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Final-Approach Spacing Aids (FASA) Evaluation For Terminal-Area, Time-Based Air Traffic Control

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Symbols and Abbreviations

AAS	Advanced Automation System
A/C	aicraft
ATA	actual time of arrival
ATC	air traffic control
ANOVA	analysis of variance
ARTS	Automated Radar Terminal System
CAS	calibrated airspeed
CCS	cross-check scans
COA	Continental Airlines
CRT	cathode ray tube
CSM	centerline slot marker display format
CTAS	Center/Tracon Automation System
DICE	direct course error (time) DICE countdown display format
DEN	Denver VOR
df	degrees of freedom (statistical)
DTP	dynamic time based planner
ER	your effort required
ETA	estimated time of arrival
F	F test statistic (in ANOVA is ratio of mean squares to test for treatment effect)
$f(t)$	probability density function of t
$F(t)$	cumulative probability distribution of t
FAA	Federal Aviation Administration
FAF	final-approach fix
FASA	final-approach spacing aid
FAST	Final-Approach Spacing Tool
FDAD	full digital ARTS display
FE	frustration you experienced
FPL	full performance level
gate	point 1 mile outside final approach fix or 5 miles from runway threshold, whichever is farther
GM	graphic marker display format
GS	ground speed
IAE	interarrival time error of sequential pair of landing aircraft
IAE$'$	IAE equivalent for manual control without FASA
IAS	indicated airspeed

IFR	instrument flight rules
ILS	instrument landing system
IMC	instrument meteorological conditions
IOC	Kiowa VOR
KIAS	knots indicated airspeed
kts	knots
MAN	manual/ARTS III display format (no FASA)
MD	mental demand
MIT	Massachusetts Institute of Technology
MIP	minimum intercept point
MOTAS	Mission-Oriented Terminal Area Simulation
N	number of data points in sample
NASA	National Aeronautics and Space Administration
OAG	Official Airline Guide
OP	own performance satisfaction
ORF	location indentifier for Norfolk International Airport
P	resultant level of significance for treatment effect in ANOVA for specific experimental conditions
PACTAS	Predictive Approach Control Tactical Advisor System
PLSD	protected least significant difference
PPI	plan position indicator
ROT	runway occupancy time
s_0^2	pooled sample estimate of population variance obtained by pooling (weighted combining of) variances of several samples
SLT	scheduled landing time
STA	scheduled time of arrival
st dev	sample standard deviation
t	controller response time defined as difference between FASA indicated delivery time and actual turn or speed reduction message delivery time
TAATM	Terminal Area Air Traffic Model
TATCA	Terminal ATC Automation
TD	temporal demand
TIMER	traffic intelligence for the management of efficient runway scheduling
TLX	Task Load Index, a workload assessment procedure developed at NASA Ames Research Center
TMA	Traffic Management Advisor
TRACON	terminal radar approach control
TWA	Trans World Airlines

UAL	United Airlines
VHF	very high frequency
VMC	visual meteorological conditions
VOR	VHF ommidirectional radio range
$\overline{x}$	sample mean of data
	average vectors per aircraft learning effect applied to manual format
α	level of significance which is probability of committing a Type I error, namely probability of erroneously rejecting true null hypothesis
μ	population mean
$\mu_{170\,\mathrm{CSM}}$, $\mu_{210\,\mathrm{CSM}}$	for hypothesis testing IAE population (as opposed to sample) variance for, respectively, 170-knot-speed-procedure centerline slot marker format and 210-knot-speed-procedure centerline slot marker format
$\mu_{170\,\mathrm{DICE}}$, $\mu_{210\,\mathrm{DICE}}$	for hypothesis testing IAE population (as opposed to sample) variance for, respectively, 170-knot-speed-procedure DICE format and 210-knot-speed-procedure DICE format
$\mu_{170\,\mathrm{GM}}$, $\mu_{210\,\mathrm{GM}}$	for hypothesis testing IAE population (as opposed to sample) variance for, respectively, 170-knot-speed-procedure graphic marker format and 210-knot-speed-procedure graphic marker format
$\mu_{170\,\mathrm{MAN}}$, $\mu_{210\,\mathrm{MAN}}$	for hypothesis testing IAE population (as opposed to sample) variance for, respectively, 170-knot-speed-procedure manual marker format and 210-knot-speed-procedure manual marker format
σ	population standard deviation
σ^2	variance
$\sigma^2_{170\,\mathrm{CSM}}$, $\sigma^2_{210\,\mathrm{CSM}}$	for hypothesis testing IAE population (as opposed to sample) variance for, respectively, 170-knot-speed-procedure centerline slot marker format and 210-knot-speed-procedure centerline slot marker format
$\sigma^2_{170\,\mathrm{DICE}}$, $\sigma^2_{210\,\mathrm{DICE}}$	for hypothesis testing IAE population (as opposed to sample) variance for, respectively, 170-knot-speed-procedure DICE format and 210-knot-speed-procedure DICE format
$\sigma^2_{170\,\mathrm{GM}}$, $\sigma^2_{210\,\mathrm{GM}}$	for hypothesis testing IAE population (as opposed to sample) variance for, respectively, 170-knot-speed-procedure graphic marker format and 210-knot-speed-procedure graphic marker format
$\sigma^2_{170\,\mathrm{MAN}}$, $\sigma^2_{210\,\mathrm{MAN}}$	for hypothesis testing IAE population (as opposed to sample) variance for, respectively, 170-knot-speed-procedure manual marker format and 210-knot-speed-procedure manual marker format

Summary

A dynamic real-time simulation study was conducted at the NASA Langley Research Center to gather comparative performance data among three candidate final-approach spacing aid (FASA) display formats. The study was funded jointly by NASA and FAA and defined in collaboration with Lincoln Laboratory MIT, and NASA Ames Research Center. The experimental results were given to the FAA for use in their Terminal ATC Automation (TATCA) Program early field implementation decisions to define the final controller's automation aid interface. Several objective measures of controller performance and their eye-scan behavior, together with subjective workload and rating questionnaires were used to obtain an in-depth assessment. The data were gathered by using 12 subject controllers provided by the FAA. For each of two representative pattern-speed procedures (a 170-knot procedure and a 210-knot procedure with speed control aiding), data were collected by using 4 final-controller display-format conditions: manual/ARTS III, graphic marker, DICE countdown, and centerline slot marker. In addition to the experimental results and a simple runway-arrival-rate analysis, key FASA issues, a rationale for selecting the tested formats and their description, are presented.

Based on objective measures, the graphic marker and DICE countdown format were both more precise than the centerline slot marker in terms of delivery time errors at the runway threshold, and both (graphic and DICE) improved delivery precision relative to the manual/ARTS III format. In addition to having the least delivery precision of the three FASA formats tested, the controller monitoring of aircraft inside the final-approach fix was less for the centerline slot marker than for the other formats. Although relatively close to each other in delivery performance, eye-scanning analysis indicated the graphic marker appears to have a quicker or more efficient information transfer process than the DICE countdown format. The 210-knot pattern-speed procedure formats provided better interarrival precision relative to the corresponding 170-knot procedure formats. This may indicate the potential benefit of automation providing speed control advisories after the base-to-final turn where a higher pattern speed is practical in that region. Depending on which pattern-speed procedures are assumed in a simple runway-arrival-rate analysis, the improved precision of a FASA, such as the graphic marker, has the potential to increase the TATCA IMC arrival rate somewhere between 6 to 16 percent over that of a TATCA system without a FASA. All FASA formats reduced the number of vectors issued by our pool of final controllers, relative to their manual/ARTS III format; however, the graphic marker and DICE countdown reductions were 1.6 to 2.1 times that of the centerline slot marker.

Based on Task Load Index (TLX, a subjective workload assessment technique) evaluation, for the 170-knot pattern-speed procedure, the centerline slot marker increased workload above the manual/ARTS III format, whereas the graphic marker reduced workload relative to the same manual baseline. The DICE TLX-rated workload fell between that of the manual and the graphic formats. On the other hand, as a group, formats for the 210-knot procedure had no TLX workload difference among its formats. Also as a group, the 210-knot procedure formats did not have higher TLX workloads than the 170-knot procedure formats as a group, even though the 210-knot delivery precisions were significantly better. Each of three format, relative rating questionnaires (formats of only the 170-knot procedure, formats of only the 210-knot procedure, and all the formats of both the 170-knot and 210-knot procedures) was designed to extract from the subjects their relative ranking of the formats with respect to three specific criteria (Workload or Effort Required to Use the Format, Ease of Adapting to or Learning to Use the Format, and Amount of Help or Benefit in Spacing Traffic on Final). In all cases, the following same FASA order of preference resulted: graphic marker, DICE, and slot marker. Additionally, when rating all the formats of both the 170- and 210-knot procedures together, in every format case, the mean rating of the 210-knot format was preferred over the mean rating of its corresponding 170-knot format. In their final debriefing, the subjects were unanimous in their feeling that automated aids would be beneficial in reducing workload and in increasing spacing precision.

1. Introduction

The FAA has established the Terminal ATC Automation (TATCA) Program to develop and test ATC automation aids for assisting controllers in the organization and control of arriving aircraft traffic in the extended terminal area (i.e., a major terminal and its enveloping en route airspace). The expected benefits are more efficient utilization of runways and reduced controller workload. The functions to be addressed by TATCA include

traffic planning aid
descent advisory
final spacing aid
converging runway display aid

Currently the underlying structure for the first three functions above is the Center/TRACON Automation System (CTAS) tools developed at the NASA Ames Research Center (refs. 1 to 3). The fourth function is described in reference 4.

This report describes a study conducted at the NASA Langley Research Center to expand the TATCA knowledge base. NASA and FAA shared the experimental cost and Lincoln Laboratory, MIT, provided inputs to the experimental design and controller subject questionnaires. Working jointly with the FAA, Lincoln Laboratory, and Ames, a Langley study was conducted to help identify the most promising final-approach spacing aid (FASA) format for use in the TATCA early field implementation. To that end, the collected data were quickly shared with these parties prior to formal publication.

The TRACON environment at early TATCA implementation is expected to still use monochrome ARTS (automated radar terminal system) displays before the introduction of the Advanced Automation System (AAS) controller suite color displays. The study was directed toward gathering final-controller comparative-performance data, among potential FASA formats using a monochrome (no color) display. The final controller's primary responsibility is the acceptance of traffic from the arrival position and merging and spacing traffic for the final approach.

Separation and delivery precision, controller eye-scan of the radar display, number of vectors (heading changes) issued, response time, workload, and questionnaire data were gathered. These multiple measures provided a broad assessment of the relative performance of the formats and, in some cases, resolved ambiguity. The data were collected from 12 subject controllers provided by the FAA, all of whom were active, full performance level (FPL) terminal area controllers. The subjects served as the final controller in a real-time TRACON (terminal radar approach control) simulation under several experimental conditions. For each of two representative approach pattern-speed procedures, the controllers ran a data session in a manual mode (no automation spacing aid) followed by data sessions employing three final-approach spacing aid (FASA) formats.

2. Background

The late 1950's, the 1960's, and the early 1970's witnessed considerable activity in the area of computer-aided spacing systems for terminal area ATC. Reference 5 contains an excellent summary and bibliography of that activity. Reference 6 lists some of the reasons why an operational computer-aided spacing system was not accepted. Among the reasons were the limitation of computer, display, and tracking technology at that time. The automation aid interface to the controller is a key component in an acceptable computer-aided spacing system for the terminal area.

Air travel delay and traffic congestion at major airports, projected increases in air travel, and severe environmental restrictions on either airport expansion or new airport construction all signal the pressing need for maximum utilization of present airport real estate. These conditions have stimulated a new effort to develop and test computer-aided, time-based air traffic control systems for the extended terminal area. References 1, 2, 3, and 6 through 15 document some of the more recent developments and tests in the area. In the United States, these events have stimulated the formation of the FAA Terminal ATC Automation (TATCA) Program briefly described in the introduction of this report.

For the near term, a computer-aided system is believed to have the potential for more consistent spacing, at current operational separations, with less controller workload than can be achieved with the present system. Even more noteworthy are the potential long-term benefits of a computer-aided, time-based air traffic control system for the extended terminal area. Final-approach longitudinal separation from the preceding aircraft is mandated by two time-based constraints: the time required for the wake vortex of the preceding aircraft to decay to a safe encounter level and its runway occupancy time. Research and developments in the area of improved aircraft flare and touchdown, runway guidance, high-speed turn-offs, accurate weather prediction, and wake vortex modeling and detection could eventually permit the use of variable time separations between approaching aircraft. These variable time separations would be updated, as a function of conditions, to the minimum times required to satisfy the two previous time-based separation constraints. There are additional potential benefits to a time-based system such as allowing aircraft to employ their onboard four-dimensional (4-D) flight management systems to precisely meet their desired metering fix times in a fuel efficient manner. Subject to constraints, this approach might later be extended to allow aircraft to meet their ground-issued scheduled landing times.

3. FASA Issues and Format Description

3.1. FASA and Approach Speed Issues

The ATC system characteristics assumed are described in this section. FASA issues, classification of types, and choices of FASA formats studied are discussed. The relation of FASA delivery precision and pattern-speed procedure is examined.

3.1.1. ATC System Environment Description

As mentioned in the introduction, the purpose of the FAA TATCA program is to develop and test ATC automation tools for assisting in the organization and control of arrival traffic in the extended terminal area. This area includes the surrounding en route traffic flow management to the terminal of interest (en route cruise and descent control) in addition to the TRACON's own feeder and final sector traffic control. This study looked at the benefits of automation assistance to the final controller with the assumption that the functional elements of the Center/TRACON Automation System (CTAS) (refs. 1 and 2) were operating. That is, the Traffic Management Advisor (TMA) assisted the Center and TRACON traffic managers with sequencing and scheduling the traffic, the Descent Advisor assisted Center controllers in meeting the TMA's schedule safely, and the Final-Approach Spacing Tool (FAST) assisted the TRACON feeder controllers in updating the initial sequence and fine-tuning the traffic flow. The FASA is the technique used to display, to the final controller, the spacing, sequence, and ATC actions suggested by the FAST.

A feature modeled in the simulation was that the algorithms (FAST) driving the FASA's had knowledge of the pilot's planned final-approach speed. The factors which primarily influence the pilot's choice of final-approach speed are wind and aircraft landing weights. It is expected that later generations of FAST will obtain the pilot's planned final-approach speed via data link in order to more precisely schedule and space aircraft. Final-speed knowledge was assumed because differences of controller performance, resulting from the FASA formats evaluated, can be experimentally differentiated more clearly under that higher capability condition. Unknown landing speeds add considerable uncertainty to landing time calculation and thus would reduce the ability to discriminate any differences in delivery performance due to the FASA formats tested.

The display environment simulated was that of an advanced ARTS monochrome display prior to the TRACON acquisition of the AAS controller suite plan position indicators (PPI') with color displays. The FAST system advisories are expected to be placed on the Full Digital ARTS Display (FDAD) briefly described in reference 16. This precluded using the discrimination power of color coding to display FASA information. In addition, the added FASA information could not displace or significantly detract from the primary ARTS information.

3.1.2. Final-Approach Control and Automation Issue

Given the ATC environment described above, this study evaluated the relative performance of the final controller in directing aircraft to final approach with consistent and proper separation under the following conditions: (1) using only manual judgment/experience (with ARTS lll display) and (2) employing the assistance of the various FASA's. It is important to note that the manual/ARTS format evaluated does not represent today's TRACON environment where the traffic flow to the final controller is the end product of a series of merges performed manually on different traffic streams by other controllers. The traffic in this study was assumed to have been organized and spaced by automation/controller interaction prior to arrival in the final controller's airspace. Generally, gaps appeared when required in the arrival stream to merge traffic and the landing order was normally self-evident. The experimental manual/ARTS format addressed the question of how precisely a controller can manually vector and separate traffic if given a well-organized stream of traffic, essentially an "ideal feed." Performance of this study's manual/ARTS format together with FASA performances addresses a bigger system issue. That issue is whether, and to what extent, a FASA is beneficial if the TATCA system (i.e., CTAS) has already been active in the organization and tentative spacing of arrival traffic prior to the final sector.

3.1.3. Classification of FASA Types

An attempt was made to classify the many approaches possible to display, on the final controller's PPI, computer assistance from a dynamic time-based planner (DTP) such as exists in CTAS. For the environment depicted in the previous section, the key issue is selecting which technique best improves the final controller's aircraft-pair spacing precision. Related are issues of safety, stress, workload, acceptance, and job satisfaction. A listing, under descriptive categories, of the viable techniques known to the authors is as follows:

Category A—DTP aircraft schedules indication

1. Sequence list with STA's: an aircraft/STA list ordered by STA values at the runway threshold
2. Time line display with STA's: a linear time scale with aircraft call signs positioned to indicate their STA's relative to current time at the runway threshold (normally at bottom of time scale)

Category B—DTP conformance indication

1. Sequence list with STA's, early or late status: category A1 together with aircraft expected arrival status information (early or late indication) if nominal approach profile is followed (i.e., if no corrective action taken)
2. Sequence list with STA's and ETA's: category A1 together with expected runway threshold time if nominal approach profile is followed
3. Sequence list with STA's, numerical expected landing time errors: category A1 together with expected aircraft landing time error (STA – ETA) if nominal approach profile is followed
4. Time line display with STA's, early or late status: category A2 together with aircraft expected arrival status information (early or late indication) if nominal approach profile is followed
5. Time line display with STA's and ETA's: category A2 together with aircraft call sign (normally on the opposite side of the time scale from the STA call sign and usually colored or displayed differently) positioned to show their ETA's relative to their STA's if nominal approach profile is followed
6. Time line display with STA's, numerical expected landing time errors: category A2 together with expected aircraft landing time error (STA – ETA) if nominal approach profile is followed
7. Expected landing time error numerically displayed in data block
8. Extended runway centerline slot marker: Indication of the desired (scheduled) position of arriving aircraft as if they were approaching along the extended runway centerline at the final pattern speed

Category C—vector heading advisor

1. Numerical heading: magnetic vector heading usually added to data block
2. Graphical heading: symbolic indication on PPI (directed line, arrow, etc.)

Category D—speed advisor

1. Numerical speed: indicated airspeed usually added to data block

Category E—advisory delivery point (position or time) indication

1. Intensity fluctuation of numerical data
2. Intensity fluctuation of aircraft position symbol
3. Graphical position indication: graphical symbol located on PPI
4. Straight clock numerical countdown: time remaining before issuing advisory
5. DICE (direct course error) numerical countdown: amount of time relative to its STA (early or late), an aircraft would be if its advisory was issued immediately
6. Symbolic clock face: pictorial representation of category E4
7. Rising or falling time column: linear representation of category E4

Another characterization of the automation aids is obtained by classifying them as either *indirect* or *direct.* Those in category A or B are classified as *indirect* because the specific manner of achieving the desired schedule is not given. A combination of an aid from category E together with one from C or D is called *direct*, since the specific advisory to achieve the DTP schedule and the specific moment to deliver the advisory are explicitly indicated. In general, greater precision would be expected from direct aids. On the other hand, the controller's job satisfaction (making decisions, being in charge) might better be served by indirect aids.

Indirect aids indicate the end goals; however, the specific control action necessary to meet that end and the point to apply it are left to controller judgment. Therefore feedback seems desirable to indicate the effectiveness of the control action taken. Category B has this desired feedback.

Early or late information in categories B1 through B7 is determined by comparing DTP scheduled arrival time with the estimated arrival time which is a function of the time to fly to and then follow a DTP assumed nominal speed and path profile from the aircraft's current speed and position in space. Because routes are generally better defined in the merge or feeder controller's area, categories B1 through B7 are better suited to the feeder than the final controller. For example, let us take an aircraft on the downwind leg with no FASA. The aircraft could be subsequently given one to three vectors and one or two speed reductions. Several combinations of legitimate controller actions could result in meeting the schedule. In that context, early or late is somewhat difficult to define if the aid is to remain indirect. Category B8 has the attribute of remaining indirect yet providing effective feedback.

The British PACTAS (Predictive Approach Control Tactical Advisor System) program (ref. 14) is a hybrid (indirect/direct) system that operates as category B7 or can operate as category E5 if the controller inputs a specific control action (heading or speed change). In its direct mode the PACTAS system provides DICE countdown information to the controller relative to the immediate initiation of the particular control action specified. This approach allows the the controller to select the "how" (specific control action) as normally done with an indirect aid and also provides the "when" (time) of a direct aid. However, the additional display and input devices required for PACTAS preclude its application in the environment described in section 3.1.1.

3.1.4. FASA Format Selected for Study

The indirect aid selected for evaluation was the extended runway centerline slot marker (ref. 12). This format displays the spatial mapping of the sequence and desired spacing of aircraft on the extended centerline of the runway and is described in detail in section 3.2.2. During busy periods at major terminals the final controller's attention is highly focused on the aircraft positions and overall flow pattern on the PPI in order to plan and control the aircraft in the controller's airspace. The actual position of aircraft as they turn on final as compared with the DTP desired positions is obtained simply and directly by displaying the centerline slot markers in the region of normal controller eye scan.

Even though it is possible to use some forms of direct aids with sequence lists or time line displays, as it relates to the final controller, we will use the term "direct" to apply only to aids displayed within the final controller's normal scan pattern directly on the PPI. The direct aids, as defined, can be broken into two additional categories. The first indicates the suggested aircraft location where specific ATC instructions should be issued. The second category indicates the suggested time when specific ATC instructions should be issued. One direct FASA representative of each of these two categories was selected for evaluation. Other factors in narrowing the choices were the desire to give the controller some lead time relative to the message delivery point and to minimize distracting clutter on the controller's display.

The location direct turning aid selected for evaluation is a monochrome modification of the color-coded graphical advisory interface described in reference 3. This reference used a two-segment symbol which conveys in a simple and direct graphical manner both the aircraft location to issue a turn instruction and the desired heading. To prevent display clutter, the graphical turn symbol in this study was changed to a three segment symbol because the symbol quickly became elongated and unwieldy if the proposed change in heading was larger than 90°. The graphic format evaluated (categories E3 and C2) is described in detail in section 3.2.4. It should be noted that the NASA Ames FAST simulation now uses an "x" and an arc symbol to indicate turns (ref. 15).

Of the time direct aids listed, only the DICE countdown and the straight clock countdown possess both the features of lead time and relatively minimum display clutter. The desired heading and countdown value are both encoded on additional lines of the ARTS III data block. Prior to a turn, the DICE countdown indicates the amount of time early or late, relative to the scheduled time, an aircraft would be if it were presently issued the turn instruction. The time difference between the SLT and the ETA is the DICE value displayed. A straight clock countdown indicates the time remaining before the turn is to be issued. The difference between the computed time to issue a turn and the current time would be displayed in the straight clock countdown.

The DICE countdown technique (category E5 with either C1 or D1) was selected as the time direct aid to evaluate for two reasons. First, it gives controllers direct information relative to their action and the desired end goal time schedule with path geometry factored in. If, for example, prior to a downwind-to-base turn, the controller wanted to reduce separation by so many seconds, DICE countdown gives that information directly. The second reason is that the straight clock countdown is a simple and common experience for everyone. Therefore, it would be more valid to evaluate DICE and then ask for a comparison or preference between the two rather than the other way around. Subject responses to countdown preference is presented in section 5.5.1.4. The DICE countdown format is described in detail in section 3.2.3.

3.1.5. Approach Speed Issues

It is common practice at high density TRACON's, during heavy-demand IMC periods, to slow the traffic entering the final-approach region to a single pattern speed (typically 170 knots) for aircraft performance compatibility between transport and commuter aircraft and for more planning time to organize the traffic. At other times, a higher pattern speed (typically 190 or 210 knots) is used to the base leg and then reduced to the slower pattern speed before the final turn. In both cases, the controllers normally fine-tune their separations on final-approach course (hereinafter called *final*), via their base-to-final turn. In all cases, the controllers check for compliance and ensure safe separation on final, but generally refrain from exercising any significant amount of control action after the final turn. At less heavily loaded terminals or at high density terminals during low-demand periods, aircraft are often kept at a higher pattern speed until turned to final and then slowed to the lower pattern speed. Airlines and pilots generally prefer higher speeds closer in because of the reduced delay and because of the higher fuel consumption resulting from high drag configurations required at slower pattern speeds.

In the FASA study, we have taken as our experimental condition the two representative conditions described above. The 170-knot approach speed procedure simulates the single pattern-speed, IMC case. The 210-knot approach procedure normally maintains aircraft at 210 knots through the base-to-final turn after which the timing of a 210- to 170-knot speed reduction is used to further fine-tune separations on final.

For the situation where aircraft are slowed to 170 knots before being turned to final, the major issue is accuracy of turn control. Assuming the base legs are flown as expected, the correct timing of the base-to-final turn is the principal factor in determining aircraft separation precision. The major concerns in this case are: (1) the precision of the controller's unaided judgment in timing the final turn for separatation from preceding aircraft (manual format), (2) the precision of the controller's judgment in timing the final turn for merging with the aircraft's own slot marker (centerline slot marker format), and (3) the precision of the final turn with the help of the two direct automation aids (graphic marker and DICE countdown formats).

The issues relative to the 210-knot procedure are somewhat more complicated and related to local practice and traffic load. Using the modest controllability available from timing a speed reduction on final has the potential to further fine-tune the separation precision achieved by turn control. However, in some facilities, there is a tendency not to routinely apply control after the base-to-final turn. Also, there seems to be more application of speed control, on final during IMC, at terminals where a straight-in arrival route is merged with other routes.

The centerline slot marker concept (ref. 12) was developed at MIT and studied there by using a Boston terminal area simulation with a two-speed pattern profile, similar to the 210-knot procedure. Under those conditions, the aircraft's centerline slot markers were used as a guide to time the speed reductions. Similarly a direct (graphic or DICE) automation aid can also be employed to indicate when or where on final the slower pattern speed should be issued to fine-tune aircraft separations. Both speed reduction aids were incorporated into the Langley TIMER simulation (ref. 6) to examine performances. Note that for the 210-knot procedure, the direct speed reduction advisories on *final* are in addition to the earlier described direct turn advisories. The combination of the turn and speed-reduction aids also raises the question of clutter and distraction in addition to the acceptance of the basic procedure of issuing speed reductions on final.

3.2. Description of Final-Approach Spacing Aids Formats

The significant features of the arrival routes in the terminal area of the Denver Stapleton International Airport that are modeled in the TIMER simulation (described in section 4.1.2) are depicted in figure 1. The arrival routes are a basic four-corner-post structure merging to a single approach path to runway 26L. Of interest in this study is the final controller's airspace which includes the western approach paths from abeam the airport eastward and the eastern base and final-approach legs. More complete discussions of the airspace and procedures simulated are contained in section 4.2.

All arriving aircraft speeds are reduced to the appropriate pattern speed (170 KIAS or 210 KIAS) before the aircraft enter the final controller's airspace. The TIMER algorithms compute ETA's at the runway threshold, for aircraft approaching the final controller's airspace, based on nominal flight paths and speed trajectories. In the 170-knot procedure, a constant indicated airspeed (170 knots) is assumed up to the final approach fix (FAF). In the 210-knot procedure, the higher indicated air speed (210 knots) is assumed to a specified distance from the FAF followed by the slower speed (170 knots) to the FAF. Aircraft within the fine-tuning region are allowed more latitude in flight paths to accommodate cumulative flight errors and schedule changes. This increased latitude is initiated at the last fixed-point update which is approximately abeam (abreast) of the active runway threshold for western arrivals and just outside of the FLOTS and WIFES intersections for eastern arrivals. At these points, the location in the arrival sequence of an aircraft crossing the point is frozen, a target scheduled landing time (SLT) is computed, and, for eastern arrivals, an appropriate base-leg heading is assigned. At a point abeam the FAF for western aircraft on downwind legs and at 6.5 n.mi. from the extended runway centerline for eastern aircraft on base legs, the target SLT is again computed. These values are held constant for the remainder of the approach except that when operating in a nonmanual (i.e., computer-aided) mode, the target SLT may be forced backward or allowed to slip forward (within limits) by changes in the ETA's of preceding aircraft.

The final-approach spacing aids are then applied to the remainder of the approach up to the FAF. In addition to a non-FASA or manual mode of operation, there are three FASA concepts integrated into the TIMER. These are centerline slot marker, DICE countdown, and graphic marker formats. The centerline slot marker concept is based on the difference between the scheduled time of arrival (STA) at the FAF and the current time of day. The latter two concepts are based on the difference between the SLT and current ETA at the active runway threshold.

3.2.1. Manual Operation Mode

Although SLT's are generated in the feeder sectors to provide an organized traffic flow, in manual operation, no advisories are generated to maintain separation in the final-approach region. Only the normal ARTS III data block is provided which contains aircraft identification, altitude, and ground speed. The controller may also select a display of aircraft type which is time shared with the altitude/ground-speed line of the data block. As the name implies, the controller is expected to use current-procedure manual vectoring techniques and speed adjustments to maintain the required separations. This mode provides a baseline or calibration of the ability of the test subject controllers' to space and turn aircraft to achieve proper interarrival separation.

An example display scenario, taken from one of the 210-knot approach-pattern-speed data runs, is depicted in figure 2. Here, "Continental 101 (COA101)" is descending through 6500 ft at 140 knots ground speed (GS) to runway 26L. "Continental 533" is about 1.2 n.mi. from the FAF at 7200 ft and 170 knots GS. "Delta 989" is in the process of intercepting the ILS for runway 26L 5.5 n.mi. from the FAF and is still at 210 knots IAS (200 knots GS due to headwind). "TWA 896" is on a base leg from the south and descending through 11 100 ft to 8000 ft at 210 knots IAS (240 knots GS). "United 280 and 720" are on their downwind legs at 210 knots IAS. "Delta 971" is approaching from the southeast with a pending hand-off from feeder to final-approach control. Its entire data block would be flashing on the display of the final-approach controller, to indicate the initiation of a handoff. Approaching from the northwest, "United 305" is still under feeder control.

3.2.2. Centerline Slot Marker Format

Figure 3 presents the same traffic scenario as in figure 2, but with the centerline slot marker format displayed on the final controller's display. The circular centerline slot marker symbol of approximately 3/4 n.mi. diameter (at the scale selected for the final-approach controller display) is centered on the extended runway centerline as a target moving at a ground speed that is equivalent to flying active-runway heading, 170 knots IAS, at an altitude of 7200 ft. The markers arrive at the FAF at the time associated with the STA of the corresponding aircraft. The three-digit flight number of the aircraft associated with a slot marker is displayed in the center of the marker whenever the aircraft coordinates are outside the marker symbol. Slot markers are not displayed between the FAF and runway.

The final controller's task is to direct the aircraft to a merger on the radar display with its corresponding slot marker. Although the landing sequence and spacing is displayed in a position/distance format, there is no explicit "when to turn" indication. In the 170-knot pattern-speed approaches, the controller is expected to use vectoring to guide the aircraft to the center of its slot marker. When operating with 210-knot approaches, the controller is expected to issue a speed reduction to 170 knots IAS after the aircraft is turned to an ILS-intercept heading such that the aircraft position symbol is in the center of the slot marker when the speed reduction is complete.

The differences in slot marker presentation between the 170- and 210-knot approach-pattern-speed procedures are minimal. In the 170-knot version, it is assumed that the aircraft will fly the assigned speed to the FAF. If the controller chooses to close a gap in the traffic that has developed in the final-approach airspace (in the 170-knot version), an increase in airspeed may cause the SLT of the subject aircraft as well as the SLT's of the trailing aircraft to slip forward (up to their forward-slippage limits). In the 210-knot version, the SLT of an aircraft is not changed by speed adjustments because it is assumed that speed adjustments will be used to mate the aircraft with its marker (i.e., attempting to match the ETA with the SLT). However, the SLT's of trailing aircraft may be affected in order to maintain separation with an ETA that results from an overcompensated speed adjustment.

In the 210-knot scenario depicted in figure 3, "Continental 533" is somewhat late as indicated by the relative positions of its slot marker and the aircraft symbol. "Delta 989" is in the proper position to begin decelerating from 210 to 170 knots IAS. "TWA 896" is probably within a mile of where its ILS-intercept vector should be issued and "United 280" should be vectored from downwind-to-base within about 2 n.mi. to follow TWA. A landing-order-sequence list all of the aircraft in the terminal area is provided in the upper-right corner of the display. This list is intended to aid the controller in anticipating the landing sequence of aircraft whose slot markers are not yet in the field of view.

3.2.3. DICE Countdown Format

Figure 4 present the same traffic scenario as in figure 2, but with the DICE countdown format displayed on the final controller's display. The DICE countdown format for vector turns consists of displaying the DICE countdown value and the recommended heading of the next flight-path segment within the aircraft data block. The DICE countdown format for speed reductions in the 210-knot procedure consists of displaying the DICE countdown value and the nominal final pattern speed (170 knots). These parameters are displayed on two subsequent lines below the altitude/ground speed in the data block. The DICE value displayed is the difference between the periodically updated ETA (recomputed every radar scan for aircraft in the final-approach fine-tuning region) and the SLT of a given aircraft. Thus, the DICE value for a vector turn indicates how early, relative to its SLT, the aircraft would be if its turn instructions were issued immediately. The display of this information is withheld until the DICE value is less than a prescribed threshold. The thresholds were chosen to turn on the DICE value display when the aircraft is within 45 sec of an anticipated turn in the 170-knot procedure. Reasoning that a larger lead time should be provided in the higher speed procedure, a threshold of 60 sec was chosen for the 210-knot procedure. Expected message length and controller/pilot response time are factored into the displayed DICE values.

The change in ETA (and consequently in DICE value) per unit time (i.e., ETA gain) is about 2 for aircraft on downwind and about 1 on base legs. The gain is about 2 on the downwind because, for each mile the downwind is extended, the aircraft must fly a corresponding extra mile on the final. As a point of interest, the ETA gain for the speed reduction from 210 to 170 knots on final approach is only 0.25 sec/sec. That is, a 1 sec delay in implementing the speed reduction would only result in 1/4 sec earlier arrival time.

When the DICE value becomes less than zero (the time when the controller should issue the advisory), the recommended value (heading or speed) flashes to further attract the controller's attention. The information is extinguished from the data block after the appropriate change in heading is initiated. Because of radar-tracker instability, DICE values are not displayed during heading- or speed-change transitions until tracking has restabilized.

During a turn from a downwind leg to a base leg, a determination is made as to whether a base leg that will allow sufficient time to generate a normal turn to intercept the ILS can be expected. If so, the DICE display is resumed as soon as the tracker stabilizes at the end of the turn to base. However, if little or no base leg is predicted, the system provides a temporary, linear, artificial countdown to assist the controller until the tracker stabilizes and generates more accurate DICE values. A significant change can occur in the displayed DICE value when the tracker settles due to discrepancies between the predicted and actual flight paths during the turn. No recommended heading is displayed during the artificial countdown. Because of larger turn radii, the artificial countdowns are generated much more often during the 210-knot operations than they are during the 170-knot operations.

3.2.3.1. DICE for 170-Knot Operation

In the 170-knot approach-pattern-speed procedure, the DICE countdown values are displayed whenever they are less than 90 sec for downwind-to-base turns and less than 45 sec for base-to-final turns. These threshold values give the controller about the same amount of lead time for both cases since the ETA gain on the downwind legs is about 2.0 and for the base legs is about 1.0. The criteria for displaying the recommended heading are that the DICE value must meet its display threshold criteria and must also be less than 60 sec. The heading value that is displayed is the heading used in the DICE ETA calculation. That is, a base-leg heading is the prescribed base-leg ground-track angle, corrected for the wind expected at the base-leg altitude. An ILS-intercept heading is based on a 20° intercept, a turn directly onto the localizer, or intercept angles in 5° increments if the aircraft is in an overshoot situation. There is no adjustment to the threshold when an overshoot is anticipated. Because the DICE parameters are not displayed until the thresholds are met, an aircraft that is predicted to have an extremely large overshoot may be quite close to the final-approach course before the DICE is displayed.

3.2.3.2. DICE for 210-Knot Operation

In the 210-knot procedure, the threshold, for displaying the DICE heading value, is based on projected time to go (clock time) to the turn point rather than on the DICE countdown value. The threshold value was set to 60 sec for all DICE turns. The time to go to the turn point to satisfy an SLT is the DICE value divided by the ETA gain. The other major difference with respect to the 170-knot procedure is in the display of final-approach-course overshoot situations. This version displays the DICE parameters as soon as an overshoot is predicted and also shows the ILS-intercept heading that will be needed when the time-to-turn point is reached. Not only does this provide more lead time but also provides the controller better information on the extent of the predicted overshoot than in the 170-knot version. Thus the controller has the option to modify an aircraft's profile on the base leg to reduce or eliminate the overshoot problem. Examples of normal (nonovershoot) DICE value displays are shown in figure 4. The data block for "TWA 896" shows a recommended ILS-intercept heading of 280° with a DICE value of 13 sec. The data block for "United 280" shows a recommended base-leg heading of 345° with a DICE value of 59 which should count down to zero in about 26 sec.

