficiency. The ideal fuel usage, for the 196-nautical-mile test scenario, associated with the two speed strategies is shown in figure 13. For any flight time other than that corresponding to the same speed schedule, the ATC Descent Advisor strategy requires additional fuel. The actual fuel usage of the TSRV simulator for the moderate traffic scenarios, which corresponds to approximately the 32-minute flight time in figure 13, is summarized in table II. Fuel usage for the minimum-fuel speed strategy produced a 2.2-percent average fuel savings (for the 196-nautical-mile test scenario) over the Descent Advisor speeds when the TSRV was allowed to fly without interruption from ATC. When ATC did interrupt the TSRV to prevent a traffic conflict, however, a 6.3-percent fuel penalty was incurred. Instead of producing the fuel savings desired by flying minimum-fuel schedules, the resulting dissimilarity with other traffic and controller vectoring was found to produce fuel penalties.

Table II. Summary of TSRV Fuel Usage

Aircraft speed strategy	Route	ATC interruption	Number of runs	Average fuel used, lb
Descent Advisor	Normal	No	6	1779 (ref.)
Minimum fuel	Normal	No	6	1740 (−2.2%)
Minimum fuel	Normal	Yes	3	1891 (+6.3%)
Minimum fuel	Offset	No	3	1800 (+1.2%)
Minimum fuel	Offset	Yes	1	1916 (+7.7%)

The route-offset scenario was generally successful in preventing the in-trail traffic conflict, as discussed earlier. The purpose of the route offset, however, was to permit the 4D-equipped airplane to save fuel by flying minimum-fuel speeds. The resulting

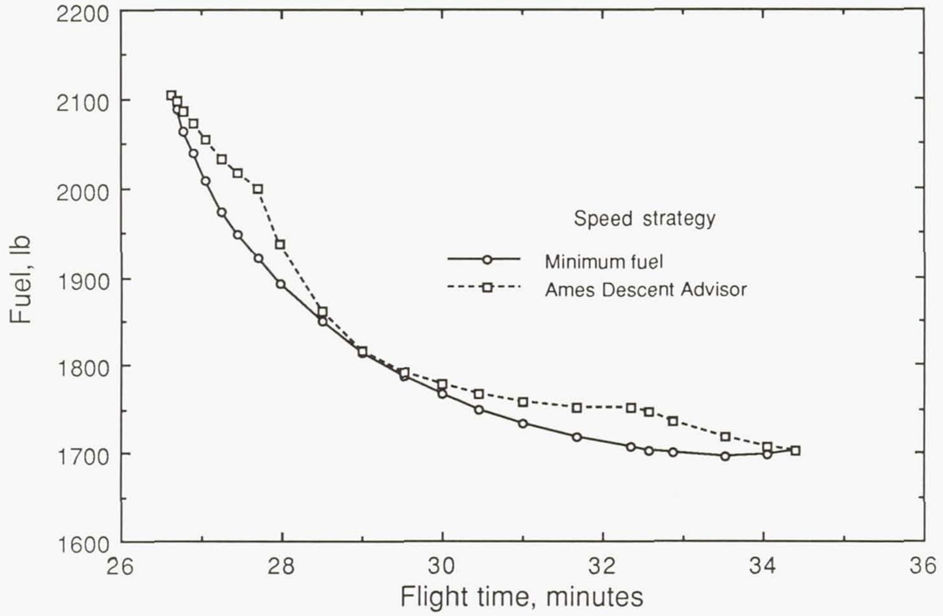


Figure 13. Fuel usage for perfectly flown 196-nautical-mile test scenario using the two speed strategies.

range flown by the airplane during the route offset was greater than the range of the standard route for the test scenario. As a result, the route offset actually resulted in greater fuel usage because of this greater range. Therefore, while the route offset has potential for alleviating in-trail separation conflicts, care must be taken to ensure that the additional range requirements do not cancel the potential fuel benefits.

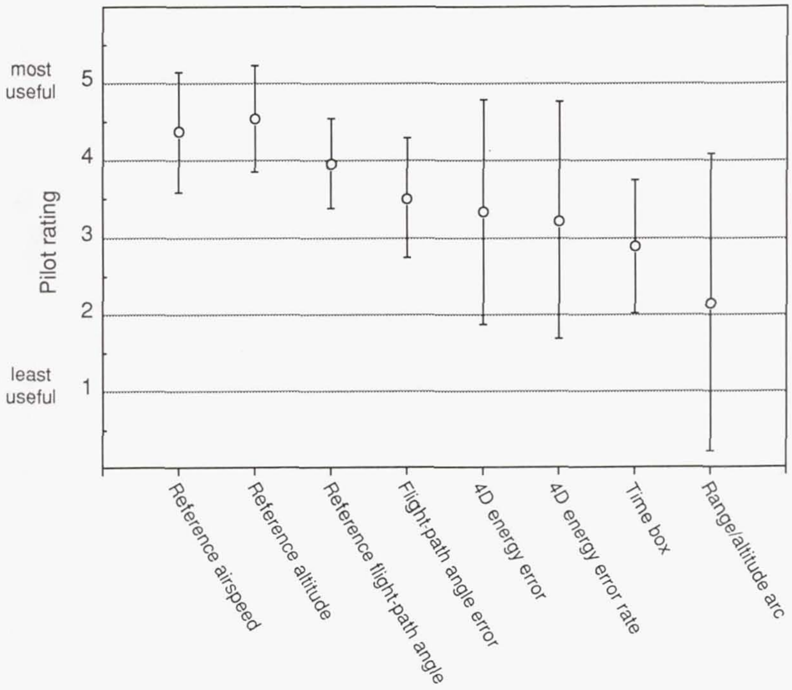
Fuel efficiency is also a concern for the heavy traffic situations where time delays require off-route path stretching. During these situations, however, the different speed strategies are of little significance since all the aircraft are flying at minimum speeds. The important consideration is to minimize the distance flown while absorbing a time delay during an off-route vector. Since the pilot is monitoring his own time delay status while performing the 4D time delay vector clearance, it is reasonable to assume that he is in a better position to determine the most efficient point at which to turn back on route. The controller is monitoring a number of aircraft and cannot be expected to turn each aircraft at the optimum time for minimum delay range.

