Pilot Evaluation of Population-Minimal Ground Tracks in the Airport Community

Richard DeLoach* and Jacob A. Houck†
NASA Langley Research Center, Hampton, Virginia

Advanced cockpit avionics systems now under development at NASA Langley Research Center will provide the means for effectively utilizing microwave landing systems technology to achieve a number of important objectives in the near-terminal airspace. A simulator study has recently been completed at NASA Langley Research Center in which guest pilots from a number of airlines were asked to fly curved ground tracks designed to avoid population centers in four airport communities. Eight two-man crews of commercial line pilots and three NASA crews each evaluated a total of eight departures and eight approaches on the basis of such factors as workload, safety, passenger acceptance, controllability, and piloting skill. Various physical measurements were also made, including cross-track errors, altitude errors, bank angles, and fuel flow rates. Half of the trajectories were curved and designed to be population-minimal, and half were designed to represent conventional ground tracks. The objective of the study was to determine if statistically significant differences could be detected between curved and conventional ground tracks on the basis of these parameters.

Introduction

NASA Langley Research Center is conducting flight management research broadly aimed at improving transport aircraft operations in the evolving National Airspace System.[1,2,3] Advanced cockpit avionics systems now under development at Langley, including CRT displays and new flight control systems, will provide the means for effectively utilizing microwave landing system (MLS) technology to achieve a number of important objectives in the near-terminal airspace. Among these objectives are reduced noise impact from ground tracks that avoid population centers and optimized metering and spacing from path-stretching, curved trajectories.

While it is clear that the technology is rapidly developing that will permit aircraft to fly complex trajectories in the near-terminal area, the impact of such flight operations on the piloting function is less clear. A potentially greater workload and operational complexity, combined with a possible adverse passenger reaction to maneuvers in the near-terminal airspace, may cause line pilots to resist unconventional ground tracks, even if MLS technology makes it possible to fly them. Furthermore, it has not been established quantitatively how fuel use rates for curved paths flown in an MLS environment will compare with those associated with conventional ground tracks. Thus, while certain benefits can be anticipated from the curved trajectories that MLS technology will permit in the near-terminal airspace, the costs associated with those trajectories, measured in terms of subjective pilot reaction as well as direct operating costs, have not been quantified.

This paper describes a simulation study designed to quantify the subjective reaction of commercial line pilots to conventional and curved ground tracks. The objective was to determine if a statistically significant difference exists between line pilots' subjective reactions to curved MLS-type paths and their reactions to paths that are commonly flown today without MLS.

Crews of commercial jet transport line pilots from a number of airlines volunteered to fly curved and conventional ground tracks in the NASA Langley Transport Systems Research Vehicle (TSRV) Simulator, a Boeing 737 simulator configured with avionics and flight control systems designed to take full advantage of MLS guidance. The pilot-in-command for each crew was asked to use a seven-point category scale to subjectively evaluate a mix of conventional and curved trajectories on the basis of such factors as workload, safety, passenger acceptance, controllability, and piloting skill required. In addition to these subjective ratings, various physical measurements of piloting performance were also made for both kinds of trajectories. These included cross-track and altitude errors, bank angles, and roll rates. Fuel consumption rates were also measured for all trajectories.

In addition to the commercial line pilots, NASA test pilots with considerable flight experience using the experimental avionics featured in this test also flew the conventional and curved trajectories. While the subjective reaction of the commercial line pilots was of greater interest than the subjective reaction of the NASA test pilots, the piloting performance of the test pilots served as a baseline. In cases where a statistically significant difference in piloting performance was found to exist between conventional and curved trajectories flown by the commercial line pilots, the NASA test pilot data were used to infer the extent to which these differences might be attributable to lack of experience with the experimental avionics and flight controls.

TSRV Simulator

Figure 1 shows the interior of the TSRV simulator used in this study. The simulator[1,4] includes a nonlinear mathematical model of a Boeing 737-100 aircraft, complete with landing gear dynamics, gust and wind models, radio navigation system models, and instrument and microwave landing system models. In addition, automatic flight control and navigation control functions have been simulated. This simulator cockpit is outfitted with advanced control and electronic display systems. These include an advanced guidance and control system (AGCS), an electronic attitude director indicator (EADI), an electronic horizontal situation indicator (EHSI), and a navigation control and display unit (NCDU).

Received Aug. 14, 1986; presented as Paper 86-2074 at the AIAA Atmospheric Flight Mechanics Conference, Williamsburg, VA, Aug. 18-20, 1986; revision received March 9, 1987.

*Research Scientist.

†Group Leader for Special Projects. Associate Fellow AIAA.