When the TIMER detects that a turn to an ILS-intercept heading has been initiated, it computes the time at which the turn should be completed. This time is then used to activate the speed-DICE procedure which advises the controller when to reduce the aircraft speed to 170 knots during the remaining final-approach flight segments prior to the approach gate (a point 1 mile outside the FAF or 5 miles from the runway threshold, whichever is farther). It should be noted that "early turn" and "early speed reduction" have the opposite effect on aircraft arrival time with respect to the SLT. Thus, the DICE value indicates how late the aircraft will be with respect to its SLT if a reduction to the recommended IAS (170 knots) is issued immediately rather than how early as in the case of vector-DICE. A more complete discussion of the vector- and speed-DICE algorithms and display criteria is contained in appendix A. Like a vector-DICE, the speed value flashes whenever the speed-DICE value is less than or equal to zero. Again referring to figure 4, the data block for "Delta 989" shows a speed-DICE value of zero indicating that the speed reduction to 170 knots should be issued. In this case, the data block field showing the recommended target speed "S170" would be flashing.

3.2.4. Graphic Marker Format

The graphic turn and speed reduction (in the 210-knot TIMER version) FASA provides a pictorial representation of where, rather than when, to initiate a flight profile (heading or speed) change. Figure 5 presents the same traffice scenario as in figure 2 but with the graphic marker format displayed on the final controller's display. The controller's objective is to initiate the change as the aircraft symbol comes in contact with the graphic marker. This is intended to be coincident with the DICE value counting down to zero.

The display thresholds for graphic turn markers are the same as for DICE heading-vector values. A turn marker is displayed to the final controller when an aircraft is within a flight-time to the predicted turn point of about 45 sec for 170-knot procedure and 60 sec for 210-knot procedure. The turn markers consist of three directed line segments. Although only two segments are required to depict the necessary information, the three segment marker avoids the unsightly graphic representation of turns greater than 90° as discussed in section 3.1.4 on FASA issues. The first segment is oriented along the projected flight path directly ahead of the aircraft. Its length is determined by the expected ground speed of the aircraft and the nominal times expected for controller communication to the pilot, pilot response, and roll-in to the turn. The second and third segments complete an approximation of a constant-radius turn with the third segment aligned with the heading necessary to maintain the ground track of the next flight leg. As in the DICE FASA when an artificial DICE countdown is generated, an early-warning ILS-intercept turn marker will be generated to assist the controller when a very short (or nonexistant) base leg is computed during a downwind-to-base turn. Again, this occurs more frequently at 210 knots than at 170 knots.

The only difference between turn markers in the 170-knot and 210-knot operations, other than in physical size due to different ground speeds, is that the orientation of the third segment of base-to-final turn markers always represents a turn from current position to intercept the ILS in the 170-knot operations but represents the expected ILS-intercept heading in the 210-knot version. This is relevant only in predicted overshoot situations where the turn marker extends beyond the localizer centerline. When this situation is detected, the base-to-final turn marker is presented to the controller immediately and may indicate a projected turn directly onto final to as much as a 35° intercept from the opposite side of the localizer, depending on the magnitude of the anticipated overshoot.

Speed-reduction markers, in the 210-knot TIMER version of the graphic marker format, are small circles enclosing an x. The graphical speed reduction symbol used is a monochrome version of the speed symbol in reference 15, which they employed to indicate speed reduction points on the approach routes prior to final. A display threshold limit of 3.0 n.mi. ahead of the aircraft is applied to the speed markers to prevent display ahead of a preceding aircraft. This reduces clutter and prevents possible inter-aircraft confusion. Also, whenever a speed marker is predicted to be displayed on the opposite side of the extended runway centerline from the aircraft to which it belongs, it is projected onto the centerline.

Examples of both types of graphic markers are shown in figure 5. "Delta 989" should be given its speed reduction to 170 knots immediately, whereas "TWA 896" and "United 280" still have some distance to go before being vectored to ILS-intercept and base-leg headings, respectively. Note that a speed-reduction marker is extinguished as soon as the speed change is initiated. For turn markers, the marker position is "frozen" just before the aircraft reaches the recommended turn point or when the appropriate change in heading is initiated and the marker remains visible until the time projected to complete the turn has elapsed.

Figure 6 presents an edited portion of the figure 2 210-knot traffice scenario with a graphic marker showing an extended runway centerline overshoot, if normal procedure is followed. Here, an ILS intercept heading of 240° is indicated for "TWA 896." Note, the runway heading was 260°, and the display was oriented in a magnetic north-up configuration. A more in-depth discussion of the graphic marker algorithms is also included in appendix A.

4. Experimental Facilities and Conditions

4.1. Experimental Facilities

A sophisticated real-time ATC simulation using the Denver Stapleton approach routes provided a realistic and dynamic environment to measure and assess final controller performance with the FASA display formats tested. A real-time version of the terminal-area air traffic model (TAATM), with the TIMER algorithms embedded (section 4.1.2), was interfaced with an air traffic controller station to provide the traffic to be controlled and the final-approach spacing aids (FASA) studied. The computer data interfaces, voice links, and controller workstations of the Langley Mission-Oriented Terminal-Area Simulation (MOTAS) Facility (section 4.1.1) interactively linked the TIMER algorithms, the subject controller, and the pseudopilot station operators.

4.1.1. Mission-Oriented Terminal-Area Simulation

The Langley Mission-Oriented Terminal-Area Simulation (MOTAS) Facility (ref. 17) provides a flexible and representative simulation of the airborne, ground-based, and communication aspects of the ATC terminal-area environment. The elements of the MOTAS facility used in this experiment are shown in figure 7. The elements include a terminal ATC model, aircraft models, pseudopilot stations, air traffic controller stations (section 4.1.3), and a simulated air/ground communication network.

All the final approach sector traffic in this study was "flown" via a pseudopilot station. The operator of a pseudo-pilot station controls the simulated aircraft by keyboard input of commands which dictate airspeed, altitude, heading, interception of the ILS, etc. In addition, the pseudo-pilot operator also provides pilot verbal radio communication to ATC. To prevent overload and ensure representative pilot-aircraft responses, the pseudopilot station servicing the final control sector was staffed by a two person team (fig. 8). One person was the keyboard operator who input, in a timely manner, the commands to control the aircraft traffic. The other person was the radio operator who simulated the radio communication of all aircraft entering and flying through the final sector. This operator was trained to use proper phraseology and radio protocol. To enhance the realism for the subject controller, the radio operator used a voice disguiser to impersonate the voice quality of multiple pilots. In addition to their primary keyboard and radio operator duties, each pseudopilot team member monitored the companion's output to ensure accuracy and realism.

In addition to controller comments to that effect, another indication of the realism and fidelity of the experimental simulation is given in figure 9. Shown is a histogram of actual pilot response times to ATC turn commands from reference 11 and a histogram of the pseudopilot response times recorded in this experiment.

4.1.2. TIMER Simulation

The time values and display locations for each of the FASA formats evaluated were obtained from the TIMER (traffic intelligence for the management of efficient runway scheduling) algorithms. TIMER is an extended-terminal-area time-based ATC concept which has many features similar to the NASA Ames CTAS system (refs. 1 through 3) which will be used in the FAA's Terminal ATC Automation (TATCA) Program. The major operational features of the TIMER concept are shown in figure 10 and were applied to the Denver Stapleton nominal approach pattern for a land-runway 26L configuration shown in figure 1. The principal TIMER model features are summarized as follows:

1. The arrival traffic stream into the extended terminal area is derandomized at the horizon of control by establishing a proposed aircraft landing sequence and building a list of aircraft SLT's based on standard ATC separation criteria (events 1 and 2 of fig. 10). The desired metering-fix time as a result of the assigned landing time is also determined.
2. Nominal estimated times of arrival used in feature 1 are based on aircraft performance models. From using these models and predicted winds, a ground-computed, fuel-saving, profile-descent trajectory, to the aim point, is determined to meet the aircraft's assigned SLT (events 3 and 4 of fig. 10).
3. Computer-generated assistance is given to the en route controller to help in meeting aircraft target times based on the en route cruise and profile descent trajectory calculations. The parameters determined are the en route cruise speed, the time to initiate and the Mach/CAS speeds to fly a flight-idle-thrust descent, and the terminal segment speeds and headings.
4. Adjustments to the SLT's and, if necessary, changes in the landing sequence are made to accommodate errors and anomalies in factors such as wind, navigation, airspeed, and heading which affect the SLT of either the own aircraft or the preceding aircraft. These schedule adjustments occur at the following points shown in figure 10: the metering fix, the speed adjustment points, and the fine-tuning region. The landing sequence is fixed and the aircraft speeds are reduced to the appropriate pattern speed (170 or 210 knots) before aircraft arrive in the fine-tuning region.
5. The aircraft trajectory is fine-tuned in the final-approach region in order to meet the aircraft's last adjusted SLT with a minimum time error. This is where the FASA indicated turn and speed maneuvers occur. The TIMER fine-tuning region is defined by the boundaries of the vector headings from the aim point for eastern arrivals (event 6 in fig. 10) and by the boundaries of the downwind-to-base turn for the western arrivals (event 5 in fig. 10). The dashed lines in both figures 1 and 10 indicate the boundaries of the fine-tuning region. Within this region, a computer-aided fine-tuning maneuver consists of timing when or locating where both the turn-to-base (event 5 in fig. 10) and the turn-to-final (event 7) maneuvers should occur. An additional fine-tuning feature was added for the 210-knot approach procedure (described in section 3.15 and 3.2). This consists of timing when or locating where, on final, the speed reduction from 210 to 170 knots should occur (event 8 in fig. 10). In all cases, a comparison of the aircraft's SLT with its estimated time of arrival (ETA) forms the basis for either the time value (the when) or the position (the where) of the FASA formats described in section 3.2. More details of the SLT and ETA computation are given in appendix A.

A more complete description of the TIMER model and algorithms is furnished in reference 6. In this study, the en route portion of the TIMER concept was only modeled in the time dimension (i.e., 4-D aircraft trajectories were not calculated; however, pertinent en route events such as initial scheduling, delays, and metering-fix time errors were computed. From the metering fix to the runway (the nominal terminal region) the entire aircraft trajectories (4-D paths) are deterministically modeled with airborne-flight-technical and ground-radar errors included. The entire extended-terminal TIMER model was operated in the study; however, only the region inside the metering fixes had live, direct controller interaction. Like the CTAS Final-Approach Spacing Tool (FAST), the TIMER simulation accommodated controller issued headings and speeds which deviated from those used in a normal traffic pattern. This robustness added to the realism of the simulation and to the validity of the results.

4.1.3. Simulation Air Traffic Controller Station

Real-time air traffic controller interaction with the TIMER simulation and the pseudopilots was accomplished via the two monochrome displays, simulation controller stations of the MOTAS facility. As shown in figure 11, the two controller stations (ATC station 1 on the left and station 2 on the right) were equipped with a plan position indicator (PPI) on which the TIMER-simulated aircraft position information was displayed. Station 1 (fig. 12) was of primary interest because it was designated as the final controller station and used by the FAA subject controllers. A coordinator was provided to assist the subject controller in performing noncontrol functions and was seated to the immediate right of the subject. Station 1 had a communication system for radio communication between the subject controller and the pseudopilot station servicing the final sector. Standard FAA type push-to-talk headsets, Plantronics model HS 0110-2E, were used with an optional foot-pedal switch. In addition, station 1 was equipped with an oculometer electro-optic head to obtain controller lookpoint data (described in section 4.1.4).

Station 2 was used by the in-house controller (former FAA terminal controller) who simulated the feeder function for all the experimental runs. This controller only modified aircraft headings, altitudes, or speeds in his sector if requested by the subject final controller, or if the feeder himself judged it necessary. (During the test, feeder modifications were only necessary during some manual, no FASA, runs.) Following acceptance of the handoff by the final controller (discussed in section 4.2.2), transfer of communication was initiated by a keyboard entry at station 2 which prompted the pseudo-pilot to perform a radio “check-in.”

The controller displays were simulated by an Evans & Sutherland Multi Picture System with a CRT measuring 23 in. in diameter and mounted vertically (figs. 11 and 12). The displays emulated a digitized radar presentation and were each configured with an appropriately scaled video map of the Denver terminal area (fig. 13). The latest radar-derived, aircraft locations were indicated by the letter symbol which corresponded to the control position responsible for the aircraft. The three past locations, at earlier radar scans, were represented by three “dots” of decreasing intensity. These dots convey trend information since no “trail” information was available with the simulation display. Each aircraft location was accompanied by its normal ARTS III alphanumeric data block and a FASA display when appropriate (section 3.2).

4.1.4. Oculometer Facility

The remote oculometer at Langley is a highly modified Honeywell Mark 3A system used to determine and record the lookpoint of a test subject. Some of its defining features are:

- The system is unobtrusive and nonrestrictive; it projects a beam of collimated near-infrared light at the subject’s eye and then processes the reflected return to a video camera
- Both hardware and real-time software have been modified at Langley to better accommodate the air traffic control environment; postprocessing software was developed in-house to correlate lookpoint data with the corresponding objects on the controller’s display
- The system tracks head movement in a 1-ft cube
- It quickly reestablishes track when subjects rotate their head and then turn back to the display
- The sample time is every 1/30 sec; it writes a data record at the end of each fixation or out-of-track event (defined later)
- The system is capable of video taping the data runs; the lookpoint, which is electronically superimposed on the PPI scene, is recorded as well as the final controller voice channel and the control room audio

The following discussion expands on some on the system features. However, more detailed information on the oculometer system, can be found in section 1. In addition appendixes A and B of reference 18 contain a detailed description of the Langley oculometer system and its use in cockpit display evaluation.

The oculometer facility computes and stores a time history of eye-scanning events. These events characterize the interaction of the controller-subject with the display as he or she directs air traffic in the simulated TRACON facility. Each event is either in-track or out-of-track. In-track events are lookpoint fixations which are characterized by a continuous focus of the subject's gaze on a small area of the display (usually in the vicinity of a display object) for multiple oculometer sample periods. Dwell time is defined as the length of a fixation. An out-of-track event or a significant movement of the lookpoint causes a fixation to end and triggers the recording of the event. Out-of-track events occur when the system loses track of the subject's eye for some period of time. This track loss occurs during blinking or if the controller turns his head for various reasons. An out-of-track always ends with an in-track, that is, the recapture of the eye. For each in-track fixation event, the system records

The location of the controller's lookpoint on the radar display

The pupil diameter

The duration of the lookpoint fixation

The system records an event as a single file record with the duration of the event being an integer multiple of the oculometer sample period. During postprocessing, out-of-track events are classified as noise when less than 4 periods in duration, as a blink when between 4 and 12 periods and as being "long" (i.e., turning head or blocking beam) when greater than 12 periods.

4.2. Experimental Conditions, Controller Task, and Subject Profile

4.2.1. Terminal Area Conditions Simulated

The arrival routes of Denver's Stapleton International Airport operating in a "land-runway 26L" configuration (fig. 14) were simulated assuming instrument meteorological conditions (IMC). The ILS runway 26L approach plate is shown in figure 15. A linear wind model using statistical coefficients for an average Denver area wind was used in all runs. The simulated wind velocity at ground level was 7.9 knots from 277° with a speed gradient of 2.37 knots per 1000 ft. In this study, the wind direction was constant at all altitudes.

The arrival traffic simulated was made up entirely of airline transport aircraft. The route-loading and aircraft-type distribution were obtained from the Official Airline Guide (OAG) information and used to construct computer-generated traffic samples representing weekday arrivals at Stapleton. All the traffic entered the terminal area at the metering fixes. The metering fixes at Stapleton are KEANN, IOC (Kiowa), BYSON and DRAKO (figs. 1 and 14). The simulated arrival traffic was distributed at the four metering fixes in the following manner:

Metering fix	Percentage of total traffic
KEANN	24
IOC (Kiowa)	29
BYSON	26
DRAKO	21

The traffic arrival rate was between 39 and 42 aircraft per hour depending on the mix of large and heavy aircraft for the particular traffic sample used. The long term average traffic mix was 87.5 percent large aircraft and 12.5 percent in the heavy category. Large aircraft are those with a maximum certified takeoff weight of between 12 500 and 300 000 lb. Heavy aircraft are those capable of takeoff weights of 300 000 lb or more regardless of their actual weight (ref. 19).

Inside the FAF, the separations briefed to the subjects and used by the FASA algorithms were a function of the weight class of both the lead and trail aircraft of a pair. By using aircraft velocities and simulated winds, the separation times for scheduling purposes in the TIMER algorithms. The distance separation criteria, used in terms of the lead and trail aircraft of a pair, conformed to current FAA standards (ref. 19) for airports where reduced separations (2.5 n.mi.) inside the FAF is authorized. The separations were as follows:

	Separation of trail aircraft, n.mi.	
Lead aircraft	Large	Heavy
Large	2.5	2.5
Heavy	5	4

4.2.2. Approach Paths and Procedures

The airspace and procedural environment closely resembled that in use at Denver Approach Control. The final controller's airspace (referred to at Denver as the *dump region*) is centered over the final-approach course, extending from the approach end of runway 26L to a point 20 n.mi. east and 8 n.mi. on either side of the final approach course (fig. 13(b) and 14). For simplicity in briefing, the dump airspace vertical limits of the simulation, surface to 10 000 ft, were slightly modified from the actual Denver operation. The feeder controller's sector is composed of essentially the arrival corridors (11 000 ft and above) and the airspace above the dump region.

There were two final-sector pattern-speed procedures modeled in TIMER to evaluate the FASA's. One version assumed a constant pattern airspeed until the reduction to final-approach speed begins in the vicinity of the FAF. In this evaluation, the constant pattern-speed value used was 170 knots and was called the *170-knot procedure*. The other TIMER version allows a higher initial airspeed through the turn-to-final then reduces to a slower pattern speed which is maintained until the final-approach speed reduction begins. In our evaluation, 210 knots were used for the initial pattern speed followed by a reduction to 170 knots after the turn-to-final and was called the *210-knot procedure*.

Figure 14 depicts the normal traffic flow in the arrival corridors and dump airspace. Speeds for all aircraft were reduced, at predetermined points outside the dump region, to an IAS of 170 or 210 knots, depending on the speed procedure being used for a given scenario. Traffic in the simulation proceeded inbound via the four arrival corridors, tracking radials to the Denver VOR (DEN, fig. 1), descending to 11 000 ft at an indicated airspeed of 250 knots. Aircraft are automatically placed in handoff status to the final sector resulting in a flashing data block on the final controller's display; the coordinator normally accepted the handoffs (transfers of control) for the final controller. Prior to simulating communications transfer, aircraft from the western fixes were turned to a 080° downwind heading; aircraft from the eastern fixes are issued headings based on traffic conditions and are issued an additional descent to 8000 ft (western aircraft are issued descent to 8000 ft by the final controller).

Once the aircraft entered the lateral limits of the dump region, the subject final controller was responsible for sequencing, spacing, and issuing vectors for the ILS RWY 26L approach (fig. 15). Sequencing and spacing was accomplished using vectors and, in the 210-knot procedure, a speed reduction was also used. During runs for which no aids were provided, the subject's own vectoring and speed control techniques were used to space and separate the traffic. However, when provided, FASA's were expected to be used to the extent possible. The final controller was also responsible for issuing the approach clearance and a frequency change to the tower.

4.2.3. TIMER/Controller Interaction

There are two levels of control in the simulation: program (TIMER control) and manual (controller commands). For the FASA studies, aircraft were ordinarily both ATC controlled and "flown" by TIMER from the time the aircraft appears in the simulation (in center airspace) until transfer of flight control to the pseudopilot stations was initiated. The transfer of flight control was initiated by the simulation feeder controller after the final (subject) controller accepted the handoff and normally prior to the aircraft entering the dump airspace. While the aircraft were normally under control of the simulation program in the feeder's airspace, the feeder controller was able to input commands by keyboard to alter the aircraft heading, speed, or altitude if he deemed it necessary or was requested to do so by the final controller.

All aircraft in the dump region were flown by the pseudopilot-stations keyboard operator in response to instructions issued by the final controller. After the approach clearance had been issued by the controller, the aircraft would automatically join the localizer and intercept the glide slope when encountered. A reduction to approach speed also occured in the vicinity of the outer marker. When the aircraft reached a height of 20 ft above the runway, the position symbol and associated data block disappeared from the display.

4.2.4. Experimental Task and Controller Subject Profile

The controller subjects were assigned the role of the final controller during simulation runs. The airspace and procedure responsibilities of the final controller were explained in section 4.2.2. The primary responsibilities were sequencing and spacing inbound aircraft and providing the approach clearance. Subjects were instructed to use the FASA when provided; however, they were briefed that they were ultimately responsible for separation of the traffic.

The 12 subjects for this study were all Full Performance Level (FPL) controllers from Norfolk (ORF) Approach Control which is a Level IV (Level V depicts busiest U.S. terminals) radar approach control facility. Two subjects were supervisors and two others were staff personnel all of which were current in the approach control facility. The total time that the subjects had worked at Norfolk Approach Control varied from 3 to 13.5 years; the average time at Norfolk for all subjects was 7 years; the average time as an FPL controller was 5.25 years with a range of 1 to 10 years. The total period of radar ATC experience among the subjects ranged from 6 to 19 years. (This time includes only experience at radar facilities where the types of ATC services provided are reasonably comparable with the nature of the task in this study.) Nine of the 12 subjects had been FPL controllers at other facilities.

4.3. Experimental Sequence and Measures

The practice and data sessions for each subject controller covered a period of 4 successive days. The first 2 days were devoted to one speed procedure, whereas the last 2 days were devoted to the other. Initially each subject was briefed on the purpose of the experiment, the simulation facility and conditions, the airspace and procedures, the two pattern speeds to be tested (170- and 210-knot procedures), and the duties and responsibilities. The controller was then given a hands-on explanation and demonstration of the ATC simulation. This was followed by a practice session using manual control (no FASA) which lasted until the subject was comfortable with the procedure and simulation and ready for the data run. After a suitable break, the manual format data run of 1 hr and 10 min was performed and the postrun questionnaire answered. The initial pattern-speed procedure used for each subject was dictated by the experimental matrix.

Each of the following 3 half-days consisted of a FASA format briefing, a practice session, and a data session of 1 hr and 10 min followed by the postrun questionnaire. The format briefings included a detailed description of the format and how it should be used. For the centerline slot marker, subjects were also briefed on suggested techniques to merge aircraft with their slots. The three FASA formats used the same speed procedure as the initial manual run. The order of the FASA formats was dictated by the experimental matrix. Table 1 gives an approximate time schedule because the length of the practice session depended on the subject feeling comfortable and prepared to begin a data-collection session.

As shown in table 1, the second 2 days consisted of the manual briefing, practice, data session, and postrun questionnaire followed by the three FASA formats using the second pattern-speed procedure. The 170- and the 210-knot speed procedures each had one practice traffic sample and six data samples (table 2) to prevent the controller from remembering traffic situations from previous data runs. The experimental matrix is shown in table 3. The runs were numbered odd for practice runs and even for data runs. Each data run is identified by the format and the traffic sample record number from either the 170- or 210-knot speed procedure. Note, the order of both the speed procedures and the FASA formats were randomized from subject to subject to minimize any learning or order effects on the experimental results.

From an ideal, experimental design viewpoint, always performing the manual format first might raise some question as to whether this favors the other formats, relative to a learning effect. The contention is that the professional experience of the subjects in using the manual format in everyday practice more than counterbalanced any concern in that regard. In fact, the approach was that the manual practice run was really an opportunity for the subject to get familiar with the airspace and the simulation environment rather than a session to gain proficiency and experience in using the manual format. This approach was selected because it gave us the maximum quality and quantity of data return for the subject time available. In addition, recall that a fair FASA comparative evaluation was the main objective.

The basis for a comparative evaluation of the FASA formats is the several parameters of controller performance and reaction that were measured. The key parameter is the separation precision but the other measures add important information in the comparative assessment. The experimental measures, in the order discussed in this report, were

1. The precision of aircraft delivery and separation in terms of standard deviation of aircraft pair interarrival error at the runway threshold
2. The mean number of vectors (heading instructions) per aircraft issued by the final controller
3. The controller response time to a "direct" FASA suggested heading and speed advisories
4. The subject controller lookpoint on the PPI as measured by the Langley oculometer system. This processed data indicates information such as areas of concentration, dwell time, number of aircraft pair cross checks.
5. The controller's reaction and acceptance from subject questionnaire and debriefing comments
6. The relative workloads of the FASA formats obtained from the task load index (TLX) technique

5. Results and Discussion of Real-Time Simulation

The previously discussed experimental measures were taken of the subject controllers' performance and reactions while serving as the final controller in a real-time, interactive TRACON simulation. For each of the two representative pattern-speed procedures, data were collected by using the four final controller display formats. Based on the approach pattern-speed procedure issues discussed in section 3.1.5, it was decided that specific interest in only one of the procedures, as well as generality of results, would be served best by presenting the analysis of each measure in three subsections. The first subsection discusses the 170-knot pattern-speed procedure results, the second presents the results of the 210-knot procedure with speed control on final, and the third compares the results of the two procedures. This section presents a detailed discussion and data analysis; major results are given in section 6.

5.1. Delivery-Time Precision at Runway Threshold

The measure used to assess control precision is the standard deviation of aircraft-pair interarrival time error (IAE), which is defined in appendix B. Briefly, IAE is the difference in the arrival time errors of a pair of sequentially landed aircraft. This error can be written in terms of aircraft actual time of arrival (ATA) and scheduled landing time (SLT) at the runway threshold for aircraft 1 and 2 of the sequential pair:

$$\mathrm{IAE} = (\mathrm{ATA}_2 - \mathrm{SLT}_2) - (\mathrm{ATA}_1 - \mathrm{SLT}_1) \quad (1)$$

By regrouping terms, IAE can also be expressed as

$$\begin{aligned}\mathrm{IAE} &= (\mathrm{ATA}_2 - \mathrm{ATA}_1) - (\mathrm{SLT}_2 - \mathrm{SLT}_1)\\ &= (\text{Actual separation time}) - (\text{Scheduled separation time}) \quad (2)\end{aligned}$$

Even though each aircraft of a pair has its own runway threshold time error, if the time error is the same for both (i.e., a constant bias), the IAE will be 0 and the pair separation will be correct. Thus, spread of the IAE's indicates variation in desired spacing and is the attribute of interest. IAE spread is characterized by the statistical measure of dispersion about the mean, the variance, or its square root, the standard deviation.

When aircraft are on instrument approaches during manual control, the controller concerns are with aircraft-pair separations conforming to the radar separation standards in effect. Therefore, in the manual runs only separations were measured and the landing order or scheduled landing times were not kept track of. The test subject controllers were instructed to aim for minimum allowable separation. For the tightly packed traffic used in the test, we assume the controller was attempting to maximize the landing rate by keeping aircraft-pair separations to the minimum distance allowed. For this case, we can treat the minimum required separation as the intended or scheduled separation. Thus for manual data runs, an equivalent manual interarrival time IAE' (defined in section B.2) can be obtained. If the aircraft threshold crossing times, the final approach speed, and the wake vortex spacing requirement are known, the IAE ' can be calculated from

$$\mathrm{IAE}' = (\mathrm{ATA}_2 - \mathrm{ATA}_1) - (\text{Time to fly scheduled separation}) \quad (3)$$

Each subject controller's numerical mean and standard deviation of interarrival time error are given in table 4 for the display formats and speed procedures tested. Also presented are the standard deviations obtained from lumping (simply combining all controller's data for a condition) and from pooling (weighing individual run standard deviations). To preserve anonymity, the controller subject numbers have been randomized and bear no relationship to the original test order appearance; however, listed subject numbers are consistent for all report data. The histograms resulting from lumping all the subject controller interarrival-time errors for a particular display format are shown in figure 16. Figure 17 shows the excess separation at threshold (actual separation distance minus wake vortex required distance) histograms for the benefit of readers more familiar with the distance domain. It should be noted that, for the dense arrival traffic condition simulated, figures 16 and 17 are an approximate time/distance domain mapping of each other.

Figures 16 and 17 present the lumped interarrival time or distance error distributions associated with each condition tested. However, note in table 4 that the mean interarrival time errors vary from controller to controller, particularly for the manual runs. When the interarrival errors from all the controllers are simply combined or lumped together, the standard deviation obtained is larger than representative of the sampled controllers' performance. The overestimation is due to the spreading effect of the difference among the means. The statistical pooled estimate of the standard deviation (s_0) was used as the measure of comparison because it overcomes this spreading limitation and more accurately characterizes the spread of the interarrival time error of the final-controller sample tested. The pooled estimate of the variance of a population from which k samples were taken is defined as

$$s_0^2 = \frac{(n_1 - 1)\, s_1^2 + (n_2 - 1)\, s_2^2 + \ldots + (n_k - 1)\, s_k^2}{n_1 + n_2 + \ldots + n_k - k} \quad (4)$$

where, respectively, $n_1,\ n_2,\ \ldots,\ n_k$ are the number of data points in each sample and $s_1^2,\ s_2^2,\ \ldots,\ s_k^2$ are the calculated variance of each sample around its mean. The pooled estimate has $n_1 + n_2 + \ldots + n_k - k$ degrees of freedom for making significance test or finding confidence intervals. Interarrival time error data collected from each controller is treated as a sample with n_i data points and s_i^2 variance. The pooled estimates of the standard deviation of the interarrival error are shown in table 4 and are plotted in figure 18 with their corresponding 95 percent confidence intervals. (Remember that at 210 knots, a speed adjustment is made on final.)

5.1.1. Time Precision of 170-Knot Pattern-Speed Procedure

Looking at the left side of figure 18 for the results of the 170-knot pattern-speed procedure, we see the standard deviations of the interarrival time error are clustered in two groups. The manual/ARTS III (18.9 sec) and the centerline slot marker (17.8 sec) formats are near each other and have higher standard deviations than the closely grouped pair of the graphic marker (14.7 sec) and DICE countdown (13.9 sec) formats. The results are presented of a systematic series of pairwise, one-sided statistical F tests performed to determine whether the following variance comparisons ($\sigma_1^2 > \sigma_2^2$) were significant:

Manual/FASA statistical comparisons:

$\sigma^2_{170\,\mathrm{MAN}} > \sigma^2_{170\,\mathrm{GM}}$	at 0.0005 level of significance (99.95 percent confidence)
$\sigma^2_{170\,\mathrm{MAN}} > \sigma^2_{170\,\mathrm{DICE}}$	at 0.0005 level of significance (99.95 percent confidence)
$\sigma^2_{170\,\mathrm{MAN}}$ not$>$ $\sigma^2_{170\,\mathrm{CSM}}$	cannot reject null hypothesis (at 0.05 level of significance)

FASA statistical comparisons:

$\sigma^2_{170\,\mathrm{CSM}} > \sigma^2_{170\,\mathrm{GM}}$	at 0.0005 level of significance (99.95 percent confidence)
$\sigma^2_{170\,\mathrm{CSM}} > \sigma^2_{170\,\mathrm{DICE}}$	at 0.0005 level of significance (99.95 percent confidence)
$\sigma^2_{170\,\mathrm{GM}}$ not$>$ $\sigma^2_{170\,\mathrm{DICE}}$	cannot reject null hypothesis (at 0.05 level of significance)

Statistically σ_1^2 was considered larger than σ_2^2 when the level of significance α was less than 0.005 or confidence greater than 99.5 percent (i.e., reject null hypothesis that (σ^2)'s are equal when there is up to 0.5 percent risk of type 1 error—up to 0.005 probability that (σ^2)'s actually were equal). Note that for a series of n pairwise tests that are each performed with level of significance α, the experimentwise or joint level of significance α' is bounded by $\alpha' \leq 1 - (1 - \alpha)^n$ (ref. 20). Thus, when $n = 6$ and $\alpha = 0.005$, the resultant α' was ≤ 0.03 ($\geq$97 percent confidence).

For the 170-knot pattern-speed procedure, statistical analyses of the test results indicate that the centerline slot marker format cannot be said to improve the precision of final spacing over that achieved manually with no final-approach spacing aid. What this result seems to show is that, when the aircraft and its slot marker are traveling at the same 170-knot speed, the judgment of when with turn the aircraft from base-to-final to merge with its slot marker is somewhat demanding. In fact, in terms of separation performance, the judgment required appears comparable to the judgement (in the manual mode) of when to perform the base-to-final turn to separate an aircraft from the preceding aircraft on final. It is worth noting that even though the slot marker IAE spread was comparable with that of the manual format, its bias (mean) for most of the subjects was less than that of the manual format. This indicates a slightly higher arrival rate (increase from 31 to 32.6 aircraft per hour based on assumptions of section 5.1.4) could be expected from the centerline slot marker because it had less excess separation.

The F test indicated there was no statistically significant difference between the delivery precision of the graphic marker format and the DICE countdown format for the 170-knot pattern-speed procedure. However, we can say, with high confidence (at least 99.7 percent for six pairwise comparisons at $\alpha = 0.0005$), that both the graphic marker and the DICE countdown improved the delivery performance relative to either the centerline slot marker or the manual format. The graphic marker and DICE countdown format improved the standard deviation of the interarrival-time-error by 4.2 to 5.0 sec over that achieved manually with no FASA.

5.1.2. Time Precision of 210-Knot Pattern-Speed Procedure

The results of the 210-knot pattern-speed procedure are included on the right side of figure 18. The standard deviations of the interarrival time error for all the FASA formats are considerably less than for the manual/ARTS III format (15.4 sec). As in the 170-knot procedure, the graphic marker format (9.4 sec) is less than the centerline slot marker format (11.2 sec). However, in this case the DICE countdown format (8.2 sec) appears to be slightly less than the graphic format. The results are presented of a series of pairwise, one-sided statistical F tests performed to determine if the following $\sigma_1^2 > \sigma_2^2$ comparisons were significant:

Manual/FASA statistical comparisons:

$\sigma^2_{210\,\mathrm{MAN}} > \sigma^2_{210\,\mathrm{GM}}$ at 0.0005 level of significance (99.95 percent confidence)

$\sigma^2_{210\,\mathrm{MAN}} > \sigma^2_{210\,\mathrm{DICE}}$ at 0.0005 level of significance (99.95 percent confidence)

$\sigma^2_{210\,\mathrm{MAN}} > \sigma^2_{210\,\mathrm{CSM}}$ at 0.0005 level of significance (99.95 percent confidence)

FASA statistical comparisons:

$\sigma^2_{210\,\mathrm{CSM}} > \sigma^2_{210\,\mathrm{GM}}$ at 0.0005 level of significance (99.95 percent confidence)

$\sigma^2_{210\,\mathrm{CSM}} > \sigma^2_{210\,\mathrm{DICE}}$ at 0.0005 level of significance (99.95 percent confidence)

$\sigma^2_{210\,\mathrm{GM}} > \sigma^2_{210\,\mathrm{DICE}}$ at 0.005 level of significance (99.95 percent confidence)

For the 210-knot pattern-speed procedure, we can say with high confidence that the test results for the centerline slot marker format show an improvement in precision of final spacing over that achieved manually with no final-approach spacing aid. The improvement measured was a reduction of 4.2 sec in the standard deviation of the interarrival time error. The graphic marker format, with speed reduction aiding on final, had an even better improvement over the manual with a reduction of 6.0 sec. The DICE countdown format with speed reduction aiding on final, had the best FASA improvement over the manual format with a reduction of 7.2 sec in the standard deviation of the interarrival time error.

5.1.3. Precision Comparison of 170- and 210-Knot Pattern-Speed Procedures

The measured reductions in the standard deviation of the interarrival time error for the 210-knot procedure were noteworthy. From figure 18, each format's standard deviaion for the 210-knot procedure was reduced relative to that for the 170-knot procedure. The results are presented of pairwise, one-sided statistical F tests to determine whether the following $\sigma_1^2 > \sigma_2^2$ comparisons, between the two pattern speeds, were significant:

$\sigma^2_{170\,\mathrm{MAN}} > \sigma^2_{210\,\mathrm{MAN}}$ at 0.0005 level of significance (99.95 percent confidence)

$\sigma^2_{170\,\mathrm{GM}} > \sigma^2_{210\,\mathrm{GM}}$ at 0.0005 level of significance (99.95 percent confidence)

$\sigma^2_{170\,\mathrm{DICE}} > \sigma^2_{210\,\mathrm{DICE}}$ at 0.0005 level of significance (99.95 percent confidence)

$\sigma^2_{170\,\mathrm{CSM}} > \sigma^2_{210\,\mathrm{CSM}}$ at 0.0005 level of significance (99.95 percent confidence)

$\sigma^2_{210\,\mathrm{MAN}}$ not $> \sigma^2_{170\,\mathrm{MAN}}$ cannot reject null hypothesis (at 0.05 level of significance)

With very high confidence (at least 99.8 percent for four pairwise comparisons at $\alpha = 0.0005$), we can say that the 210-knot pattern-speed procedure, with its speed reduction control, improved the delivery precision relative to that of the 170-knot pattern speed for the manual format and each of the FASA formats tested. The reduction in standard deviation for the manual format was 3.5 sec and the reductions for the FASA formats were between 5.3 and 6.6 sec. What is particularly noteworthy is that the arrival precision of the 170-knot procedure graphic marker format could not be considered different from that of the 210-knot manual format. These results indicate that the application of speed control aiding, on final approach, to a FASA has the potential to significantly improve aircraft separation precision at facilities where an initial higher pattern speed on final is practical. Recall from section 3.1.5 that slower pattern speeds offer more planning time to organize traffic. Another aspect to consider is that when the center and approach elements of TATCA (the Center/TRACON Automation System (CTAS)) are operating, higher pattern speeds closer in may be more feasible than in today's environment with no automation decision aids.