Pilot Guidance

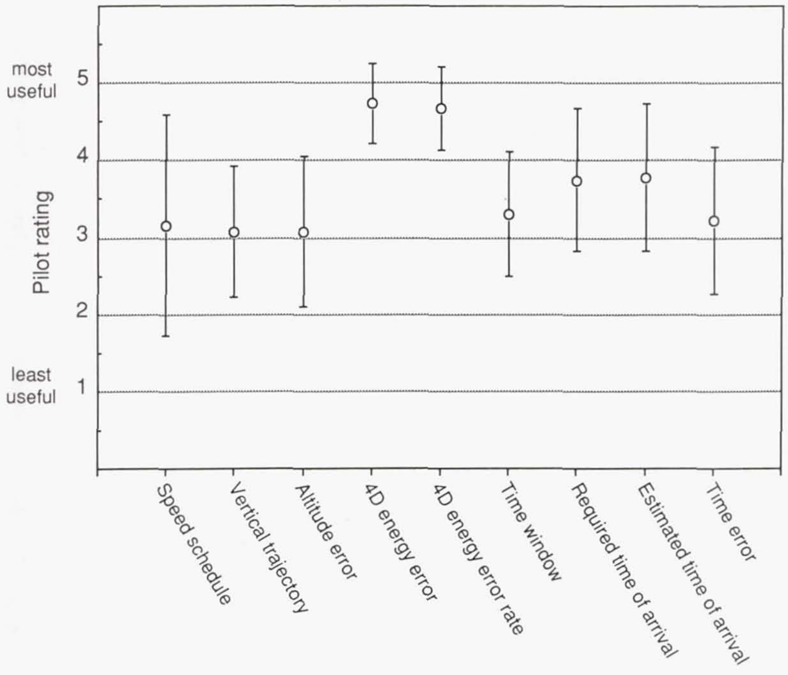
One of the objectives of this study was to evaluate the effectiveness of the flight guidance provided in the TSRV simulator for flying the 4D trajectories. Because of the limited number of test subjects and situation-dependent test scenarios, this evaluation was primarily limited to qualitative measures. While the primary interest was in the time guidance, the basic airspeed and altitude guidance were also discussed. Actual arrival performance at the metering fix, which was the end goal of the guidance, was the only quantitative measurement.

Trajectory tracking. To achieve the final objective of arriving at the metering fix at the specified altitude, speed, and time, a variety of display elements were provided. At the conclusion of each simulated flight, the pilot was asked to rate the usefulness of specific display elements for flying the trajectory. Figure 14 shows the results of these ratings for all the data runs flown by the pilots.

The reference airspeed, altitude, and flight-path angle information provided on the primary display consistently received high ratings. The trajectory information on the vertical situation display (speed schedule, vertical trajectory, and altitude error) was found to be less useful. All the pilots, however, complained about the situational nature of the primary flight guidance. While they rated the primary flight information as most useful for flying the trajectory, they also stated that it would be unacceptable for airline operations without a significant amount of training. Current airline displays are designed around the



(a) Primary and navigation displays.



(b) Vertical situation display.

Figure 14. Pilot ratings on usefulness of display guidance for flying the 4D trajectories (mean and standard deviation).

flight director method of flight guidance. Situational displays, such as those in the TSRV simulator, require the pilots to change the way they normally fly the airplane. The pilots felt that this added an unnecessary complexity to the primary flight task in this study.

The 4D energy information received high ratings on the vertical situation display. The identical information presented on the primary flight display received lower ratings. Pilot comments indicated that it was much easier to see the 4D energy bug on the vertical situation display and therefore easier to use. The pilots acknowledged that the 4D energy guidance should probably be shown on the primary flight display; however, the location and size of the symbology used in this study were not adequate. These results are similar to those reported in reference 6.

Time capability. The display of time information received mixed ratings with no single element cited as the most useful. Pilot comments indicated some confusion over the meaning of the time error and estimated time of arrival (ETA), which may have contributed to the mixed ratings. In addition, the time information was not required for actually flying the trajectory once a 4D profile had been calculated. The displayed time information was therefore needed only for a very small portion of the flight. The consensus of opinions was that the displayed time window, ETA, RTA, and time error were overemphasized and occasionally inconsistent during most of the flight. While no specific objections were raised over the nature of the time display, no specific favorable comments were expressed either.

Arrival performance. The end goal of the airborne guidance was to deliver the airplane at the metering fix at the correct altitude, airspeed, and time. Table III presents the results for all the simulation data runs. The achieved values fell within the target maximum range. The time error, in particular, was significantly better than the prespecified target value. The altitude and speed errors, while generally within the target range, were greater than expected during some simulations. This was assumed to be a result of the pilot's unfamiliarity with the situational format of the primary flight displays. A more familiar flight director format may have improved the altitude and speed performance. Actual performance of an operational system would depend on the specific guidance provided by that system.

When these results are compared with those obtained in earlier tests at NASA Ames involving piloted simulation of non-4D aircraft flying the Descent Advisor speeds (ref. 7), the potential advantage of airborne 4D systems becomes apparent. For similar calm wind scenarios adjusted for straight-in descents, the non-4D aircraft recorded a mean arrival time error of between 4 and 6 seconds late with a standard deviation of about 12 seconds. The crossing airspeed errors for the non-4D aircraft (mean of −5 knots with standard deviation of 5 knots) were similar to those attained in this study by the 4D TSRV; however, altitude errors of the non-4D aircraft in reference 7 were significantly greater at a mean of −155 feet and standard deviation of 292 feet. Overall, the potential arrival accuracy of a 4D FMS aircraft, in time, airspeed, and altitude, could significantly enhance the operation of a 4D ATC system.

Table III. TSRV Delivery Performance

	Time error, sec	Altitude error, ft	Airspeed error, knots
Mean	0.6	50.2	−0.6
Standard deviation	2.9	81.8	6.4
Target maximum range	±20.0	±250.0	±10.0

Concluding Remarks

A simulation study was conducted to explore the integration of an aircraft equipped with four-dimensional (4D) nagivation into a 4D air traffic control (ATC) system. The following remarks are based on the results of piloted simulations.

The 4D ATC procedures and operation of the flight management computer were found to be easily accommodated by the airline pilot test subjects. Cockpit work load, even during the most demanding scenarios, was unaffected by the new procedures. The 4D clearances as tested, however, were somewhat lacking in clarity when additional ATC constraints were applied. The pilots felt that the actual 4D clearances needed further refinement before they would be acceptable for routine airline operations. In addition, the use of a digital data link for transmission of clearances and restrictions may prove necessary for successful 4D operations.