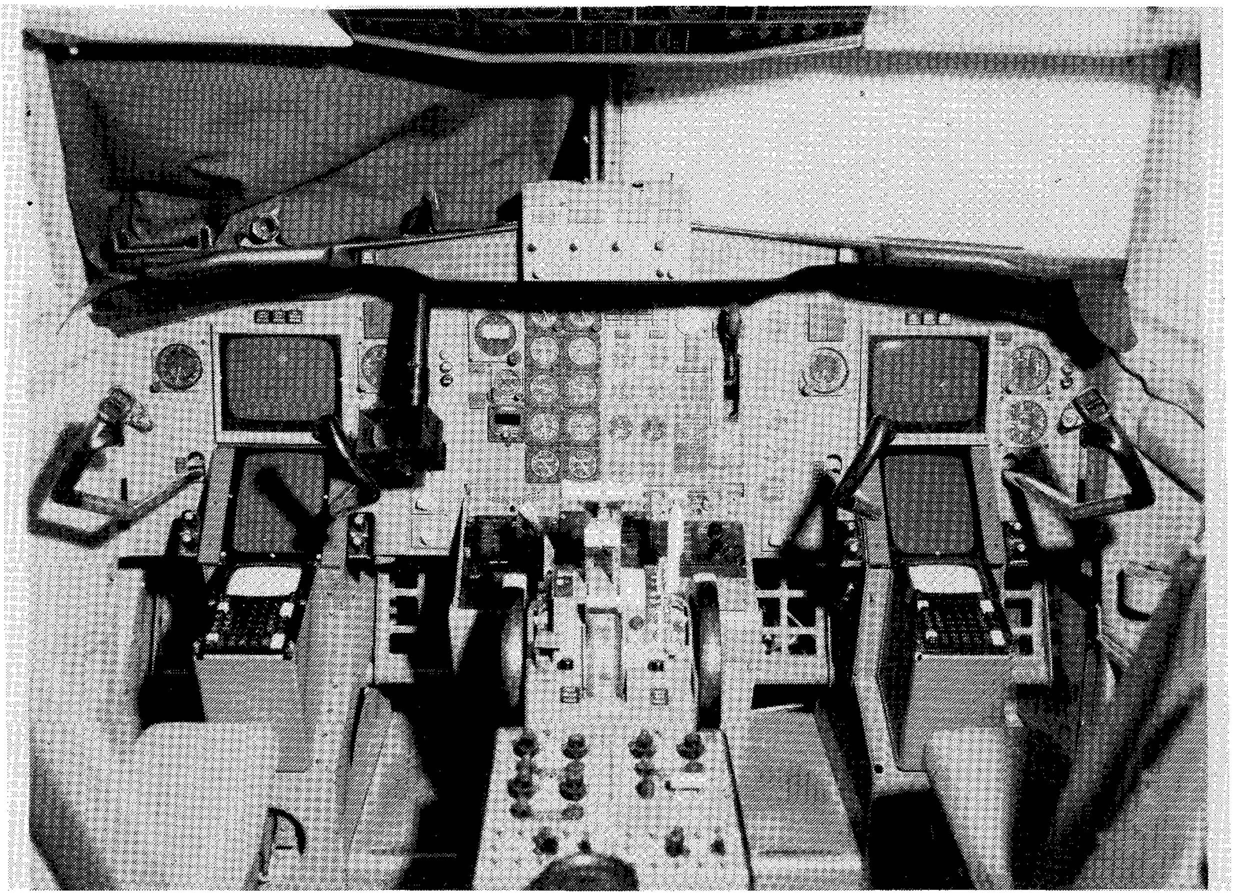

Fig. 1 TSRV simulator cockpit.

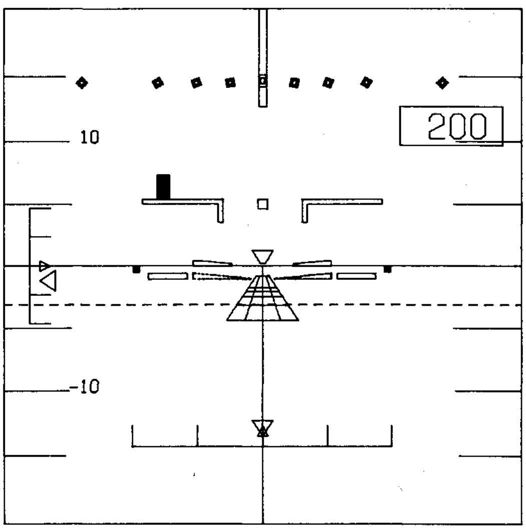

Fig. 2 Electronic attitude director indicator.

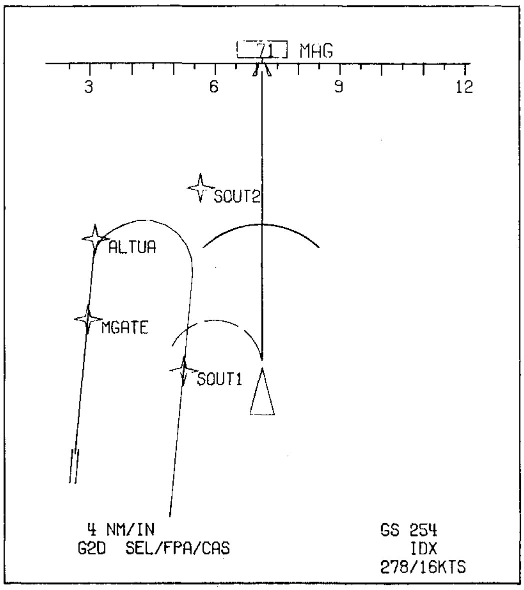

Fig. 3 Electronic horizontal situation indicator.