5.1.4. Runway Arrival Rate Benefit Assessment

A simple single runway arrival rate model, contained in appendix C, was used to give an indication of what capacity effect the various measured FASA control precisions would have on a time-based TATCA system. The conditions assumed are

Arrival only runway, IMC with constant demand

Runway occupancy times are less than aircraft pair separation times

Two classes of aircraft—heavy (H) and large (L)

Traffic is 85 percent large, 15 percent heavy

Final speed of heavy aircraft past FAF is 140 knots GS

Final speed of large aircraft past FAF is 130 knots GS

5.5 n.mi. from final-approach fix to threshold

Separation violations restricted to 5 percent

Arrival rates are plotted in figure 19 for the following separation requirements:

Lead aircraft	Separation for trail aicraft, n.mi.	
	Large	Heavy
Large	2.5	2.5
Heavy	5	4

Lead aircraft	Separation for trail aicraft, n.mi.	
	Large	Heavy
Large	2	2
Heavy	4.5	3.5

With the use of the 2.5/4/5 n.mi. separation curve, the arrival rate difference between that of the manual format and that of the graphic marker format was used to represent the potential benefit of a TATCA system with FASA as compared with a TATCA system without FASA. Thus, a FASA theoretically would increase the IMC arrival rate 6.6 percent for the 170-knot pattern-speed procedure. For the 210-knot pattern-speed procedure, there would be a potential FASA increase of 10.6 percent. If the 170-knot manual format is used as the baseline to compare against the arrival rate possible by implementing a higher approach speed on final together with turn and speed reduction aiding, the potential improvement would be a more dramatic 16.5 percent in the IMC landing rate.

Thinking farther into the future, a more advanced integrated TATCA system would use refined weather prediction, wake vortex modeling and detection together with precise aircraft flair and touchdown, high-speed turnoffs, and runway guidance to dynamically adjust separation times to the minimums possible under the atmospheric conditions. When the weather would permit the use of time separations which transform to 2/3.5/4.5 n.mi. distance separations, this advanced TATCA system (using the 210-knot approach speed with appropriate FASA) could theoretically land 44.3 aircraft per hour. This translates to a 36.2 percent increase over the baseline manual format, 170-knot pattern-speed procedure, IMC arrival rate.

5.2. Vectors Per Aircraft In Final Sector

Each subject controller's mean number of vectors (heading changes) per aircraft in the final sector is shown in figure 20(a) for the display formats and speed procedures tested. Also shown are the combined means of all the controller subjects for each FASA display format of both pattern-speed procedures. These combined means are plotted in figure 20(b). Note that the mean vectors per aircraft were for all aircraft landed during the data period. They consisted of both eastern aircraft, on base, which required at least one heading change to intercept the ILS and western aircraft, on downwind, which normally required at least two heading changes.

5.2.1. 170 Knot Pattern-Speed-Procedure Vectors Per Aircraft

The display format, number of vectors per aircraft, for the 170-knot pattern-speed procedure, appear to fall into three levels—the manual format (2.7 vectors/aircraft) has the highest mean value, the centerline slot marker format (2.2 vectors/aircraft) is next, and the DICE countdown (1.6 vectors/aircraft) and the graphic marker (1.5 vectors/aircraft) formats have the lowest number of vectors per aircraft in the final sector. A single-factor (display format), repeated measure analysis of variance yielded a P value of 0.0001 for treatment differences. The results are presented for Fisher PLSD (protected least significant difference) post hoc, paired comparisons to determine whether the differences in measured vectors per aircraft were statistically significant:

Manual/FASA statistical comparisons:

$\mu_{170\,\mathrm{MAN}} > \mu_{170\,\mathrm{CSM}}$	at 0.0005 level of significance (99.5 percent confidence)
$\mu_{170\,\mathrm{MAN}} > \mu_{170\,\mathrm{DICE}}$	at 0.0005 level of significance (99.5 percent confidence)
$\mu_{170\,\mathrm{MAN}} > \mu_{170\,\mathrm{GM}}$	at 0.0005 level of significance (99.5 percent confidence)

FASA statistical comparisons:

$\mu_{170\,\mathrm{CSM}} > \mu_{170\,\mathrm{DICE}}$	at 0.0005 level of significance (99.5 percent confidence)
$\mu_{170\,\mathrm{CSM}} > \mu_{170\,\mathrm{GM}}$	at 0.0005 level of significance (99.5 percent confidence)
$\mu_{170\,\mathrm{DICE}}$ not $> \mu_{170\,\mathrm{GM}}$	cannot reject null hypothesis (at 0.05 level of significance)

The analyses indicated that there was no statistically significant difference between the mean vectors per aircraft of the graphic marker format and that of the DICE countdown format for the 170-knot pattern-speed procedure. However, with high statistical confidence (99.5 percent), we can say both the graphic marker and DICE countdown formats reduced the mean number of vectors per aircraft relative to that of both the manual and centerline slot marker formats. The measured mean reduction of both the graphic and the DICE relative to the manual format was 1.1 vectors/aircraft and their average measured reduction relative to the centerline slot marker was 0.6 vectors/aircraft. Also with high statistical confidence (99.5 percent), we can say that the subjects when operating with the centerline slot marker format, on the average, used fewer vectors per aircraft than when operating manually with no FASA. The centerline slot marker measured reduction relative to the manual format was an average 0.5 vectors/aircraft in the final sector.

The graphic marker and DICE countdown formats indicated suggested turn location and headings based on a classic squared approach pattern (downwind parallel to final and base perpendicular to final). On the other hand, the manual technique varied from controller to controller, depending on training and procedures learned at current and earlier facilities in their careers. As the individual subject results for the 170-knot procedure indicate (fig. 20(a)), a third to a half of the controllers strongly tended to issue intermediate vectors rather than a single downwind-to-base or base-to-final heading. A fair question to raise is whether the manual format, vectors per aircraft measured from the test subjects, fairly represents U.S. controllers. In other words, did the subject sample have a larger proportion who tended to use intermediate vectors for spacing (as opposed to squared turns) than contained in the general controller population? We do not have the data to answer the question. However, while more pronounced for subjects 4, 5, 8, 10, and 11, all the subjects had lower average vectors per aircraft for their DICE countdown and graphic marker formats than they did for either their manual or centerline slot marker formats.

For the population of controllers tested, the roughly 40-percent reduction in average vectors per aircraft observed (between the manual and that of either the graphic or DICE format) has the potential to reduce the current communication congestion experienced at major terminals during peak traffic periods. The reduction in the number of vectors also appears to have some impact on the distribution of aircraft in the simulation's dump airspace. This relation is complicated somewhat by the fact that imprecision of timing vectors (for instance being late on downwind-to-base turn) can also spread aircraft in the dump airspace as well as the process of issuing more vectors per aircraft (intermediate vector technique). Figure 21, which plots the aircraft positions every 20 sec, shows the final sector flow pattern for the 170-knot procedure for all formats (manual, centerline slot marker, DICE, and graphic). Clearly the manual format (with the most vectors per aircraft and less vectoring precision) has the most widely dispersed (less concentrated) flow pattern of the four. The graphic marker and DICE formats (with the least vectors per aircraft and most vectoring precision) have the more concentrated dump flow pattern of the formats in figure 21.

5.2.2. Vectors Per Aircraft for 210-Knot Pattern-Speed Procedure

As for the 170-knot pattern-speed procedure, the display formats vectors per aircraft for the 210-knot procedure also appears to fall into three levels (fig. 20(b)). The format order is also the same. However the spread between the extreme values is reduced somewhat. The manual format (2.3 vectors/aircraft) has the highest mean value. The centerline slot marker (1.8 vectors/aircraft) is next. The graphic marker and DICE countdown formats (each with 1.5 vectors/aircraft) have the least number of vectors per aircraft in the final sector. A single factor (display format), repeated measure analysis of variance yielded a P value of 0.0001 for treatment differences. The results are presented for Fisher PLSD (protected least significant difference) post hoc, paired comparisons to determine whether the differences in measured vectors per aircraft were statistically significant:

Manual/FASA statistical comparisons:

$\mu_{210\,\mathrm{MAN}} > \mu_{210\,\mathrm{CSM}}$	at 0.0005 level of significance (99.5 percent confidence)
$\mu_{210\,\mathrm{MAN}} > \mu_{210\,\mathrm{DICE}}$	at 0.0005 level of significance (99.5 percent confidence)
$\mu_{210\,\mathrm{MAN}} > \mu_{210\,\mathrm{GM}}$	at 0.0005 level of significance (99.5 percent confidence)

FASA statistical comparisons:

$\mu_{210\,\mathrm{CSM}} > \mu_{210\,\mathrm{DICE}}$	at 0.01 level of significance (99 percent confidence)
$\mu_{210\,\mathrm{CSM}} > \mu_{210\,\mathrm{GM}}$	at 0.01 level of significance (99 percent confidence)
$\mu_{210\,\mathrm{DICE}}$ not $> \mu_{210\,\mathrm{GM}}$	cannot reject null hypothesis (at 0.05 level of significance)

The results for the 210-knot pattern-speed procedure parallels those for the 170-knot procedure. No statistically significant difference was found in the mean vectors per aircraft for the graphic marker and the DICE countdown formats. However, with high statistical confidence (99.5 percent), we can say that the graphic marker and DICE countdown formats reduced the mean number of vectors per aircraft relative to the manual format and, with high confidence (99 percent), that the same two reduced the number of vectors relative to the centerline slot marker format. The measured mean reduction of both the graphic and DICE formats relative to manual format was 0.7 vectors/aircraft and the same two's mean reduction relative to the centerline slot marker was 0.3 vectors/aircraft. Also with high statistical confidence (99.5 percent), we can say that the subjects used fewer vectors per aircraft when operating with the centerline slot marker than when operating manually with no FASA. The measured reduction for the centerline slot marker format relative to the manual format was 0.5 mean vectors/aircraft in the final sector.

When operating with the 210-knot patten-speed procedure, the population of controllers tested used about 30 percent fewer vectors per aircraft for the graphic or DICE formats than they used for the manual format. As stated earlier, this has the potential to reduce communication congestion at the major terminals during peak traffic periods. As in the 170-knot speed procedure there appears to be a correlation between vectors per aircraft and the spread of aircraft in the dump airspace, although precision of vector timing also had an effect. Figure 22 indicates the final sector dump flow patten for the 210-knot procedure for all formats (manual, centerline slot marker, DICE, and graphic). Clearly the manual format (with the most vectors per aircraft and less vectoring precision) has the most widely dispersed (less concentrated) flow pattern of the four. The graphic marker and DICE countdown formats (with the least vectors per aircraft and most vectoring precision) have the most concentrated dump flow pattern of the formats in figure 22.

5.2.3. Vectoring Comparison for 170- and 210-Knot Pattern-Speed Procedures

From figure 20(b), both the manual and the centerline slot marker formats appear to have fewer mean vectors per aircraft in the 210-knot procedure than in the 170-knot pattern-speed procedure. A two-factor (pattern-speed procedure, display format) repeated measure analysis yielded a P value of 0.0026 for pattern-speed effect. The results are presented of paired contrast performed to determine whether the measured differences in format, mean vectors per aircraft, between the two pattern-speed procedures were significant:

$\mu_{170\,\mathrm{MAN}} > \mu_{210\,\mathrm{MAN}}$	at 0.002 level of significance (99.8 percent confidence)
$\mu_{170\,\mathrm{CSM}} > \mu_{210\,\mathrm{CSM}}$	at 0.006 level of significance (99.4 percent confidence)
$\mu_{170\,\mathrm{DICE}}$ not$> \mu_{210\,\mathrm{DICE}}$	cannot reject null hypothesis (at 0.05 level of significance)
$\mu_{170\,\mathrm{GM}}$ not$> \mu_{210\,\mathrm{GM}}$	cannot reject null hypothesis (at 0.05 level of significance)

With high confidence (99.8 percent) we can say that the 210-knot pattern-speed procedure reduced the manual format vectors per aircraft relative to the corresponding 170-knot procedure. With high confidence (99.4 percent) we can make the same claim for the 210-knot procedure centerline slot marker format relative to the corresponding 170-knot procedure. However, as might be expected, there was no statistically significant difference between the 210-knot pattern-speed procedure and that of the 170-knot procedure for either the DICE countdown or graphic marker format.

No difference between the pattern-speed procedures was expected for the DICE and graphic formats because the suggested turn location and heading were based on the same classic squared approach pattern (downwind parallel to final and base perpendicular to final) in all cases. However, the fewer vectors in the 210-knot procedure than in the 170-knot procedure for both the manual and centerline slot marker formats was not expected. Apparently the additional separation fine-tuning control available in the 210-knot pattern-speed procedure, from selecting the point of speed reduction, eliminated the need for some separation adjustment vectors. For both the manual and centerline slot marker formats, there was an approximate 16-percent reduction in the mean vectors per aircraft in going from the 170-knot to the 210-knot pattern-speed procedure.

5.2.4. FASA Learning Effect On Number of Vectors Issued

Debriefing discussions and controller comments suggested a learning or training effect after operating with the graphic marker and DICE countdown formats. After using the direct automation aids (graphic and DICE formats), there seemed to be a tendency among subject controllers toward using more squared downwind/base vectors (classic trombone pattern) rather than intermediate vectors (cutting corners) in subsequent manual and centerline slot marker runs. Recall from section 4.3, the manual format was always the first format tested in both pattern-speed procedure series. The purpose of appendix D is to determine whether the previous vectors per aircraft conclusions are voided if this learning effect existed. We asserted that the comparisons and trends are correct and if anything the "true" mean vectors per aircraft for the manual and centerline slot marker formats are somewhat higher than those shown in figure 20(b).

The result of the appendix D analysis supports the assertion that the subject controllers did change the mean number of vectors per aircraft issued, for both the manual and centerline slot marker format, after being exposed to the direct automation aid graphic marker and DICE countdown formats. This change was a mean reduction of about 0.4 vectors/aircraft for the manual format and about 0.3 vectors/aircraft for the centerline slot marker format. In addition the analysis reinforced that all earlier mean trend comparisons were valid, particularly that the graphic marker and DICE countdown formats had significantly fewer mean vectors per aircraft than either the manual or centerline slot marker formats. In fact, the differences are likely larger than shown in figure 20(b). Appendix D showed that the mean vectors per aircraft for both the manual and centerline slot marker formats in figure 20(b) are likely underestimated by approximately 0.2 vectors/aircraft.

5.3. Response Time Of Subject Controllers To Direct FASA Aids

The controller response time to the direct aid category FASA's is defined as the difference between the ideal message delivery time indicated by the FASA and the actual message delivery time. By definition (section 3.1.2), this can only apply to direct category FASA's which have both a specific advisory and desired delivery time. Indirect category FASA's, which only indicate the desired end goal, cannot have a response time as defined. With this in mind, response time data were collected on the subject controllers when using the two direct category FASA's tested, the graphic marker and the DICE countdown formats. Data were taken on the base-to-final turn of both the 170- and 210-knot pattern-speed procedures and the nominal 210- to 170-knot speed reduction of the 210-knot pattern-speed procedure.

When considering aircraft-pair separation, the variation or spread in controller response time to a FASA aid is much more of interest than the bias. For example, if two aircraft are both turned late by the same amount (i.e., a constant bias in the response time), separation will be preserved if all factors are constant. Figures 23 through 26 plot the response time data gathered. The actual message delivery time data were obtained from the final controller's coordinator activating a timing button when hearing the controller issue a heading or speed reduction command. This process contributed a small amount of imprecision to the measured controller's time of delivery. However, postexperiment test indicated the clocker's (human activating the timer) standard deviation was roughly a third or less that of the controller's response time. Thus the standard deviations measured are a close approximation (only over estimated by about 5 percent) to actual controller performance.

The response time performance, between the 170-knot and the 210-knot pattern-speed procedures, for the graphic marker final-turn advisory, were almost the same. Consequently, results from both speed procedures were combined to estimate controller's response to the turn advisories with the graphic marker format as shown in figure 23. The same situation existed for the DICE format case. Therefore, figure 24 represents the combined 170-knot and 210-knot procedures response times to the DICE format's final turn advisory. It should be pointed out that the data in figures 23 through 26 are not a straight combination of all controller results. Because of the difference in the mean response times among subject controllers, a simple combination of the subjects data would result in an unrepresentative picture of the controllers' response time scatter or standard deviation. As a result, each subject controller's response data were normalized to the mean of the combined sample such that deviations from each subject's mean were plotted as deviations from the combined sample mean.

The results are presented of one-sided statistical F tests performed to determine whether there was statistical significance to the differences in measured response time standard deviation between the graphic marker and the DICE countdown formats:

Comparison of graphic/DICE final-turn-advisory response-time:

$\sigma^2_{\mathrm{GM}} > \sigma^2_{\mathrm{DICE}}$ at 0.00003 level of significance (99.997 percent confidence)

Comparison of graphic/DICE final-speed-reduction-advisory response-time:

$\sigma^2_{\mathrm{DICE}} > \sigma^2_{\mathrm{GM}}$ at 0.02 level of significance (98 percent confidence)

With very high statistical confidence (99.997 percent), we can say that the standard deviation of the controllers' response times to the turn advisories of the DICE countdown format (3.3 sec) was less than that to the graphic marker turn advisories (3.7 sec). Recalling the results from section 5.1 as:

Standard deviation of 170-knot pattern-speed procedure interarrival error:

Graphic marker—14.7 sec

DICE countdown—13.9 sec

Standard deviation of 210-knot pattern-speed procedure interarrival error:

Graphic marker—9.4 sec

DICE countdown—8.2 sec

The statistically distinct difference in standard deviaion of turn advisory response time, though numerically small, appears to account for the slight separation precision advantage measured for the DICE countdown format.

With 98 percent confidence, we can say that the standard deviation of the controllers' response times to the speed advisories of the graphic marker format (4.1 sec) was less than that to the DICE countdown format (4.5 sec). The comparative outcome is reversed from that obtained for the turn advisories. We believe the dynamics of the DICE speed advisor countdown was the cause of this reversal. As discussed in sections 3.2.3 and A.3, the DICE speed advisor countdown rate changed slowly (approximately 1 count change for every 4 sec). This pace did not tend to hold the controllers' attention as did the more rapid DICE turn advisor countdown. Thus, the controllers' response time scatter (standard deviation) for the DICE speed advisor was not only greater than that for the DICE turn advisor but also greater than that for the graphic marker speed advisor.

5.4. Evaluation of Lookpoint Data

The oculometer system basically records and measures where the subject is looking; thus it indicates what is being looked at and how long any single fixation lasts. This doesn't necessarily identify what the controller is thinking. However, eye-tracking data are objective and cannot be reliably acquired from another type of source, certainly not from interrogating the subject himself. By summing fixation times over particular objects (such as the aircraft position symbols, data blocks), an understanding of the scan pattern develops. Likewise, summing over areas of the display (zones) demonstrates that the scan is not uniformly distributed along the nominal routes. For example, figures 27 (manual) and 28 (CSM) are lookpoint scatter diagrams of two of the 96 test runs. They each show the position of about 6000 lookpoints or fixations. During a 70-min test, the subject is fixating and being recorded by the oculometer about 85 percent of the time. Comparing figures 27 and 28 (lookpoints) with figures 21 and 22, which show aircraft positions during two typical runs, the nonuniformity of the scan distribution along the pattern routes is evident. The final controllers looked more frequently along the final-approach course and the base legs. Also, notice in figure 28 (CSM) the fixations along the extension of the final approach where the slot markers appear.

We examined three measures of lookpoint behavior as a function of the tested display formats. The first measure was the amount of time the oculometer had the subject in track which was treated as follows: as a percentage of test time, as a percentage of time divided among display object types, or as a percentage of time divided among regions of the controller's display. The second measure was average fixation time duration by display object type. The third measure was number of cross-check scans which indicated the number of uninterrupted fixations alternating between two display objects. Cross-check scans are further defined in section E.6. Appendix E also contains more information on the oculometer system, lookpoint analysis, and related data files.

In the following sections for each lookpoint measure, a single-factor (display format) repeated measure analysis of variance was performed for each patten-speed procedure to determine whether the display format differences in the particular lookpoint measure were statistically meaningful at level of significance of 0.05 (95 percent confidence level). If significant, then a Fisher PLSD post hoc, paired contrast test was performed to determine which paired differences were significant. Also a two-factor (pattern-speed procedure, display format) repeated measure analysis of variance was performed to determine whether there were statistically meaningful differences in the particular lookpoint measure between the two speed procedures. The numerical values obtained from the above test are presented in the final section of the lookpoint discussion (sec. 5.4.7).

5.4.1. Oculometer In-Track Time as Percent of Total Time

During the experiments, the controllers had some discretion as to when to monitor the display and could spend part of the time looking away from the display while talking casually with the feeder controller or coordinator. For the oculometer in-track time measurement, the working hypothesis relative to task difficulty is as follows: the more difficult the task, the higher the in-track time is because there is less discretionary or spare time to look away from the display. The analysis in this section uses this apparent behavior pattern to differentiate between the display formats.

The data in figure 29 are the time the subject's eye was being tracked by the oculometer as a percent of total test time. The figure presents the mean of the 12 subjects for each of the four display formats and for each of the two pattern speeds, a total of 96 runs of 70 min each. At the 210-knot pattern speed, there were no statistically significant differences among the four formats. At the 170-knot pattern speed, the graphic format required a statistically significant, lower percentage of attention or viewing time than either the manual or centerline slot marker format. The percentage of in-track time for the DICE format was between that of the graphic and the centerline slot marker and was not statistically significantly different from either. This closely agrees with the TLX workload results of section 5.5.2. Also of interest, the data show that the subjects spent about 80 percent of the test runs looking at the radar display. Or put another way, the discretionary time on the average was about 20 percent.

The differences in the in-track time as a percent of total run time between the 170- and 210-knot pattern-speed procedures were not statistically significant at the 0.05 level. The result was that the null hypothesis (in-track time as a percent of total run time for the two speed procedures are equal) could not be rejected at the 0.05 level of significance. Therefore the 210-knot pattern-speed procedure did not affect in-track time as compared with the 170-knot procedure.

5.4.2. In-Track Time by Display Object Type

A discussion of how much of the total test time was spent looking at the radar display was presented in section 5.4.1. Now we will address the question of how the subject budgets in-track times over the various objects on the display and how, if at all, the display formats influence this lookpoint pattern. In-track times for various display objects are presented in figure 30. Section 5.4.3 addresses how the total in-track time is budgeted among display zones, and section 5.4.5 examines the average length of individual fixations broken down by type of display object and test treatment.

The four principal display object types chosen for this analysis are the data block, the aircraft position symbol, the FASA and the combination of the aircraft position symbol and FASA. The first two of these exist for all formats and need no other explanation. For the 170-knot procedure GM runs, the FASA was the turn marker, whereas for the 210-pattern-speed procedure, the GM FASA also included the speed reduction advisor. For the CSM tests the FASA was the numerical part of an aircraft call sign enclosed in a circle moving along the extended runway centerline. For the DICE runs, we defined the FASA to be the data block whenever the DICE countdown was proceeding whether for a turn or a speed change. If the subject looked at the data block for some other reason such as to obtain the aircraft identification while the countdown was proceeding, it was still counted as a fixation on the DICE FASA. The reason was because the oculometer position resolution did not allow the determination of what the subject is looking at within the data block; this introduced an ambiguity and resulted in fixations that should have been assigned to the data block being assigned to the FASA during DICE countdown. A similar problem was caused by the close proximity of the data block and aircraft position symbol. On formats other than DICE, errors due to assigning fixations to aircraft position symbols rather than to data blocks and vice versa tend to cancel one another. On the DICE format, however, because of the position of the countdown in the last line of the data block, a bias toward overassigning fixations to the aircraft position symbol occurred. The fourth principal display object type, the combination, only applies to the GM and CSM formats. For these formats when the aircraft position symbol got very close to the FASA (within 0.57 in.), we chose to assign the fixation to this combination rather than assign the fixation to the closer object of the two. Data are presented out separately in the tablulation of figure 30(a), but in the graph (fig. 30(b)) the combination data are stacked above either the GM or CSM FASA as appropriate.

From 6 to 8 percent of the time, a display object could not be found within the required 0.57-in. proximity to the fixation point. These occurrences were tabulated in a no-identification (NO-ID) category, which was assumed to be a measurement deficiency until looked into further. We had expected to find these fixations clustered around some object that had been inadvertently omitted from our list of possible display objects. However, a scatter plot of these points shows a fairly random position distribution in the display area of interest. In addition, the average length (section 5.4.5) of a given fixation in this category was, in a statistical sense, significantly shorter than those associated with a known display object. Therefore, we conclude that these unattached fixations are part of normal scan behavior and are included in the tabulation (fig. 30(a)) for completeness. Other display object types (such as lines, navaids, or the arrival aircraft sequence list) are not discussed here and are not plotted in figure 30(b), but they are included in a category called "other" in the tabulation (fig. 30(a)).

5.4.2.1. In-Track Time Display Object for 170-Knot Pattern-Speed Procedure

From figure 30(b) we see time spent on the data block for the 170-knot pattern-speed procedure was about equal for the three FASA's (≈ 37 percent) and, in a statistical sense, was significantly less than the manual format (≈ 46 percent). For the aircraft position symbol fixations the GM and CSM were about equivalent (≈ 22 percent) and were, in a statistical sense, significantly less than the manual and DICE which are about equivalent (≈ 34 percent). However, recall the value of the DICE A/C position was biased, with the consequences to the data as explained subsequently. For fixations on the FASA or FASA & A/C combination, the GM and CSM are about equivalent (≈ 26 percent) and, in a statistical sense, both were significantly greater than the DICE (≈ 20 percent). However, the DICE FASA value could have been somewhat biased. Notice that the majority of time spent on the FASA for both GM and CSM was spent on the combination category, that is, when the aircraft position symbol was very close to the FASA. Because of oculometer resolution limitation described earlier in this section, the authors believe that for the DICE format some of the A/C position symbol fixations should have been shifted to the FASA and some of the FASA shifted to the data block. This would have tended to further level out the differences between the three FASA's for the data block category, reducing the DICE aircraft position percentage; thus, the net effect on the DICE FASA percentage was uncertain.

Even though the measure of the fixation time among display objects did not clearly discriminate among FASA formats, overall there was a reduction of approximately 8 percent in the in-track time spent on the data block of the three FASA formats as compared with the manual format. Similarly, there was a reduction of approximately 13 percent of in-track time spent on the isolated aircraft positions; this accounted for most of the about 25 percent of in-track time spent on the FASA's. Clearly the FASA formats have altered the scan pattern of the subjects from the manual format. This was to be expected since time spent fixated on a FASA must be taken from objects normally appearing in the manual format.

5.4.2.2. In-Track Time by Display Object for 210-Knot Pattern-Speed Procedure

From the graph in figure 30(b), it is apparent that the FASA display formats have altered the scan pattern of the subjects from the manual format. Average percent of in-track time spent on data blocks was about equal for the GM and CSM (≈ 33 percent) and was, in a statistical sense, significantly less than the manual format (≈ 48 percent). Time spent on the data block during DICE tests was, in a statistical sense, significantly lower (≈ 26 percent) than the other three formats, but the measurement system tended to bias it low. For the aircraft position symbol fixations, the manual (≈ 33 percent) was about equivalent to the DICE (≈ 32 percent) and both were, in a statistical sense, significantly higher than the CSM (≈ 23 percent), which was in turn significantly higher than the GM (≈ 18 percent). However, like the 170-knot case, the DICE A/C position value was biased too high. For fixations on the FASA or FASA & A/C combination, the DICE and CSM were about equivalent (≈ 29 percent) and both less than the GM (≈ 34 percent). Notice that the majority of time spent on the FASA for both GM and CSM was spent on the combination category, that is, when the aircraft position symbol is very close to the FASA. As explained earlier, due to oculometer resolution limitation, the authors believe that for the DICE format some of the aircraft position symbol fixations should have been shifted to the FASA and some of the FASA to the data block. This shifting would have tended to further level out the differences between the three FASA's for the data block category, and reduced the DICE-aircraft position percentage; thus, the net effect on the DICE FASA percentage was uncertain.

Even though the measure of the fixation time among display objects did not clearly discriminate among FASA formats, overall there was a reduction of approximately 15 percent in the in-track time spent on the data block of the three FASA formats as compared with the manual format. Similarly, there was a reduction of approximately 13 percent in the in-track time spent on the isolated aircraft positions. This accounted for most of the about 31 percent of in-track time spent on the FASA's. As was true for the 170-knot procedure, the 210-knot procedure FASA formats have altered the scan pattern of the subjects from the manual format.

5.4.2.3. Comparison of Display Object In-Track Time for 170- and 210-Knot Pattern-Speed Procedures

No significant difference was found in the total in-track time spent on the aircraft position symbols of the 170-knot and the 210-knot procedure. However, the pattern speed was a significant factor for the data block ($\alpha = 0.01$), for the FASA ($\alpha = 0.001$), and for the aircraft position symbol and FASA combination ($\alpha = 0.02$). For the higher pattern speed, more time was shifted to the FASA's from the aircraft position symbols and data blocks. For the DICE and GM, the simple explanation was that the added speed advisory means that the FASA was encountered one more time per arrival. For the CSM, the effect was less pronounced and came from using the aircraft's proximity to the slot marker as a cue to reduce to the lower pattern speed (170 knots).

5.4.3. In-Track Time by Display Zones

In this section we examine how the subjects budget their fixation time over the entire area of the display. In section 5.4.1, the subjects were fixated on the display on an average of about 80 percent of the test time. In section 5.4.2, this time was divided among the specific display object types. The focus here is on where the subject is looking rather than at what. The final controller's PPI display is illustrated in figures 12 and 13(b). For analysis purposes the final sector display was divided into four zones:

1. Final-approach leg
2. Base legs
3. Downwind legs
4. Everything else

Figure 31 is a graphical representation of these zones. Note that the zones are not strict areas but are defined by a combination of the TIMER approach phase status (section 4.1.2) and the heading. For instance, the base leg was defined to be within a range of headings relative to the nominal base leg (perpendicular to final course) and could be at a different location for each aircraft.

Figures 21 and 22 showed that the aircraft position symbols were distributed over the display more or less uniformly along the nominal pattern paths. However, as discussed earlier, the scatter plots of fixations (figs. 27 and 28) indicated the controller fixations were not correspondingly uniformly distributed. Data of in-track time by display zone verified those observations. Only about 4 percent of the controller's time is spent in zone 4, whereas between 76 and 82 percent of their time is spent in zone 1 or 2. This section is concerned with describing the scan behavior of the subjects referenced to zones and showing how, if at all, the various display formats influence this behavior. Figure 32 is a plot of controller means for the relative amount of in-track time spent in each zone for the four display formats and both pattern speeds.

5.4.3.1. In-Track Time by Zone for 170-Knot Pattern-Speed Procedure

From figure 32, significantly (as used in this section, in a statistical sense) more time was spent observing the final approach during the CSM tests ($\approx$57 percent) than was spent observing this area for the other three format tests. The manual format ($\approx$51 percent) was the second highest and it was significantly higher than GM and DICE which were about equal ($\approx$44 percent). For the base legs, the situation was reversed with GM and DICE about equal ($\approx$33 percent) and significantly higher than the manual and the CSM ($\approx$26 percent). For the downwind legs, GM and DICE were again about equal ($\approx$13 percent) and significantly higher than the manual ($\approx$10 percent), which was in turn significantly higher than CSM ($\approx$8 percent). For the CSM, the focus on the spatial relation between the aircraft position marker and the slot marker increased the observation intensity along the final, whereas for the GM and DICE, the focus was on the base legs or downwind legs where the FASA's were displayed. This same effect could also be seen for the 210-knot pattern speed. For the manual format, the controller was concentrating on separation and speed along the final-approach course. The subject tended to monitor the data block for aircraft decelerations, concerned that the aircraft will close on the one ahead. When using the FASA's, especially the DICE and GM, the controller tended to use the FASA to turn the aircraft rather than using the relative position of the aircraft ahead on the final. This favored zone 2 and 3 over zone 1. With the FASA, some controllers assumed that separation and speed on the final approach would be taken care of without intervention. During CSM runs, the controllers were encouraged to make the turn to base leg from the downwind leg based on preceding traffic rather than keying on the slot marker.

5.4.3.2. In-Track Time by Zone for 210-Knot Pattern Speed Procedure

From figure 32, qualitatively the 210-knot data look very much like the 170-knot data. Significantly (in a statistical sense) more time ($\approx$61 percent) was spent on the final approach during the CSM tests than during the other three format tests. The manual format was the second highest ($\approx$57 percent) and was significantly higher than GM and DICE, which were about equal ($\approx$50 percent). For the base legs, the situation was reversed with the GM and DICE about equal ($\approx$28 percent) and significantly higher than the manual and the CSM ($\approx$21 percent). On the downwind legs, GM and DICE were again about equal ($\approx$11 percent) and significantly higher than the manual and CSM ($\approx$8 percent). For the CSM, there was an increase in observation around the turn onto the final approach, whereas for the GM and DICE, activity had shifted to the base legs and downwind legs. The effect was stronger in the 210-knot procedure than in the 170-knot procedure.

5.4.3.3. Zone In-Track Time Comparison 170- and 210-Knot Pattern-Speed Procedures

The pattern speed is a significant factor in zone 1 ($\alpha = 0.001$), zone 2 ($\alpha = 0.0002$), and in zone 3 ($\alpha = 0.02$). The 170- and 210-knot pattern speeds appear similar qualitatively, but there is a definite shift toward the final approach and away from the base legs and downwind legs with the 210-knot procedure. The 210-knot procedure speed reduction on final seems to account for the attention shift.

5.4.4. In-Track Time Inside Final-Approach Fix

The Final Approach Fix (FAF) is shown in figures 1 and 31. The amount of controller monitoring inside the FAF is critical because of both the separation compression that normally occurs in the vicinity of the outer marker as well as the differences in individual aircraft speeds on final approach. The concern was that aircraft separation monitoring inside the FAF might decrease as a result of the automation. Figure 33(a) gives the subject controllers' time spent inside the FAF, as percentages of their in-tract time, for the various test conditions. Figure 33(b) shows the mean for all subjects combined. The findings indicate a significant reduction in the monitoring with the centerline slot marker format; this is particularly relevant when one recalls that the CSM had the worst delivery precision of the FASA's (section 5.1). From controller comments (section 5.5.1) and workload analysis (section 5.5.2), the CSM reduction in monitoring relative to the GM and the DICE seems to be because of the difficulty and workload of initially separating aircraft on final with CSM.

The 12 subjects spent significantly less time (fig. 33) looking at aircraft positions or data blocks inside the final-approach fix during the CSM sessions than during any of the other three formats. For the 170-knot pattern-speed procedure, the percentage of in-track time for the manual, DICE, and GM were about equivalent (7 percent) and were significantly higher than the CSM (3.5 percent). For the 210-knot pattern-speed procedure, the manual tests had the highest percentage (11.2 percent) of time spent in this area of the display. The percentage of in-track time for the DICE and GM were about equivalent (8 percent) and were significantly lower than the manual and higher than the CSM (4 percent).

As a group, the 210-knot pattern-speed procedure did not affect the percentages of in-track time spent inside the FAF as compared with the 170-knot procedure. However, as can be seen from a comparison of the manual format at the two speeds in figure 33, a notable difference occurs between those two means. A likely explanation for the significantly different fixation time spent inside the final-approach fix for the 210-knot manual case was that additional time was devoted to monitoring aircraft pairs when the following aircraft was issued a speed reduction. Particularly close scrutiny was given to this situation while the following aircraft was decelerating, during which time, in many instances, the lead aircraft had passed the final-approach fix.

5.4.5. Mean Dwell Times by Display Object Type

Longer average dwell times can be indicative of either more information being transferred or, for the same amount of information, a slower information transfer process. For the results presented in this section, the mean dwell time for a display object type (for a given subject) was averaged over the test. The composite controller means are broken down by display object type, FASA display format, and pattern speed and are presented in figure 34.