Dissimilarities between airborne and ATC-generated 4D speed strategies were found to be primarily an efficiency problem during moderate traffic conditions. Traffic conflicts induced by the different speed strategies were handled by active controller intervention which resulted in fairly significant fuel penalties. An offset routing of the 4D-equipped aircraft successfully avoided conflicts; however, no fuel advantage was observed. It was found to be more efficient for the 4D-equipped aircraft to remain on the established route and adapt to the ATC speed strategy when traffic conditions required speed control by ATC.

A potential operational benefit of the airborne 4D flight management system (FMS) occurred when time delays forced off-route path stretching. The pilots were able to consistently fly controller vectors to absorb time delays using their FMS to decide when to turn back on course. This procedure showed potential for relieving controller work load while improving efficiency. The pilot could minimize the delay range by closely monitoring his own delay situation and determining the earliest opportunity for turning back.

The airborne 4D guidance proved effective in delivering the aircraft to the metering fix at the required arrival time. The standard deviation of time error at the metering fix was 2.9 seconds for all the data runs. Previous piloted simulations involving non-4D aircraft flying ground-derived Descent Advisor speeds resulted in a standard deviation of approximately 12 seconds for similar scenarios. The pilots in this study had difficulty with the unfamiliar TSRV primary flight display which presented situational rather than flight director primary guidance. All the pilots expressed the desire to see 4D energy guidance incorporated into a more conventional flight director for routine 4D airline operations. Such an implementation, in the opinion of the pilots, would permit consistent arrival time performance as demonstrated in this experiment.

NASA Langley Research Center
Hampton, VA 23665-5225
January 16, 1991

Appendix A

4D Profile Generation Algorithm Description

General

The profile generation algorithm (called PGA4D) used in this simulation study was a modified version of a stand-alone program developed for analytical studies involving 4D vertical-trajectory-generation techniques. The original program contained options for computing nearly-optimal vertical trajectories using energy state approximations and optimal control theory (ref. 8). Also included was a Mach/CAS trajectory-generation technique which expanded on the methods developed and flight tested in the NASA TSRV airplane in reference 9. The latter Mach/CAS method was utilized for the current simulation study.

The PGA4D program provided a means for isolating the vertical trajectory generation from the horizontal path definition. A special way-point reference buffer was established which contained the horizontal path definition as well as the vertical profile constraints at each way point. The PGA4D executive would analyze the way-point reference buffer and generate the appropriate inputs for the vertical-trajectory-generation routines. Constraints imposed at way points would define the initial and end conditions for vertical-trajectory generation. Multiple calls to the vertical routines could be generated by the PGA4D executive, depending on the number of way points with constraints. The executive would then piece the vertical trajectories together into a single reference profile.

Interface With TSRV Simulation

The PGA4D program was implemented as a "black box" routine called by the real-time TSRV simulation program. Because of memory limitations of the real-time CYBER 175 computer, PGA4D was actually implemented on a separate CYBER 175 computer communicating via shared memory locations. A real-time executive routine, residing on the TSRV simulation computer would generate the required input information for PGA4D and pass it to the PGA4D executive on the other computer. Similarly, the PGA4D executive would pass output information back to the real-time computer.

Horizontal path definition. The baseline TSRV horizontal (or 2D) area navigation (RNAV) guidance buffer was utilized to construct the horizontal path for the PGA4D program. The horizontal information required at each way point consisted of the elapsed range from the initial way point to the center of turn of the current way point and the true course from the current to the next way point.

Weather model. A separate weather buffer contained wind and temperature conditions at each way point defined in the way-point reference buffer. Wind speed and direction, as well as temperature deviation from standard day, could be defined for up to five altitude levels at each way point. The PGA4D program would interpolate the wind and temperature information in both altitude and range to compute the ground speeds at each point on the synthesized trajectory. In addition, the program could update the modeled winds and temperatures at the next way point on the path using the actual conditions at the aircraft's current position and the weather values at the last way point crossed by the aircraft. The weather model would be modified by the PGA4D program only at the next way point on the path. Pilot inputs were required to modify subsequent way points.

Vertical path constraints. Each way point was assigned a type designation which controlled the options and constraints for the vertical-trajectory generation. All way points associated with a terminal departure were designated departure way points and had preassigned altitude and calibrated airspeed constraints. Similarly, all way points of a terminal arrival were designated arrival way points with preassigned altitude and calibrated airspeed constraints. These constraints consisted of values which the aircraft must observe when crossing the way point. All other way points were designated as en route and did not have vertical constraints. The pilot could manually assign an airspeed or altitude constraint at an en route way point by entering a value in the control display unit. The designation of the way point was then changed to en route arrival.

The first terminal arrival way point was designated the metering fix and became the reference point for the time guidance. The pilot was required to manually enter a crossing time constraint at the metering fix way point in order to activate the 4D calculation of the vertical trajectory. If no time constraint was specified at the metering fix, the PGA4D program would compute a 3D vertical profile using the predefined cost index to determine the speed schedule.

Vertical-Trajectory Generation

Profile structure. The vertical trajectory was synthesized from the current location of the airplane to the final way point (or arrival runway threshold) in the flight plan using the information in the way-point reference and weather buffers. A full trajectory consisted of a departure segment with predefined airspeeds and altitudes, a fuel-optimized en route climb, cruise, and descent segment from the last departure to the first arrival way point, and an arrival segment from the metering fix to the runway. The departure and arrival segments were computed using a simple average ground speed between way points. The fuel-optimized en route segment was computed using the Mach/CAS trajectory-generation option.

Figure A1 illustrates the structure of the fuel-optimized en route profile. Depending on the initial position of the airplane and the location and vertical constraints of the metering fix way point, the en route profile could have as few as 1 or as many as 12 segments. Computation began at the metering fix and worked backward to the end of cruise (segments 1 through 6 in fig. A1). Climb was then computed from the initial position to the beginning of cruise (segments 12 through 8). The remaining range was assigned to segment 7 cruise. If insufficient range was available for the climb and descent, the program would abort with an error message. If the aircraft was already in cruise and requested a profile with insufficient range for descent, the initial position of the aircraft was displaced back in range by the required amount to permit the descent. The resulting profile would show the aircraft above the desired vertical flight profile and allow the pilot to maneuver horizontally and/or utilize speed brakes to recover and fly the trajectory.

Speed selection. In general, climb, cruise, and descent speeds are chosen on the basis of the speed strategy selected by the calling program. Two strategies were available for this experiment which provided cruise and descent speed selection for the test scenarios.