For this study, the TSRV simulator was configured in the following manner. During an arrival, the pilot flew the aircraft using the velocity control-wheel steering (VCWS) and autothrottle control systems. For a departure, the pilot used the manual throttle control system instead of the autothrottles. The control-wheel steering mode is a computer-augmented manual control mode that allows the pilot to input rate commands through the column and/or wheel and to hold attitude when a zero-rate is commanded. In particular, VCWS[5] allows the pilot to control the orientation of the aircraft's velocity vector as defined in an inertial axes system. Vertical flight-path angle and track angle are the principal orientations controlled by VCWS with the addition of a bank-angle hold mode for bank angles exceeding 2.5 deg. The status of the flight-path angle is available to the pilot on the EADI display (Fig. 2),[6] and the track angle is available on the EHSI display (Fig. 3).[7] In addition, a curved trend vector (Fig. 3) is available on the EHSI display, predicting where the aircraft will be located 30, 60, and 90 s ahead in time based on the aircraft's present ground speed and bank angle, thus a very useful symbol when flying curved ground tracks and when at-

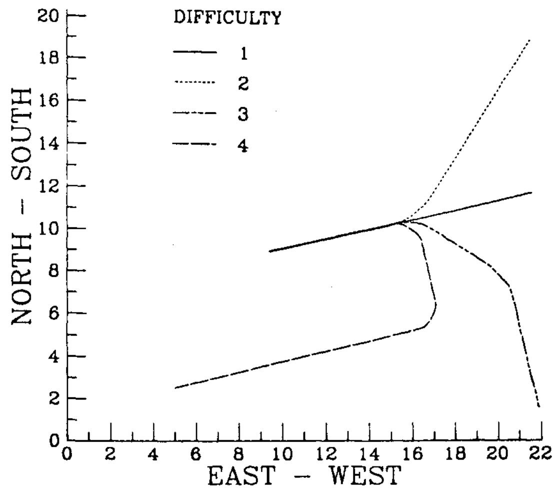

Fig. 4 Conventional ground tracks.

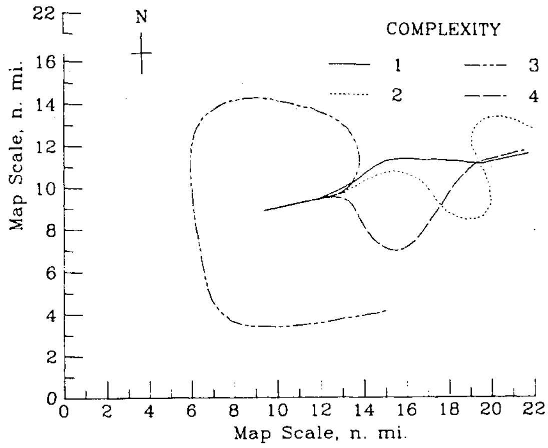

Fig. 5 Curved approach tracks.

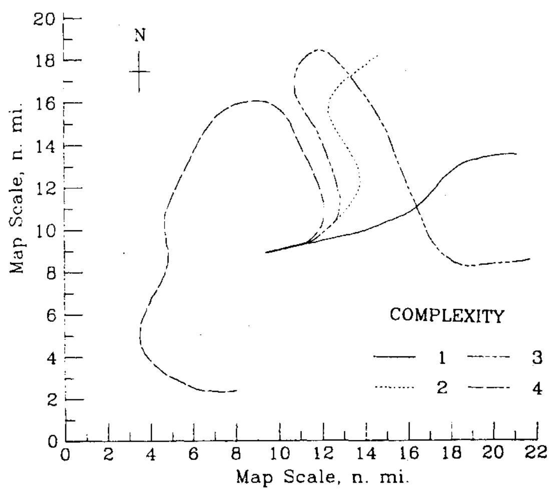

Fig. 6 Curved departure tracks.

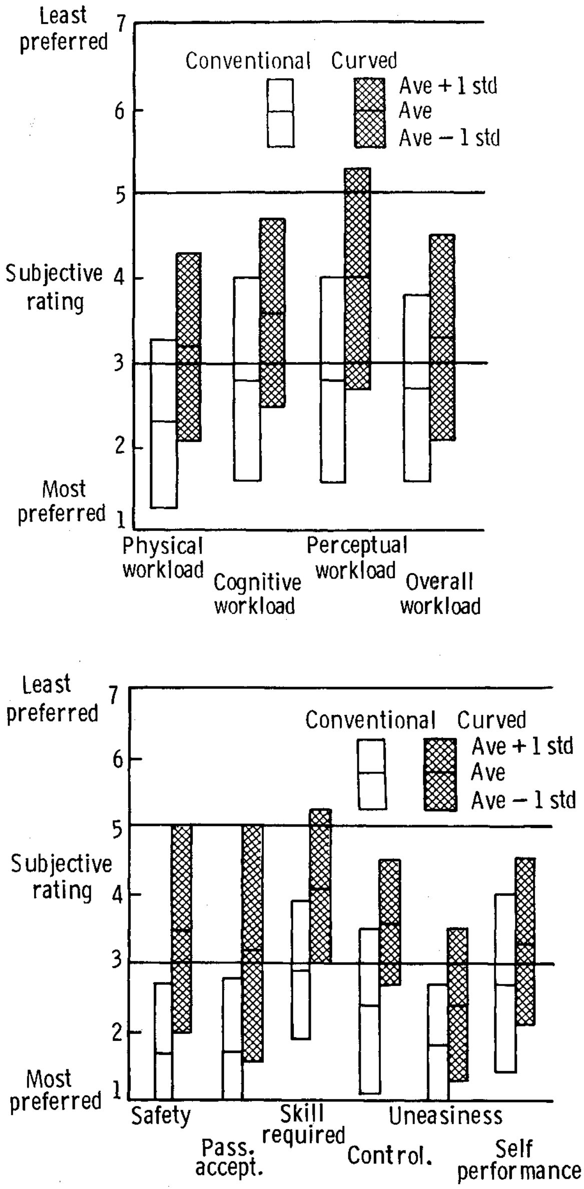

Fig. 7 Subjective ratings of approach sheet.

tempting to arrive at a certain position at a specified time. Finally, an altitude-range arc symbol (Fig. 3) is available on the EHSI display, indicating where along the ground track the aircraft will reach a specified altitude if a given vertical flight-path angle is maintained.