A previous section (5.4.2) presented a discussion of the total in-track time by display object types and of some biases in the data collection process. The assertion was that because of the bias, some of the DICE FASA fixations probably belonged to the data block category which would tend to even out the effect of the FASA, that is, to increase the shorter amount of in-track time spent on the normal data block and decrease the longer amount of in-track time spent on the DICE countdown aid. However, in the present section, the same bias has the opposite effect. Removing the shorter, misallocated, dwell times from the computation of the DICE FASA mean would make the mean dwell time (while the FASA was active) even longer than shown, that is, would amplify further the effects of the DICE FASA.

5.4.5.1. Mean Dwell Time by Display Object for 170-Knot Pattern-Speed Procedure

The mean dwell times for the data block were about equal for the manual and GM (0.7 sec), slightly higher for the CSM (0.8 sec), and barely lower for the DICE (0.65 sec). For the aircraft position symbol fixations the manual, GM, and DICE were about equivalent (0.7 sec) and were significantly less than the CSM (0.8 sec). For fixations on the FASA, the GM and CSM were about equivalent (0.7 sec) and both were significantly shorter than the DICE (1.3 sec). For the combination category (when the A/C position symbol is very close to the FASA), the GM and CSM were about equivalent (1.0 sec). The most prominent feature of figure 34(b) is that the longest dwell times were associated with the FASA in the DICE format when the countdown is active even though the estimates presented are conservative due to the bias already discussed. The next longest dwell times were associated with the combination of aircraft position symbol and FASA for the GM and CSM which occur when the FASA and A/C are in close proximity at turn points. Dwell times on the data block were very long when the DICE was active. They were longer than dwell times for the graphic marker or slot marker taken by themselves or when combined with the aircraft in close proximity. Since the mean DICE dwell time was computed for fixations close to the time to turn as well as earlier, perhaps a better measure would be to compare the DICE FASA average with the weighted average of the two object categories, FASA and FASA & A/C for both graphic and slot marker. This measure resulted in the 1.26 sec for the DICE being compared with 0.92 sec for the GM and 0.80 sec for the CSM. Clearly the DICE mean dwell times are considerably longer.

Another general point of interest was the active, constantly darting nature of the controller's scan, which was seen on video tapes of the controller's display with the lookpoint electronically superimposed. Even when a turn was nearing, the controller's lookpoint did not stay focused on the FASA but darted to other traffic and then returned to the FASA only slightly before the indicated turn issue time. For example, the graphic marker FASA & A/C combination mean dwell time was only about 1 sec even though that category denotes an impending turn. This means that on the average, the lookpoint remained focused on the graphic turn FASA & A/C combination for no longer than a second and then darted to another object. This constant motion scanning behavior was observed for all formats and pattern-speed procedures.

5.4.5.2. Mean Dwell Time by Display Object for 210-Knot Pattern-Speed Procedure

The mean dwell times for the data block was about equal for the manual, GM, and DICE (0.7 sec) and slightly higher for the CSM case (0.8 sec). For the aircraft position symbol fixations, the manual and GM were about equivalent (0.7 sec) and were significantly less than the DICE (0.8 sec) and CSM (0.9 sec). For fixations on the FASA, the GM and CSM were about equivalent (0.7 sec) and both were significantly shorter than the DICE (1.3 sec). For the combination category (when the A/C position symbol is very close to the aid), the GM (1.0 sec) was significantly lower than the CSM (1.3 sec).

Dwell times on the data block when the DICE was active were very long. They were longer than dwell times for the graphic marker or slot marker taken by themselves and longer than the FASA & A/C combination for the graphic marker. They were about equivalent for the FASA & A/C combination for the slot marker. However, by using the approach discussed for the 170-knot procedure, when the DICE was compared with the weighted average of the two object categories, FASA and FASA & A/C, for both graphic and slot marker, this measure resulted in the 1.26 sec for the DICE as compared with 0.85 sec for the graphic marker and 0.94 sec for the slot. The DICE format clearly stands out as having the longest average dwell times.

5.4.5.3. Comparison of Mean Dwell Time by Display Object for 170- and 210-Knot Pattern-Speed Procedures

The pattern speed was a significant factor for data block ($\alpha = 0.02$), aircraft position symbol ($\alpha = 0.01$), and for the FASA and aircraft position symbol combination ($\alpha = 0.02$). These effects were mainly due to the increase in fixation times during the CSM tests. The greatest difference between the two pattern speeds was in the FASA and aircraft position symbol combination for the CSM case. This very significant increase (from 1 to 1.3 sec) at the 210-knot speed was probably due to the subject using the slot marker to help make a judgment on when to slow the aircraft. Notice that at both speeds the NO ID phenomenon, as discussed in section 5.4.2, stands out for having short mean dwell times. Also, at either speed, when the aircraft got close to its FASA, there was a significant increase in mean dwell time for both the GM and CSM.

5.4.5.4. Comparison of DICE and Graphic Marker Mean Dwell Time

Instrument bias errors discussed earlier tend to reduce the measured DICE mean dwell time (true value longer than plotted). Another factor which had the opposite effect was the controller's practice of looking at an aircraft call sign just before issuing control instructions. After the final focus on the graphic turn-FASA/aircraft combination before issuing the turn, it was normal for the controller to look up to the data block for the aircraft call sign. Because of instrument resolution limitation, when a similar scan sequence occured with the DICE format, the time spent on the aircraft call sign in the data block was credited as part of the DICE dwell time. Thus, the measured dwell time for the final DICE focus only during each countdown was inflated. The opposing bias factors created a slight uncertainty in the value of the DICE mean dwell time; thus, relative to the simple hypothesis, in a strict statistical sense, we cannot make quite as strong a conclusion as that so very strongly indicated by the average dwell time data values.

The starting hypothesis about dwell time was that longer mean dwell times are indicative of either more information being transferred or, for the same amount of information, a slower information transfer process. The graphic marker and DICE appear to provide equivalent information but in different form. If the hypothesis is accepted, the fact that the mean dwell times were longer for fixations using the DICE countdown than the graphic marker suggests a more efficient information transfer process for the graphic marker format. Intuitively, there seems to be some truth to that conclusion particularly because controllers are accustomed to using position data on their display to make decisions. It is tempting to reason that a pictorial representation is easier to assimilate than digital information depicting the same situation. At a glance the graphic marker indicates distance remaining before a turn, whereas with a countdown (particularly a DICE countdown) there could be a tendency to linger momentarily to get a sense of the countdown rate for the same information.

5.4.6. Cross Check Scans by Zone Pairs

Cross-check scans (CCS) indicate the number of uninterrupted dwell points alternating between two display objects and are also discussed in section E.6. For a pair of display objects A and B, the lookpoint sequence A-B is counted as a CCS of order 2, the sequence A-B-A is counted as a CCS of order 3, A-B-A-B is of order 4, and so forth. For the zones defined in section 5.4.3, a cross-check scan between two zones is simply a cross check between two objects located in each of the zones. For analysis purposes three redundant groups of zone pairs were selected to emphasize the role of the three major zones: final-approach leg, base legs, and downwind legs. The zone pairs are nondirectional (i.e., Z1/Z2 = Z2/Z1). Each group contains the sum of three zone pairs as follows:

$$\begin{aligned} \mathrm{Z1/All} &= \mathrm{Z1/Z1} + \mathrm{Z1/Z2} + \mathrm{Z1/Z3} \\ \mathrm{Z2/All} &= \mathrm{Z2/Z1} + \mathrm{Z2/Z2} + \mathrm{Z2/Z3} \\ \mathrm{Z3/All} &= \mathrm{Z3/Z1} + \mathrm{Z3/Z2} + \mathrm{Z3/Z3} \end{aligned} \tag{5}$$

Figures 35(a) and (b) contain the number of cross-check scans, of order four or greater, per run for the three groups of zone pairs, broken down by subject controller and display format. Figure 35(c) graphs the mean cross-scans for the 12 subjects. Each point on the plot represents the average of 12 70-minute trials for the indicated pattern speed and display format.

For the controller, cross-check scans consist of sequentially examining relative positions of aircraft to other aircraft, as well as aircraft to geographical (or other significant) points on the display. The normal purpose of cross checking is to either perform some control action or to monitor separation. The hypothesis was that a reduction in the number of cross-checks primarily indicated a reduction in the amount of comparison or judgment required to properly time a control action if the amount of monitoring is assumed to be relatively constant. According to this hypothesis, the results indicate a significant graphic marker advantage relative to the amount of position comparisons performed.

Most of the cross-check scanning involves checking positions along the final-approach course or, to a lesser degree, along the base legs, this agrees with the other eye scanning measurements and seems to indicate the priorities of controllers. On the downwind legs at both speeds, the average CCS's for GM and CSM look about equal (13) and less than for the manual and DICE (19). However, because there are so few in this group, we hesitate to draw any firm conclusions.

5.4.6.1. Cross-Check Scans by Zone Pairs for 170-Knot Pattern-Speed Procedure

At the 170-knot pattern-speed procedure on both the final-approach and base legs (zones 1 and 2), the graphic marker has significantly lower average CCS's than do the other three formats (fig. 35(c)). Also, the DICE and CSM are about equal and are significantly less than the manual. Therefore, the data indicate that on the critical base legs and final-approach leg, the manual is associated with the highest average CCS's, the graphic with the lowest average and the other two formats are in between.

5.4.6.2. Cross-Check Scans by Zone Pairs for 210-Knot Pattern-Speed Procedure

At the 210-knot pattern-speed procedure on the final approach, the graphic marker has significantly lower mean CCS's than do the other three formats (fig. 35(c)). On the base legs, the graphic and CSM are about equal and significantly less than the manual and DICE. Therefore, the data indicate that on the base legs and final-approach leg, the manual is associated with the highest average CCS's, the graphic with the lowest mean and the other two formats are in between.

5.4.6.3. Comparison of Cross-Check Scans by Zone Pair for 170- and 210-Knot Pattern-Speed Procedures

The pattern speed is a significant factor ($\alpha = 0.01$) only in zone 1 (Z1/All). That is, a greater number of CCS's occurred at the higher pattern speed on the final approach. This result is consistent with the added requirement of slowing the aircraft to 170 knots on the final-approach course.

5.4.6.4. Comparison of DICE and Graphic Marker Cross-Check Scans

Clearly the graphic marker has less CCS's than the other formats particularly in the Z1/All and Z2/All comparisons. As was stated in section 5.4.5.4, the graphic marker and the DICE appears to provide equivalent information but in different forms. Why the observed differences in CCS's? When the GM appears on the display it is immediately apparent in the subject's parafoveal vision so that the subject does not have to scan for the occurrence of the event. However, with the DICE when an aircraft is on the downwind leg, the parafoveal vision does not clue the subject that a turn is imminent. Consequently subject controllers tended to use one of two distinct eye scanning patterns with the DICE FASA.

One scan pattern compares the position of the aircraft on the downwind leg and final-approach leg to estimate when the turn should be issued and then the subject starts to monitor the countdown more closely. This DICE scan pattern resembles a traditional manual scan pattern and tends to have more aircraft cross checking relative to the graphic. The fact that the DICE is nonlinear on the downwind amplifies this effect. With the GM, the subject has a better feel for time remaining. The subject can pick up this information without as much cross checking. The other scanning pattern for the DICE seems to consist of scanning the data block searching for the existence of a DICE countdown. The second pattern results in more data block cross checking relative to DICE.

Since both the DICE eye-scan patterns described tend to increase DICE CCS's relative to GM, the net result is that there is more overall cross checking in the DICE format than in the GM format. Does use of the first DICE scan pattern result in maintaining a better overall traffic picture than use of the second DICE scan pattern? Does the graphic format result in a better traffic picture than either of the DICE scan patterns? Our data provided no answer to these two interesting questions or to the more general question of whether reliance on a FASA affects controller traffic awareness.

5.4.7. Summary of Lookpoint Data Statistical Test

This section presents the F-test statistic (F) and the resultant level of significance (P) values from a single-factor (display format) repeated-measure analysis of variance (ANOVA). The ANOVA was performed, for each patten-speed procedure to determine whether the display format differences in the lookpoint measures, were statistically meaningful at a level of significance of 0.05 (95 percent confidence level). If the ANOVA for a pattern speed indicated significance ($P < 0.05$), a Fisher PLSD post hoc, paired contrast test (second table or tables of each measure) was then performed for that pattern speed to determine which paired differences were significant ($P < 0.05$). In addition, a two-factor (pattern-speed display format) repeated-measure ANOVA was performed to determine whether there were statistically meaningful differences in the particular lookpoint measure between the two speed procedures. These statistical test data are presented in the following tables.

In-Track Time (section 5.4.1 and fig. 29):

	ANOVA results for—		
	Format comparison for 170 knots	Format comparison for 210 knots	Format comparison for 170 & 210 knots
F	3.395	0.413	2.171
P	0.029	0.744	0.169

Format	P of Fisher PLSD post hoc for 170-knot format constant scan		
	GM	DICE	CSM
MAN	0.008	0.090	0.744
GM		0.296	0.018
DICE			0.165

In-Track Time Spent on Data Block (section 5.4.2 and fig. 30):

	ANOVA results for—		
	Format comparison for 170 knots	Format comparison for 210 knots	Format comparison for 170 & 210 knots
F	10.900	24.156	9.838
P	0.000	0.000	0.010

Format	P of Fisher PLSD post hoc for 170-knot format constant scan		
	GM	DICE	CSM
MAN	0.000	0.000	0.000
GM		0.106	0.968
DICE			0.098

Format	P of Fisher PLSD post hoc for 210-knot format constant scan		
	GM	DICE	CSM
MAN	0.000	0.000	0.000
GM		0.016	0.795
DICE			0.008

In-Track Time Spent on Aircraft Positions (section 5.4.2 and fig. 30):

	ANOVA results for—		
	Format comparison for 170 knots	Format comparison for 210 knots	Format comparison for 170 & 210 knots
F	18.287	16.942	1.683
P	0.000	0.000	0.221

Format	P of Fisher PLSD post hoc for 170-knot format constant scan		
	GM	DICE	CSM
MAN	0.000	0.136	0.000
GM		0.000	0.870
DICE			0.000

Format	P of Fisher PLSD post hoc for 210-knot format constant scan		
	GM	DICE	CSM
MAN	0.000	0.535	0.000
GM		0.000	0.045
DICE			0.002

In-Track Time Spent on FASA (section 5.4.2 and fig. 30):

	ANOVA results for—		
	Format comparison for 170 knots	Format comparison for 210 knots	Format comparison for 170 & 210 knots
F	31.175	59.569	61.095
P	0.000	0.000	0.010

Format	P of Fisher PLSD post hoc for 170-knot format constant scan	
	DICE	CSM
GM	0.000	0.221
DICE		0.000

Format	P of Fisher PLSD post hoc for 210-knot format constant scan	
	DICE	CSM
GM	0.000	0.016
DICE		0.000

In-Track Time Spent on FASA & A/C Combination (section 5.4.2 and fig. 30):

	ANOVA results for—		
	Format comparison for 170 knots	Format comparison for 210 knots	Format comparison for 170 & 210 knots
F	0.291	0.008	8.809
P	0.600	0.930	0.013

In-Track Time Spent in Zone 1 (Final-Approach-Course Leg) (section 5.4.3 and fig. 32):

	ANOVA results for—		
	Format comparison for 170 knots	Format comparison for 210 knots	Format comparison for 170 & 210 knots
F	63.019	24.472	21.832
P	0.000	0.000	0.001

Format	P of Fisher PLSD post hoc for 170-knot format constant scan		
	GM	DICE	CSM
MAN	0.001	0.000	0.002
GM		0.526	0.000
DICE			0.000

Format	P of Fisher PLSD post hoc for 210-knot format constant scan		
	GM	DICE	CSM
MAN	0.000	0.000	0.037
GM		0.199	0.000
DICE			0.000

In-Track Time Spent in Zone 2 (Base Leg) (sectioin 5.4.3 and fig. 32):

	ANOVA results for—		
	Format comparison for 170 knots	Format comparison for 210 knots	Format comparison for 170 & 210 knots
F	13.003	12.067	29.715
P	0.000	0.000	0.000

Format	P of Fisher PLSD post hoc for 170-knot format constant scan		
	GM	DICE	CSM
MAN	0.001	0.000	0.269
GM		0.773	0.000
DICE			0.000

Format	P of Fisher PLSD post hoc for 210-knot format constant scan		
	GM	DICE	CSM
MAN	0.000	0.000	0.907
GM		0.919	0.000
DICE			0.000

In-Track Time Spent in Zone 3 (Downwind Leg) (section 5.4.3 and fig. 32):

	ANOVA results for—		
	Format comparison for 170 knots	Format comparison for 210 knots	Format comparison for 170 & 210 knots
F	14.260	15.195	7.554
P	0.000	0.000	0.019

Format	P of Fisher PLSD post hoc for 170-knot format constant scan		
	GM	DICE	CSM
MAN	0.015	0.001	0.020
GM		0.367	0.000
DICE			0.000

Format	P of Fisher PLSD post hoc for 210-knot format constant scan		
	GM	DICE	CSM
MAN	0.000	0.001	0.351
GM		0.325	0.000
DICE			0.000

In-Track Time Inside FAF (section 5.4.4 and fig. 33):

	ANOVA results for—		
	Format comparison for 170 knots	Format comparison for 210 knots	Format comparison for 170 & 210 knots
F	4.900	18.061	2.724
P	0.006	0.000	0.127

Format	P of Fisher PLSD post hoc for 170-knot format constant scan		
	GM	DICE	CSM
MAN	0.453	0.800	0.010
GM		0.618	0.001
DICE			0.005

Format	P of Fisher PLSD post hoc for 210-knot format constant scan		
	GM	DICE	CSM
MAN	0.013	0.002	0.000
GM		0.451	0.000
DICE			0.000

Mean Dwell Time of Fixations on Data Block (sectioin 5.4.5 and fig. 34):

	ANOVA results for—		
	Format comparison for 170 knots	Format comparison for 210 knots	Format comparison for 170 & 210 knots
F	12.877	5.511	7.666
P	0.000	0.004	0.018

	P of Fisher PLSD post hoc for 170-knot format constant scan		
Format	GM	DICE	CSM
MAN	0.182	0.000	0.098
GM		0.006	0.004
DICE			0.000

	P of Fisher PLSD post hoc for 210-knot format constant scan		
Format	GM	DICE	CSM
MAN	0.468	0.833	0.002
GM		0.350	0.012
DICE			0.001

Mean Dwell Time of Fixations on Aircraft Positions (section 5.4.5 and fig. 34):

	ANOVA results for—		
	Format comparison for 170 knots	Format comparison for 210 knots	Format comparison for 170 & 210 knots
F	10.088	14.165	10.895
P	0.000	0.000	0.007

	P of Fisher PLSD post hoc for 170-knot format constant scan		
Format	GM	DICE	CSM
MAN	0.065	0.883	0.001
GM		0.048	0.000
DICE			0.002

	P of Fisher PLSD post hoc for 210-knot format constant scan		
Format	GM	DICE	CSM
MAN	0.649	0.003	0.000
GM		0.001	0.000
DICE			0.071

Mean Dwell Time of Fixations on FASA (section 5.4.5 and fig. 34):

	ANOVA results for—		
	Format comparison for 170 knots	Format comparison for 210 knots	Format comparison for 170 & 210 knots
F	23.946	39.751	0.067
P	0.000	0.000	0.800

	P of Fisher PLSD post hoc for 170-knot format constant scan	
Format	DICE	CSM
GM	0.000	0.047
DICE		0.000

	P of Fisher PLSD post hoc for 210-knot format constant scan	
Format	DICE	CSM
GM	0.000	0.063
DICE		0.000

Mean Dwell Time of Fixations on FASA & A/C Combinations (section 5.4.5 and fig. 34):

	ANOVA results for—		
	Format comparison for 170 knots	Format comparison for 210 knots	Format comparison for 170 & 210 knots
F	0.753	23.035	8.912
P	0.404	0.001	0.012

	P of Fisher PLSD post hoc for 210-knot format constant scan
Format	CSM
GM	0.001

Mean Cross Check Scans for Z1 (Final)/All Zone-Pair Combinations (section 5.4.6 and fig. 35):

	ANOVA results for—		
	Format comparison for 170 knots	Format comparison for 210 knots	Format comparison for 170 & 210 knots
F	9.679	22.297	11.093
P	0.000	0.000	0.007

	P of Fisher PLSD post hoc for 170-knot format constant scan		
Format	GM	DICE	CSM
MAN	0.000	0.007	0.018
GM		0.019	0.007
DICE			0.684

	P of Fisher PLSD post hoc for 210-knot format constant scan		
Format	GM	DICE	CSM
MAN	0.000	0.000	0.000
GM		0.000	0.004
DICE			0.312

Mean Cross Check Scans for Z2 (Base)/All Zone-Pair Combinations (section 5.4.6 and fig. 35):

	ANOVA results for—		
	Format comparison for 170 knots	Format comparison for 210 knots	Format comparison for 170 & 210 knots
F	8.433	13.248	1.372
P	0.000	0.000	0.266

	P of Fisher PLSD post hoc for 170-knot format constant scan		
Format	GM	DICE	CSM
MAN	0.000	0.044	0.007
GM		0.007	0.047
DICE			0.427

	P of Fisher PLSD post hoc for 210-knot format constant scan		
Format	GM	DICE	CSM
MAN	0.000	0.317	0.000
GM		0.000	0.139
DICE			0.005

Mean Cross Check Scans for Z3 (Downwind)/All Zone-Pair Combinations (section 5.4.6 and fig. 35):

	ANOVA results for—		
	Format comparison for 170 knots	Format comparison for 210 knots	Format comparison for 170 & 210 knots
F	3.742	5.829	0.001
P	0.020	0.003	0.979

	P of Fisher PLSD post hoc for 170-knot format constant scan		
Format	GM	DICE	CSM
MAN	0.021	0.699	0.079
GM		0.008	0.544
DICE			0.035

	P of Fisher PLSD post hoc for 210-knot format constant scan		
Format	GM	DICE	CSM
MAN	0.064	0.080	0.120
GM		0.001	0.752
DICE			0.002

5.5. Controller Questionnaires and Verbal Debriefing

The subjective data were collected in the form of questionnaires and a verbal debriefing conducted at the conclusion of the data runs. The types of questionnaires and the time and order of their administration to a test-subject controller, were as follows.

At the completion of each data run:

Format questionnaire (section 5.5.1)

Task Load Index (TLX) format rating relative to six workload factors (section 5.5.2)

At completion of all four format data runs for a given pattern-speed procedure:

Rating and ordering of the four test display formats for a speed procedure (section 5.5.3)

At completion of all data runs:

Combined rating and ordering of the test display formats of both speed procedures (section 5.5.3)

Pair-wise comparison of the six TLX source-of-workload factors (section 5.5.2)

Comparison of 170- and 210-knot turn-to-final procedures (section 5.5.4)

Final debriefing questionnaire (section 5.5.4)

Verbal final debriefing (section 5.5.4)

5.5.1. Format Questionnaires

The format questionnaires administered at the conclusion of each data run consisted of questions regarding the format just tested along with some general questions about the simulation. These questionnaires, including the subject responses, are provided in section F.2. The present section provides a summary of the format questionnaire results.

5.5.1.1. Questions Common to Two or More FASA Formats

Subjects were asked whether they believed that the FASA's created too much clutter. Most responded that, although there is inherent clutter brought on by displaying additional information, clutter was not a problem. One subject did speculate that with a "busier" video map, it could be a problem. (Figure 13(b) depicts the video map used by the final controller in the study.) As to the time when the DICE countdown or graphic marker appeared on the display, the subject controllers overwhelmingly felt that there was neither too much nor too little warning prior to the time the command should be issued. Subjects also generally agreed with the automation's choice of where or when to issue turns and speed reductions. The sequence list that appeared on the right side of the controllers display for all runs using display FASA's was generally felt by the subjects to be of little use because of the well-spaced and ordered traffic flow which resulted in an obvious landing sequence. The vast majority of subjects strongly favored the use of FASA's in response to the question regarding their reaction toward having a computer suggest when or where to turn an aircraft. This reaction is also supported by comments received in the final debriefing sessions.

5.5.1.2. Manual Format Questionnaire

5.5.1.2.1. 170-knot procedure

As described in section 3.1.2, the simulated traffic flow into the final sector had the properties of having been organized and spaced by automation/feeder–controller interaction. Based on this organization and spacing, all subjects strongly felt that the landing sequence was apparent. In terms of the effort required to "set up" the landing sequence, the consensus (10 subjects) was that the automation was helpful as compared with an operation in which no automation existed to meter the traffic and resolve ties. The simulated radar display and the initial briefing were considered fully adequate by 10 and 9 subjects, respectively. The remaining subjects noted minor deficiencies; however, none of the subjects felt that the simulated radar display nor the briefing was inadequate. Several questions addressed the realism of different simulation components, for example, aircraft fight paths and maneuvers, communications with pseudopilots, and interaction with the feeder controller. These elements of the simulation were evaluated by most subjects to be somewhat realistic to realistic.

5.5.1.2.2. 210-knot procedure

As in the 170-knot procedure, it was strongly felt by all subject, that the landing sequence was apparent based on the flow of traffic from the automation/feeder–controller interaction. Accordingly, most controllers (10) indicated that the effort required to set up the landing sequence was reduced. For the 210-knot manual procedure, subjects were briefed to employ the same speed control strategy used by the automation, that is, issue the speed reduction after the turn to final. In response to this procedure as compared with operating practices the subjects were accustomed to, opinion was generally divided between no difference and a slight difference. Nine subjects added comments for this question; three indicated that they would have slowed aircraft at a point prior to the turn to final whereas four others indicated that they rarely use speed control. Most subjects (11) did feel that based on the traffic situation during the test run, a pattern speed of 210 knots through turn to final was acceptable.

5.5.1.3. Graphic Marker Format Questionnaire

5.5.1.3.1. 170-knot procedure

All the subjects agreed that it was "easy" adapting to the graphic marker. In response to whether the graphic marker should continue to be displayed after the turn has been issued (as implemented in this study), five subjects said that this resulted in no perceivable clutter, two subjects said that this produced excessive clutter, and the remainder fell between these endpoints. The response to whether focus on aircraft-to-graphic turn-marker position relationship affected the aircraft-to-aircraft attention was that it was only somewhat affected or not affected according to slightly over half (seven) the subjects. Ten of the 12 subjects felt that there was at least slightly more precision in spacing of aircraft using the graphic marker versus a manual operation with no automation assistance. In response to a question comparing the turn positions suggested by the turn marker versus where subjects would have turned the aircraft unaided, no respondents indicated a "strong" difference.

5.5.1.3.2. 210-knot procedure

Almost all (11) of the subjects felt that it was "somewhat easy" to "easy" adapting to the graphic marker. Subjects generally felt that use of the speed reduction advisories provided by the graphic resulted in more precise spacing than they were able to provide in a manual operation and their workload was reduced. Most (10) felt that focus on the speed reduction advisor had little effect on attention to either aircraft-to-aircraft spacing or the overall traffic picture. In response to a question comparing the turn positions suggested by the turn marker versus where subjects would have turned the aircraft, no respondents indicated a "strong" difference. Eleven subjects felt that the speed reduction points suggested by the program either agreed or closely agreed with the point where they would have issued the reduction had no FASA's been provided.

5.5.1.4. DICE Countdown Format Questionnaire

5.5.1.4.1. 170-knot procedure

In terms of adapting to using the DICE with the 170-knot procedure, eight subjects indicated that it was either "somewhat easy" or "easy" adapting to using the format while the other four said that it was "neither easy nor difficult". All subjects agreed an improvement in spacing precision resulted by using the DICE as compared with a manual operation with no automation FASA's. The subjects were divided on the question of whether focus on the DICE countdown value affected attention to aircraft-to-aircraft spacing; six felt that there was little or no effect, five felt that attention was reduced, and one subject didn't feel either way. The subjects were also divided as to whether it was necessary to have the computer suggested headings in the data block. Of those respondents who felt the headings were necessary, the indication was they were "nice to have" rather than necessary. The implementation of the DICE countdown in the simulation was based on an aircraft's performance relative to its schedule and therefore was not a straight clock countdown. Subjects were asked if they would prefer another type of countdown. Two indicated a desire to have an alternate form of countdown, four preferred the type of countdown implemented in the study, and six were neutral.

5.5.1.4.2. 210-knot procedure

Ten subjects felt that it was either "somewhat easy" or "easy" adapting to the use of the DICE with the 210-knot procedure. In terms of workload, 9 subjects indicated a reduction with the DICE turn indication, and 10 indicated a reduction with the DICE speed advisory. Opinion was divided as to whether the DICE turn advisory affected the subjects attention to aircraft-to-aircraft spacing—nine felt that their spacing of aircraft was more precise when using the speed advisory versus a manual operation with no automation FASA's and three subjects did not feel that their spacing was either more or less precise.

5.5.1.5. Centerline Slot Marker Format Questionnaire

5.5.1.5.1. 170-knot procedure

Adapting to using the centerline slot marker at 170 knots was evaluated by nine subjects to be either "somewhat difficult" or "difficult". This evaluation is supported by a number of verbal comments during those data runs and during the postrun debriefings. Opinions were widely divided regarding workload when using this format with seven subjects noting a workload increase. Nine subjects considered the information provided by the slot markers to be "somewhat useful" or "useful". A slim majority (7) of the subjects would like to have an FASA, such as turn advisories, vector advisories, to help them deliver aircraft into their slots.

5.5.1.5.2. 210-knot procedure

Subjects responses were divided on the question of adapting to the use of the slot markers at 210 knots; five, "somewhat difficult"; four, "somewhat easy"; three "neither difficult or easy". Most subjects (8) indicated that their focus on aircraft-to-slot marker relationship reduced attention to aircraft-to-aircraft spacing. Ten subjects felt that the slot markers provided useful information. One subject commented that the slot markers "gave guidance as to correct spacing—especially good with heavy aircraft." Seven of the subjects would like to have FASA, such as turn advisories, vector advisories, to help them deliver aircraft into their slots.

5.5.2. TLX Workload Assessment

The principal means of assessing subject controller workload was the Task Load Index (TLX) procedure. The TLX is a multidimensional rating developed at NASA Ames Research Center (ref. 21), and it uses subjective ratings of six workload contributing factors that are relatively weighted by each subject. It is a simple, quick, and systematic process for compiling workload ratings.

Example TLX questionnaires, and the individual controller subjects' format ratings and source-factor weightings plots are presented in section F.3. Each subject controller's TLX-assessed workload is given in figure 36(a) for the display format and speed procedure tested, and the mean and standard deviation are also given for all subject workloads for each of the tested display formats of both pattern-speed procedures. They are plotted in figure 36(b).

5.5.2.1. TLX-Assessed Workload for 170-Knot Pattern-Speed Procedure

A step-shaped pattern characterized the TLX workload of the formats for the 170-knot pattern-speed procedure in figure 36(b). The centerline slot marker had the highest workload value (63.6); the manual format was next (52.9); the graphic marker format appears to be the lowest (38.7); the DICE format (46.7) fell between that of the manual and the graphic marker workloads. A single-factor (display format), repeated-measure analysis of variance yielded a P value of 0.0002 for treatment differences. Following are the results of a single factor (display format) repeated measure analysis of variance with Fisher PLSD post hoc test to determine whether differences in the TLX-assessed workload values were statistically significant for the 170-knot pattern-speed procedure:

Manual/FASA statistical comparisons:

$\mu_{\mathrm{MAN}} > \mu_{\mathrm{CSM}}$	at 0.045 level of significance (95.5 percent confidence)
μ_{MAN} not $> \mu_{\mathrm{DICE}}$	cannot reject null hypothesis ($\alpha > 0.05$)
$\mu_{\mathrm{MAN}} > \mu_{\mathrm{GM}}$	at 0.01 level of significance (99.0 percent confidence)

FASA statistical comparisons:

$\mu_{\mathrm{CSM}} > \mu_{\mathrm{DICE}}$	at 0.005 level of significance (99.5 percent confidence)
$\mu_{\mathrm{CSM}} > \mu_{\mathrm{GM}}$	at 0.005 level of significance (99.5 percent confidence)
μ_{DICE} not $> \mu_{\mathrm{GM}}$	cannot reject null hypothesis ($\alpha > 0.05$)

The analysis indicated there was no statistically significant difference between the TLX-assessed workload of the graphic marker and the DICE format or between that of the manual and DICE format with the 170-knot pattern-speed procedure. However, with acceptable statistical confidence (95.5 percent), we can say that the centerline slot marker workload was higher than that of the manual format. With high statistical confidence (99.5 percent), we can say that the TLX-assessed workload of the centerline slot marker was higher than that of either the graphic marker or the DICE countdown format. In addition, with high confidence (99 percent), we can say that the graphic marker workload was lower than that of the manual format.

5.5.2.2. TLX-Assessed Workload for 210-Knot Pattern-Speed Procedure

From figure 36(b), for the 210-knot pattern-speed procedure, we see that the centerline slot marker (59.2 TLX workload), the manual (50.2 TLX workload), and the DICE formats (44.4 TLX workload) have the same descending staircase relation to each other as was the case in the 170-knot procedure although the incremental workload differences are less. Unlike the 170-knot procedure, however, the workload rating of the graphic marker format is higher than that of the DICE format with practically the same value as the manual format. The graphic format workload characteristic of the 210-knot procedure is discussed further in the next section where the 170- and 210-knot procedure workloads are compared. A single-factor (display format) repeated-measure ANOVA for the 210-knot pattern-speed procedure indicated the null hypothesis (all format workloads are equal) could not be rejected at the 0.05 level of significance.

5.5.2.3. Comparison of TLX-Assessed Workload for 170- and 210-Knot Pattern-Speed Procedures

Workload difference between the 170- and 210-knot pattern-speed procedures were tested via a two-factor (speed procedure, display format) repeated measure analysis of variance. The result was that the null hypothesis (workloads between the two speed procedures are equal) could not be rejected at the 0.05 level of significance. Therefore the 210-knot pattern-speed procedure did not significantly change the workload of the formats as a group relative to the formats of the 170-knot procedure as a group. This finding is important. Recall from section 5.1 that the runway separation precision improved across all formats for the 210-knot procedure and from section 5.2 that the vectors/aircraft was reduced for both the manual and centerline slot marker formats for the 210-knot procedure. Therefore, for the experimental conditions, it was concluded these these benefits were obtained without any significant increase in controller workload.

When comparing the 170- and 210-knot procedure formats, the 210-knot graphic marker workload was puzzling. The difference in the TLX-assessed workload values between the 170- and 210-knot procedures was less than 4.5 for the CSM, MAN, and DICE format comparison. Further, the the workload for the 210-knot procedure was less in each format. On the other hand, the TLX workload difference was 11.6 between the 170- and 210-knot graphic-marker comparison and the trend noted above was reversed with the 210-knot procedure having the higher workload than the 170-knot procedure.

The strong trend reversal noted was caused by five subjects (7, 8, 10, 11, and 12) whose TLX evaluations of the graphic marker format were considerably higher for 210 knots than for 170 knots (fig. 36(a)). Relative format workload ratings by the five subjects for the separate 170- and the 210-knot procedures (section 5.5.3.2) as well as the combined speed relative rating (section 5.5.3.3) were cross-checked with their TLX workload evaluation and found to be consistent. Four of these five subject controllers rated the graphic marker to be their preferred format in the 170-knot evaluation; however, none of these five subjects rated the 210-knot graphic as their preferred format in either the 210-knot or the combined 170- and 210-knot evaluation.

Comments from these five subject controllers indicate that the perceived higher workload, for the graphic marker 210-knot format relative to the 170-knot format, was the lack of conspicuousness of the 210-knot procedure speed reduction marker. The speed marker location was such that it may not "stand out" sufficiently from the video map depiction of the final-approach course (fig. 5). Initially we believed that there was a tendency to fixate on the speed marker. However, subsequent review of the oculometer data (statistical and video tapes) disproved this idea. For these five subjects, time measurements were taken to determine the amount of time between when a graphic first appears and when the controller first looks at it. The mean time was 1.1 sec for the turn marker compared with 1.5 sec for the speed marker. The difference between these two times does not seem to be as great as subjective comments seem to indicated. Four controllers stated in the format questionnaires and final debriefing comments that they would have preferred another implementation of the graphic speed marker. Two controllers stated that they missed the initial appearance of the graphic speed marker and thought that the speed marker should either flash or be color coded when it first appears on the display. Two other subjects stated that they thought that the speed marker should flash if the command was not issued on time. Reactions indicate that subjects thought that a graphic speed advisor was desirable in concept. However, investigation of alternatives for identifying the speed reduction point could be beneficial.

5.5.2.4. Source-of-Workload Weightings and Ratings of TLX Factors

The TLX-assessed workload obtained from a subject is influenced by the subjects weighting and scaled ratings of six workload source factors. Definitions of the six factors are contained in section F.3.1 and reference 21 The process of computing the workload is detailed in reference.