The first, referred to as the "minimum-fuel" strategy, utilized a parameter called cost index for computing cruise Mach number. The cost index was the ratio of time cost (dollars per hour) divided by fuel cost (dollars per pound) scaled by 1/100 to produce a 3-digit integer. The range of cost indices for the TSRV Boeing 737-100 airplane was −40 to 200, which corresponds to −\$400 to \$2000 per hour operating cost at fuel cost of \$0.10 per pound (\$0.67 per gallon). The negative operating costs are required to allow the aircraft to fly at the minimum airspeeds needed to absorb the maximum time delays. Cruise Mach number was programmed as a nonlinear function of cost index and altitude. Descent Mach number was set equal to cruise Mach number. Descent calibrated airspeed was a function of cruise Mach number and initial altitude for climb and final altitude for descent. The empirical formulas for cruise Mach number and descent calibrated airspeed were obtained from curve fits of minimum-fuel speed schedules of Mach/CAS combinations computed using the batch version of PGA4D. For specified arrival times, the minimum-fuel strategy iterated on cost index to satisfy the arrival time constraint.

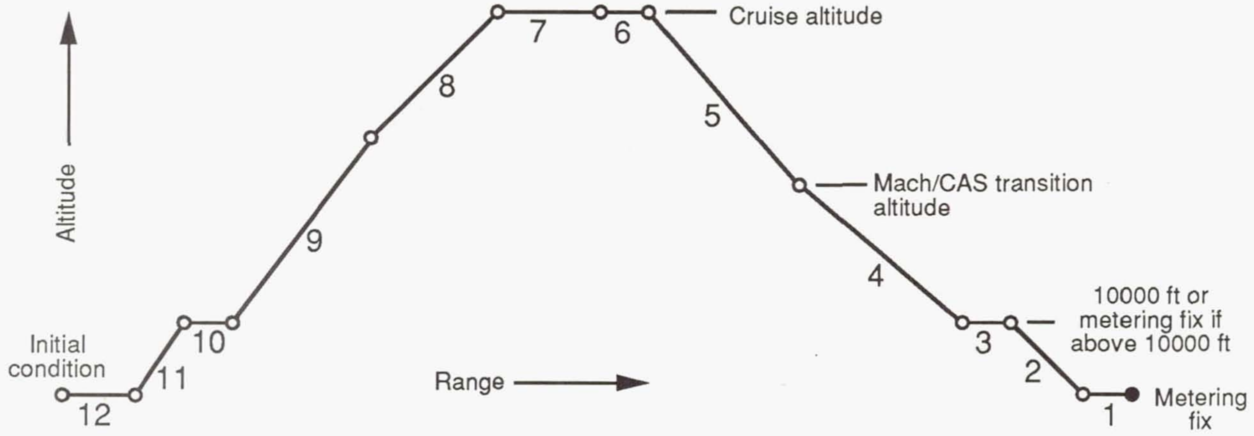
The second strategy, referred to as the Descent Advisor strategy, was included to duplicate the ATC ground-generated speed strategy utilized in the NASA Ames Descent Advisor algorithm. This strategy assigned a nominal speed profile based on aircraft type (Mach 0.74 cruise and descent CAS of 280 knots for the 737). When a specific arrival time was required for an aircraft, the algorithm iterated on cruise Mach number leaving descent CAS fixed at the nominal value. If additional time capability was needed, the algorithm then adjusted descent CAS while leaving cruise Mach at the extreme value.

Empirical performance model. The times and distances required to fly the segments defined by the horizontal route and speed selection were computed using an empirical model of the TSRV airplane performance. Altitude rate at both climb and idle thrust was modeled as a function of altitude for both constant Mach number and constant calibrated airspeed. Corrections were included for variations in aircraft gross weight, vertical wind shear, and temperature deviations from standard day. Similarly, acceleration and deceleration rates were modeled as a function of calibrated airspeed and altitude. The modeling techniques were similar to those described in reference 9; however, the drag polar and engine performance models of the TSRV simulator were used to compute the empirical relations.

Descent range constraint. The PGA4D program was designed to provide vertical trajectory guidance to the pilot even when insufficient range was available to make an idle descent and satisfy the metering fix crossing restrictions. This was accomplished by moving the initial conditions of the calculated trajectory back to a range which allowed a proper idle descent. The pilot could then steepen his descent using speed brakes and/or maneuver horizontally while recomputing provisional profiles back to his destination. When the computed top of descent corresponded to his actual location he could resume a normal idle descent and "accept" the provisional path.

Program Output

Vertical trajectory. The primary output of the PGA4D program was a vertical trajectory array which provided the basis for the vertical guidance. The trajectory consisted of time, altitude, calibrated



Segment	Description
1	Deceleration from 250 knots to metering fix crossing speed
2	Descent from 10000 feet to metering fix altitude at 250 knots
3	Deceleration from descent CAS to 250 knots (or metering fix speed)
4	Descent at constant CAS
5	Descent at constant Mach number
6	Deceleration from cruise to descent Mach number or CAS
7	Cruise at constant Mach number
8	Climb at constant Mach number
9	Climb at constant CAS
10	Acceleration from 250 knots to climb CAS
11	Climb at 250 knots
12	Acceleration from initial speed to 250 knots

Figure A1. Structure of fuel-optimized en route vertical trajectory.

airspeed, and ground speed as a function of elapsed range along the flight plan. Also included was a flag indicating the flight phase (climb, cruise, or descent) which triggered the display options on the vertical situation display. The guidance computations derived from the vertical trajectory are described in appendix B.

Way-point crossing values. The way-point reference buffer was also modified by PGA4D to include interpolated values of time, altitude, calibrated airspeed, and ground speed at the way points defining the horizontal path. These values were displayed on the CDU route leg page(s). Also returned by PGA4D were the computed top of descent (TOD) and bottom of descent (BOD) way points. The latitude and longitude of the TOD and BOD way points were computed by the TSRV simulation program and displayed on the navigation display. These way points, however, were not included on the CDU route legs or progress pages because of software limitations in the TSRV simulation. Only way points used for horizontal path definition could be shown as part of the flight plan route on the CDU. Including computed TOD and BOD way points in the horizontal path definition was found to change the horizontal path when they were located within the turn radius of an existing way point. The addition of so-called soft way points to the CDU-displayed flight plan, which would not affect the horizontal path definition, was identified as a future requirement for the TSRV simulation.

Time window. In addition to the vertical trajectory and computed way-point crossing values, PGA4D returned the maximum and minimum arrival time capability of the airplane at the metering fix way point. These values were displayed to the pilot on the vertical situation display (VSD) both digitally and graphically as a window of available arrival times. Included with the time window information were cruise Mach number and descent calibrated airspeed required to fly the computed trajectory. This information was also displayed on the VSD.