Tests

There were three phases to the tests described in this paper. The first phase involved defining the curved and conventional ground tracks that would be evaluated by the guest pilots. In the second phase, the guest pilots received training on the advanced avionics and flight control systems they would use in the Langley TSRV simulator. The final phase comprised approaches and departures flown for evaluation.

Conventional Ground Tracks

Four ground tracks were selected as representative of conventional aircraft approach and departure paths. These were designed to cover a range of piloting difficulty commonly encountered in normal flight operations. The least demanding conventional track was a simple straight extension of the runway centerline with no turns. Another track was defined with a single 45 deg turn five miles from the end of the runway, and a third track was similar to the second except that it had two 45 deg turns separated by five miles. Finally, a standard downwind/base leg/final track was defined which was composed of five-mile segments separated by 90 deg turns. Figure 4 illustrates these conventional ground tracks. These same four ground tracks were flown on approach and departure.

Curved Ground Tracks

In principle, any arbitrarily shaped curved tracks could have been used for comparison with the conventional tracks

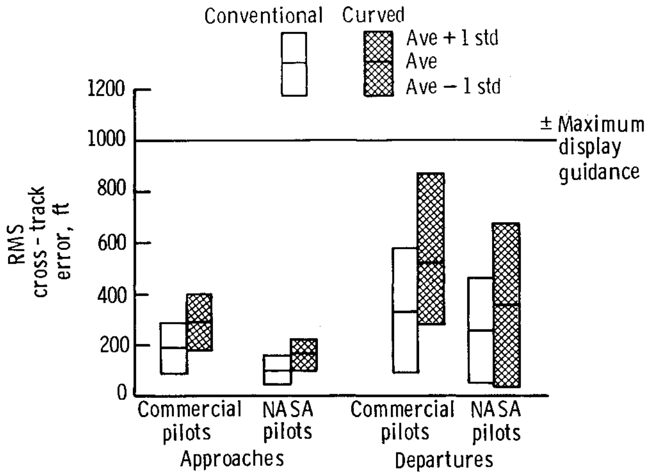

Fig. 8 Comparisons of rms cross-track errors averaged across crews.

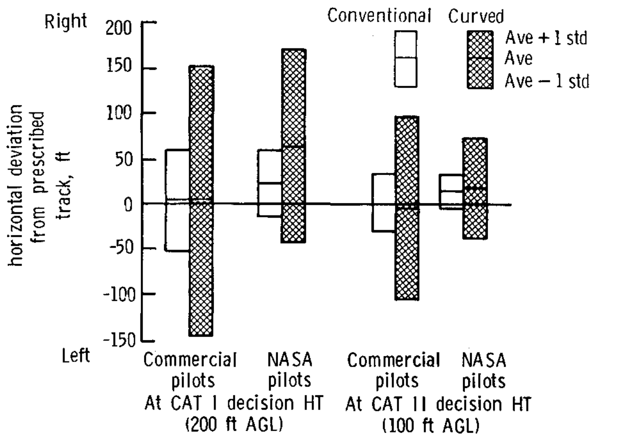

Fig. 9 Fixed-point approach cross-track errors averaged across crews.

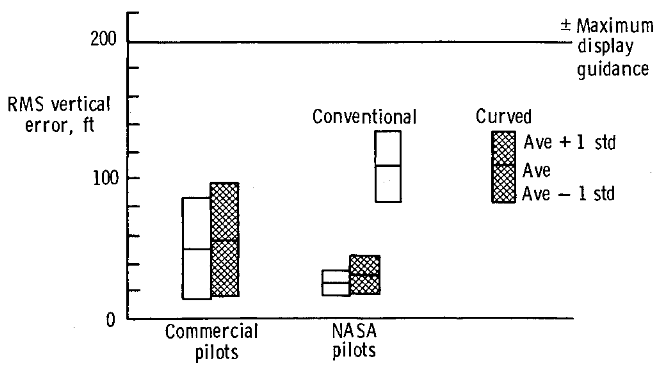

Fig. 10 Root-mean-square vertical approach errors averaged across crews.

previously described. But if the tracks were completely arbitrary, no conclusions could be drawn about curved tracks likely to be encountered in a mature MLS environment. Considerable attention was therefore paid to the definition of curved tracks used in this study, with the goal of selecting tracks that would cover a wide range of operational complexity and yet be representative of curved tracks likely to achieve some operational benefit in an MLS environment. It was decided to define curved ground tracks designed to minimize noise impact by avoiding population centers in specific airport communities. To design these tracks, the actual population distributions around four representative U.S. airports were determined from 1980 U.S. Census data. These airports (LaGuardia, Miami, San Antonio, and Sioux Falls) were selected to represent a wide range of population densities. Noise impact-minimal ground tracks were defined with the aid of an airport community noise model described in Refs. 2 and 3 as follows.

The ground tracks were defined by arbitrarily selecting airport community entry/exit points and determining the ground tracks overflying the smallest total number of people from these points to the ends of the runways. The community entry/exit points were selected by simply extending each runway centerline until it intercepted the side of a 20-mile square centered on the airport. The space within this square was represented mathematically as a network in "people-space." With this representation, a population-minimal ground track connecting the end of any runway with any of the selected community entry/exit points could be defined by solving the classic shortest path problem for this population network. Such a path is not generally the shortest geographical path, but it is the path guaranteed to overfly the smallest number of people between specified start and end points, since the shortest path problem is known to have a global solution. And these population-minimal paths are, in general, curved, except for the uninteresting case of a uniform population distribution.