The extent to which a subject's scaled rating, of each of the six contributing factors, influences the workload of the specific task being evaluated (i.e., controlling final traffic with a specific FASA format) is determined by the factor weightings for the general type or class of activity (i.e., controlling final traffic) to which the specific evaluated task belongs. The weights, resulting from a pairwise comparison of the factors, indicate the relative impact each has on the general activity or task. Thus the weights provide insight about the general task (in this case controlling final traffic). The mean of the factor weights of all 12 subject controllers are listed in figure 37(a). These values indicate how, on the average, our group of subjects weighted the impact of each of the six TLX workload factors on their final controller function. The higher the weight, the more critical is the factor to a terminal final-controller's workload. The mean factor weights in order of importance are given in following table:

Factor	Weight
Mental demand (MD)	4.25
Own performance satisfaction (OP)	3.17
Temporal demand (TD)	3.08
Your effort required (ER)	2.83
Frustration you experienced (FE)	1.67
Physical demand	0

Note, the above weights sum to 15 as is the case for an individual test subject's pairwise comparison process.

The rating of a factor reflects the subject's judgment of the relative scaled magnitude of that factor when employing the specific display format being evaluated. The mean of the factor ratings of all 12 subjects are listed in figure 37(a). These values indicate how, on the average, our group of controllers rated the six factors relative to each tested display format. These individual workload contributing factor means are plotted in figure 37(b) along with the mean of the individual subject workloads for each display format. Note that physical demand was not plotted because of its 0 weight, which meant that physical demand ratings did not influence the TLX-assessed workload.

Figure 38 is a depiction of the data in figure 37(a) in the conventional TLX format (ref. 21). Another form of mean workload can be obtained by using the mean weights and mean ratings to compute an overall workload by the TLX procedure as was done for the individual subject workloads. These alternate means are listed in figure 37(a) and plotted in figure 38 for each display format. Even though this method is not mathematically identical to the mean of the subjects' individually calculated TLX workloads, the two methods should give approximately the same values. A comparison of the data in figures 36(a) and 37(a) shows the two mean values for each format in close agreement (maximum difference was 1.6).

Because of the number of display format measures in our study, we restricted our statistical evaluation to conventially calculated TLX-assessed workload via repeated measure ANOVA on the data of figure 36(a). The TLX workload contributing factors could themselves be treated as dependent variables for statistical analysis if one were interested in further pursuit along this vein. A rough sense of such an analysis can be obtained from visual comparison of the mean factor ratings in figure 39.

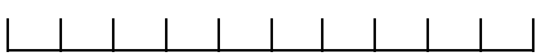
5.5.3. Relative Rating of Display Format

Three relative rating questionnaires were designed to acquire from the subjects their relative ranking of the formats with respect to three specific criteria:

1. Workload or effort required to use the format
2. Ease of adapting to or learning to use the format
3. Amount of help or benefit in spacing traffic on final

The applicability of the manual format to criteria 2 and 3 was determined to be questionable. Therefore, the "manual" responses were removed and the placement of the remaining three formats adjusted accordingly. Subjects completed three separate ratings, one after each of the two pattern-speed procedures and a final combined rating, for all the formats of both pattern-speed procedures as a group at the completion of all data runs. The questionnaire form is shown in section F.4.

For each criterion, a rating scale (as shown below) consisting of ten positions with the appropriate endpoint descriptors defining the ends of the scale (e.g., most workload and least workload) was provided. An example of a scale is as follows:



most workload — least workload

Subjects were instructed to first determine which formats represented the endpoints and then position the remaining formats in their relative positions along the scale. This approach is equivalent to taking what would be the difference between the lowest and highest ratings on an absolute scale and blowing it up for resolution or differentiation. These results will have meaning only in a relative position sense. For example, a mean rating of 8 does not imply 4 times better than a low mean rating of 2. However, some measures such as workload are not always evaluated relative to absolute human capability but often have relative meaning only in the domain of interest, which in our case was final controller reaction or performance with the tested display formats relative to each other.

5.5.3.1. Relative Rating of Formats for 170-Knot Pattern-Speed Procedure

Figure 39 shows the distribution of the subjects according to their format rating for the workload or effort required to use the format for the 170-knot pattern-speed procedure. Nine subjects rated the graphic marker as having the least workload or effort required to use the format. Although not rated as high as the graphic, the majority (8) of the subjects felt that the DICE represented an overall reduction in workload relative to the manual or the centerline slot marker. Three subjects commented that the DICE format requires more concentration than the graphic marker. However, they further stated that the information is in a desirable location, i.e., near the aircraft position symbol and the standard data block information. Opinion was divided for the manual format, and seven subjects felt that the slot markers generated more workload than the other formats. (Fewer subjects (3) evaluated the manual format as having the most workload than those (7) making the same evaluation for the slot markers.) For the 170-knot procedure, a comparison of the graph showing questionnaire mean workload rating and the TLX results (fig. 40) shows a strong ranking correlation between the two workload assessments.

Figure 41 indicates the distribution of the subject controllers according to their format rating criterion 2 ("ease of adapting or learning to use format"). Nine subjects rated the graphic as the easiest format to adapt to, whereas 10 subjects evaluated the slot markers as being the most difficult. No subjects evaluated the graphic as being the most difficult nor the slot markers as being the easiest format with which to adapt. Individual practice time did not always indicate how difficult it was to adapt to a format because of the order of the pattern-speed procedure and the order of the formats themselves in the test sequence. However for the 170-knot procedure, the composite mean practice time used by the subjects prior to the data runs correlates with and supports results of the "ease of adapting" rating (fig. 42).

Figure 43 depicts the distribution of the subject controllers according to their format rating for "amount of help or benefit in spacing traffic on final" criterion. In terms of this criterion, eight subjects found the graphic marker the most helpful, eight stated that the slot markers were the least helpful, and ratings were divided about the helpfulness of the DICE.

5.5.3.2. Relative Rating of Formats for 210-Knot Pattern-Speed Procedure

Six subject controllers rated the graphic to have the least workload for the “workload or effort required to use the format” criterion for the 210-knot procedure (fig. 44) as compared with nine in the 170-knot procedure (fig. 39). Four subjects evaluated the slot marker as having the most workload for the 210-knot procedure as compared with seven for the 170-knot procedure. Six subjects rated the manual as having the most workload for the 210-knot procedure as compared with three for the 170-knot procedure. This increase in the number of subjects may have been the result of the normal operational practices used by several subjects as stated in the verbal debriefing, i.e., many controllers at ORF do not use speed control regularly to space traffic on final. Therefore, the additional effort in determining the location to issue a speed reduction may have been perceived as requiring more effort. Figure 40 depicts the relationship between the ratings for “workload or effort required to use the format” criterion and the TLX results. For the 210-knot procedure, the mean rating for the graphic format was the lowest of all formats, whereas the TLX results indicated a slight workload magnitude increase for the graphic over the DICE. However, recall there was no statistical significant difference between TLX outcome of the graphic marker and DICE countdown formats.

Again shown in figure 40, and as discussed earlier in section 5.5.2.3, the TLX workload assessment for all the formats, except the graphic marker, was less for the 210-knot pattern-speed procedure than for the 170-knot procedure. This increase for the graphic marker was attributable to five particular subject contollers (section 5.5.2.3) whose TLX workload ratings were considerably higher for the 210-knot procedure than the 170-knot procedure. Figure 45 presents the distribution of the relative format workload ratings of these five subjects for the 170- and 210-knot procedures. The same pattern can be seen as was observed for the TLX ratings. A similar breakdown of the distribution of the combined display format relative ratings for both speed procedures is included in section 5.5.3.3 for these five subjects as well as for the other seven subjects.

Figure 46 indicates the distribution of the subject controllers according to their format rating for the “ease of adapting to or learning to use the format” criterion. In this figure, the order of preference for the FASA formats relative to each of the three criteria is the same as for the 170-knot procedure. Essentially, most subjects (9) found adapting to the graphic format easiest, and the slot markers most difficult. However, two subjects rated the graphic as the most difficult to adapt to in the 210-knot procedure as compared with none in the 170-knot procedure; two rated the slot marker the easiest to adapt to in the 210-knot procedure, whereas none of the subjects rated the slot markers as the easiest in the 170-knot procedure. A comparison between the “ease of adapting to or learning to use the format” criterion rating and the practice time used is provided in figure 42. Overall nine subjects felt that the graphic was the easiest format to adapt to, even though slightly more mean practice time was used for the graphic that the DICE. However, there was not any statistical significant difference between the two practice times.

Figure 47 depicts the distribution of the subject controllers according to their format rating for the “amount of help or benefit in spacing traffic on final” criterion. In terms of this criterion, again as in the 170-knot procedure, the most controllers (8) selected the graphic format as the most helpful. However, the graphic marker had two ratings of least helpful. On the other hand, DICE had five most helpful but no least helpful ratings. This contrasts with DICE which received four least helpful ratings in the 170-knot procedure. As a result, the means of the rating distributions, relative to the ”amount of help or benefit in spacing traffic on final” criterion, were equal for the graphic and DICE formats. Among the three formats, clearly the centerline slot marker had the consensus rating (10 subjects) as least helpful, even though it received two high ratings.

5.5.3.3. Relative Rating of Combined Formats for Both Pattern-Speed Procedures

After all runs for both pattern-speed procedures were completed, each subject controller performed combined format relative ratings for both pattern-speed procedures. These combined ratings (who distributions according to subject count shown in figs. 48, 49, and 50) consisted of relatively rating, as a group of eight, all the formats together of both the 170- and 210-knot procedures, according to the same three criteria used in the individual pattern-speed format ratings. The results of the combined rating in terms of format preference were consistent with the ratings of the individual speed procedures for all three criteria, that is, “workload or effort required to use the format” (fig. 48), “ease of adapting to or learning to use the format” (fig. 49), and “amount of help or benefit in spacing traffice on final” (fig. 50). Additionally, in all but one case, both speed procedures for a particular format were preferred over the subsequent format choice (e.g., graphic 210 knots, graphic 170 knots, DICE at 210 knots, ...). The only exception, as such, was the mean workload rating tie between the centerline slot marker at 210 knots and the manual format at 170 knots. Another very significant finding in the combined ratings was that, in every criteria and display format case, the mean rating for the 210-knot format was higher than its corresponding mean rating for the 170-knot format.

For the “workload or effort required to use the format” criterion, the mean ratings between the two speed procedures for each format were all relatively close except the ones for the centerline slot markers. This difference for the slot markers may be attributable to the overall difficulty that subjects had in working with the slot markers in the 170-knot procedure. The graph of the rating for “workload or effort required to use the format” criterion and the TLX (fig. 51) shows a ranking correlation between the two independent ratings.

To further support the TLX discussion of section 5.5.2.3, a breakdown of the combined format workload rating between five particular subjects and the remaining seven subjects is shown in figure 52. These five subjects (7, 8, 10, 11, and 12) had a TLX mean rating (6.9) indicating higher workload assessments for their 210-knot graphic marker format (210GM) than did the other seven controllers (8.8). For the group of five, the 210-knot graphic marker format ranked third among all formats as opposed to first for the group of seven. These separate and independent, combined ratings paralleled those of the individual pattern-speed speed ratings (section 5.5.3.2) and further supported the workload results obtained from the TLX for the 210-knot pattern-speed procedure.

Considering all the ratings for “ease of adapting to or learning to use format” criterion, the most universally held opinion for both speed procedures was that the centerline slot marker was the hardest format to adapt to using. There were no subjects that evaluated the graphic format on the least helpful end of the scale for the “amount of help or benefit in spacing traffic on final” criterion. The only other consistent result in the combined speed rating for this criterion was that most subjects (8) found the slot markers at 170 knots to be the least helpful.

The results of the subject evaluations for “workload or effort required to use the format,” “ease of adapting to or learning to use the format,” and “amount of help or benefit in spacing traffice on final” criteria are remarkably consistent throughout all formats as shown in figure 53. Overall there is a consensus ranking among the FASA’s, as to controller preference, relative to all three of these criteria. The graphic marker emerges as the consensus first choice and the centerline slot marker as the consensus last choice. In addition, the controllers preferred the 210-knot procedure for each format, particularly for the centerline slot marker format. Even though it was the first choice overall, a sizable minority (5 of 12 subjects) downgraded the 210-knot graphic marker format relative to workload because they felt that the speed reduction marker should have been more conspicuous than was used in the test.

5.5.4. Questionnaire Comparison of 170- and 210-Knot Procedures

At the completion of all data runs subjects were asked to evaluate, for each of the four formats, the level of difficulty associated with spacing aircraft on final using the 210-knot pattern-speed procedure as compared with the 170-knot procedure. This questionnaire and responses are presented in section F.5. It should be noted that according to the subjects, speed control on final is not extensively used for spacing traffic at Norfolk Approach Control (where the controller subjects are based). However, when asked which of the two speed procedures used in the study more closely approximated their operation, 11 of the 12 subject controllers said the 210-knot procedure more closely approximated the speed profiles flown by aircraft not issued speed restrictions.

Overall, the 210-knot procedure was considered to be easier to use for spacing aircraft than the 170-knot procedure. Although the reason for this consideration is not readily apparent from comments made on this questionnaire (appendix F), five subjects stated in debriefing sessions that the speed adjustment provided for in the 210-knot procedure, which allows for fine tuning of spacing, was quite helpful. For the manual and the slot markers, the 210-knot procedure was evaluated as harder to use for spacing traffic by two and zero subjects respectively. For both the graphic and the DICE formats, the 210-knot procedure was rated harder by three subjects. Depending on the format, somewhere between 9 to 12 controllers felt that the 210-knot pattern-speed procedure was as easy or easier than the 170-knot procedure, for the same format. This outcome follows the same pattern as seen in the combined format rating (section 5.5.3.3). All subjects felt that vectoring to the slot markers was easier with the

210-knot procedure. Debriefing comments received from seven subjects indicated significant difficulty, and sometimes frustration, in trying to vector the aircraft into the slot marker when both the aircraft and slot markers moved at the same speed.

5.5.5. Final Debriefing Questionnaire, Verbal Debriefing, and Other Controller Comments

Following all the data runs, the subjects completed a final debriefing questionnaire and participated in a verbal debriefing. The final debriefing questionnaire targets the subjects' opinions about the realism and adequacy of the simulation facilities. The verbal debriefing provides an opportunity for the subjects to provide final comments on specific subject areas such as the formats themselves, possible concerns in using the aids. Additionally, the subjects were given an opportunity and encouraged to comment on any aspect of the simulation, FASA's, automation in general, or any subject area that they chose. The final debriefing questionnaires along with the subject responses are presented in section F.6. The format for the verbal debriefing is included in section F.7.

The final debriefing questionnaire contains questions related to the test environment and simulation. There was unanimous agreement that the test sessions were conducted in a controlled, serious, and professional manner. Overall, the subjects felt that the simulation was reasonably realistic. Both the simulated radar display and the communications were evaluated to be adequate for the required task. However, the following comments were made by two subjects: "When instructions were issued to the wrong aircraft, pseudopilots did not question the calls" and "Pilots made very few errors and responded too quickly." In response to the effect of the "physical environment" on the subjects' test performance, it was generally felt that performance was "neither improved nor degraded." All subjects evaluated the initial briefings on the Denver airspace and procedures and the format briefings to be adequate. Feelings were also unanimous that the training received during the format practice runs was adequate.

In the verbal debriefing, the subjects were asked for comments on each of the formats. The most positive comments were received for the graphic turn marker; in general, subjects felt that the graphic was easy to use and provided information in an easy to interpret manner, requiring a minimal amount of adaption time. Typical comments about the graphic turn marker were "easy to use" and "required less attention than DICE or slots." The graphic speed advisor was well liked by all but one subject. Several subjects did, however, suggest that the speed marker needs to be more conspicuous. The following suggestions were offered: the speed marker should flash at the first appearance, flash at the time the command should be issued, and color could be used to accent the speed marker. The DICE time-to-turn advisor received less support than the graphic. However, the consensus was that it is not difficult to adapt to and the information is in a location which is close to other data block information and the aircraft position symbol. In the format questionnaire only two subjects indicated a preference for an alternative form of the DICE countdown used in the study (section 5.5.1.4). However, during the debriefing discussions, a total of four subjects stated a desire for a straight clock countdown (i.e., 8, 7, 6, 5, 4, ...). Comments on the DICE time-to-speed-reduction advisor were basically the same as those for the time-to-turn advisor. Finally, most subjects felt that the centerline slot marker was the most difficult of the FASA's to adapt to and the most difficult to use. Four subjects felt that another aid such as the graphic or DICE could be used to assist in merging aircraft with slots.

In response to the question of fixation (excessive focus on situation or location), clutter, and distractions, most subjects stated that there were minor problems in at least one of the three areas with one or more formats. Occasional fixations were reported by five subjects in the use of the DICE, five subjects in the use of the centerline slots, and one subject in the use of the graphic marker. The only comments regarding clutter were noted by three subjects, all with the graphic turn marker; the subjects stated that the clutter was minor and did not present a problem.

Nine of the 12 subjects were enthusiastic about the overshoot prediction feature in the 210-knot procedure. The feature provided advance warning about an aircraft on the base leg which the automation predicted would need to overshoot the localizer, to preserve separation, unless some additional action (speed reduction or vector) is taken prior to the turn-to-final.

The subjects were asked several questions to solicit their opinions on the use and potential impact of FASA's. There was not a common denominator among the responses from the subjects relative to the question of "Did the system change the mental tasks involved in controlling traffic?" However, there were interesting comments: "Mental demand lessened, lowered"; "Felt like a robot"; "Controller reacts to system as opposed to formulating." When asked

"Do you feel that an automated advisory system will create any special problems with controller training or proficiency?", comments were wide: "No, after awhile controller would work traffic like the computer"; "No, I'll take all the help I can get"; "Controllers will have to develop new expectations from their careers"; "[FASA's] could extend the productive life of a controller." The subjects were unanimous in their feeling that automated aids would be beneficial in reducing workload and in increasing spacing precision. Subjects were asked if they had any final thoughts, opinions, or suggestions that were not previously covered; by and large, only minor comments were made.

6. Major Results

Working jointly with the FAA and in collaboration with Lincoln Laboratory, MIT, and NASA Ames Research Center, this study was conducted at the NASA Langley Research Center to gather comparative performance data among three candidate final-approach spacing aid (FASA) formats. Several objective measures together with subjective questionnaire data were used to obtain an in-depth assessment. The data were gathered from the performance and reactions of 12 subject controllers provided by the FAA. The performance measures were obtained in a dynamic real-time TRACON simulation with varied display formats and pattern-speed procedures. For each of two representative pattern-speed procedures (a 170-knot pattern-speed procedure and a 210-knot pattern-speed procedure with speed control aiding), data were collected by using four final-controller, display-format conditions: manual/ARTS III, graphic marker, DICE countdown, and centerline slot marker. The following sections are a summary of the experimental results.

6.1. Aircraft Delivery and Separation Precision

The measure used to assess precision of aircraft delivery and separation was the standard deviation of aircraft-pair interarrival errors at the runway threshold. For the 170-knot pattern-speed procedure, the centerline slot marker format did not statistically improve controller delivery precision relative to the manual/ARTS III format value (18.9 sec). However, both the graphic marker and DICE countdown formats improved controller delivery precision, over the manual format, by statistically equivalent increments (range of reductions from 4.2 to 5.0 sec). For the 210-knot pattern-speed procedure, all the FASA formats improved controller delivery precision relative to the manual/ARTS III format value (15.4 sec). Controller use of the DICE countdown resulted in the most delivery improvement (7.2-sec reduction), the graphic marker resulted in slightly less improvement (6.0-sec reduction), and the centerline slot marker resulted in the least improvement (4.2-sec reduction). For all formats, operating with the 210-knot procedure resulted in statistically improved controller delivery precision relative to the comparable 170-knot procedure format. The 210-knot manual/ARTS III format improvement was 3.5 sec, whereas the 210-knot improvements for the three FASA's were between 5.3 to 6.6 sec over their respective 170-knot formats.

In terms of delivery precision, for both the 170- and the 210-knot pattern-speed procedures, the graphic marker and DICE countdown formats are both superior to the centerline slot marker format. The graphic marker and DICE countdown gave similar precision results with the DICE having a minor edge in the 210-knot procedure. The measured improvement in delivery precision obtained from the final-region speed-reduction cueing of the 210-knot procedure, relative to the constant speed of the 170-knot procedure, was a significant finding. This indicate that the application of speed control aiding, on final approach, to a FASA has the potential to significantly improve aircraft separation at facilities where an initial higher pattern speed on final is practical. A simple analysis of runway arrival rate indicated that the improved precision of a FASA, such as the graphic marker, has the potential to increase the TATCA IMC runway arrival rate over that of a TATCA system without a FASA. The magnitude of the increase depends on which pattern-speed procedures are assumed in the comparison. For example, the arrival rate increase was 6.6 percent for the 170-knot procedure, 10.6 percent for the 210-knot procedure, and a more dramatic 16.5 percent when the manual format for the 170-knot procedure was compared with the 210-knot pattern-speed procedure with its turn and speed reduction aiding.

6.2. Vectors Per Aircraft Issued In Final Sector

Data were gathered on the mean number of vectors per aircraft issued by the final controller in merging and spacing traffic for final approach. For the 170-knot procedure, all the FASA formats reduced the mean number of vectors per aircraft relative to the manual/ARTS lll format value (2.7 vectors/aircraft). Both the graphic marker and DICE countdown formats reduced the mean vectors per aircraft by equivalent increments (1.1 vectors/aircraft), whereas the centerline slot marker had less reduction (0.5 vector/aircraft). The results for the 210-knot procedure were similar, where all the FASA formats also reduced the mean number of vectors per aircraft relative to the manual/ARTS III format value (2.2 vectors/aircraft). For the 210-knot procedure, both the graphic marker and DICE countdown also reduced the mean vectors per aircraft by equivalent increments (0.7 vectors/aircraft), whereas the centerline slot marker had less reduction (0.5 vectors/aircraft). When the 210-knot procedure is compared with the 170-knot procedure, the 210-knot procedure reduced the mean number of vectors per aircraft by equal amounts (0.4 vector/aircraft) for both the manual/ARTS III and centerline slot marker formats relative to their 170-knot procedure counterparts. However, the graphic marker and DICE countdown formats had no significant change between the two pattern-speed procedures.

For the Denver approach routes modeled and the pool of subject controllers used, the graphic marker and DICE countdown format both gave equivalent, larger reductions in mean vectors per aircraft (42 percent for 170 knots and 32 percent for 210 knots), relative to the corresponding manual/ARTS III format, than the centerline slot marker (19 percent for 170 knots and 20 percent for 210 knots). Therefore, a TATCA system with a final-approach spacing aid not only has the potential to improve delivery precision but also could potentially reduce the average vectors per aircraft in the final region. The extent of the vectoring reduction would depend on the specific TRACON geometry and procedures. Note that a reduction in the number of vectors issued would have the additional benefit of reducing somewhat the communication channel congestion.

6.3. Controller Response Time to Direct FASA

FASA's which have both a suggested advisory and delivery time are classified as *direct* aids in this report. Controller response time to a direct aid is the difference between the indicated delivery time and the actual turn or speed message delivery time. Histograms of controller response time were plotted to the FASA base-to-final turn indication and, in the 210-knot procedure, to the reduction-to-170 knot FASA indication for the graphic marker and the DICE countdown formats. These response time models have potential application in advanced system analysis and ATC simulation modeling where automated direct aiding is a feature of the system under study.

The standard deviation of response time for the base-to-final advisory of the DICE countdown (3.3 sec) was slightly less than that of the graphic marker (3.7 sec). This small, though statistically significant difference, appears to account for the slight delivery precision advantage of the DICE countdown format. It should be emphasized that a balanced consideration of all factors, not only separation precision or response time, should dictate format selection. For instance, lookpoint data and controller comments indicated some tendency toward fixation on the DICE countdown turn advisory, which probably explains its observed response time edge. However, because of the potential adverse effect fixation could have on scanning behavior, controllers tended to rate the DICE countdown format below the graphic marker format.

6.4. Lookpoint Measurement

The Langley oculometer system was used to gather data on subject controller eye-scan behavior as a function of the tested display formats. Of the many proposed lookpoint measures, three were selected for analysis. The first measure is the amount of time the oculometer had the subject in-track which can be treated as follows: as a percentage of experimental test time, as a percentage of time divided among display object types, or as a percentage of time divided among regions of the controller's display. The second measure is average dwell time by display object type. The third measure is the number of cross-check scans, which indicates the number of alternating, uninterrupted fixations between two display objects.

For the oculometer in-track time measurement, the working hypothesis relative to task difficulty is as follows: the more difficult the task, the higher is the in-track time because there is less discretionary or spare time to look away from the display. For the 170-knot pattern-speed procedure, the graphic marker format had significantly lower in-track time than all the other formats. No significant differences in percentage of in-track time were found among the display formats of the 210-knot procedure. These results closely agreed with and supported the TLX workload analysis.

As might have been expected, changes in the scan behavior were observed for all FASA formats when compared with the manual format. Less time was spent on the conventional aircraft position symbol and data blocks and this time was transferred to the aid presentation. The changes in scan behavior relative to display zones confirmed the above display object scan observations. The location of the centerline slot markers, along the extended runway centerline, resulted in more total time in that region than the other formats. On the other hand, more time was spent in the base and downwind regions where the turn aids were located, with the graphic marker and DICE countdown formats than was spent in those regions with either the manual or centerline slot marker.

The subject controllers spent significantly less time scanning the area inside the final-approach fix with the centerline slot marker than was spent with the other three formats. This characteristic does not appear to be desirable when one considers that the delivery precision of the centerline slot marker was the worst of the tested FASA's. The graphic marker and DICE were providing almost equivalent information but in different forms. The longer average dwell time of fixation for the DICE countdown aid compared with that for the graphic marker suggests a more efficient information transfer process for the graphic marker format.

For both pattern-speed procedures, all three aids had significantly less cross-checking involving the base and extended centerline region than the manual format. The graphic marker had the least cross-checks involving all the display regions evaluated and had significantly less cross-checks than all the other formats for the base and extended centerline regions. For the cross-checking measurement, the model assumed that the controller's purpose for examining relative position (i.e., cross-checking) was to either perform some control action or monitor separation. The hypothesis was that a reduction in the number of cross-checks primarily indicated a reduction in the amount of comparison or judgment required to properly time a control action if the amount of monitoring is assumed to be relatively constant. Accordingly, the results indicate a graphic marker advantage, relative to required comparisons, in making control action judgments.

6.5. TLX Workload Assessment

The Task Load Index (TLX) procedure was used to collect relative workload data among the tested formats. For the 170-knot procedure, the centerline slot marker significantly increased rated workload relative to the manual/ARTS III format, whereas the graphic marker format significantly reduced the rated workload relative to the manual/ARTS III format. The rated workload of the DICE countdown format fell between that of the manual/ARTS III and the graphic marker with the difference, relative to either, not statistically significant.

For the 210-knot pattern-speed procedure, the workload rating differences among the formats were not statistically significant. For the centerline slot marker format, this reflects that the additional control (obtained via the 210-to-170-knot speed reduction) coupled with the inherent speed reduction cueing (given by the slot marker positions) appear to relieve the 170-knot speed procedure pressure of having to make such precise turns to align the aircraft in their slot marker. The requirement of an additional speed reduction could have been perceived as an added workload for the other formats of the 210-knot procedure. However, a comparison of the 170- and 210-knot procedures indicated there was no statistically significant difference in the overall rated workload between the two pattern-speed procedures. Note that a sizable minority (5 of 12) of the subjects perceived their workload with the 210-knot graphic marker format to be higher than their workload with the 170-knot graphic marker format because they felt the speed reduction marker should have been more conspicuous than implemented in the test.

6.6. Questionnaires and Debriefing Findings

Overall comments indicated enthusiasm for the use of FASA's to improve the final controller's performance. Most of the subjects (between 9 to 12 for both speed procedures) felt that the advisories provided by the graphic marker and the DICE countdown display formats resulted in more precise spacing than they were able to accomplish unaided. Responses indicated some reduction in attention to aircraft-to-aircraft spacing for the graphic and DICE formats relative to the manual procedure. The responses between "affected" and "strongly reduced" were: 5 for 170GM, 5 for 210GM, 6 for 170DICE, and 7 for 210DICE. In terms of clutter, the consensus was that the additional information provided on the display by the FASA's did not present a problem; this was true even for the centerline slot markers which were continually displayed along the final-approach course up to the final-approach fix. Relative to preference for the DICE or for the straight clock countdown, two responses preferred the clock countdown, four preferred the DICE, and the remaining six indicated either countdown would be acceptable. For both speed procedures, adapting to using the formats was easy for all subjects in the graphic marker case and most subjects (8 at 170 knots, 10 at 210 knots) for the DICE. Adapting to using the slot marker was difficult for half the subjects in the 210-knot procedure and for most subjects (nine) in the 170-knot procedure. Most subjects

(9 at 170 knots, 10 at 210 knots) felt the slot marker provided useful information. However, the task of merging aircraft with their slots was considered to be difficult, particularly in the 170-knot procedure. Accordingly, a slim majority (seven) felt that advisories to assist in merging aircraft with their slots would be helpful. For both the 170- and 210-knot procedures, eight subjects indicated that their attention to aircraft-to-aircraft spacing was between "affected" and "strongly reduced" when using the slot marker display format. In the manual/ARTS III format, for both speed procedures, all subjects felt that the landing sequence was apparent based on the flow from the automation/feeder. Recall that the traffic flow was 'organized' and regulated by the automation prior to the final sector. Accordingly, most controllers (10) felt that little effort was required to "set up" the landing sequence.

Questionnaires for relatively rating the display formats (formats of only the 170-knot procedure, formats of only the 210-knot procedure, and all the formats of both the 170-knot and 210-knot procedures together) were designed to acquire from the subjects their relative ranking of the formats with respect to three specific criteria: "workload or effort required to use the format," "ease of adapting to or learning to use the format," and "amount of help or benefit in spacing traffic on final." In all cases, the following same FASA order of preference resulted: graphic marker, DICE, and slot marker. Additionally, when rating all the formats of both the 170- and 210-knot procedures together, in every format case, the mean rating of 210-knot format was preferred over the mean rating of the corresponding 170-knot format. This result was consistent with that of the comparison of difficulty question for the two speed procedures of each display format. The number of controllers rating the 210-knot procedure as equal to or less difficult than the 170-knot procedures were 12 for the slot marker, 10 for the manual, 9 for the graphic, and 9 for the DICE.

Final questionnaire responses and debriefing comments indicated that, overall, subjects felt that the simulation was reasonably realistic and that both the airspace/procedural and format briefings were adequate. Subjects strongly reiterated their support and enthusiasm for having a computer aid them in performing the final controller's job. In terms of the formats, the most positive comments were received for the graphic turn marker. In general, subjects felt that the graphic marker was easy to use and provided information in an easy to interpret manner, requiring a minimum amount of adaptation. The slot marker was generally perceived to be the most difficult of the aids to adapt to, the most difficult to use, and required the most concentration. In terms of the potential effects of using FASA's, concerns were raised that controllers would react to the FASA's instead of formulating their own plan and thereby become "robots." Other comments reflected a wide range of ideas on the potential long-range impact of automation aids. Several subjects felt that their professional careers would be prolonged because of workload and stress reduction, however several others felt that pride and job satisfaction would be taken away, and the possibility was raised that the use of automation aids might require changing the personality type of individuals that are recruited to be controllers.

7. Concluding Remarks

Measured results resolved the TATCA issue of whether a FASA is beneficial if the TATCA automation (CTAS) has already organized and tentatively spaced arrival traffic prior to the final sector. Some FASA's significantly improved the runway delivery precision and reduced the average vectors per aircraft relative to the unaided format when both the FASA and the unaided format had TATCA automation act on the traffic before the final sector. Depending on which pattern-speed procedures are assumed in a basic single runway arrival benefit analysis, the improved precision of a FASA, such as the graphic marker, has the potential to increase the TATCA IMC arrival rate somewhere between 6 and 16 percent over that of a TATCA system without a FASA. Additionally, for the slower pattern-speed procedure tested, there was significant workload reductions for the graphic marker format relative to the unaided case. Among the formats tested, the above potential benefits appear feasible without the subject controllers perceiving a problem with the possible drawbacks of FASA interface, namely display clutter and fixation.

If FASA's could improve the final controller's performance, then which offers the most benefit? Two types of direct aid (graphic marker and DICE countdown) and one type of indirect aid (centerline slot marker) were tested. The graphic marker and DICE countdown aids were superior in measured performance and also preferred by the controller subjects over the centerline slot marker aid. The objective measures of performance for the graphic marker and for the DICE countdown formats were close in value, however, the subjective evaluation indicated a consensus preference for the graphic marker format.

Experimental findings are relevant to the issue of what pattern-speed procedure is used in the final approach area of a TATCA-aided TRACON. Two representative pattern-speed procedures (170 knots and 210 knots with speed control aiding on final) were tested. The slower speed procedure was representative of many high density TRACON's where the practice, in heavy demand periods, is to reduce aircraft to slower pattern speeds before the turn-to-final or even earlier in the approach in order to achieve aircraft performance compatibility and provide planning time to organize traffic. At less heavily loaded terminals or at high density terminals during nonpeak periods, aircraft are often kept at a higher pattern speed, until after turned to final, before being slowed to a lower pattern speed. The experimental approach taken was to simulate this higher pattern-speed profile with dense traffic and, in the FASA format, use automation to indicate the desired position or time, on final, to perform the nominal 210-to-170-knot speed reduction. There were significantly improved delivery precisions measured with the 210-knot pattern-speed procedure for every format relative to its corresponding 170-knot format precisions. Even though requiring an extra speed-reduction control action per aircraft approach, as a group the 210-knot procedure formats did not have heavier TLX-determined workload than the 170-knot procedure formats. In addition, via three separate ranking criteria (workload, ease of adapting, and benefit to spacing), when all the formats of both speed procedures were ranked together as a group, the mean subject ratings of the 210-knot formats were preferred over those of their corresponding 170-knot formats. Note that further study of the graphic marker speed reduction symbol is needed, since a significant minority (5 of 7 controllers) felt that the workload for the 210-knot graphic format was heavier than the for 170-knot graphic because the speed symbol was not sufficiently conspicuous. Overall, these findings indicate the potential for future consideration of FASA speed control aiding at facilities where higher pattern speeds are practical after the base-to-final turn.

This study employed several objective and subjective measures to gain an in-depth and broad perspective on relative FASA performance and also to cross check findings. In this pursuit, the application of an oculometer to gather controller lookpoint data was somewhat of an innovation in reported ATC display research. Unlike fixed-position cockpit instruments, in previous NASA pilot scan studies, aircraft locations are constantly moving across the controller's display. Postprocessing algorithms were developed to correlate stored lookpoint coordinates with corresponding displayed information on the PPI from ATC simulation data. ATC specific lookpoint measures were also defined. These techniques and software were detailed in a separate report (NASA CR-191559) for use by the ATC research community. Worth mentioning was the reaction of the subject controllers to the oculometer technology upon viewing video tapes from an earlier data run of theirs with their own lookpoint electronically superimposed on the PPI scene. They were fascinated with observing their eye-scanning behavior and could instantly describe what was happening and why. All subjects suggested this capability had great potential as a diagnostic and teaching tool in the training of air traffic controllers.

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Appendix A

Implementation of 210-Knot Pattern-Speed Procedure

A.1. General Description

The TIMER (traffic intelligence for the management of efficient runway-scheduling) model is discussed in reference 4 for constant-approach pattern-speed operation. This appendix addresses the enhancements to the TIMER simulation program employed to provide realistic flight-time estimates for higher pattern speed operation with a timed speed reduction following the base-to-final turn. Without these algorithm enhancements, successive direct course error (DICE) value computations on which the final-approach spacing aids (FASA) displays studied are based are unstable in certain situations.

A.2. Base-Leg Vector-DICE Algorithm in 210-Knot Procedure

A DICE advisory algorithm in its basic form provides a numeric feedback to help an air traffic controller to time the delivery of a control message (e.g., a turn vector message) to the pilot of an aircraft under his or her control for meeting a schedule. Thus, a vector-DICE algorithm computes, on a regular time interval, the estimated time of arrival (ETA) at the runway threshold assuming the vector control message is to be issued immediately. This ETA is, in general, earlier than the scheduled landing time (SLT) as vector-DICE calculations usually start well before the time to turn. Their difference, SLT − ETA, gives the error in arrival time at the runway threshold called the DICE value (DICEV) which would result if the vector turn was made immediately. Each successive ETA computation gives a smaller DICEV, and this trend of decreasing DICEV prepares the controller for the delivery of the control message to coincide with the point when DICEV reaches zero.