The time window, speed schedule, and trajectory information were computed, returned, and displayed in less than 2 seconds in this implementation on the TSRV simulation. This relatively quick computation was necessary to permit the automatic 10-second update of provisional horizontal and vertical profiles utilized during the time delay vector scenarios in this study. More complex trajectory-generation techniques, such as the optimal trajectory method described in reference 8, would not be suitable for the time-critical calculation of arrival time capability. In the TSRV simulation, all provisional calculations for the time window were obtained using the empirical method regardless of the actual method to be used for the final trajectory generation. Only after the pilot had accepted the profile would a call be made to PGA4D requesting the full profile.

Appendix B

Time and Energy Error Calculations

Time guidance information was presented to the pilot on the vertical situation display (fig. 8) in both a strategic manner for provisional flight planning and a tactical manner for active flight guidance. The strategic time guidance consisted of the calculation of maximum and minimum arrival times at the selected metering fix way point. Once an active profile was computed, tactical time guidance consisted of an estimated arrival time at the selected metering fix way point and a 4D energy error indication based on the aircraft's state relative to the reference vertical trajectory. Details for the calculations involved for both the strategic and the tactical time guidance are provided in this appendix.

Strategic Time Guidance

The pilot's arrival time capability at the selected metering fix way point was indicated on the vertical situation display. This time capability, referred to as the arrival "time window," was obtained by calling the vertical profile generation program (PGA4D) at regular intervals using the current aircraft state as initial conditions. The returned values of maximum and minimum arrival times were computed using the minimum and maximum operational speeds, respectively, which the aircraft could fly and still satisfy all constraints contained in the provisional way-point reference buffer. The pilot was therefore assured that any arrival time specified within the displayed time window could be achieved without violating any constraints imposed on the flight plan.

The time window was updated at 30-second intervals when the vertical situation display (VSD) was in the active guidance mode. Whenever the pilot made a modification to the flight plan that affected the vertical trajectory, active time guidance was removed and the VSD entered the provisional mode. Estimated arrival time was erased, and time error was referenced to the time window and required time of arrival (RTA). An ON TIME message was displayed if the RTA was within the time window, that is, if an active profile could be computed to satisfy the time constraint. An RTA value greater than the maximum arrival time or less than the minimum arrival time would prompt an EARLY or LATE message, respectively, with the digital number of seconds that the RTA was outside the time window. The pilot could force calculation of a time window at any time by pressing a special COMPUTE VERTICAL key on the control display unit CDU. The pilot returned to active guidance by pressing the EXECUTE key on the CDU.

Both horizontal and vertical trajectories, with corresponding time window calculations, were automatically updated when the pilot selected DIRECT TO a way point on his flight plan. A new way point, referred to as PPOS for present position, was generated by projecting the aircraft location 10 seconds in the future at current speed and heading. A horizontal path was then generated linking the PPOS way point with the selected DIRECT TO way point and the remainder of the flight plan. The vertical trajectory program was then called with the PPOS location as initial conditions. This process was repeated every 10 seconds, providing a continuous update of the provisional capability. The pilot would press the EXECUTE button when satisfied with displayed provisional profile information.

Tactical Time Guidance

Once an active reference profile was calculated and the VSD was in the active guidance mode, time guidance was derived from the reference vertical trajectory.

Reference profile. The reference vertical trajectory consisted of time, altitude, and ground speed provided by the PGA4D program as a function of range along the reference horizontal path. The distance between range points on the reference vertical trajectory was referred to as a "segment" of the profile.

Instantaneous time error. An instantaneous time error was computed by dividing the distance between the aircraft's actual range and reference range at the current time by the current ground speed of the aircraft. The reference range for a given time was calculated by assuming a linear acceleration in each vertical trajectory segment. This assumption closely approximated the constant Mach number and constant calibrated airspeed descent profiles used in the vertical profile generation. This reference linear acceleration was computed as

$$\dot{V}_{g,\mathrm{ref}} = c_1\,\Delta t + c_2 \tag{B1}$$

$$V_{g,\mathrm{ref}} = \frac{1}{2}c_1\,\Delta t^2 + c_2\,\Delta t + c_3 \tag{B2}$$

$$\Delta x_{\mathrm{ref}} = \frac{1}{6}c_1\,\Delta t^3 + \frac{1}{2}c_2\,\Delta t^2 + c_3\,\Delta t + c_4 \tag{B3}$$

where

$V_{g,\mathrm{ref}}$	reference ground speed
Δt	elapsed time into segment
Δx_{ref}	elasped range into segment

and

$$c_1 = \frac{6[(V_1 + V_2)t_{\mathrm{seg}} - 2d_{\mathrm{seg}})}{t_{\mathrm{seg}}^3} \tag{B4}$$

$$c_2 = \frac{2[3d_{\mathrm{seg}} - t_{\mathrm{seg}}(2V_1 + V_2)]}{t_{\mathrm{seg}}^2} \tag{B5}$$

$$c_3 = V_1 \tag{B6}$$

$$c_4 = 0 \tag{B7}$$

where

V_1	ground speed at past trajectory point
V_2	ground speed at next trajectory point
d_{seg}	segment distance
t_{seg}	segment time

Instantaneous time error is then computed as

$$t_{\mathrm{err},i} = \frac{x_{\mathrm{ref}} - x_{\mathrm{ac}}}{V_{g,\mathrm{ac}}} \tag{B8}$$

where

x_{ac}	current range of aircraft
$V_{g,\mathrm{ac}}$	current aircraft ground speed
x_1	range at past trajectory point

and

$$x_{\mathrm{ref}} = x_1 + \Delta x_{\mathrm{ref}} \tag{B9}$$

Energy error. The calculation of energy error ΔE included the altitude, ground speed, and time errors of the aircraft relative to the reference vertical trajectory. The details of these calculations are as follows:

$$\Delta E = \Delta E_{\mathrm{3D}} + \Delta E_t \tag{B10}$$

where

$$\Delta E_{\mathrm{3D}} = (h_{\mathrm{ac}} - h_{\mathrm{refx}}) + \frac{1}{2g}(V_{g,\mathrm{ac}}^2 - V_{g,\mathrm{refx}}^2) \tag{B11}$$

$$\Delta E_t = \frac{d_{\mathrm{mf}}^2}{2g}\left[\frac{1}{(t_{\mathrm{mf}} - t_{\mathrm{ref}})^2} - \frac{1}{(t_{\mathrm{mf}} - t)^2}\right] \tag{B12}$$

and

h_{ac}	current aircraft altitude
h_{refx}	reference altitude at current aircraft range
g	acceleration due to gavity
$V_{g,\mathrm{refx}}$	reference ground speed at current range
d_{mf}	distance to metering fix
t_{mf}	time at metering fix
t	current time

and

$$t_{\mathrm{ref}} = t + t_{\mathrm{err},i} \tag{B13}$$

Estimated arrival time. The estimated time of arrival, or ETA, displayed on the VSD was obtained from a combination of the instantaneous time error and an energy time error derived from the total energy error. The goal was to provide the pilot with an estimate of the arrival time that he would achieve given his current energy corrections as indicated by the energy error display. As the metering fix was approached, the energy error contribution to the time error was washed out and the instantaneous time error contribution was increased.