A total of over 40 population-minimal paths were defined at the four airports by means of the shortest path method described here. From these, four approach tracks (Fig. 5) and four departure tracks (Fig. 6) were selected for the study, ranging from paths that featured shallow, gradual curves to paths that were considerably more serpentine.

There were thus a total of 16 flight tracks evaluated by each crew, eight approaches and eight departures. Half of the approaches followed conventional tracks and half followed population-minimal tracks. Departures followed a similar pattern.

Crew Training

Eight two-man crews (captain and first officer) were invited to participate in these tests. Each participant completed a training program designed to familiarize him with the advanced display and control systems located in the TSRV simulator.

The training program is made up of several techniques commonly found in self-paced instructional programs. These are pilot training manuals, a series of computer-based education lessons and exercises, in-simulator instruction, and finally, practice flights in the simulator. The training program is discussed in detail in Refs. 6–9.

Test Procedure

The guest crews consisted of practicing line pilots (one captain and one first officer) from commercial airlines. In addition to the eight airline crews, three crews consisting of NASA test pilots and a NASA simulator training coordinator also participated in the tests. The data from the NASA pilots are analyzed separately from the guest airline pilot data.

The ground tracks depicted in Figs. 4–6 were programmed into the flight computer of the TSRV simulator so that each one could be commanded to appear on the EHSI map display. The presentation order was balanced across crews using a Latin Square design in order to compensate for learning and fatigue effects.[9] The piloting task consisted of landing the aircraft or taking off while minimizing the deviations between the actual aircraft position and the programmed ground track as displayed on the EHSI. A further piloting task involved hitting certain crossing altitude and speed targets displayed as waypoints on the EHSI map display. Unlike the approaches, in which an initial cruise altitude and a 3-deg glideslope were prescribed, no vertical profile constraints were placed upon the crew for departures. The actual vertical profile flown by the crew on departure was determined by the crew, with the only constraint being that certain crossing altitudes had to be achieved. It was felt that this climbout flexibility was more realistic than requiring the crew to fly a rigidly prescribed vertical profile on departure. Reference 9 contains a detailed discussion of the landing and takeoff procedures and pilot callouts used in this study.

On approach, the initial conditions consisted of level flight approximately 10 miles from the airport at a radar altitude of 1,670 ft with gear up, 15-deg flaps, an airspeed of 170 knots, and autothrottles engaged. For departure, the initial conditions were zero altitude, 15-deg flaps, 30 knots starting roll from brake release, gear down, and autothrottle disengaged.

Data Recording

The physical and subjective data were recorded in the forms of time-history strip charts, digital data, and pilot questionnaires. The physical data included the following parameters: cross-track error, vertical path error, altitude, rate of climb, airspeed, pitch angle, bank angle, heading, pitch rate, roll rate, yaw rate, wheel and column inputs, thrust, fuel flow rate, and fuel used. The run time, distance along path, X and Y position of the aircraft, and flap setting were also recorded.

In addition to the physical data described, a rating sheet was administered to the pilot-in-command after each trajectory was flown. The rating sheet[9] contained 10 seven-point scales featuring bipolar adjective pairs that dichotomized the following ground track flight descriptors: 1) physical workload, 2) cognitive workload, 3) perceptual workload, 4) overall workload, 5) safety, 6) anticipated passenger acceptance, 7) skill required, 8) controllability, 9) uneasiness, and 10) piloting performance.

A list of rating sheet definitions[9] was presented to the pilot before the tests began, and this definitions list was available to him as he filled out the rating sheets after each trajectory. The pilots were instructed specifically to neglect air traffic control considerations in making their safety judgments; i.e., they were asked to assume that theirs was the only aircraft in the terminal airspace. This restriction was imposed simply to reduce the number of variables the pilot had to consider in making this important judgment and because the simulation did not include the tower communications which would accompany a multiaircraft terminal airspace environment.

Analysis and Discussion

The primary objective of this study was to determine if a significant difference could be detected between pilot subjective reaction to the curved paths that a mature MLS system permits and conventional paths flown without MLS near-terminal guidance. Differences in piloting performance between the two cases, measured by position errors and roll dynamics along the ground track, were also quantified, and fuel use rate comparisons were made. Separate analyses for approaches and departures were performed; i.e., comparisons were made for conventional approaches vs curved approaches and conventional departures vs curved departures. Comparisons were also made between curved approaches and departures and conventional approaches and departures. In each case, the data for each subjective rating and physical measurement were averaged across all eight guest pilot crews, and calculations were performed to see if statistically significant differences could be detected between these averages.

Results of Pilot Ratings

The seven-point category scale ratings made by the pilot-in-command after each flight were converted to a number in the range of 1–7 for each subjective descriptor, where a 1 represented the most favorable rating (lowest workload, least skill required, etc.) and a 7 represented the least favorable rating. Average ratings across all crews were then computed for each of the subjective descriptors on the pilot survey questionnaire for each of the four flight track categories. Each average was computed from four tracks by eight crews, or 32 measurements.

One must exercise care in interpreting these data. In particular, one must not draw inferences strictly from the fact that for a given subjective descriptor, the average pilot rating was higher for one type of flight path than another. Except for pure coincidences, the averages of two sets of measurements will generally be different from each other, and one average will be larger than the other. The relevant question therefore is not whether a difference exists, but whether that difference is statistically significant.