To add a graphical aid to the numerical DICE advisory mechanism, a graphical marker needs to be placed at a scheduled point to turn, that is, at the point where DICEV reaches zero. A simple way to estimate the location of this point with respect to the aircraft position is to use the concept of ETA_GAIN, which is defined as the amount of ETA increase for each unit of elapsed time while the turn is delayed. In other words, ETA_GAIN gives the slope of the changing DICEV with respect to elapsed time. Therefore, at the current time, T_NOW, given the ETA_GAIN, the current ground speed of the aircraft VH, and the current computation of its ETA and SLT, the amount of time that must be delayed in issuing the vector command can be estimated by

$$\mathrm{T\_TO\_GO} = (\mathrm{SLT} - \mathrm{ETA})/\mathrm{ETA\_GAIN} = \mathrm{DICEV}/\mathrm{ETA\_GAIN} \tag{A1}$$

And, the position of the graphical marker to issue the vector command is at a distance, D_TO_GO, ahead of its current position on the projected path:

$$\mathrm{D\_TO\_GO} = \mathrm{VH}(\mathrm{T\_TO\_GO}) = \mathrm{VH}(\mathrm{DICEV})/\mathrm{ETA\_GAIN} \tag{A2}$$

ETA_GAIN can be estimated in either of the following two ways:

1. ETA_GAIN can be estimated from the change of the path geometry as the result of the turn. For example, in the downwind DICE where the downwind leg is parallel to the final-approach path but is flown in the opposite direction, the gain is 2.0 if the speed is the same on the part of both legs which are lengthened because of the delay of the turn. If the speed on the final leg is less than the speed on downwind leg, as is true with the 210-knot approach pattern speeds when the aircraft is abeam of the minimum intercept point (MIP), the gain is increased by an amount due to speed difference, that is, $2 + (\mathrm{VH} - \mathrm{VL})/\mathrm{VL}$, where VH is the aircraft ground speed on the downwind leg and VL is the ground speed on the final approach. However, an enhanced speed profile in the final approach region in the 210-knot version (to be described later) makes significant deviations from this calculation especially for ETA_GAIN in the base-leg-vector DICE computations.

2. ETA_GAIN can be estimated from the differences of ETA's computed at (any) two different times under the same condition

$$\mathrm{ETA\_GAIN} = (\mathrm{ETA\_1} - \mathrm{ETA\_2})/(\mathrm{TIME\_1} - \mathrm{TIME\_2}) \tag{A3}$$

The second method is better than the first approach as ETA computations incorporate all the specific details on path geometry and speed profile of an aircraft. However, taking differences makes ETA_GAIN sensitive to any system noises such as those in the radar-acquired positions and ground speeds of the aircraft used as initial conditions in ETA computations. For example, consider the case in which ETA's computed on successive scans are used in estimating the ETA_GAIN in the DICE turn on the base leg where the geometric path gains are near 1.0 and flight time to the runway is on the order of 200 sec. A mere 1-percent error in the estimated flight time due to radar position noise from one scan to the next will result in a 2-sec noise in ETA differences for each 4-sec scan and that gives a 50-percent noise level in the computed ETA_GAIN. Therefore, when ETA's from successive scans are used for estimating ETA_GAIN's in TIMER, a smoothing algorithm is applied to filter out influences from the radar noise.

This basic approach of using ETA_GAIN to estimate the position of the graphical marker is usable as long as the assumption of a linear model of ETA change with respect to time is valid. For base-leg vector-DICE in the 210-knot version, the validity of this assumption is seriously eroded by the joint influence of two factors: (1) predicted overshoot of the ILS localizer and (2) speed reduction after the base-to-final turn.

The first factor happens in those cases where the aircraft under the base-leg DICE advisory is so early with respect to its schedule that an overshoot across the final-approach path is predicted to delay the aircraft's arrival at the runway threshold. While the base-leg DICE path geometry normally calls for a 20°. ILS intercept, overshoot paths are variable-angle ILS intercepts aiming at the gate in 5°. increments up to a 35°. intercept depending on the amount of delay needed. Thus, the values of ETA_GAIN in the overshoot regions are significantly different from those in the normal (undershoot) DICE region; furthermore, it is not even linear. Figure A1 is a generic representation of the relationship between ILS-intercept paths and the ETA's that might be computed using those segments. The left side of the figure shows several possible 20°. intercept segments that might be used in successive ETA updates. The change in ETA's for these segments is linear with respect to time as can be seen in the right side of the figure. The shaded part of the figure shows the relationship between ILS overshoot segments and the nonlinearity of resulting ETA's. Referring to figure A1, if the normal ETA_GAIN's (computed from successive ETA updates using the 20° intercept paths while the aircraft is still flying toward final) are used to predict the time to turn (intersection of the dashed lines), the turn marker would be placed in an overshoot position farther ahead of the aircraft than necessary. As the aircraft flies across the localizer centerline and ETA_GAIN's start to pick up values closer to the true gain (nonlinear ETA gain region of fig. A1), the position of the turn marker shifts toward the aircraft to the correct location. Sometimes, large and random noises in initial ETA_GAIN's cause the marker position to shift wildly in a very annoying manner.

The second factor is due to the enhanced speed-reduction profile in the final approach legs (including the ILS intercept leg) designed to enhance the controllability of the speed-DICE advisory which follows the base-to-final vector-DICE advisory in the 210-knot procedure. The mandatory speed-reduction point is set at the MIP, 2.0 n.mi. upstream from the gate. In order to allow aircraft to maintain higher speeds on the final-approach leg for as long as reasonable while reserving some catch-up capability, vector-DICE ETA computations (all downwind DICE and all base-leg DICE except when overshooting final is predicted) assume a nominal speed-reduction (to 170 knots) point at 2.0 n.mi. from the MIP (i.e., 4.0 n.mi. from the gate). This reserves about 8 sec of catch-up capability—the amount of ETA difference if an aircraft maintains 210 knots all the way to MIP instead of decelerating at the nominal speed-reduction point. This also, in all except for the minimum eastern arrival base leg, allows 3 n.mi. or more from the end of base-leg DICE turn to the nominal speed-reduction point for delay capability. This allows the speed-DICE marker to be positioned well ahead of the aircraft after the base-to-final turn for the controller to respond to. However, if an aircraft on its base leg is so early that TIMER predicts and advises that overshooting the final is needed for delay, it makes sense that some or all of the delay capability in the speed-DICE phase should be used on the base leg to reduce the amount of overshoot. Thus, if all delay capability in the speed-DICE phase is to be sacrificed for the sake of reducing the amount of overshoot, the ETA computation would assume that the aircraft is to reduce speed right after the DICE turn instead of at the nominal speed reduction point farther down the path. This usage of a different speed reduction profile in the overshoot region from that in the undershoot region causes the ETA_GAIN in the overshoot region to deviate farther from that in the undershoot region.

To achieve the goal of deriving a stable and accurate DICE advisory, the following multistep refinements in the base-leg vector-DICE algorithm are implemented in the 210-knot pattern-speed procedure.

Step 1: At the start of the base-leg DICE advisory and all subsequent advisories while an aircraft is still in the normal undershoot region (i.e., while the aircraft is still flying toward final), compute the ETA with the assumption that the aircraft is to make the base-to-final turn immediately—this is the same ETA computed in the basic vector-DICE. Use the nominal speed-reduction point in the speed profile for the final-approach leg. If this ETA is close enough to the SLT of the aircraft, say within one-half of a scan interval, then the recommended vector turn is imminent and no more computation is needed. If this ETA is later than the SLT, then the aircraft has already passed its recommended vector-turn position and no more computation is needed. Otherwise, proceed to compute additional ETA's. If the aircraft has already flown across the final-approach course and is in the overshoot region; proceed to step 4.

Step 2: Compute ETA_FINAL_VL with the assumption that the aircraft continues its present course until reaching a point in time T_FINAL when a direct turn onto the final-approach course can be made. If its present speed VH is above VL (170 knots), then assume an immediate speed reduction to 170 knots right after the turn. ETA_FINAL_VL gives the latest time the aircraft can make without overshooting the final.

Step 2.1: If the SLT is later than ETA_FINAL_VL, then overshooting the final approach course is predicted; proceed to step 4.

Step 2.2: Otherwise, compute ETA_FINAL_VH at T_FINAL, with the assumption that a speed reduction at the nominal speed-reduction point. (If VH is less than or equal to VL, then ETA_FINAL_VH is the same as ETA_FINAL_VL.)

Step 2.2.1: If the SLT is between ETA_FINAL_VH and ETA_FINAL_VL, then T_FINAL is where the turn marker advisory should be placed and

$$\mathrm{T\_TO\_GO} = \mathrm{T\_FINAL} - \mathrm{T\_NOW} \tag{A4}$$

Proceed to the final step 5.

Step 2.2.2: Otherwise, proceed to step 3.

Step 3: The SLT is between the ETA (turn to 20° ILS intercept at T_NOW) and ETA_FINAL_VH (turn to final at T_FINAL). Compute the ETA-gain in the undershoot region by interpolation:

$$\mathrm{ETA\_GAIN\_UNDERSHT} = (\mathrm{ETA\_FINAL\_VH} - \mathrm{ETA})/(\mathrm{T\_FINAL} - \mathrm{T\_NOW}) \tag{A5}$$

From the ETA-gain, compute the time-to-go before the turn should be initiated by

$$\mathrm{T\_TO\_GO} = (\mathrm{SLT} - \mathrm{ETA})/\mathrm{ETA\_GAIN\_UNDERSHT} \tag{A6}$$

To make certain that this is a usable solution, compute the ETA, ETA_SOLN, assuming that the aircraft is to turn at T_SOLN = T_NOW + T_TO_GO and assuming the nominal speed profile on final. If ETA_SOLN is within the threshold delta of SLT, then proceed to step 5. Otherwise, the ETA_GAIN_UNDERSHT and T_TO_GO is refined one more time by using either [(ETA, T_NOW), (ETA_SOLN, T_SOLN)] pair or [(ETA_SOLN, T_SOLN), (ETA_FINAL_VH, T_FINAL)] pair, depending on whether the SLT falls on the interval (ETA, ETA_SOLN) or on (ETA_SOLN, ETA_FINAL_VH); that is,

Step 3.1: If ETA < SLT < ETA_SOLN, then compute

$$\mathrm{ETA\_GAIN\_UNDERSHT} = (\mathrm{ETA\_SOLN} - \mathrm{ETA})/(\mathrm{T\_SOLN} - \mathrm{T\_NOW}) \tag{A7}$$

$$\mathrm{T\_TO\_GO} = (\mathrm{SLT} - \mathrm{ETA})/\mathrm{ETA\_GAIN\_UNDERSHT} \tag{A8}$$

Step 3.2: Otherwise, ETA_SOLN < SLT < ETA_FINAL_VH; compute

$$\text{ETA\_GAIN\_UNDERSHT} = (\text{ETA\_FINAL\_VH} - \text{ETA\_SOLN})/(\text{T\_FINAL} - \text{T\_SOLN}) \tag{A9}$$

$$\text{T\_TO\_GO} = (\text{SLT} - \text{ETA\_SOLN})/\text{ETA\_GAIN\_UNDERSHT} \tag{A10}$$

In either case, proceed to step 5. Note that with adequate computing power, this iterative process can be continued to improve the solution.

Step 4. This step is taken when SLT is found to be later than ETA_FINAL_VL in step 2 or when the aircraft is already in the overshoot region and its SLT is still later than its ETA. Compute ETA_MAX at T_MAX assuming the maximum overshoot path (a 35° ILS intercept at the gate) and slowest speed profile (deceleration right after the base-to-final turn).

Step 4.1: If the SLT is greater than ETA_MAX, then ETA_MAX is the best solution. In this case, set

$$\text{T\_TO\_GO} = \text{T\_MAX} - \text{T\_NOW} \tag{A11}$$

Step 4.2: Otherwise, ETA < SLT < ETA_MAX. Interpolate to find the overshoot path (closest 5° interval) to meet its SLT:

$$\text{ETA\_GAIN\_OVERSHT} = (\text{ETA\_MAX} - \text{ETA})/(\text{T\_MAX} - \text{T\_NOW}) \tag{A12}$$

$$\text{T\_TO\_GO} = (\text{SLT} - \text{ETA})/\text{ETA\_GAIN\_OVERSHT} \tag{A13}$$

Step 5: Having computed T_TO_GO, delta time from T_NOW, the final step is to compute the distance ahead of the aircraft D_TO_GO where the turn marker is to be placed and the equivalent DICE value at T_NOW:

$$\text{D\_TO\_GO} = \text{VH}(\text{T\_TO\_GO}) \tag{A14}$$

$$\text{DICEV} = \text{T\_TO\_GO}(\text{ETA\_GAIN}) \tag{A15}$$

where ETA_GAIN is either ETA_GAIN_UNDERSHT or ETA_GAIN_OVERSHT, depending on which region the SLT falls. Although the DICEV is no longer equal to SLT – ETA, it gives a steadier countdown and reaches zero at the solution point.

This refinement yields a more stable and correct turn marker position because

1. A more correct ETA_GAIN is used in deriving the solution
2. ETA_GAIN is computed by using ETA's computed in the same scan; the radar noise in parameters such as aircraft position and ground speed has the same influence in the ETA computations, and when a difference of ETA's is taken, the effect of the noise tends to cancel out yielding the change of ETA due to path differences only. Also, the ETA differences are taken over a larger time interval than the scan interval which further stabilizes the results.

A.3. Speed-Reduction Advisory Algorithm in 210-Knot Procedure

The speed-DICE advisory mode is invoked by TIMER control logic on an aircraft that:

1. Has completed its base-to-final turn to either an ILS intercept heading or the final-approach heading
2. Has not crossed the minimum intercept point (MIP) on final
3. Has an indicated air speed greater than 170 knots

The speed advisory consists of either

1. A speed-DICE count-down with the value of zero marking the time when the controller should issue a speed-reduction message to the pilot
2. A circular graphical marker on the projected path of the aircraft under control marking the point where the speed-reduction message should be delivered

The speed-DICE countdown value, called DICESP, is recomputed during each equivalent radar sweep update

1. The ETA at the runway assuming an immediate (after a predefined verbal message delivery time) deceleration to 170 knots
2. The difference between the ETA and the TIMER-maintained SLT which gives the current DICE value; that is,

$$\text{DICESP} = -(\text{SLT} - \text{ETA}) \tag{A16}$$

Note that the difference (SLT − ETA) for speed-reduction advisories counts up instead of down because as the speed reduction is delayed, successive ETA's decrease instead of increase as in vector-DICE updates. Therefore, DICESP's are negated to maintain the "countdown" philosophy consistent with vector-DICE updates.

The position of the speed graphical marker is derived on each scan by the usage of the concept of ETA-gain due to speed change, the computation of which is described as follows:

1. Let VH be the current ground speed and VL be the ground speed of 170 knots IAS at a projected altitude of 7200 ft at the gate (note that VH must be greater than VL for the speed-DICE mode to be activated)
2. Let T_DECEL and D_DECEL be the time and distance needed for the deceleration from VH to VL
3. Let D_DELTA be the distance from the current position of the aircraft to be traveled at VH before the deceleration from VH and VL is to take place
4. Let T_TO_RNWY be the remaining estimated flight time (to runway) after D_DELTA and D_DECEL
5. Let T_NOW be the current time (adjusted by the message delivery time)

Then, the ETA for a delayed deceleration ETA_VH is

$$\text{ETA\_VH} = \text{T\_NOW} + (\text{D\_DELTA}/\text{VH}) + \text{T\_DECEL} + \text{T\_TO\_RNWY} \tag{A17}$$

On the other hand, the ETA based on immediate deceleration from VH to VL is

$$\text{ETA} = \text{T\_NOW} + \text{T\_DECEL} + (\text{D\_DELTA}/\text{VL}) + \text{T\_TO\_RNWY} \tag{A18}$$

Therefore, the change in ETA brought about by delaying the issuing of the deceleration command (until after D_DELTA) is

$$\begin{aligned} \text{ETA\_DELTA} &= \text{ETA} - \text{ETA\_VH} \\ &= (\text{D\_DELTA}/\text{VL}) - (\text{D\_DELTA}/\text{VH}) \\ &= \text{D\_DELTA}\{(\text{VH} - \text{VL})/[\text{VL}(\text{VH})]\} \end{aligned} \tag{A19}$$

The time delay corresponding to D_DELTA, T_DELTA, is simply the amount of time for the aircraft to travel D_DELTA at the present speed VH, that is,

$$\text{T\_DELTA} = \text{D\_DELTA}/\text{VH} \tag{A20}$$

Thus, ETA_GAIN, defined as the amount of ETA-change due to delaying the deceleration command by a unit time, is

$$\text{ETA\_GAIN} = \text{ETA\_DELTA}/\text{T\_DELTA} = (\text{VH} - \text{VL})/\text{VL} \tag{A21}$$

Now, if SLT is the target time to meet and assuming that SLT is earlier than ETA, the amount of time that must be delayed in the issuing of the speed-reduction command can be estimated by

$$\text{T\_TO\_GO} = (\text{ETA} - \text{SLT})/\text{ETA\_GAIN} = \text{DICESP}/\text{ETA\_GAIN} \tag{A22}$$

The position of the graphical marker where the speed-reduction command should be given is at a distance D_TO_GO ahead of the aircraft on the its projected path:

$$\text{D\_TO\_GO} = \text{VH}(\text{T\_TO\_GO}) = \text{VH}(\text{DICESP})/\text{ETA\_GAIN} \tag{A23}$$

The accuracy of this computation depends upon the following assumptions:

1. The deceleration time and distance from VH to VL are the same whether the deceleration is performed now or at a later time
2. The ground speed remains constant during the time T_DELTA

Although these assumptions are, in general, not true because an aircraft may change its altitude while holding its indicated air speed and may even change its heading (for example, from an ILS-intercept heading to the final-approach heading), the effects of these deviations from the assumptions are relatively small and do not affect the usefulness of the computation results. Furthermore, the DICE process is a self-correcting process. The closer the aircraft is to its speed-reduction point, the more correct are the initial values, such as the heading and altitude, and hence, VH and VL, and therefore, the more correct the computed ETA and DICESP are.

In the final implementation of this algorithm in TIMER, the following refinements are used:

1. With an ETA_GAIN of about 0.25 for a speed-change from 210 knots to 170 knots, any small error in the computation of ETA is amplified fourfold in the final value of D_TO_GO and this results in undesirable shifting of the graphical marker. In order to obtain a more stable ETA, a straight-line projected path to the runway at the final-approach heading is used regardless of whether there will be a change in heading of the aircraft (e.g., turning onto the localizer from an ILS-intercept heading).
2. To prevent the controller's display from being cluttered by a large number of graphical symbols or confusion as to which aircraft the advisory is intended, the speed-reduction graphical symbol of an aircraft in the speed-DICE mode will not be displayed if the D_TO_GO is greater than 3.0 n.mi.
3. A TIMER-induced speed reduction is forced upon the aircraft if it crosses the MIP at a speed higher than that allowed at the gate. This emulates real-world events where a pilot would either request a speed reduction or initiate a discretionary deceleration in preparation for executing the instrument approach.

Since the ETA-gain is about 0.25 (for a reduction from 210 to 170 knots), there is about a 1-sec error in arrival time at the runway threshold for every 4 sec of error in the speed-reduction message-delivery time. This feature is what makes the speed-reduction advisory such a fine-tuning mechanism for delivery-time precision. The total amount of control available to vary the SLT, however, is fairly small. If one assumes that 5 n.mi. are available after the base-to-final turn before the reduction to 170 knots must begin, then the total range of time control is about 20 sec. (The time difference to travel a given approach distance, at a speed of 170 knots versus 210 knots, is about 4 sec/n.mi.)

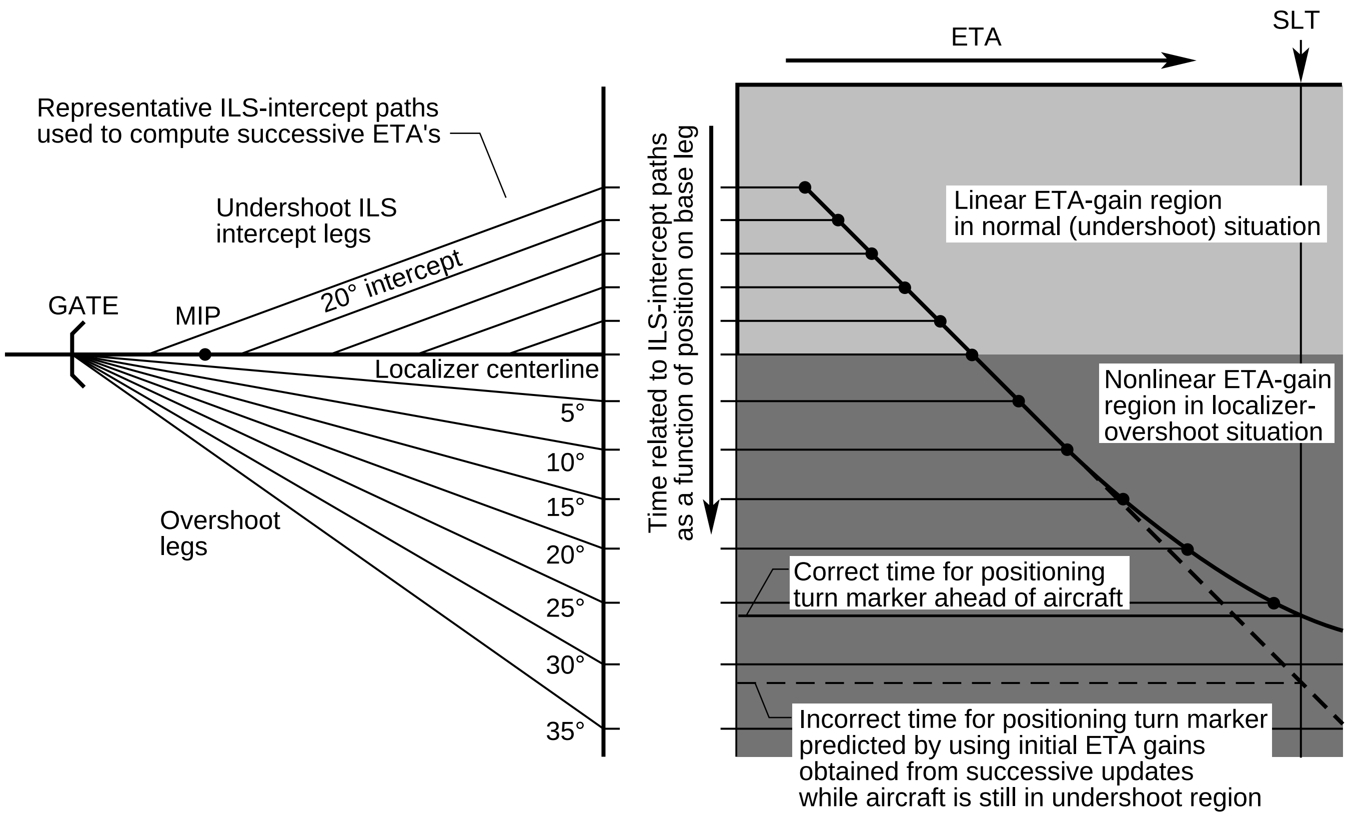


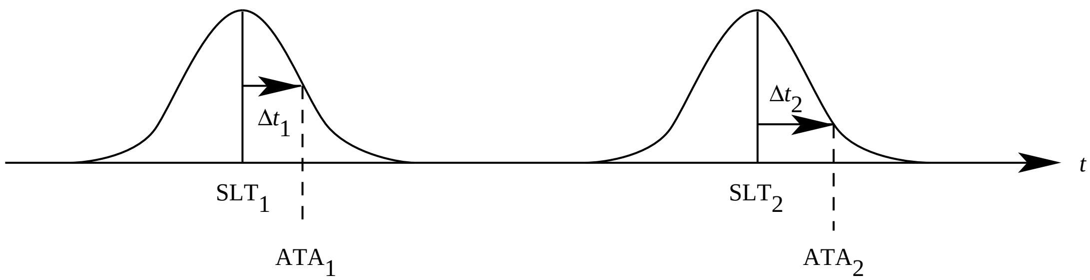
Figure A1. Effect of ETA gain on position of predicted-overshoot graphic turn marker.

Appendix B

Definition of Interarrival Error

B.1. Time-Based Control

Given a time-based air traffic control process with a pair of sequential arrival aircraft with the following time relations:



where

SLT_1 and SLT_2	scheduled landing times at runway threshold for aircraft 1 and 2 of a pair
ATA_1 and ATA_2	actual times of arrival of aircraft 1 and 2 at the runway threshold

The delivery time errors of aircraft 1 and 2 at the threshold (Δt_1 and Δt_2) are defined by

$$\Delta t_1 = \mathrm{ATA}_1 - \mathrm{SLT}_1 \tag{B1}$$

$$\Delta t_2 = \mathrm{ATA}_2 - \mathrm{SLT}_2 \tag{B2}$$

with the delivery-time-error density distributions shown above.

The aircraft-pair interarrival time error (IAE) is defined as

$$\mathrm{IAE} = \Delta t_2 - \Delta t_1 \tag{B3}$$

which in terms of the aircraft pair SLT's and ATA's is

$$\mathrm{IAE} = (\mathrm{ATA}_2 - \mathrm{ATA}_1) - (\mathrm{SLT}_2 - \mathrm{SLT}_1) \tag{B4}$$

$$\mathrm{IAE} = (\text{Actual separation time}) - (\text{Scheduled separation time}) \tag{B5}$$

Even though each aircraft of a pair has a runway threshold time error, if the time error is the same for both (i.e., a constant bias), the IAE will be 0 and the pair separation will be correct. Thus, a spread of interarrival time errors indicates variation in desired spacing and is the attribute of interest. IAE spread is characterized by a statistical measure of dispersion about the mean, the variance, or its square root, the standard deviation.

B.2. Manual Distance Separation

Aircraft are not apriori assigned individual scheduled threshold crossing times during manual control. When aircraft are on instrument approaches, the controller concerns are with aircraft pair separations conforming to the radar separation requirements in effect on final approach. The test subject controllers were instructed to aim for minimum wake vortex separation. For tightly packed traffic we assume the controller is attempting to maximize the landing rate by keeping aircraft-pair separations to the minimum distance allowed. For this case, we can treat the minimum required separation as the intended or scheduled separation. When the first airplane of an aircraft pair is at the runway threshold, excess separation $\Delta d_{1,2}$ is defined by

$$\Delta d_{1,2} = (\text{Actual separation}) - (\text{Required separation}) \tag{B6}$$

If we rewrite equation (B6) in terms of corresponding time separation, we get

$$\Delta t_{1,2} = (\text{Time to fly actual separation}) - (\text{Time to fly scheduled separation}) \tag{B7}$$

which is equivalent to equation (B5). Thus for manual data runs, an equivalent manual interarrival time IAE' can be obtained. Knowing the aircraft threshold crossing times, the final-approach speed, and the wake vortex spacing requirement, IAE' can be calculated from

$$\text{IAE}' = \Delta t_{1,2} = (\text{ATA}_2 - \text{ATA}_1) - (\text{Time to fly scheduled separation}) \tag{B8}$$

Appendix C

Single Runway Theoretical Arrival Rate

C.1. Perfect Delivery Arrival Rate

In general when $g(x, y)$ is a function of 2 random variables x and y, then the mean or expectation of $g(x, y)$ is

$$E\{g(x, y)\} = \int_x \int_y g(x, y)\, f(x, y)\, dx\, dy \tag{C1}$$

with $f(x, y)$ being the joint density function of random variables x and y. For the case where x and y are discrete, we can write the mean or expectation of $g(x, y)$ as

$$E\{g(x, y)\} = \sum_k \sum_n g(x_k, y_n)\, [(x_k, y_n) \tag{C2}$$

where $p(x_k, y_n)$ is the joint probability function of x and y.

For our case let i and j be subscripts which are random variables, each which take on values between 1 and m where

m	number of aircraft types in traffic mix
i	lead aircraft of pair on final approach
j	trail aircraft of pair on final approach
V	aircraft speed on final

Let us define

$g(i, j) \equiv t_{ij} \equiv$ Time interval between aircraft i and aircraft j when aircraft i is at end of final-approach segment of length L.

For the situation when $V_j \geq V_i$, the minimum required separation S_{ij} for that aircraft pair occurs when aircraft i is at the threshold and is

$$t_{ij}(V_j \geq V_i) = \frac{s_{ij}}{V_j} \tag{C3a}$$

For the case when $V_i > V_j$, the minimum required separation S_{ij} for that aircraft occurs when aircraft i is at the beginning of the final approach segment and the separation opens until aircraft i reaches the threshold where

$$t_{ij}(V_i > V_j) = \frac{S_{ij}}{V_j} + L\left(\frac{1}{V_j} - \frac{1}{V_i}\right) \tag{C3b}$$

From equation (C2), we can write the mean interarrival-time spacing $(\bar{t}_{ij})$ as

$$\bar{t}_{ij} = E(t_{ij}) = \sum_{j=1}^{m} \sum_{i=1}^{m} t_{ij} p_{ij} \tag{C4}$$

where P_{ij} is the probability that an aircraft pair will consist of aircraft type i followed by aircraft type j.

For independent arrivals and first-come first-serve sequencing

$$p_{ij} = p_i p_j \tag{C5}$$

where p_i and p_j are the probabilities of type i and type j aircraft being in the traffic mix. Thus equation (C4) can simply be rewritten as

$$\bar{t}_{ij} = E(t_{ij}) = \sum_{j=1}^{m} \sum_{i=1}^{m} t_{ij} p_i p_j \tag{C6}$$

and, for the situation when runway occupancy is not a limiting factor, the average flow rate λ is

$$\lambda = \frac{1}{t_{ij}} \tag{C7}$$

Bear in mind that the separation S_{ij} used in the calculation of t_{ij} is the exact separation required. Therefore, the flow rate calculated in equation (C7) is for perfect delivery precision.

C.2. Effect of Interarrival Spacing Precision

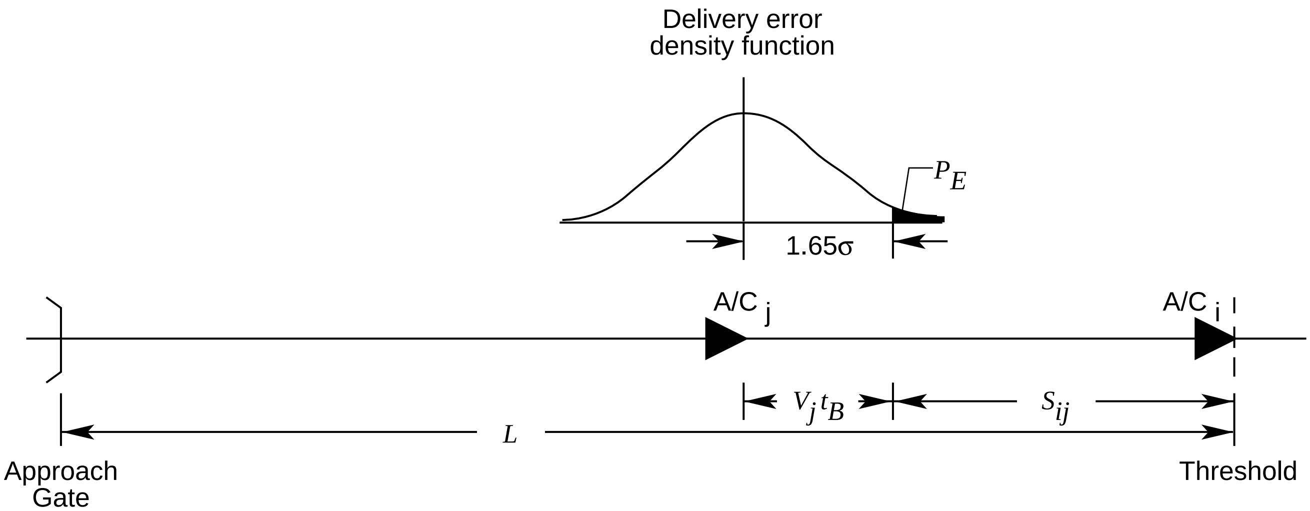
An operational time-based scheduling system would separate aircraft by the minimum required plus additional buffer separation to account for the uncertainty of aircraft delivery. If one assumes that the uncertainty is Gaussian with a standard deviation of σ, then we can determine the size of the average buffer time t_B needed to keep the probability of separation violation or error less than some specified probability value P_E. For the probability of violation P_E less than 5 percent, we need a buffer time t_B of 1.65σ.

For both the overtaking ($V_j \geq V_i$) and opening ($V_i \geq V_j$) cases of a pair of aircraft on final, figure C1 illustrates the total separation scheduled by a time-based system as a function of delivery error buffer and minimum required separation on final. The effect of interarrival spacing precision, parameterized by the standard deviation of the spacing uncertainty ($t_{ij,\sigma}$), can be determined by rewriting equations (C3) as

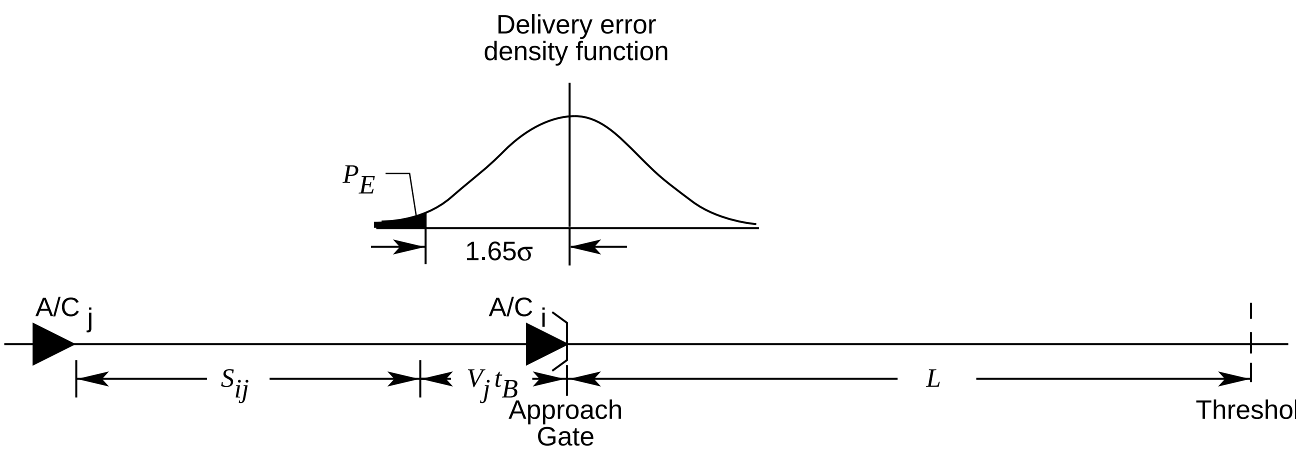
$$\left.\begin{aligned} t_{ij,\sigma}(V_j \geq V_i) &= \frac{S_{ij}}{V_j} + 1.65\sigma \\ t_{ij,\sigma}(V_i > V_j) &= \frac{S_{ij}}{V_j} + L\left(\frac{1}{V_j} - \frac{1}{V_i}\right) + 1.65\sigma \end{aligned}\right\} \tag{C8}$$

For the situation when runway occupancy is not a limiting factor, the resulting flow rate with a time buffer t_B added to the spacing becomes

$$\lambda = \frac{1}{t_{ij,\sigma}} \tag{C9}$$



(a) Overtaking case when $V_j \geq V_i$.



(b) Opening case when $V_i \geq V_j$.

Figure C1. Illustration of time-based total separation as function of delivery error buffer and minimum required separation for pair of aircraft on final with different speeds.

Appendix D

FASA Learning Effect On Number of Vectors Issued Per Aircraft

Debriefing discussions and controller comments suggested a learning or training effect after operating with the graphic marker and DICE countdown formats. After using the direct automation aids (graphic and DICE formats), there seemed to be a tendency, among those subjects who used intermediate vectors (cutting corners), toward using more squared downwind/base vectors (classic trombone pattern) in subsequent manual and centerline slot marker runs. The manual format was always the first format tested in each pattern-speed procedure.

The purpose of this appendix is to determine whether the vectors per aircraft conclusions (section 5.2) were voided if this learning effect existed. We assert that the comparisons and trends were correct and if anything the "true" mean vectors per aircraft for the manual and centerline slot marker formats were somewhat higher than those shown in figure 21. To support this assertion, the data in figure 20(b) were separated by subject controllers performing the 170-knot procedure first and those performing the 210-knot procedure first, as shown in table D1.