The calculation of the energy component of time error was essentially a reverse calculation of the ΔE_t energy error term. The reference time was replaced by the required arrival time, and the actual time replaced by the estimated arrival time:

$$\Delta E = \frac{1}{2g}\left(V_{g,\mathrm{rta}}^2 - V_{g,\mathrm{eta}}^2\right) \tag{B14}$$

$$\Delta E = \frac{d_{\mathrm{mf}}^2}{2g}\left(\frac{1}{\Delta t_{\mathrm{rta}}^2} - \frac{1}{\Delta t_{\mathrm{eta}}^2}\right) \tag{B15}$$

where

$V_{g,\mathrm{rta}}$	average ground speed required for RTA
$V_{g,\mathrm{eta}}$	average ground speed required for ETA
Δt_{rta}	elapsed time to RTA
Δt_{eta}	elapsed time to ETA

Solving for Δt_{eta} results in

$$\Delta t_{\mathrm{eta}} = \sqrt{\frac{\Delta t_{\mathrm{rta}}^2}{1 - 2g\dfrac{\Delta E\,\Delta t_{\mathrm{rta}}^2}{d_{\mathrm{mf}}^2}}} \tag{B16}$$

Energy time error was then computed as

$$t_{\mathrm{err},e} = \Delta t_{\mathrm{eta}} - \Delta t_{\mathrm{rta}} \tag{B17}$$

Total time error was computed as a combination of energy time error and instantaneous time error using the following relation:

$$f_{\mathrm{te}} = \frac{600 - \Delta t_{\mathrm{rta}}}{600} \tag{B18}$$

$$t_{\mathrm{err}} = f_{\mathrm{te}} t_{\mathrm{err},i} + (1 - f_{\mathrm{te}}) t_{\mathrm{err},e} \tag{B19}$$

Estimated time of arrival was then computed as

$$t_{\mathrm{eta}} = t_{\mathrm{mf}} + t_{\mathrm{err}} \tag{B20}$$

Appendix C

Pilot Instructions and ATC Clearances

Scenario Description

General. In this scenario, you will be simulating the final cruise and descent segments of a flight into the Denver terminal area. Air traffic controllers at NASA Ames will be simulating the pertinent high- and low-altitude en route sectors of the Denver ARTCC, as well as the Denver TRACON. Computer-generated pseudo aircraft will be used to represent other air traffic in the scenario. Pseudo pilots at computer terminals at Ames will provide voice communications for the computer-generated traffic and control the motion of the aircraft as directed by the air traffic controllers. All airspace and procedures simulated in this scenario, with the exception of the new 4D procedures, will be patterned after present-day Denver operations.

Initial conditions. At the start of the scenario, you will be in cruise at flight level 310, Mach 0.74, westbound on jet route 114. Your programmed flight plan will take you to runway 26L at Denver Stapleton International Airport via the KEANN arrival. Approximately 5 minutes into the flight, you will be instructed to contact Denver Center and initiate communications with the controllers at NASA Ames. Your call sign is NASA 515.

Final conditions. The metering fix for the KEANN arrival route in this scenario is designated KEAMF in your navigation data base. It is the first way point of the STAR KE26L. The preassigned altitude and calibrated airspeed at this way point are 11 000 feet and 210 knots, respectively. This way point is actually located in Denver TRACON airspace and corresponds to the nominal point where traffic is vectored off the Denver VOR radial onto base leg for landing on runway 26. Unless instructed otherwise by the TRACON controller, you are to cross the KEAMF way point in a left turn following your preprogrammed STAR path. After you have crossed the way point, the scenario will be completed and the simulator will RESET. On several of the runs, a TRACON controller will instruct you to continue the flight to touchdown on runway 26L. For these conditions, we will be assisting Ames to evaluate their TRACON simulation and will not be flying time guidance.

Specific guidelines. While flying the TSRV simulator in this experiment the following guidelines should be observed:

1. You will be required to handle all communications with ATC in addition to flying the simulator.
2. Velocity-vector control-wheel steering (VCWS) will be used for manual control of the aircraft through the side-stick controller. At pilot discretion, horizontal and vertical autopilot navigation modes may be used during the flight. Autothrottle may *not* be used at any point during the flight.
3. An engineer will fly in the right seat to assist in the flight management system CDU operation and flap and gear deployment. You will be briefed on the CDU capabilities and may operate the unit if desired. This is *not* an experiment to evaluate the CDU. Comments on the operation of the unit, however, will be solicited at the conclusion of the simulation.
4. Fly this mission as you would a revenue airline flight. Do not make sudden or abrupt maneuvers which would disturb the passengers and avoid throttle and speed brake activity that would waste fuel.

ATC Clearances

The following clearances and procedures are designed to take full advantage of the unique capabilities of a 4D-equipped aircraft. The 4D aircraft in this simulation will be capable of

1. Meeting a time clearance at the metering fix.
2. Path stretching to absorb a time delay.
3. Area navigation (RNAV).

There are six clearances which may be used to control the arrival time of a 4D-equipped aircraft. Each clearance is outlined in terms of its purpose, context, and use. The example phraseology represents the minimum information which must be communicated to complete each clearance.

Time clearance

Purpose: The TIME clearance transfers the responsibility of meeting a metering fix time to the pilot. It allows the pilot to use the on board flight management computer (FMC) to optimize the descent. The pilot selects the speeds necessary to meet the clearance and performs the descent at his discretion (all descents will be to the metering fix at a final altitude and speed of 11 000 ft and 210 KIAS).