A statistical test described in Ref. 9 was applied to the data to see if differences in the average subjective rating across crews from one type of flight path to another was significant (at the 95% confidence level) for each of the 10 subjective rating criteria used in this study. Note that to say that the difference in rating for one type of path compared to another is "significant" is to say only that a difference in rating can be detected in the data with a given level of confidence. This does not indicate how important the magnitude of the difference is, however. In the remainder of this report, when it is said that no difference is detected between path types for a particular parameter such as workload or cross-track error, it means that differences between averages across all crews are not statistically significant at the 95% confidence level.

As one might expect, the guest pilots reported no difference in their evaluation of conventional approaches vs conventional departures. That is, they did not perceive any difference in workload, safety, anticipated passenger acceptance, piloting skill required, aircraft controllability, or personal uneasiness between conventional approaches and departures of the kind they are accustomed to flying, nor did the evaluations of their own performance differ between conventional approaches and departures. A similar result was obtained for comparisons of curved approaches and curved departures; no statistically significant differences were reported for any of the ratings except safety, for which the curved departures were rated slightly safer than the curved approaches (with average ratings of 2.7 vs 3.5 on a 1–7 scale, where 1 is the safest rating).

While few statistically significant differences were observed in the comparisons of approaches to departures for either curved or conventional paths, differences were observed for the more interesting case of curved paths compared to conventional paths. This was especially evident in the approaches, for which curved paths were rated less desirable than conventional paths in every category. Figure 7 compares the average guest pilot ratings of conventional vs curved approaches, including standard deviations about the averages. All differences revealed in this figure are resolvable at the 95% confidence level.

Two horizontal lines divide the category scale of Fig. 7 into three equal regions, the "best" (or lowest) 1/3 of the scale, the "worst" (or highest) 1/3 of the scale, and a middle 1/3 of the scale. Average ratings of conventional approaches fall in the bottom (or "best") third of the figure for every rating category, while only one of the average ratings of curved approaches, pilot uneasiness, falls in this region. The remainder of the curved approach average ratings fall in the midregion between the "worst" and "best" ends of the scale.

The spread in the approach path rating data is also interesting. Referring again to Fig. 7, the ± 1 standard deviation bands drawn about the mean rating values illustrate that most of the conventional approach ratings were at the "best" end of the scale (with some midscale ratings), while most of the curved path ratings fell in the midscale region, except for the pilot uneasiness ratings previously noted. None of the ratings of conventional approach paths overlapped into the high (or "worst") region of the scale with their ± 1 standard deviation bands, while the 1 standard deviation bands for perceptual workload and piloting skill for the curved approaches did overlap slightly into this region.

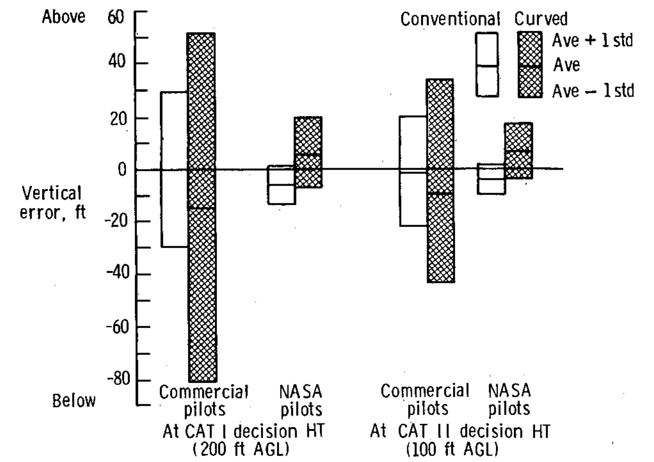

Fig. 11 Fixed-point vertical approach errors averaged across crews.

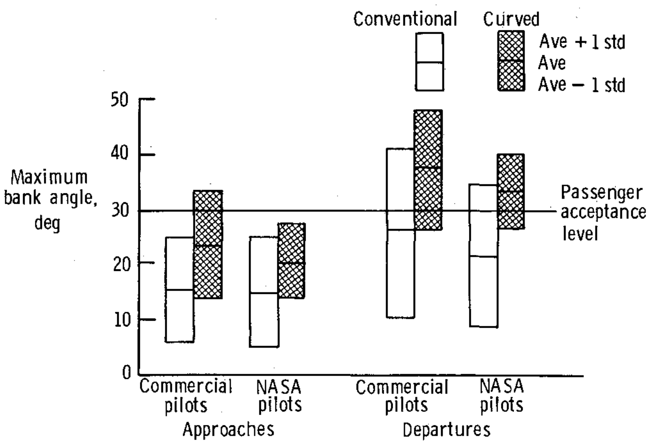

Fig. 12 Maximum bank averaged across crews.

By contrast with approaches, very few differences were reported between curved and conventional departures. The only statistically significant rating differences observed between curved departures and conventional departures were in anticipated passenger acceptance (3.3 for curved paths vs 2.1 for conventional paths) and piloting skill required (3.8 vs 3.0). No statistically significant difference between curved and conventional departures was detected in the average pilot ratings of physical workload, cognitive workload, perceptual workload, overall workload, safety, controllability, or uneasiness, nor did the pilots report any difference in their own piloting performance between curved and conventional departures.

Summarizing the subjective evaluation of curved vs conventional flight paths, it is clear that the greatest difference in subjective reaction occurred for approaches, with curved approaches judged less desirable than conventional approaches. For departures, the pilots seem to be saying that curved paths will require more piloting skill to fly than conventional paths, and passengers are likely to prefer conventional departures, but that curved departures involve no higher workload than conventional departures, nor are they any less safe to fly, nor do they cause more difficulty in controlling the aircraft. Curved departures did not make the pilots feel any more uneasy than conventional departures, and the pilots rated their own performance about the same for curved and conventional departures.