These data appear to support the existence of a change in the vectors per aircraft after using the automated direct aids particularly for the manual format. We used a simple linear model based on an observed condition and an assumption to estimate the automation learning influence on the manual format. The observed condition was that there was an inherent difference in the mean vectors per aircraft between the 210-knot and the 170-knot speed-procedure for the manual format. The assumption was that the learning effect for the graphic and DICE formats was the same whether the subject controller was exposed first to the 170-knot speed procedure or the 210-knot speed procedure. Following is an analysis using this assumption and a simple linear model:

$\overline{V}_{\mathrm{LM}} \equiv$ Mean learning effect on manual format vectors per aircraft

$\overline{V}_{\mathrm{RM}} \equiv$ Mean reduction in vectors per aircraft in going from 170- to 210-knot pattern-speed procedure for manual format

$\overline{V}_{\mathrm{170M/170\,1st}} \equiv$ Mean vectors per aircraft of 170-knot manual format when 170-knot procedure was first

$\overline{V}_{\mathrm{170M/170\,2nd}} \equiv$ Mean vectors per aircraft of 170-knot manual format when 170-knot procedure was second

$\overline{V}_{\mathrm{210M/210\,1st}} \equiv$ Mean vectors per aircraft of 210-knot manual format when 210-knot procedure was first

$\overline{V}_{\mathrm{210M/210\,2nd}} \equiv$ Mean vectors per aircraft of 210-know manual format when 210-knot procedure was second

The linear model is written as

$$\overline{V}_{\mathrm{170M/170\,1st}} - \overline{V}_{\mathrm{LM}} - \overline{V}_{\mathrm{RM}} = \overline{V}_{\mathrm{210M/210\,2nd}}$$

$$\overline{V}_{\mathrm{210M/210\,1st}} - \overline{V}_{\mathrm{LM}} - \overline{V}_{\mathrm{RM}} = \overline{V}_{\mathrm{170M/170\,2nd}}$$

Substituting values from table D1

$$2.92 - \overline{V}_{\mathrm{LM}} - \overline{V}_{\mathrm{RM}} = 2.11$$

$$2.46 - \overline{V}_{\mathrm{LM}} + \overline{V}_{\mathrm{RM}} = 2.38$$

Solving these simultaneous equations gives

$$\overline{V}_{\mathrm{LM}} = 0.45 \text{ vectors/aircraft}$$

Two ways exist to estimate the vectors per aircraft for the 170-knot procedure manual format prior to any learning effect. One is to use, as our estimate, the value of $\overline{V}_{\mathrm{170M/170\,1st}}$ given in table D1(a), which is

$$\overline{V}_{\mathrm{170M/170\,1st}} = 2.92 \text{ vectors/aircraft}$$

With the use of the value of $\overline{V}_{170\text{M}/170\,\text{2nd}}$ given in table D1(b), the other estimate is calculated from

$$\overline{V}_{170\text{M}/170\,\text{2nd}} + \overline{V}_{\text{LM}} = 2.38 + 0.45 = 2.38 \text{ vectors/aircraft}$$

We used as our best estimate of the 170-knot procedure, manual vectors per aircraft, prior to any graphic or DICE format learning effect ($\widehat{V}_{170\text{M}}$), the average of the above two estimates, which is

$$\widehat{V}_{170\text{M}} = 0.5(2.83 + 2.92) = 2.88 \text{ vectors/aircraft}$$

Similarly, there are two ways to estimate the vectors per aircraft for the 210-knot procedure manual format prior to any learning effect. One is to use the value of $\overline{V}_{210\text{M}/210\,\text{1st}}$ given in table D1(b), which is

$$\overline{V}_{210\text{M}/210\,\text{1st}} = 2.46 \text{ vectors/aircraft}$$

With the use of the value of $\overline{V}_{210\text{M}/210\,\text{2nd}}$ given in table D1(a), the other estimate is calculated from

$$\overline{V}_{210\text{M}/210\,\text{2nd}} + \overline{V}_{\text{LM}} = 2.11 + 0.45 = 2.56 \text{ vectors/aircraft}$$

Our best estimate ($\widehat{V}_{210\text{M}}$) of the vectors per aircraft for the 210-knot procedure manual format prior to any graphic or DICE format learning effect, is the average of the above two 210-knot estimates, which is

$$\widehat{V}_{210\text{M}} = 0.5(2.56 + 2.46) = 2.51 \text{ vectors/aircraft}$$

Unlike the manual format, which was always first, the test position of the centerline slot marker in the first pattern-speed procedure series varied from subject to subject. Sometimes the centerline slot marker was performed immediately after the manual format and before subject exposure to the graphic or DICE formats. Other times the centerline slot marker was performed after both graphic and DICE formats and the subject was exposed to a possible full learning effect. There was of course the intermediate case where the centerline slot marker was performed between that of the graphic and the DICE formats. As a consequence, obtaining an estimate for the centerline slot marker vectors per aircraft, prior to a learning effect, was not as direct as for the manual format.

Two assumptions were made in order to estimate the mean vectors per aircraft for the centerline slot marker prior to a learning effect. The first assumption was that most of the learning effect had occurred during the practice and data runs of both the graphic marker and DICE countdown formats in the first speed procedure series and before starting the second speed procedure series. The second assumption was that the inherent difference in mean vectors per aircraft between the manual format and the centerline slot marker format is not changed by the learning effect. Using these assumptions, the difference between the mean vectors per aircraft for the manual format ($\overline{V}_{170\text{M}/170\,\text{2nd}}$) and the mean vectors per aircraft for the centerline slot marker format ($\overline{V}_{170\text{C}/170\,\text{2nd}}$) after the learning effect has occurred is

$$\overline{V}_{170\text{M}/170\,\text{2nd}} - \overline{V}_{170\text{C}/170\,\text{2nd}} = 2.38 - 1.99 = 0.39 \text{ vectors/aircraft}$$

Using our best estimate of the vectors per aircraft for the manual format 170-knot procedure ($\widehat{V}_{170\text{M}}$), the estimated vectors per aircraft for the 170-knot centerline slot marker ($\widehat{V}_{170\text{C}}$), prior to any graphic or DICE effect, was

$$\begin{aligned}\widehat{V}_{170\text{C}} &= \widehat{V}_{170\text{M}} - (\overline{V}_{170\text{M}/170\,\text{2nd}} - \overline{V}_{170\text{C}/170\,\text{2nd}}) \\ &= 2.88 - 0.39 = 2.49 \text{ vectors/aircraft}\end{aligned}$$

Similarly , the difference between the manual mean vectors per aircraft ($\overline{V}_{210\text{M}/210\,\text{2nd}}$) and the centerline slot marker vectors per aircraft ($\overline{V}_{210\text{C}/210\,\text{2nd}}$), after the learning effect has occurred, is

$$\overline{V}_{210\text{M}/210\,\text{2nd}} - \overline{V}_{210\text{C}/210\,\text{2nd}} = 2.11 - 1.70 = 0.41 \text{ vectors/aircraft}$$

Again using our best estimate of the vectors per aircraft for the manual format, 210-knot procedure ($\widehat{V}_{210\mathrm{M}}$), the estimated vectors per aircraft for the 210-knot centerline slot marker ($\widehat{V}_{210\mathrm{C}}$), prior to any graphic or DICE effect, was

$$\widehat{V}_{210\mathrm{C}} = \widehat{V}_{210\mathrm{M}} - (\overline{V}_{210\mathrm{M}/210\,2\mathrm{nd}} - \overline{V}_{210\mathrm{C}/210\,2\mathrm{nd}})$$

$$= 2.51 - 0.41 = 2.10 \text{ vectors/aircraft}$$

The result of this analysis supports the assertion that the subject controllers did change the mean number of vectors per aircraft issued, for both the manual and centerline slot marker format, after being exposed to the direct automation aid graphic marker and DICE countdown formats. This change was a mean reduction of about 0.4 vector per aircraft for the manual format and about 0.3 vector per aircraft for the centerline slot marker format. In addition the analysis reinforced that all earlier mean trend comparisons were valid (section 5.2), particularly that the graphic marker and DICE countdown formats had significantly fewer mean vectors per aircraft than either the manual or centerline slot marker formats.

Table D1. Mean Vectors Per Aircraft for Display Formats

[Subjects are divided according to testing order of speed procedures. To preserve anonymity, controller subject numbers have been randomized and bear no relationship to original test order appearance; however, listed subject numbers are consistent for all report data.]

(a) Subjects performing 170-knot procedure first

Controller test subject	Mean vectors per aircraft							
	170-knot procedure first				210-knot procedure second			
	MAN	GM	DICE	CSM	MAN	GM	DICE	CSM
2	2.571	1.400	1.588	2.000	2.146	1.500	1.500	1.755
5	3.116	1.489	1.347	2.556	2.408	1.429	1.510	1.804
8	3.065	1.510	1.429	3.267	2.727	1.565	1.510	1.250
9	1.958	1.489	1.667	1.717	1.479	1.429	1.404	1.457
10	3.756	1.596	1.532	2.375	2.400	1.565	1.580	2.022
11	3.381	1.490	1.578	2.085	1.980	1.711	1.563	1.956
12	2.565	1.451	1.429	2.146	1.620	1.388	1.451	1.633
Mean	2.916	1.489	1.510	2.307	2.109	1.512	1.503	1.697
St dev	0.598	0.060	0.112	0.501	0.449	0.111	0.061	0.274

(b) Subjects performing 210-knot procedure first

Controller test subject	Mean vectors per aircraft							
	170-knot procedure second				210-knot procedure first			
	MAN	GM	DICE	CSM	MAN	GM	DICE	CSM
1	2.224	1.565	1.659	1.933	2.580	1.592	1.630	1.729
3	2.143	1.360	1.449	1.932	2.327	1.667	1.420	1.898
4	2.731	1.816	2.065	2.356	2.843	1.565	1.520	2.490
6	2.362	1.500	1.526	2.089	2.404	1.429	1.426	1.938
7	2.432	1.612	1.531	1.638	2.136	1.383	1.540	1.714
Mean	2.378	1.571	1.646	1.990	2.458	1.527	1.507	1.954
St dev	0.227	0.167	0.246	0.262	0.268	0.118	0.087	0.316

Appendix E

Lookpoint Data Recording, Development and Analysis

E.1. Facility Description and Recording Methodology

The oculometer facility computes and stores a time history of eye-scanning events. The block diagram (fig. E1) includes the components of the system. The oculometer projects a collimated near-infrared beam of light onto the subject's eye. The system depends on algorithms that can compute a lookpoint given the relative position of two reflections from a single eye of the subject. The computer compares the large back lighted pupil reflection to the much smaller and more intense corneal reflection. By using split image techniques, the system directs the illuminating beam through the same tracking mirror system (block 4) that collects the reflected images. It uses the angles of the two automatic tracking mirrors and the manually controlled focus of the eye-camera optics to correct the lookpoint calculation for subject head position. The oculometer electro-optic head (blocks 4 and 5) is located directly in front of the subject (block 8) and just below the simulated radar display. This location is well outside the final controller's normal scan area, which is concentrated around the center of the display. The subject can detect only a dull red light in the head's mirror system. For the purposes of calibration and monitoring real-time performance, the system mixes (block 9) the computed lookpoint position with the PPI video signal that is nonobtrusively recorded (block 11) from a repeater display (block 10), also shown in figure E2. The resulting combined display (fig. E1, block 12) contains a small circle of light representing the lookpoint as it moves among the display symbols. An observer can monitor in real time both system and subject performance by viewing this combined signal. A video recorder (block 13) stores this signal on tape for postrun analysis.

Most of the components of the oculometer system are located in the Human Engineering Methods (HEM) laboratory one floor below the TRACON simulation facility. Figure E3 is a photograph taken in the HEM laboratory. In the background corner one can see a display monitor that has the mixed video with the controller PPI display and the controller's lookpoint superimposed. The three 5-in. video monitors in front of the main system operator (in the foreground) are used for system monitoring and control. (Details of these displays do not show well in the photograph.) The left monitor is a duplicate of the mixed PPI/lookpoint display. The central monitor shows the bright corneal reflection on the much larger and darker pupil reflection in the background. The right monitor shows the subject's entire head. The operator uses this camera to observe the subject and as an aid to recapture the subject's eye after losing track. The signal on the cathode-ray tube above the monitors is the sweep from the eye camera used to determine the relative position of the two reflections. The central narrow peak indicates the corneal reflection. The broader peak at about half-voltage represents the pupil reflection and the low voltage baseline represents the rest of the eye. By keeping track of video sweep count and timing when voltages cross specified levels, the system determines the center of each of the two reflections and thus their relative position on the camera vidicon.

Figure E3 does not include the oculometer computer. However, it does show several of the digital readouts and control inputs for the oculometer computer such as potentiometers, a standard typewriter keyboard, and a joystick (under the operator's right hand). Their principal use is for prerun calibration, but the operator also uses them to dynamically compensate for the subject's posture adjustments. The mirror tracking is automatic and works well. The joy stick is a manual augmentation for the mirror tracking. The operator uses it to override the search algorithm when the eye is out of track and the system is trying to reacquire. He does not use the joy stick often but when used it speeds up reacquisition considerably. The operator controls the mirrors, the eye camera focus, and collimated infrared beam intensity. The operator also determines and enters system parameters during calibration. These include parameters to adjust for intersubject differences in corneal curvature. The microcomputer in the background of figure E3 collects and stores the visual events in real time in its random access memory. At the end of each run, the operator copies the records to a disk file for long-term storage. Each record spans a variable time duration that is an integer multiple of the oculometer sample period (30 samples per second). There are four data fields per record containing lookpoint coordinates (2 dimensions), pupil diameter, and time duration of event. For an out-of-track event, the system records lookpoint coordinates as zero and stores a status code in the pupil diameter field. Once per rotation of the simulated TRACON radar, that is, every fourth second, the system stores one other field on a second file.

This field contains the sequence number of the visual event last completed as the ATC simulation radar frame started. The data reduction algorithms use this information later for synchronizing the recorded simulation data with the oculometer data.

E.2. Data Reduction

The eye-scanning event file and the PPI/oculometer synchronizing file were both recorded in the oculometer facility as discussed in section E.1. In addition, the ATC simulation simultaneously wrote a third real time file. This third file contained the state of the display including the position of aircraft, the tag information, and the state of any currently active graphic aids. The simulation computer updated the display and saved one of these records each radar sweep. Postprocessing synchronized the three files, that is, assigned each fixation to its corresponding radar sweep. Then, a filtering process reduced the oculometer data. It removed a few known bad records (less than 0.003 percent) and some of the short (noise) out-of-track records. In addition, the process combined adjacent records that pertain to the same fixation into a single record with a longer duration. This pattern occurred, for example, when a noise record or blink interrupted a fixation. A separate report (ref. 22) documents in detail the data reduction process for applying an oculometer to an ATC controller-display evaluation. The report also describes the details of the computer programs developed for the collection, reduction, and analysis of the data.

E.3. Display Object Identification

After filtering, the algorithms assigned each member of the filtered set of fixations to a display object by searching the corresponding radar sweep data. If they found no display object near the lookpoint, they classified the fixation display object as unknown. In order for a lookpoint to be coupled with a display object the distance between them had to be less than 0.57 in. on the screen or just over 1 n.mi. for the display scale used in the experiment. In most cases, if two display objects were within this distance of the lookpoint, the algorithm assigned the fixation to the closer of the two. The exception was when an aircraft was very close to its graphic turn marker, graphic speed marker or centerline slot marker. In those cases, the lookpoint, when within 0.57 in. of both the aircraft and the FASA, was assigned to an appropriate combination category of special interest in this study.

E.4. Resulting Files

The "merge" files resulting from this postprocessing data reduction and display-object identification process consisted of both in-track and out-of-track records, one file per run. The merge file fixation records contain the coordinates of both the lookpoint and the display object as well as the distance between. They also contain information on the state of the FASA. For example, if the controller was looking at an aircraft during a DICE run, the record would contain the countdown and heading information but only if the display provided that information during that particular radar update. The following are means from the 24 (12 controllers at 2 approach speeds) manual runs:

The mean number of records per run was 5648 after filtering

The mean in-track time was about 85 percent of total test time

The time for unknown display object fixations was about 8 percent of in-track time

The mean time duration for all fixations was 0.68 sec

These merge files are the basis for the lookpoint analysis presented in the main text.

E.5. Analysis

These merge files contain large amounts of data, typically over 600 000 bytes per file. There is a total of 96 files excluding practice runs (12 controllers using 8 test conditions). These data were used to address two general types of questions. The first type of questions concerns the scan pattern of the controllers: Where are they looking and at what, and how do they budget their fixation time over types of display objects or over areas (zones) of the display? This would be very difficult to determine objectively or accurately without an oculometer. The second type of question concerns the existence and identification of parameters in the scan pattern that are statistically sensitive to changes in the display. After establishing a correlation between these changes in scan patterns and the display changes, the next step was to evaluate the implications of these changes with respect to the merits of particular display characteristics.

E.6. Types of Statistics

In this study, three general types of statistics were examined:

1. Mean fixation time.
2. Percentages such as "in-track time as a percent of total time" or "time spent looking at aircraft as percent of total in-track time."
3. Number of cross-check scans (CCS) and corresponding time spent as a percentage of total in-track time. A CCS is defined as a succession of fixations on a pair of display objects. It represents an ordered scan pattern which is alternating between the two objects of the pair, uninterrupted by a third display object or long out-of-track time. For a pair of display objects A and B, the lookpoint sequence A-B is counted as a CCS of order 2; the sequence A-B-A is of order 3, et cetera. The occurrence of high-order CCS's is considered bad because it indicates increased controller concern or information gathering. In this study, CCS's of order 2 to 4 and (5 or greater) were tallied. The cross-check scan measure is potentially a significant concept which has not been formally documented by its originator, Randall L. Harris of the NASA Langley Research Center.

These 3 types of statistics were accumulated for each display object and display object pair as well as for display zones. Four zones in the terminal area were defined: downwind, base, final and "everywhere else." The zones are depicted in figure E4. A further breakdown of the statistics was based on the occurrence of an event such as "while speed marker was on" or "while DICE was showing in data block."

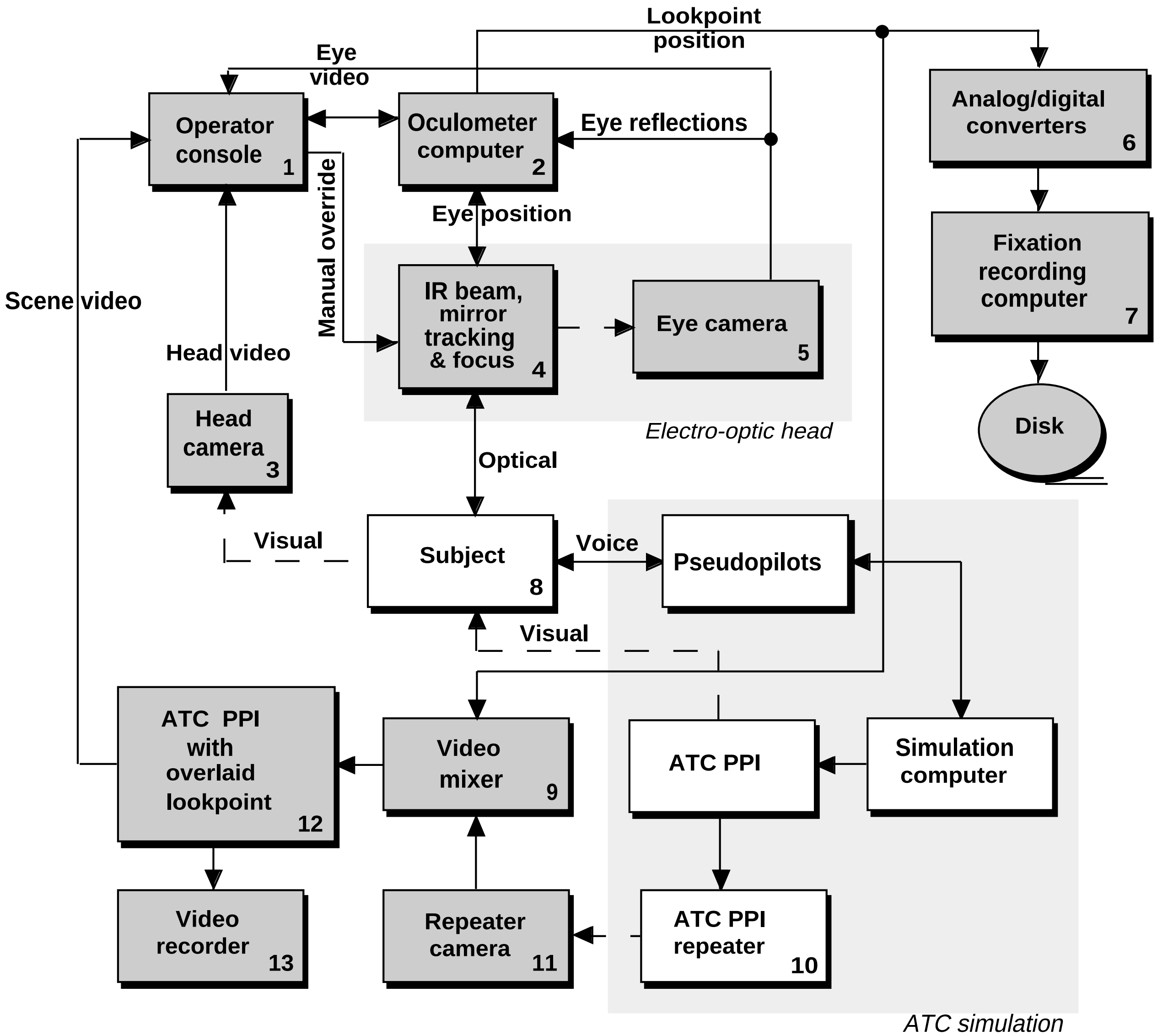


Figure E1. Operational block diagram of oculometer system interactioin with ATC simulation.

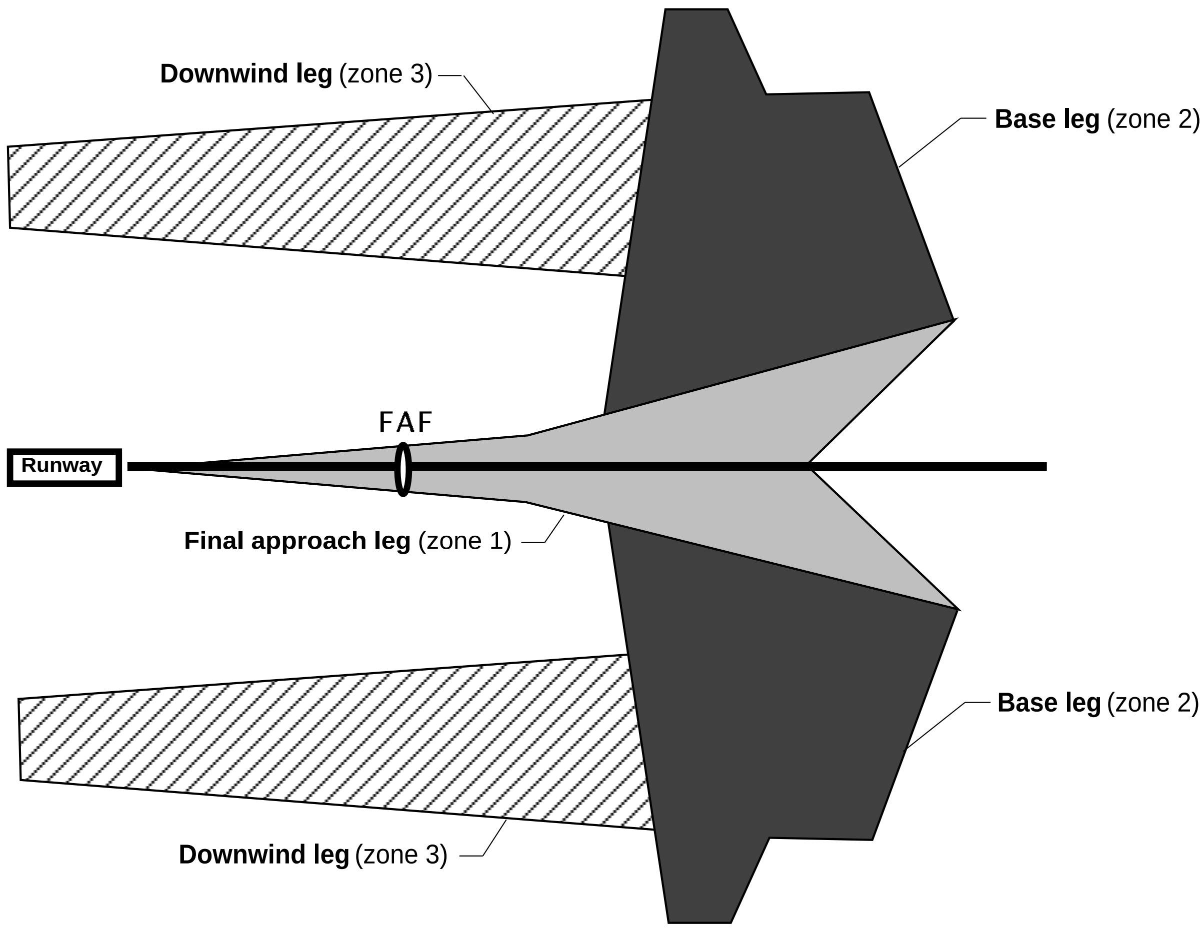


Figure E4. Illustration of zones defined on final controller's display for look point analysis. Zone 4 is everywhere on display not defined by zones 1, 2, and 3.

Appendix F

Controller Questionnaires And Responses

F.1. General Description

This appendix includes all questionnaires and responses (evaluations and comments) of the questionnaires except the graphed results included in the main text and the comments from the verbal debriefing session. In the interest of conserving space, instructions for completing each type of questionnaire are included only once, and the print size has been reduced from that used in the original questionnaire. Types of questions and sections they appear in are as follows:

F.2. Specific Format Questionnaires—Combined Subject Evaluations and Comments

This section contains the results of the format questions which were administered at the completion of each format data run. Each question is provided along with the number of responses for each of the five positions along the graphic scale. All subject comments are also included.

F.2.1 Format Questionnaires for 170-Knot Pattern-Speed Procedure

F.2.1.1 Manual Format For 170-Knot Procedure

Note: For each experimental condition, the specific-format questionnaire was headed by a set of instructions (such as shown below). However for report purposes, these general instructions are not included in all subsequent corresponding questionnaires requiring a simple response to a scale defined by end-point descriptors.

SUBJECT CONTROLLER QUESTIONNAIRE

Condition - Manual Control (170 kts Final Turn)

Instruction: Carefully read each of the following statements, then on the associated scale enter an "X" in the box which most closely represents your position, feeling, or judgment concerning the statement. Each scale has two endpoint descriptors that define the scale. For example:

The representation of a TRACON operating under IFR conditions in the test environment was

	1	2	3	4	5	
unrealistic						realistic

Marking the box labeled "1" indicates you feel the test environment was seriously unrealistic. Box "2" indicates the simulation was primarily unrealistic with a few realistic features. Box "3" indicates roughly equal number of realistic and unrealistic features. Box "4" indicates the simulation was primarily realistic with minor shortcomings. Box "5" indicates the test environment was realistic in representing an operational IFR TRACON condition.

There is room for additional comments below each scale. Any comments which clarify or explain your view will be helpful information for our evaluation of controller opinion.

---

1. The simulation of a TRACON operating in IFR conditions (single runway configuration) during a moderate to busy traffic period was...

unrealistic	0	1	1	9	1	realistic

Comments

- My only comment was separation on short final would normally be adjusted by tower for the final controller.
- No variable performance aircraft had to be mixed.
- Once the tower had the aircraft they could issue advisories on speed and even issue speed reductions to insure separation.

2. Given the organization of traffic performed by the feeder and automation in this session, the landing sequence was...

not obvious	0	0	0	2	10	readily apparent

Comments

- Feeder gave excellent spacing, but not too much interval between traffic.

3. In today's manual TRACON environment there is no automation to aid the feeder in organizing traffic for the final controller. Given the aircraft spacing and organization performed by the feeder/automation interaction in this session, the effort required to set up the landing sequence as compared to today's manual environment was...

greatly increased	0	0	2	7	3	greatly reduced

Comments

None

4. Based on your experience with aircraft performance in IMC, the simulated aircraft flight paths and maneuvers were...(Please identify any deficiencies.)

unrealistic	0	1	4	5	2	realistic

Comments

- Due to the high altitude I felt the aircraft turns to final were somewhat slower than normal.
- Real pilots tend to miss more instructions.
- Aircraft inside the marker seemed to "DIE".
- I think the speed would change too much between 7 miles and 4 miles on final.

5. Communication with pseudo pilots was...(Please identify any deficiencies.)

unrealistic	0	1	2	2	7	realistic

Comments

- Compared to the real world the pseudo pilots here are very organized in their transmissions. In real life blocked transmissions block out everything.
- About as good as simulation can be.
- A few times the voice disguiser made transmissions difficult to understand.

6. The interaction and coordination with the feeder controller were...(Please identify any deficiencies.)

unrealistic	0	1	3	6	2	realistic

Comments

- Would be easier with an interphone/intercom button.
- No landlines, buttons to press, other traffic diverting his attention.

7. The suitability of the simulated radar display to perform the required control task was...(Please identify any deficiencies.)

seriously deficient	0	0	1	1	10	adequate

Comments

- Unable to adjust to personal specs.
- It is adequate, but it obviously lacks the primary target and beacons control slash.

8. The initial briefing and training on Denver airspace/procedures and the simulation interface necessary to do a representative job of controlling traffic was...(Please identify any deficiencies.)

seriously deficient	0	0	0	3	9	adequate

Comments

- I would like to look at the ILS APP. charts and if you have them, the profile descent into Den.

9. Relative to my normal state of alertness, awareness, and responsiveness, while controlling traffic, I feel my state in this session was...(If not normal, please indicate reason.)

below normal	0	2	10	0	0	above normal

Comments

- I still am feeling my way around the airspace configuration and simulator characteristics.
- Overall concerned with trying to maintain proper position for oculometer.

10. Additional comments on performance or conditions, if any.

- Very enjoyable and educational so far.
- I felt a little helpless once the a/c were cleared for the approach because I couldn't have strung them out on the downwind or separation without impacting the feeder.

F.2.1.2. Graphic Marker Format For 170-Knot Procedure

1. Adapting to the use of the graphic turn advisor was...

difficult	0	0	0	0	12	easy

Comments

- Extremely valuable automation aid, it helped me be much more aware of all aspects of airspace and separation involved.

2. The turn positions indicated by the graphic turn advisor, as compared to the positions you would have turned aircraft for spacing on final...

strongly differed						closely agreed
	0	0	4	6	2	

Comments

- They were probably more accurate then my own.

3. The tabular sequence list presented on the right of the display was... (If useful, how was it used?

Comments

- I never used the list once.
- Once again, I didn't use it.
- Checked sequence between ties.
- Referred to it occasionally.
- Hard for me to read - actually alpha numerics are on the whole smaller than I prefer.

4. Indicate how the graphic turn advisories (170 kts procedure) affected your workload, as a final controller, as compared to manual operation (170 kts procedure) with no computer aid.

increased						reduced
	0	1	0	5	6	

Comments

- Greatly enhanced my ability to insure separation and give more quality turn-on's.
- Fewer decisions had to be made.

5. Indicate how the graphic turn advisories (170 kts procedure) affected your spacing on final approach as compared to manual operation (170 kts procedure) with no computer aid.

less precise						more precise
	0	1	1	5	5	

Comments

- There was less guess work and more evident or obvious spacing, and I was able to adjust spacing easier.
- The computer was more accurate.

6. In terms of display clutter, the addition of the graphic turn marker symbol to the display generated......

excessive clutter						no perceptible clutter
	0	0	4	5	3	

Comments

- No real distraction in this environment.

7. Relative to the point where aircraft were to be turned, the graphic turn advisories appeared ahead of the aircraft at a distance that was...

too far						too close
	0	0	12	0	0	

Comments

- Very acceptable distance.
- About right.
- Most of the time, the turns were good, but a few times the turns were off. The computer needs too much time to recalculate when strange things happen.

8. Indicate how your focus on the aircraft/graphic-turn-marker position relationship affected your attention to aircraft-to-aircraft spacing.

strongly reduced	1	3	1	4	3	not affected

Comments

- I was very confident in the automation and it never really hampered my attention to spacing.
- My scan was reduced, however, I feel the graphic reduced my scan more.

9. **Indicate how your focus on the aircraft/graphic-turn-marker position relationship affected your attention to the overall traffic picture.**

strongly reduced	0	3	3	4	2	not affected

Comments

- I was more tuned to the final but overall no change.
- As I became comfortable with the system my scan was not affected. Initially I felt I watched the markers longer.

10. **Having a numerical heading advisory along with the displayed graphic turn advisor would be...**

undesirable	4	1	3	2	2	desirable

Comments

- It wouldn't change the fact that under normal conditions a controller is going to adjust to what suits him/her regardless.
- I think unnecessary would be a better word.

11. **Having the graphic turn advisor displayed until aircraft completed their turn (to monitor turn performance) resulted in...**

excessive clutter	1	3	1	2	5	no perceptible clutter

Comments

- Again, in this environment no clutter at all.
- Once the turn has been issued the marker has served its purpose and no longer needs to be displayed.
- Occasionally I would have to look at the graphic turn advisor to see which aircraft it was meant for.

12. **Rather than the graphic advisor made up of the three line segments, as used in the test, a different form of graphic turn advisor format would be...(Please indicate your preference if any. Some examples include a turn arc ( ), a symbol made up of two directed line segments ( ), or a simple symbol at the position along the path where the turn instruction is to be issued.)**

not preferable	4	2	3	2	1	preferable

Comments

- The line segments are more distinguishable, therefore, they were more useful.
- No preference.
- This seemed fine, but an arc may have worked well also.
- ARC - aircraft do not make 90 degree turns.

13. **Relative to the final controller's job, indicate your reaction and feeling to having a computer suggest where aircraft should be turned for spacing.**

undesirable	1	1	2	2	6	desirable

Comments

- A very useful and stress reducing tool, I would work with it tomorrow.

- Personally I would not enjoy the job the way I do today. Working airplanes is fun, monitoring a CRT is boring.
- The computer is too rigid and takes too much time for recalculation.

14. Relative to my normal state of alertness, awareness, and responsiveness, while controlling traffic, I feel my state in this session was...(If not normal, please indicate reason.)

below normal	0	0	8	3	1	above normal

Comments

- I was curious to see my reaction to the automation, and was more relaxed and attentive with it, versus manual control.

15. Additional comments on performance or conditions, if any.

Comments

- This was the easiest to work with of the aids for me.
- In some cases it appeared that aircraft did not perform as expected when within FAF.
- I felt very comfortable with this format.

F.2.1.3. DICE Countdown For 170-Knot Procedure

1. Adapting to the use of the DICE turn advisor was...

difficult	0	0	4	2	6	easy

Comments

- More data block information than I'm used to working with, but it didn't deter my control.
- Felt that I could initiate my own turns - instead, I waited for prompts.

2. The times-to-turn indicated by the DICE turn advisor, as compared to the times you would have turned aircraft for spacing on final...

strongly differed	1	2	0	7	2	closely agreed

Comments

- When I could accurately catch the turns they were very accurate, however, if it indicated I would be through the localizer I went with my own turns entirely with what I feel were better results.
- My tendency is to get aircraft established on final approach course further out, but this was good to see.
- When you had a situation out of the ordinary or an aircraft got extended, the computer did not give updated headings.

3. The tabular sequence list presented on the right of the display was...(If useful, how was it used?)

useless	5	2	3	1	1	very useful

Comments

- I never used it.
- I don't believe I referred to the tab list once.
- Detracted somewhat - it distracted my attention from the aircraft.
- It is annoying and distracting. It is another thing to look at. If you change the sequence, the tab sequence will confuse you.

4. Indicate how the DICE turn advisories (170 kts procedure) affected your workload, as a final controller, as compared to manual operation (170 kts procedure) with no computer aid.

increased	1	1	3	3	4	reduced

Comments

- Depending on the situation, if I had no distractions the turn advisor was a great tool. However, if I would have to resolve a conflict in normal conditions away from final, it really didn't change my control of the situation, I'd tend to go manually.
- Reduced my workload a great deal.
- I was sometimes concentrating too much on the prompts and less on the separation.

5. **Indicate how the DICE turn advisories (170 kts procedure) affected your spacing on final approach as compared to manual operation (170 kts procedure) with no computer aid.**

less precise	0	0	0	8	4	more precise

Comments

- With the advent of this software, my spacing was probably much better than manually.

6. **In terms of display clutter, the DICE countdown and suggested heading value which are added to the data block, generated...**

excessive clutter	0	1	2	4	5	no perceptible clutter

Comments

- Again in this environment it was no distraction. I personally do not prefer a lot of writing in the data block.

7. **Relative to the time when aircraft were to be turned, the DICE time-to-turn advisories appeared in the data block at a time that was...**

to early	0	0	12	0	0	too late

Comments

- I leaned toward my own headings when a/c were late to turn on, however, when there was no late turn, the advisory was perfect.
- Adequate.
- Hard to tell - sometimes, I felt like I was turning at exactly the right time, but it seemed too late.
- Sometimes the countdown jumps too quick and it is tough to keep an eye on it. You end up focusing on this countdown instead of scanning the whole scope.

8. **Indicate how your focus on the DICE countdown value affected your attention to aircraft-to-aircraft spacing.**

strongly reduced	1	4	1	5	1	not affected

Comments

- Aside from this simulation, if I had to closely monitor final accuracy spacing, I would not have been able to use the Dice as effectively.
- My scan was reduced to ensure I turned the a/c at the appropriate time.
- Initially, focus on the countdown rate seemed to take precedence over focus on actual spacing.
- At first I was double-checking but it seemed to be providing good spacing - so I began to rely more on it and less on myself.