Context: In general, the TIME clearance is issued by ATC prior to the top of descent. Implicit to the command is a clearance to descend at the pilot's discretion. It is to the aircraft's advantage to receive the TIME clearance as early as possible to plan the most efficient descent. When practical, the controller should issue the TIME clearance soon after the traffic manager sets the schedule.

Use: The TIME clearance may be issued or amended at any time; however, the number of amendments should be kept to a minimum. This clearance is only to be used when the 4D aircraft is established on a path known to both the pilot and controller (e.g., jet airway, DIRECT TO WAY POINT, or ROUTE INTERCEPT). If the path is changed (e.g., new routing or free vectoring), the time command should be confirmed. If the metering time is not achievable by speed control alone (i.e., the 4D aircraft's scheduled arrival time is outside of the controller's time range bar and pilot's time box), an altitude change and/or vector may be added to achieve the desired delay.

Example:

> "NASA 515,
> CLEARED FOR THE (KEANN/DRAKO) ARRIVAL,
> CROSS METERING FIX AT (specified time, min:sec)"

Cruise speed clearance

Purpose: The CRUISE SPEED clearance constrains the pilot to fly an ATC-specified cruise speed until further advised by ATC or the top of descent is reached. This clearance is used to resolve local traffic conflicts that would occur if the 4D aircraft were to continue cruise at its present speed.

Context: In general, this clearance will be given after ATC has assigned a metering time. Although the TIME clearance gives the pilot discretion to select his cruise/descent speed profile to meet the time, ATC may need to constrain the cruise speed to avoid a conflict prior to the metering fix. In some cases, prior to the issuance of a TIME clearance, ATC may issue a speed change to avoid a conflict with a departure or overflight.

Use: The CRUISE SPEED clearance may be issued or amended at any time prior to the top of descent. It is intended to be used in conjunction with a TIME clearance to avoid local traffic conflicts. The pilot is to comply with the speed clearance until ATC amends the speed or until the pilot approaches the top of descent necessary to meet the TIME clearance based upon the amended cruise speed. As the pilot of the 4D aircraft approaches his desired top of descent for the assigned time (based upon the CRUISE SPEED clearance), he should advise ATC and may begin the descent at his discretion and at his desired speed.

Example:

> "NASA 515,
> REDUCE (INCREASE) SPEED TO (knots or Mach)
> FOR SEQUENCING"

Altitude clearance

Purpose: The ALTITUDE clearance is used to change the aircraft's cruise altitude to either avoid a local conflict or to shift the aircraft's range of possible arrival times along a route.

Context: It is to the aircraft's advantage to establish its final cruising altitude as early as possible to plan the most efficient descent. An ALTITUDE clearance may be beneficial to a 4D aircraft if it is helpful in clearing the 4D aircraft's path of potential conflicts thus allowing the 4D aircraft the maximum flexibility in planning its descent.

Use: This clearance may be issued by ATC any time prior to the top of descent. A new cruise altitude may be assigned before or after a TIME clearance is issued. This clearance requires the pilot to maintain the cleared altitude until further advised by ATC or until the pilot approaches the top of descent necessary to meet an assigned time (based on the amended cruise altitude). As the pilot of the 4D aircraft approaches his desired top of descent, he should advise ATC and may begin the descent at his discretion.

Example:

> "NASA 515,
> DESCEND (CLIMB) AND MAINTAIN (flight level)"

Direct to way point clearance

Purpose: The DIRECT TO WAY POINT clearance (also known as DIRECT TO or WAY POINT CAPTURE) allows the controller to create a direct path from the aircraft's present position and course to a way point on a defined route (e.g., jet airway). The new path then follows the defined route. This is the most precise clearance for stretching or shortening an aircraft's path. It may also be used to resolve a local conflict between a pair of aircraft.

Context: For the majority of cases, this clearance is only used once an aircraft is off a route and is being vectored back onto a route. However, it is conceivable that a DIRECT TO WAY POINT clearance may be used to take an aircraft off one route and onto another.

Use: This clearance may be issued to aircraft that are both on and off defined routes. It may also be used in conjunction with a TIME clearance or a TIME DELAY VECTOR clearance. The controller may advise an initial heading to turn to so that the aircraft may be directed toward the desired way point. However, once the aircraft is cleared direct to a way point, the pilot is free to follow his onboard guidance. The pilot is required to turn in the direction indicated by ATC.

Example:

"NASA 515,
TURN (RIGHT/LEFT) HEADING (degrees),
PROCEED DIRECT TO (way point)"

Route intercept clearance

Purpose: The ROUTE INTERCEPT clearance allows the controller to direct an off-route aircraft onto a defined route (jet airway). This clearance anticipates a direct path from the aircraft's current position to the desired route while using the aircraft's current course to intercept the route. This clearance differs from the DIRECT TO clearance in two ways: it does not define the intercept point on the new route; and it does not involve an initial turn to intercept.

Context: This clearance is designed specifically for a non-RNAV-equipped aircraft. However, it is conceivable that a controller may wish to exercise this type of vectoring with the more sophisticated aircraft.

Use: This clearance may only be used when the aircraft's current course intercepts a route which is defined for ROUTE INTERCEPT. The ROUTE INTERCEPT clearance, like the DIRECT TO WAY POINT clearance may be used in conjunction with the TIME clearance.

Example:

"NASA 515,
PROCEED DIRECT TO (route)"

Time delay vector clearance

Purpose: The TIME DELAY VECTOR clearance transfers the responsibility of meeting an arrival time at the metering fix to the pilot when there is significant delay (i.e., a delay that cannot be absorbed by speed control alone). This clearance involves a path-stretching procedure, short of holding, which allows an aircraft to absorb large delays. This procedure is designed to take full advantage of the capability of 4D aircraft to assist the controller in distributing a delay.

Context: This clearance is useful once the aircraft's scheduled arrival time falls outside the aircraft range of possible arrival times (indicated by the controller's time range bar or the pilot's time box).

Use: The TIME DELAY VECTOR clearance combines a TIME clearance with vectoring instructions. If the scheduled arrival time is within a minute or so of the aircraft's range of possible times, the controller may issue vectoring instructions to the 4D aircraft allowing it to S turn along a route. The pilot may path-stretch within the "vectoring bounds" set by ATC until the pilot is satisfied that the scheduled time is achievable with speed control alone. Once the path stretching is completed, the pilot is required to notify ATC and continue along the route. If the scheduled arrival time requires significantly more delay, the controller may vector the 4D aircraft off of the route and clear the aircraft to return to the route at the pilot's discretion (once the pilot is satisfied that the scheduled time is achievable with speed control alone). ATC must define the return path with a DIRECT TO WAY POINT clearance. Once the path stretching is completed, the pilot is required to notify ATC and return to the route as per ATC instructions.