Physical Measurements

Measurements were made of vertical and cross-track errors to compare piloting performance for curved and conventional tracks on approach and departure. Maximum bank angles were also recorded, as were fuel use rates in lb/n.mi. As in the case of subjective ratings, calculations were performed to determine if differences in physical measurements from curved to conventional ground tracks were statistically significant at the 95% confidence level.

The difference between actual horizontal position and prescribed horizontal position is called cross-track error in this paper. It was measured 32 times/s on each flight. The root-mean-square (rms) average cross-track error along the entire flight path was then computed for every run. These were averaged across crews for each of the four classes of flight trajectory—conventional approaches and departures and curved approaches and departures.

For both approaches and departures, a statistically significant difference was observed between the crew-averaged rms cross-track errors for conventional paths vs curved paths, with the average cross-track errors for the curved paths higher than for the conventional paths. A similar result was found for the NASA pilots, although the NASA pilots tended to have somewhat smaller average cross-track errors than the commercial pilots and the standard deviations in the NASA pilot data are smaller than in the commercial pilot data, especially for approaches (Fig. 8).

While the curved path cross-track errors tended to be larger than those of the conventional path, both were a small fraction of the ± 2 n.mi. corridor width currently prescribed for aircraft using area navigation equipment in the near-terminal area.[10] The average cross-track error for curved approaches was only 294 ft, or less than 3% of the prescribed corridor width while, for the curved departures, the average cross-track error was 532 ft, or less than 5% of this corridor width. The corresponding numbers for the NASA pilots were 169 ft (2%) and 362 ft (3%). The relatively small cross-track errors are attributed to the advanced avionics and flight control systems of the TSRV simulator. Based upon comments from the guest pilots, the consensus was that this degree of tracking accuracy would be difficult to achieve with conventional avionics and flight controls.

In addition to rms cross-track errors, single-point cross-track error measurements (Fig. 9) were made on approach at the points along the ground track, where a 3-deg glideslope would place the aircraft at the category I and category II decision heights (200 and 100 ft above ground level, respectively). The commercial pilot data revealed no statistically significant differences between curved path and conventional path cross-track errors at either the category I or category II decision height. Furthermore, while there were exceptions in individual runs, the average cross-track errors at the category I and category II decision heights were well within the lateral confines of a typical extended runway, as required by the guidelines in Ref. 11.

Root-mean-square vertical position errors (Fig. 10) were computed analogously to the horizontal cross-track errors previously described, except that comparisons were made for approaches only, as no specific vertical profiles were prescribed for departures. No statistically significant differences were observed between curved path and conventional path rms vertical errors. As for the horizontal rms cross-track errors, the NASA pilots had lower average vertical errors and a smaller standard deviation in their results. This difference in both accuracy and precision is attributed to the greater experience of the NASA pilots, who had logged many flight hours prior to this experiment using the TSRV control and display systems.

Approach vertical errors measured at the category I and category II decision heights are presented in Fig. 11. As with the category I and category II cross-track errors, there were no statistically signficant differences between curved and conventional paths for the commercial pilots. While there were exceptions in individual runs, the average vertical deviation from glideslope at the category II decision point was within the guidelines prescribed in Ref. 11 for both conventional and

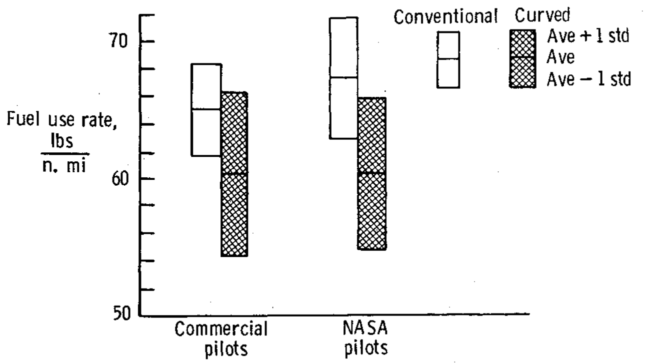

Fig. 13 Fuel consumption on departure averaged across crews.

curved paths. Standard deviations were smaller for the NASA pilots than for the commercial pilots, again suggesting that their greater experience with the TSRV control and display systems was a factor.

Because of its relevance to likely passenger acceptance, maximum bank angles were measured on approach and departure for both the curved and conventional paths (Fig. 12). The data reveal a difference on departure for both the commercial and NASA pilots, while on approach, differences were seen for the commercial pilots but not for the NASA pilots. The crew-averaged maximum bank angles on approach were below the 30-deg value commonly used as an industry standard for passenger acceptance. This was true for both conventional and curved approaches and for both the commercial and NASA crews. Crew-averaged bank angles on departure were higher than on approach, and while the average bank angles for conventional departures were below the 30-deg passenger acceptance criterion, the curved-path departures had crew-averaged maximum bank angles exceeding the 30-deg criterion for both the commercial and NASA crews.

The final physical variable to be discussed in this paper is the average fuel consumption rate, defined as the weight of the total fuel consumed along the path divided by the length of the path. No statistically significant differences were observed on approach between the fuel use rates for curved and conventional paths although, interestingly enough, the consumption rate was marginally lower for the curved paths than for the conventional paths in the case of the NASA pilots (about 1.3%, which is not statistically significant at the 95% confidence level).