Examples: For fine path stretching along a route,

"NASA 515,
CLEARED FOR THE (KEANN/DRAKO) ARRIVAL,
CROSS METERING FIX AT (specified time, min:sec),
DELAY TURNS APPROVED WITHIN (miles) OF THE (route),
ADVISE WHEN BACK ON ROUTE"

"DENVER CENTER, NASA 515,
DELAY TURNS COMPLETE"

For gross path stretching using DIRECT TO WAY POINT,

"NASA 515,
CLEARED FOR THE (KEANN/DRAKO) ARRIVAL,
CROSS METERING FIX AT (specified time, min:sec),
TURN (RIGHT/LEFT) HEADING (degrees) TO ABSORB DELAY,
THEN CLEARED DIRECT TO (way point) AT YOUR DISCRETION,
ADVISE WHEN INBOUND TO (way point)"

"DENVER CENTER, NASA 515,
HEADING DIRECT TO (way point)"

Appendix D

Pilot Questionnaires

Post-Run Questionnaire

1. Please rate the following 4D-related display elements as to their usefulness in flying the 4D trajectory.

Display element	Least useful				Most useful
I. Vertical situation display					
a) Speed schedule	1	2	3	4	5
b) Vertical trajectory	1	2	3	4	5
c) Altitude error	1	2	3	4	5
d) 4D energy error bug	1	2	3	4	5
e) 4D energy error rate	1	2	3	4	5
f) Time window	1	2	3	4	5
g) Required time (RTA)	1	2	3	4	5
h) Estimated time (ETA)	1	2	3	4	5
i) Estimated time error	1	2	3	4	5
II. Primary flight display					
j) Airspeed	1	2	3	4	5
k) Altitude	1	2	3	4	5
l) Flight-path angle	1	2	3	4	5
m) Flight-path angle error	1	2	3	4	5
n) 4D energy error	1	2	3	4	5
o) 4D energy error rate	1	2	3	4	5
III. Navigation display					
p) Time box	1	2	3	4	5
q) Range/altitude arc	1	2	3	4	5

Comments:

2. Please rate the 4D clearances and procedures used during the previous flight.

	Low				High
a) Overall acceptability	1	2	3	4	5
b) Clarity	1	2	3	4	5
c) Work load relative to non-4D	1	2	3	4	5

Comments:

Final Questionnaire

Please indicate your response to the following statements:

1. The 4D ATC clearances used in this experiment would be acceptable for airline operations.

Strongly agree	1	2	3	4	5	6	Strongly disagree

2. I was comfortable with the 4D ATC clearances at the conclusion of this experiment.

Strongly agree	1	2	3	4	5	6	Strongly disagree

3. The 4D guidance used in this experiment would be acceptable for airline operation.

Strongly agree	1	2	3	4	5	6	Strongly disagree

4. I was comfortable with the 4D guidance at the conclusion of this experiment.

Strongly agree	1	2	3	4	5	6	Strongly disagree

References

1. Staff of NASA Langley Research Center and Boeing Commercial Airplane Co.: *Terminal Configured Vehicle Program—Test Facilities Guide.* NASA SP-435, 1980.
2. Tobias, Leonard; Volckers, Uwe; and Erzberger, Heinz: *Controller Evaluations of the Descent Advisor Automation Aid.* NASA TM-102197, 1989.
3. Erzberger, Heinz; and Nedell, William: *Design of Automated System for Management of Arrival Traffic.* NASA TM-102201, 1989.
4. Abbott, Terence S.; Nataupsky, Mark; and Steinmetz, George G.: *Effects of Combining Vertical and Horizontal Information Into a Primary Flight Display.* NASA TP-2783, 1987.
5. Steinmetz, George G.: *Development and Evaluation of an Airplane Electronic Display Format Aligned With the Inertial Velocity Vector.* NASA TP-2648, 1986.
6. Vicroy, Dan D.: Guidance Concepts for Time-Based Flight Operations. *Aircraft Trajectories, Computation—Prediction—Control, Volume 2—Air Traffic Handling and Ground-Based Guidance of Aircraft,* AGARD-AG-301, Vol. 2, May 1990, pp. 24-1–24-12.
7. Davis, Thomas J.; and Green, Steven M.: *Piloted Simulation of a Ground-Based Time-Control Concept for Air Traffic Control.* NASA TM-101086, 1989.
8. Williams, David H.; and Knox, Charles E.: 4D Descent Trajectory Generation Techniques Under Realistic Operating Conditions. *Aircraft Trajectories, Computation—Prediction—Control, Volume 2—Air Traffic Handling and Ground-Based Guidance of Aircraft,* AGARD-AG-301, Vol. 2, May 1990, pp. 25-1–25-22.
9. Knox, Charles E.; and Cannon, Dennis G.: *Development and Test Results of a Flight Management Algorithm for Fuel-Conservative Descents in a Timed-Based Metered Traffic Environment.* NASA TP-1717, 1980.

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16. Abstract

Advanced air traffic control (ATC) systems are being developed which contain time-based (four-dimensional) trajectory predictions of aircraft. Airborne flight management systems (FMS) exist or are being developed with similar 4D trajectory-generation capabilities. Differences between the ATC-generated profiles and those generated by the airborne 4D FMS may introduce system problems. A simulation experiment was conducted to explore integration of a 4D-equipped aircraft into a 4D ATC system. The NASA Langley Transport Systems Research Vehicle cockpit simulator was linked in real-time to the NASA Ames Descent Advisor ATC simulation for this effort. Candidate procedures for handling 4D-equipped aircraft were devised and traffic scenarios established which required time delays absorbed through speed control alone or in combination with path stretching. Dissimilarities in 4D speed strategies between airborne and ATC-generated trajectories were tested in these scenarios. The 4D procedures and FMS operation were well received by airline pilot test subjects, who achieved an arrival accuracy at the metering fix indicated by a time error with standard deviation of 2.9 seconds. The amount and nature of the information transmitted during a time clearance were found to be somewhat of a problem using the voice radio communication channel. Dissimilarities between airborne and ATC-generated speed strategies were found to be a problem when the traffic remained on established routes. It was more efficient for 4D-equipped aircraft to fly trajectories with similar, though less fuel-efficient, speeds which conform to the ATC strategy. Heavy traffic conditions, where time delays forced off route path stretching, were found to produce a potential operational benefit of the airborne 4D FMS.

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