A more interesting result occurred for the departures (Fig. 13) where, contrary to intuitive expectations, a statistically significant reduction in the fuel consumption rate was observed in going from the conventional to the curved paths. This was observed for both the commercial and NASA pilots. The commercial pilots used fuel at a rate that was 7.4% less for curved paths than for conventional paths, while for the NASA pilots, the fuel use rate was 10.4% less for curved paths than for conventional paths. The reduced fuel use rate for curved paths is attributed to the fact that lower throttle settings were used to negotiate the curves. For the conventional paths, which were characterized by long straight segments, there was more of a tendency to apply higher throttle settings.

Conclusions

A simulation study has been conducted in which eight two-man crews of practicing line pilots each used the NASA Langley Research Center Transport Systems Research Vehicle Simulator to fly 16 ground tracks comprised of eight departures and eight approaches. Three NASA crews also flew the same tracks. Half of the approaches and half of the departures were designed to avoid population centers in specific airport communities, while the other half were representative of conventional ground tracks. Calculations were made to determine if statistically significant differences could be detected between the commercial pilots' subjective evaluation of conventional paths and their evaluation of the curved, population-minimal paths. Evaluations were made on the basis of workload, safety, anticipated passenger acceptance, piloting skill required, controllability, uneasiness, and pilot self-performance. In addition to the subjective evaluations, tests were made for statistically significant differences between curved and conventional ground tracks on the basis of the following physical measurements: cross-track error, vertical error, maximum bank angle, and average fuel consumption rate.

The following conclusions are drawn:

1) For approaches, statistically significant differences were detected between the subjective evaluations of curved and conventional ground tracks for every category measured. In each case, conventional paths were rated more desirable than curved paths.

2) Curved departure paths were rated as less desirable than conventional paths for passengers.

3) Curved departure paths were judged to require more piloting skill than conventional departures.

4) No statistically significant difference was detected between curved and conventional departures with respect to pilot workload, safety, controllability, or pilot uneasiness.

5) The pilots evaluated their own performance as being the same for curved departures as for conventional departures.

6) Root-mean-square cross-track errors computed along the entire flight path were greater for curved paths than for conventional paths, but the advanced avionics and flight control systems of the TSRV simulator permitted even the curved tracks to be flown with rms cross-track errors less than 5% of the currently prescribed corridor widths in the near-terminal airspace.

7) No statistically significant difference was observed between curved path and conventional path cross-track errors at either the category I or category II decision height on approach.

8) Average cross-track errors at the category I and category II decision heights were within the lateral confines of a typical runway extended for both curved and conventional approach paths.

9) No significant differences were observed between curved path and conventional path rms vertical errors.

10) No significant difference between curved and conventional paths was observed in vertical errors measured at the category I or category II decision height.

11) The average maximum bank angles for curved approaches were less than the 30-deg level informally used as an industry standard for passenger acceptance, but average maximum bank angles exceeded this level for curved departures. The average maximum bank angles were less than 30 deg for conventional approaches and departures.

12) No statistically significant differences were detected between fuel consumption rates for curved approaches and conventional approaches.

13) For departures, a statistically significant difference was observed between fuel consumption rates for curved paths and conventional paths, with curved paths having the lower fuel use rate. Curved departures flown by commercial pilots resulted in a 7.4% reduction in the fuel use rate compared to conventional departures, while NASA pilots flying curved paths had average fuel use rates that were 10.4% less than those for conventional paths.

References

[1]Staff of NASA Langley Research Center and Boeing Commercial Airplane Company, "Terminal Configured Vehicle Program—Test Facilities Guide," NASA SP-435, 1980.

[2]DeLoach, R., Donaldson, J., and Johnson, M., "Airport-Noise Levels and Annoyance Model System's Reference Manual," NASA TM-87694, 1986.

[3]DeLoach, R., Donaldson, J., and Johnson, M., "Airport-Noise Levels and Annoyance Model User's Guide," NASA TM-87695, 1986.

[4]Houck, J. A., "A Simulation Study of Crew Performance in Operating an Advanced Transport Aircraft in an Automated Terminal Area Environment," NASA TM-84610, 1983.

[5]Steinmetz, G. G., "Simulation Development and Evaluation of an Improved Longitudinal Velocity-Vector Control-Wheel Steering Mode and Electronic Display Format," NASA TP-1664, 1980.

[6]Gandelman, J. and Holden, R., "A Pilot Training Manual for the Terminal Configured Vehicle Electronic Attitude Director Indicator," NASA CR-159195, 1980.

[7]Houck, J. A., "A Pilot Training Manual for the Terminal Configured Vehicle Electronic Horizontal Situation Indicator," NASA TM-81959, 1981.

[8]Houck, J. A. and Markos, A. T., "Development of a Multi-Media Crew-Training Program for the Terminal Configured Vehicle Mission Simulator," *Proceedings of the 1980 Summer Computer Simulation Conference*, Aug. 1980, pp. 377–382.

[9]DeLoach, R. and Houck, J. A., "Pilot Evaluation of Experimental Flight Trajectories in the Near-Terminal Area," AIAA Paper 86-2074, Aug. 1986.

[10]"Minimum Operational Performance Standards for Airborne Area Navigation Equipment Using VOR/DME Reference Facility Sensor Inputs," RTCA SC137, DOC. DO-180, *Radio Tech. Comm. Aeronaut.*, Sept. 1982.

[11]"Criteria for Approving Category I and Category II Landing Minima for FAR 121 Operations," AC 120-29, FAA Advisory Circular, Sept. 1970.