9. **Indicate how your focus on the DICE countdown value affected your attention to the overall traffic picture.**

strongly reduced	0	5	1	4	2	not affected

Comments

- I tended to concentrate on getting the Dice advisor to do the work and at times it consumed most of my attention.

- The Dice offers the controller more time to become complacent.
- Distracted attention from overall picture. Less thinking and planning on my part involved.

10. Generally the base and final turn headings are predictable and constant. As an aid to the final controller, do you feel the numerical heading advisories in the data tag were...

unnecessary	2	2	4	2	2	necessary

<u>Comments</u>

- I could see in bad weather this software would be a great assistance but in normal conditions I feel the controller will trust his own headings.
- It's my feeling that depending on the a/c position from the airport and localizer I could make the heading assignment.
- In the test environment it is needed but after working with the system, It could possibly be inhibited.
- The headings are nice to have.
- Probably not necessary but were helpful and utilized.

11. Rather than the DICE countdown format, as used in the test, a different form of time information in the data block for suggesting the time-to-turn would be...(Please indicate any suggestions for improving the display format.)

not preferable	5	1	4	2	0	preferable

<u>Comments</u>

- A slower type of countdown system. Instead of letting it go from 75 to 64 to 53 to 28, etc. have it start at 7,6,5,4,3,etc.
- Graphic position symbols.

12. Relative to the final controller's job, indicate your reaction and feeling to having a computer suggest when a aircraft should be turned for spacing.

undesirable	1	0	2	6	3	desirable

<u>Comments</u>

- I feel if the software is a viable concept and appeals to all I think it is greatly needed.
- While I was running the problem I tended to get a little bored. The Dice makes the job very easy and takes away from my own personal satisfaction.
- It's a little tedious, but certainly reduces anxiety levels. Also have a tendency not to concentrate as hard.
- Would need more time to evaluate - maybe I'd get used to it and choose on a case by case basis when it could be valuable.
- It's desirable when you agree 100disagree, the computer does not seem to be that much of a help.

13. Relative to my normal state of alertness, awareness, and responsiveness, while controlling traffic, I feel my state in this session was...(If not normal, please indicate reason.)

below normal	0	3	6	2	1	above normal

<u>Comments</u>

- I found that because of the precise nature of this aid I had to be much more aware of my tasks.
- My alertness would compare to a slow session in the manual mode.
- It became a little tedious, but I don't believe in the real world it would be quite so, due to more human and uncontrollable factors.
- It took me out of the decision-making process quite a lot - thereby, I was responding to more than initiating the traffic flow.

14. Additional comments on performance or conditions, if any.

None.

F.2.1.4. Centerline Slot Marker Format For 170-Knot Procedure

1. Adapting to the use of the centerline slot marker was...

difficult						easy
	3	6	0	3	0	

Comments

- Extremely hard process to make the scheduled "circle", I felt a little more adapted after the second run but not confident.

2. The sequence indicated by the centerline slot marker, as compared to the sequence you would have chosen without the slot markers...

strongly differed						closely agreed
	0	2	1	5	4	

Comments

- A couple of times, aircraft were inbound that I would have changed sequence on immediately, contrary to what the centerline marker was instructing me to do.
- On two occasions I would have changed sequence.
- Except for one situation - I think that the sequence was what I'd have used.
- I would have changed the sequence 3 or 4 times.

3. Indicate how the centerline slot marker (170 kts procedure) affected your workload, as a final controller, as compared to manual operation (170 kts procedure) with no computer aid.

increased						reduced
	3	4	2	2	1	

Comments

- Greatly increased my workload by making me concentrate on final and spacing close in.
- Had to adjust to using it - after repetitive usage it would become more natural.
- The slot marker posed more of a problem at the 170 kt procedure.
- Probably would decrease workload when I become more used to working with it.

4. In the normal case (when slot markers were not noticeably shifted to adjust for spacing errors) vectoring aircraft into their slot markers was...

difficult						easy
	0	5	1	6	0	

Comments

- I had a hard time hitting the slot markers on a consistent basis. This of course could be different given more exposure to it.
- Not easy, but manageable. I sometimes had to use additional vectors.

5. Indicate how often an extra effort was made to precisely center the aircraft in its slot marker.

never						always
	0	1	1	8	2	

Comments

- Often I had to adjust headings and speeds to compensate for centering.
- It was more difficult when the slot marker kept jumping backward because it thought the front aircraft would not hit the slot marker.

6. In terms of display clutter, the slot markers displayed on the extended runway centerline generated...

excessive clutter						no perceptible clutter
	0	2	2	4	4	

Comments

- No more or less than the other automation system.

7. Indicate how your focus on the aircraft/slot-marker-position relationship affected your attention to aircraft-to-aircraft spacing.

strongly reduced	2	5	1	3	1	not affected

Comments

- I concentrated much more on aircraft spacing than any other aspect this session.
- I was less likely to scan A/C inside the FAF.
- Somewhat reduced since my concentration was shifted to the slot rather than the aircraft.

8. Indicate how your focus on the aircraft/slot-marker-position relationship affected your attention to the overall traffic picture.

strongly reduced	1	3	3	5	0	not affected

Comments

- I was paying way too much attention to centering aircraft in their slots and spacing involved.
- I found I spent more time fine tuning my sequence to hit the marker. Without a marker I am much easier on myself if I miss a hole by 1/4 mile.
- I just assumed the slot marker would hold separation down to the runway. In two cases it did not.

9. In spacing/sequencing aircraft on final, to what degree do you feel the slot markers provide useful information. (If useful, how?)

not useful	0	1	2	5	4	useful

Comments

- My only feeling is it prompted me to turn aircraft to base much more expeditiously.
- Once a/c are on final, a marker could be used to make the separation, however, vectoring to intercept at the slot marker I found too demanding.
- Help to focus on the position the aircraft should be on final.
- Determines your sequence. Make it easier to identify separation problems (too much or not enough).
- Gave aid in spacing.
- In cases where I was ahead of the slot I was reminded to review spacing.
- Useful for separation at the runway threshold.

10. Rather than the centerline slot marker format, as used in this test, a different centerline format would be...(Please indicate any suggestions for improving the display format.)

not preferable	3	2	6	1	0	preferable

Comments

- No change needed.
- A single line shown on final with a numeric value display a speed adjustment that would open or close the separation to the minimum required separation. This would be displayed once the a/c are on the localizer.
- I prefer the display.

11. Having additional aids (such as turn advisories, vector advisories, or speed advisories) to help me deliver aircraft into their slot markers would be...(Please indicate your preference, if any.)

unnecessary	0	1	4	3	4	desirable

Comments

- Maybe in addition to the slot markers also the line segments only if the slot marker were going to be something I had to work with.
- If you had to have the slot marker, a graphic turn display would help.
- Not sure, I would have to try it. It would probably be too much to concentrate on slots, vector advisories, etc (too much distraction).
- Graphic display.
- Headings could be helpful in some cases but not necessary. Some controllers might prefer that.
- Graphic markers.

12. Determining which aircraft were supposed to go into which slot marker was...

difficult	0	0	1	2	9	easy

Comments

- The slot markers explained very easily where aircraft were meant to be.
- Getting them there was the problem.
- Most cases seemed natural - I didn't need the tab list as in vector advisories (Dice).
- Sometimes the computer sequenced incorrectly.

13. Relative to the final controller's job, indicate your reaction and feeling to having a computer suggest where an aircraft should be positioned on final.

Comments

None

14. Relative to my normal state of alertness, awareness, and responsiveness, while controlling traffic, I feel my state in this session was...

below normal	0	1	6	3	2	above normal

Comments

- This system takes all my alertness and awareness to perform properly.

15. Additional comments on performance or conditions, if any.

Comments

- Have some way to change slots.
- Tended to mentally berate myself if I missed a slot - maybe that would lessen with continued usage.
- I felt it got away from me because I wasn't looking ahead to the sequence.

F.2.2. Format Questionnairs for 210-Knot Pattern-Speed Procedure

F.2.2.1. Manual Format For 210-Knot Procedure

1. Given the organization of traffic performed by the feeder and automation in this session, the landing sequence was...

not obvious	0	0	0	4	8	readily apparent

Comments

- The scheduling system is very accurate and the feeder position was excellent.

- The test should have a few sequencing decisions. It is unlikely that a controller would work this volume of traffic without a tie.
- During the scenario there were maybe two or three instances where I had to make a judgement call as to which a/c would go first.
- Feeder controller vectored inbounds as necessary to avoid possible conflicts.

2. **In today's manual TRACON environment there is no automation to aid the feeder in organizing traffic for the final controller. Given the aircraft spacing and organization performed by the feeder/automation interaction in this session, the effort required to set up the landing sequence as compared to today's manual environment was...**

greatly increased	0	0	1	6	5	greatly reduced

Comments

- Projecting ahead, I feel the automation interaction was better than I could have foreseen.
- Let's put it in at ORF.
- Most controllers do a good job of setting up a workable sequence.

3. **Communication with pseudo pilots was...(Please identify any deficiencies.)**

unrealistic	0	1	2	5	4	realistic

Comments

- Realistically the communication sequence is not as organized. The pilots did well.
- Pilots responded accurately and quickly. You have to listen more carefully because of the computer generated different type voice.

4. **The interaction and coordination with the feeder controller were...(Please identify any deficiencies.)**

Note: One subject stated there was no interaction during the run and therefore did not respond.

Comments

- Although no verbal communication between us existed, this session of the interaction was very good in traffic flow.
- Didn't coordinate with feeder during this scenario.
- Didn't really use any this session, but in reality would use a lot.
- I only made a couple of coordinations, but they were timely and the feeder concurred.

5. **During this data run, the procedure of 210 kts in the pattern followed by a normal reduction to 170 kts, after the turn-to-final, was used. Indicate how this procedure compares to what you typically use during IMC, with moderate to heavy traffic. (If different please explain.)**

strongly differed	1	5	4	1	1	closely agreed

Comments

- Personally I tend to reduce a/c much sooner, say on base leg or downwind instead of turn to final.
- I typically will reduce a/c prior to turning final unless I am running a long final in excess of 15 miles. I find it's easier to sequence a/c with more compatible speeds.
- Traffic sometimes is slowed earlier during busy traffic.
- At Norfolk we often don't use/need speed reduction as in this situation. There are times we use it, but usually its for air carriers succeeding twin or single engine a/c.
- A speed of 210 to 8.5 DME might be a little fast for some aircraft. You cannot have a 3 mile final for 30 miles using this procedure.
- I tend to use speed reduction very often but towards the end of the problem it felt comfortable.
- Military, civil mix at ORF and changes greatly how you apply speed adjustments.

6. Given the traffic situation during this test run, a pattern speed of 210 kts through the turn-to-final was ...(If not acceptable, please explain.)

not acceptable						acceptable
	0	0	1	3	8	

Comments

- It kept the pattern moving and traffic flow was much more expeditious, however, it differs from what I do.
- For the most part it worked out fine however its final turn to final could be more precise if a/c are slowed to 180 -170 on base leg.
- The speed of 210 kts is very acceptable. They are easy to use when computing distances traveled.

7. Relative to my normal state of alertness, awareness, and responsiveness, while controlling traffic, I feel my state in this session was...(If not normal, please indicate reason.)

below normal						above normal
	0	2	6	3	1	

Comments

- I felt like I normally felt in a manual environment, no real change.
- I felt fatigued the second session.
- The fact that I was being watched made me be more aware and pay more attention.
- It is after all, a test scenario. If I was working live traffic, I would have other means at my disposal.

8. Additional comments on performance or conditions, if any.

Comments

- I felt my overall ability to control this particular simulated pattern was greatly enhanced by the automation aids I had used in the previous runs.
- In my normal work environment speed control is not used very often. This was somewhat of a learning experience to use speed control with every aircraft.
- Speeds seem to drop too fast inside of the marker.

F.2.2.2. Graphic Marker Format For 210-Knot Procedure

1. Adapting to the use of the graphic turn advisor with the 210 kts procedure was...

difficult						easy
	0	1	0	5	6	

Comments

- By far the best combination automation I've worked with yet.
- At times it seemed more confusing than the 170 kt graphic turn scenario - maybe it was me. The graphics hopped around a few times.
- It was very easy adapting to the graphic turn advisor. Little or no concentration needed.

2. The turn positions indicated by the graphic turn advisor, as compared to the positions you would have turned aircraft for spacing on final...

strongly differed						closely agreed
	0	1	4	4	3	

Comments

- They were very accurate turns by the advisor and I believe mine would have overall continued.
- I would normally run closer downwind, therefore, I probably would have adjusted the downwind heading.
- There were a number of times I'd have turned base later, so as not to get into an overshoot of the localizer for proper sequence.

3. **Indicate how the graphic turn advisories (210 kts procedure) affected your workload, as a final controller, as compared to manual operation (210 kts procedure) with no computer aid.**

increased	0	3	1	5	3	reduced

Comments
- I had much more time to scan more airspace and better monitor final.
- Workload was reduced a lot. At one point I was lulled to sleep.

4. **Indicate how the graphic turn advisories (210 kts procedure) affected your spacing on final approach as compared to manual operation (210 kts procedure) with no computer aids.**

less precise	0	0	0	9	3	more precise

Comments
- Once again almost too accurate in getting lulled into a false sense of security. However, with the turn and speed advisories so accurate I was able to better watch final spacing close in at my own pace and technique.
- A couple of times I noticed spacing near the threshold slightly less than 2 1/2 - I don't know if it was because of me or the graphic turn advisor.

5. **In terms of display clutter, the addition of the graphic turn marker symbol to the display generated...**

excessive clutter	0	4	5	1	2	no perceptible clutter

Comments
- Even in this environment there was a lot of lines and markers but that is a small distraction to the overall usefulness of the advisor.
- I fell behind the computers suggested turns at that time when I was catching up. The graphic turn marker was a minor distraction.
- Not really a problem.
- Again, with a cluttered map, it could be a problem.

6. **Indicate how your focus on the aircraft/graphic-turn-marker position relationship affected your attention to aircraft-to-aircraft spacing.**

strongly reduced	1	3	1	4	3	not affected

Comments
- Separation on final was so constant my attention was very evenly distributed.
- Minimal reduction in a/c awareness.
- I paid a lot of attention to the X and the graphics - especially if they moved a lot.
- I did not watch the spacing as closely as I would have with the manual operation.

7. **Indicate how your focus on the aircraft/graphic-turn-marker position relationship affected your attention to the overall traffic picture.**

strongly reduced	0	4	2	4	2	not affected

Comments
- I was better able to watch all aspects of my airspace because of the advisories efficiency.
- Attention was drawn toward the turn monitor to see if aircraft was following the turn.
- Slightly reduced.
- I tried to force myself to see the overall picture.

8. **Relative to the final controller's job, indicate your reaction and feeling to having a computer suggest where aircraft should be turned for spacing.**

undesirable	0	1	2	6	3	desirable

Comments

- If I could have this system at Norfolk right now!
- With additional practice, could be helpful. Difficult to tell with just this session.
- It was nice to have something assist you working the final.

9. **The speed reduction points indicated by the graphic speed-reduction advisor, as compared to the positions you would have slowed aircraft for spacing on final...**

strongly differed	0	1	0	8	3	closely agreed

Comments

- I saw no drawbacks and agreed totally.
- I tended to reduce the aircraft about 1 mile sooner than the graphic.
- The advisor was later than what I would have done.

10. **Indicate how the graphic speed-reduction advisories (210 kts procedure) affected your <u>workload</u>, as a final controller, as compared to manual operation (210 kts procedure)with no computer aid.**

increased	0	1	2	6	3	reduced

Comments

- My job with this system is nothing more than a monitor, therefore, I could spend much more time on other responsibilities in my airspace.
- Made the job easier. Less pre-planning required.

11. **Indicate how the graphic speed-reduction advisories (210 kts procedure) affected your spacing on final approach as compared to manual operation (210 kts procedure) with no computer aids.**

less precise	0	0	2	7	3	more precise

Comments

- As precise as I've seen - simple, straightforward advisory.
- Not sure.
- I would have slowed the aircraft a little earlier than the aid.

12. **In terms of display clutter, the addition of the graphic speed-reduction marker symbol to the display generated...**

excessive clutter	0	3	2	5	2	no perceptible clutter

Comments

- More than I'm used to but a minor drawback.

13. **Relative to the position were aircraft speeds were to be reduced to 170 kts, the graphic speed advisories appeared ahead of the aircraft at a time that was...**

too early	0	0	11	1	0	too late

Comments

- Very satisfactory.

- The speed reduction for a/c behind a heavy jet seemed a little early.
- Several times when the advisor appeared it was already under the aircraft.
- In a few or more cases there didn't seem to be a "heads up".
- The graphic speed advisory was generally on early enough to see it, sometimes a little too early.

14. Indicate how your focus on the aircraft/graphic-speed reduction-marker position relationship affected your attention to aircraft-to-aircraft spacing.

strongly reduced	0	1	1	8	2	not affected

Comments

- I was able to monitor spacing much more accurately with this system than before.
- My scan was less effected by speed than by the dice countdown.

15. Indicate how your focus on the aircraft/graphic-speed reduction-marker position relationship affected your attention to the overall traffic picture.

strongly reduced	1	0	1	8	2	not affected

Comments

- Because of the system efficiency I was free to attend to more airspace - more quality overall.

16. Relative to the final controller's job, indicate your reaction and feeling to having a computer suggest where aircraft should be reduced (from 210 kts) for spacing.

undesirable	0	1	0	6	5	desirable

Comments

- If it reduces workload like this system does, yes.
- If the X was a different color or blinked until speed reduction was accomplished maybe it would be good.

17. Relative to my normal state of alertness, awareness, and responsiveness, while controlling traffic, I feel my state in this session was...(If not normal, please indicate reason.)

below normal	0	5	4	3	0	above normal

Comments

- This system relaxes you and helps you maintain an even, positive mental posture.
- With the computer making all the decisions for me, my awareness is not as focused.

18. Additional comments on performance or conditions, if any.

Comments

- I feel the markers would be less distracting and cause less clutter if they were disabled earlier..i.e.... as soon as aircraft started their turn.
- Overall adds clutter to display, not unmanageable but more than I like.
- This was the easiest and most advantageous system for me.

F.2.2.3. DICE Countdown Format For 210-Knot Procedure

1. Adapting to the use of the DICE turn advisor with the 210 kts procedure was...

difficult	0	1	1	3	7	easy

Comments

- Very adaptable and accurate in spacing, at 210 kts it was a snap to use.
- I learned to trust the advisor after the first run and learned when the overshoot advisory could be compensated for with speed reduction.

2. **The times-to-turn indicated by the DICE turn advisor, as compared to the times you would have turned aircraft for spacing on final...**

strongly differed	0	0	4	6	2	closely agreed

<u>Comments</u>

- Only once or twice did I trust my instincts instead of the DICE and that was during overshoots.
- Didn't know.

3. **Indicate how the DICE turn advisories (210 kts procedure) affected your workload, as a final controller, as compared to manual operation (210 kts procedure) with no computer aide.**

increased	0	3	0	3	6	reduced

<u>Comments</u>

- Here in simulation my workload was very light in that all I was concerned with was base or downwind turns.
- I liked the speed reduction prompt. It required less concentration.
- Slightly more than average because I had to dwell on whose DICE instruction took priority. I also had to consciously remember (remind myself) to check spacing, overall picture etc.

4. **Indicate how the DICE turn advisories (210 kts procedure) affected your spacing on final approach as compared to manual operation (210 kts procedure) with no computer aids.**

less precise	0	0	2	6	4	more precise

<u>Comments</u>

- The spacing just about always was exact. The only drawback would be ignoring final spacing on my part because of the efficiency of the DICE.

5. **In terms of display clutter, the DICE-turn-advisor countdown value and suggested-heading value which are added to the data block, generated...**

excessive clutter	0	1	0	4	7	no perceptible clutter

<u>Comments</u>

- Not in this environment, with a real sector it could be increasingly cluttered.

6. **Indicate how your focus on the DICE-turn-advisor countdown value affected your attention to aircraft-to-aircraft spacing.**

strongly reduced	1	4	2	3	2	not affected

<u>Comments</u>

- The spacing was always taken care of by DICE except if I was to have an overshoot then I would reduce the speeds of aircraft earlier than suggested.
- Once again if I reduced the a/c when I was prompted to do so, I felt my sequence would hold to the airport and did not recheck as often as I normally would.
- Concentrating on the countdown rates decreased my focus on aircraft inside the marker.

7. **Indicate how your focus on the DICE-turn-advisor countdown value affected your attention to the overall traffic picture.**

strongly reduced	0	4	3	4	1	not affected

<u>Comments</u>

- I did have to pay extreme attention to the speed indicators (more than I would normally) to ensure proper spacing.

- After learning the timing of each countdown DICE was a big help.
- Didn't watch the final inside the marker as closely as in manual mode.
- At first I was trying to pay too much attention to the turn advisor on downwind to base.

8. Relative to the final controller's job, indicate your reaction and feeling to having a computer suggest when a aircraft should be turned for spacing.

undesirable	0	0	1	6	5	desirable

Comments

- It is interesting to see how the computer agrees or disagrees with what headings I would use.

9. The speed reduction times indicated by the DICE speed-reduction advisor, as compared to the times you would have reduced aircraft speed for spacing on final...

strongly differed	0	0	3	7	2	closely agreed

Comments

- The DICE was probably more accurate than my own spacing.
- On 2 or 3 occasions I would have reduced aircraft on base.

10. Indicate how the DICE speed-reduction advisories (210 kts procedure) affected your workload, as a final controller, as compared to manual operation (210 kts procedure) with no computer aide.

increased	0	1	1	8	2	reduced

Comments

- I was always confident in proper spacing and speed due to DICE, therefore, I had a decrease in workload.
- Didn't really reduce it, because instead of looking at spacing and deciding when to reduce speed - I looked at DICE advisories and had to decide which was higher priority - then, if it was late reducing - I worried that spacing might be off.

11. Indicate how the DICE speed-reduction advisories (210 kts procedure) affected your <u>spacing</u> on final approach as compared to manual operation (210 kts procedure) with no computer aid.

less precise	0	0	3	3	6	more precise

Comments

- As precise as I have ever seen in air traffic control.
- Under a controlled environment, I would not be able to compete.
- HA! - HA!
- How about changing the heading above to "too precise". I'm not that good.

12. In terms of display clutter, the DICE-speed-reduction countdown value and suggested-speed value which are added to the data block, generated...

excessive clutter	0	2	1	3	6	no perceptible clutter

Comments

- Not in this simulation, in a real radar sector maybe.
- Flashing caused a bit more clutter - but necessary.

13. Relative to the time when aircraft speeds were to be reduced to 170 kts, the DICE speed-reduction advisories appeared in the data block at a time that was...

too early	0	2	9	1	0	too late

Comments

- The advisories appeared to give me ample time unless I had altered the scenario.
- In some cases the speed reduction advisory flashed prematurely (when a/c on an already assigned heading was given an approach clearance.

14. Indicate how your focus on the DICE-speed-reduction countdown value affected your attention to aircraft-to-aircraft spacing.

strongly reduced	1	5	2	4	0	not affected

Comments

- I was most likely to be too confident that the aircraft were separated.

15. Indicate how your focus on the DICE-speed-reduction countdown value affected your attention to the overall traffic picture.

strongly reduced	0	4	3	5	0	not affected

Comments

None

16. Relative to the final controller's job, indicate your reaction and feeling to having a computer suggest when aircraft should be reduced (from 210 kts) for spacing.

undesirable	0	0	1	6	5	desirable

Comments

- Based on personal experience it would be hard in a normal sector to spend that much time monitoring the data blocks effectively.

17. Relative to my normal state of alertness, awareness, and responsiveness, while controlling traffic, I feel my state in this session was...(If not normal, please indicate reason.)

below normal	0	0	7	4	1	above normal

Comments

- I was more alert to when to slow aircraft and turn them due to the printout nature of the DICE.
- Attention was directed to the a/c that was next on final and turning base, while a/c on final were not really being scanned.

18. Additional comments on performance or conditions, if any.

Comments

- Although concentrating on the countdown time took away from my scan inside the marker, I found that when I did scan the area, traffic was spaced well in most cases.
- I do not normally give 90 degree turns to final.
- Good aid.
- The DICE simulation was much easier to work than the manual simulation. It did reduce my attention of the spacing of the traffic because I was watching the countdown. This simulation was fine in a sterile situation.
- With the addition of a tower controller monitoring the final, this program could greatly reduce separation in the pattern on final approach. It's a good training aid also.

F.2.2.4. Centerline Slot Marker Format For 210 Knot Procedure

1. **Adapting to the use of the Centerline Slot Marker with the 210 kts procedure was...**

difficult	0	5	4	3	0	easy

<u>Comments</u>

- Still a very skill-oriented procedure, the final turn-ons were easier, however there was still great effort required to turn accurate base leg turns.
- I see where the slot marker could become beneficial, however adjusting to it was frustrating.
- I felt that I got better with practice and could do this on an everyday basis.

2. **Indicate how the Centerline Slot Marker (210 kts procedure) affected your workload, as a final controller, as compared to manual operation (210 kts procedure) with no computer aids.**

increased	0	5	1	6	0	reduced

<u>Comments</u>

- Increase in work due to the mental calculations involved with turns and closure rates.
- The slot marker initially is more of a hindrance than a help.
- The moving slot markers seem to distract me from concentrating on traffic inside the marker, however, it gave me a fairly consistent final and a good point to apply speed control.
- Required a great deal of concentration on slots and when to reduce the aircraft. I looked less at spacing between a/c and more on whether they hit the slot.
- Using the slot marker was harder than using the DICE, but easier than the manual system.

3. **In the normal case (when slot markers were not noticeably shifted to adjust for spacing errors) vectoring aircraft into their slot markers with the 210 kts procedure was...**

difficult	0	3	4	4	1	easy

<u>Comments</u>

- Vectoring to final spacing was the easiest aspect of the system.
- On one occasion I can remember the slot marker shift helping me out. The remainder of the time I felt behind.

4. **Indicate how often an extra effort was made to precisely center the aircraft in its slot marker.**

never	0	1	2	6	3	always

<u>Comments</u>

- Speed reductions were in order, or more precise turns were needed for the centering to occur.

5. **In terms of display clutter, the slot markers displayed on the extended runway centerline generated...**

excessive clutter	0	2	6	1	3	no perceptible clutter

<u>Comments</u>

- For this environment not any distraction.
- I do remember having to wait to read a callsign I had forgotten when I missed the slot marker in front.
- Not much of a problem on centerline.

6. **Indicate how your focus on the aircraft/slot-marker-position relationship affected your attention to aircraft-to-aircraft spacing.**

strongly reduced	1	6	1	3	1	not affected

Comments

- By using the system properly aircraft to aircraft spacing was assured more often.
- I noticed that I was less concerned with a/c inside the marker.
- I counted on the fact that if they were in the slot, they were spaced well. Only if I missed the slot (ahead or behind) did I scrutinize the spacing.
- As in the Dice system, I did not watch the traffic as close as I would have with the manual system.

7. Indicate how your focus on the aircraft/slot-marker-position relationship affected your attention to the overall traffic picture.

strongly reduced	1	5	1	5	0	not affected

Comments

- This type system really requires great attention to detail and focus.
- This is new, old controllers say they used to turn the ARTS off when they got busy. When it initially came out.

8. In spacing/sequencing aircraft on final, to what degree do you feel the slot markers provide useful information. (If useful, how?)

not useful	0	2	0	8	2	useful

Comments

- Spacing suggested was extremely accurate.
- I know when I miss a hole, now everybody else does.
- It gave a reference point to apply space adjustment.
- Gave indication of spacing.
- They give guidance as to correct spacing - especially good with heavy a/c.
- Once you get used to it you can go on to other duties after the a/c is positioned in the marker.
- Projection/looking ahead.

9. Having additional aids (such as turn advisories, vector advisories, or speed advisories) to help me deliver aircraft into their slot markers would be...(Please indicate preference, if any.)

unnecessary	2	1	2	3	4	desirable

Comments

- As I mentioned before possibly coupled with line segments.
- A turn advisory could initially help.
- Speed reductions.
- Heading and speed advisories would be useful.
- Too much to think about.
- Vectors to hit slot markers would definitely be an aid.
- Speed control would be very advantageous and maybe a mark for a normal base leg to final with mileage markers.

10. Determining which aircraft were supposed to go into which slot marker was...

difficult	0	0	1	0	11	easy

Comments

- Self-explanatory tags in the circles. No problem!
- It required a slightly greater effort to assure proper a/c in proper slot.

11. Relative to the final controller's job, indicate your reaction and feeling to having a computer suggest where an aircraft should be positioned on final.

undesirable	0	0	3	6	3	desirable

Comments

- With the sequence so obvious we agreed on all calls.
- Hard to say - would require more practice.
- It is desirable in a sterile situation.

12. Relative to my normal state of alertness, awareness, and responsiveness, while controlling traffic, I feel my state in this session was...

below normal	1	0	3	5	3	above normal

Comments

- With this system I am very alert and tend to even lean toward aggressiveness to achieve proper spacing and system success.

13. Additional comments on performance or conditions, if any.

Comments

- The 210 format is preferable to the 170 because it allows some flexibility.
- Problem became easier towards the end as I was more comfortable with how to control the traffic to hit the slots.

F.3. Task Load Index—Individual Subject Controller Results

F.3.1. TLX Description

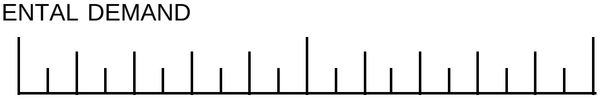
The primary questionnaire used to assess workload was the Task Load Index (TLX). The TLX is a multidimensional rating procedure that provides an overall workload score based on weighted averages.

At the completion of each run, the subject rates the experience during the run for each of six workload contributing factors on a scale consisting of 20 increments. The factors are mental demand (MD), physical demand (PD), temporal demand (TP), own performance satisfaction (OP), your effort required (ER), and frustration you experienced (FE). The rating sheet used for the evaluation is shown below.

Instruction: Circle the vertical graduation mark on ech scale that indicates your relative rating of the following six workload-contributing factors, as experienced in the task just performed.

FACTORS ARISING FROM TASK ITSELF

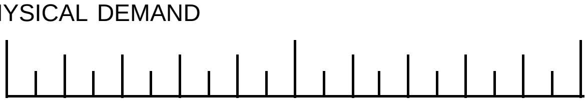
MENTAL DEMAND



Low High

How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

PHYSICAL DEMAND



Low High

How much physical activity was required (e.g. pushing, pulling, turning, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

TEMPORAL DEMAND

Low High

How much time pressure did you feel due to the rate or pace at which the tasks or task elements occured? Was the pace slow and leisurely or rapid and frantic?

FACTORS ARISING FROM YOUR INTERACTION WITH TASK

OWN PERFORMANCE SATISFACTION

Good Poor

How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

YOUR EFFORT REQUIRED

Low High

How hard did you have to work (mentally or physically) to accomplish your level of performance?

FRUSTRATION YOU EXPERIENCED

Low High

How insecure, discouraged, irritated, stressed and annoyed verses secure, gratified, content, relaxed and complacent did you feel during the task?

At the completion of all data runs, the subject is tasked with making "pair-wise" comparisons of the six different workload contributing factors by selecting the preference of a factor pair in each of 15 comparisons. The result of the pairwise comparisons is a "weight" representing the relative degree to which the subject feels that each factor has contributed to the workload of the task. The matrix used in making the pair-wise comparison is as follow.

Pair-Wise Comparison of Source-of-Workload Factors

Factor Pairs

Effort required	Own performance	Physical demand	Frustration experience	Mental demand	Physical demand
Temporal demand	Effort required	Physical demand	Temporal demand	Frustration experience	Mental demand
Own performance	Frustration experience	Temporal demand	Mental demand	Own performance	Mental demand
Physical demand	Own performance	Frustration experience	Effort required	Mental demand	Effort required
Temporal demand	Frustration experience	Own performance	Temporal demand	Effort required	Physical demand

F.3.2. Individual Subject Controller Results

The graphed data for each subject/data run is provided in figure F1. The width of the bars represent the weight as determined by the pairwise comparison; the maximum width for any of the factors is five increments. The height of each bar is the result of the ratings performed at the end of each run. Note that on all graphs only five of the six workload factors are represented; this is because all of the subjects felt that physical demand (PD) was less of a workload contributing factor than each of the other five factors in their pairwise comparisons. For greater detail on the TLX refer to reference 18.

F.4. Rating and Ordering Test Formats—Questionnaire Only

Subjects rated and ordered the test formats on this questionnaire with respect to three specific criteria: workload or effort required, ease of adapting to or learning to use the format, and the degree of help or benefit in spacing aircraft on final. Only the instructions and form are given. The responses are presented in section 5.5.3.

Based on your experience and judgment as a controller, please rate and order the formats that you were tested with on the scales below, with respect to each of the following three criteria:

1. Workload or effort required to use the format.
2. Ease of adapting to or learning to use the format.
3. Amount of help or benefit in spacing traffic on final.

With respect to the criteria being evaluated, place the format(s) symbol at each end of the scale which you feel best fit(s) the endpoint description. Arrange the remaining formats along the scale to reflect your evaluation of the formats with respect to your endpoint choices. Note that you can evaluate two or more formats equally, either at the endpoints or any position on the scale, by placing their symbols in the same scale location. This is not an absolute rating relative to some ideal format, what we are after is your comparative rating of the tested formats with respect to each other.

<u>Example for discussion with coordinator.</u>
For instance, let us say 8 formats have been tested: A, B, C, D, E, F, G, and H. Assume they are being rated and ordered on the workload criteria and format C has the least workload, while format E requires the most workload. If you feel the formats are fairly evenly spaced with respect to workload, the scale would look something like:

most workload											least workload
	E		G	H		B D		F	A	C	

On the other hand, if you felt one format stood out as having a much higher workload relative to all the other formats, the scale would look something like:

most workload											least workload
	E						G H	B D	F	A C	

The symbols to be used on the following scales are:

M1 - Manual or no automation aid (170 kts final turn)
M2 - Manual or no automation aid (210 kts final turn)
G1 - Graphic position-to-turn advisor (170 kts final turn)
G2 - Graphic with both position-to-turn and position-to-speed reduction advisories (210 kts final turn)
S1 - Centerline slot marker (170 kts final turn)
S2 - Centerline slot marker (210 kts final turn)
D1 - DICE time-to-turn advisor (170 kts final turn)
D2 - DICE with both time-to-turn and time-to-speed reduction advisories (210 kts final turn)

1. **Workload or effort required to use the format.**

most workload											least workload

2. **Ease of adapting to or learning to use the format.**

hardest to adapt | | | | | | | | | | | easiest to adapt

3. **The degree of help or benefit in spacing aircraft on final.**

least helpful | | | | | | | | | | | most helpful

F.5. Comparison of Format Questionnaires for 170- and 210-Knot Pattern-Speed Procedures—Subject Evaluation and Comments

The questionnaire and results of the comparison between the 170- and the 210-knot pattern-speed procedures, for each format, are presented in this section. Each comparison includes the total number of responses for each of the five positions along the scale, as well as all subject comments.

1. **For the manual cases with no automation aids, evaluate the level of difficulty associated with spacing aircraft on final using *a speed of 210 kts and reducing after the turn-to-final as compared to the constant 170 kts before the turn-to-final.***

much harder						much easier
	0	2	1	6	3	

Comments

- Same speeds manually has no guesswork, at 210 kts there is a bit of an increase.
- Speed can be used to cover up a late turn-on.
- When you tie someone down to one speed, you take a valuable tool from a controller.
- Due only to the fact this is a procedure not practiced in the field. It would be otherwise to controllers who constantly do this.

2. **For the graphic advisor cases, evaluate the level of difficulty associated with spacing aircraft on final using**
a speed of 210 kts for the turn-to-final together with both the position-to-turn and the position-to-reduce speed advisories as compared to
a speed of 170 kts for the turn-to-final with only the position-to-turn advisory

much harder						much easier
	0	3	2	4	3	

Comments

- Graphic advisor with speed reduction at 210 kts keeps things moving expeditiously, safely, and more accurately than any of the other systems.

3. **For the centerline slot marker cases, evaluate the level of difficulty associated with vectoring aircraft to their slots using *a speed of 210 kts and reducing after the turn-to-final as compared to a constant 170 kts before the turn-to-final.***

much harder						much easier
	0	0	0	7	5	

Comments

- Difficult system either way, slightly easier with 210 kt format.

4. **For the DICE countdown advisor cases, evaluate the level of difficulty associated with spacing aircraft on final using**
a speed of 210 kts for the turn-to-final together with both the time-to-turn and the time-to-reduce speed advisories as compared to
a speed of 170 kts for the turn-to-final with only the time-to-turn advisory

unrealistic	1	2	3	4	2	realistic

Comments

- This system works well either way, a slight edge to reduce time but overall a steady system which could work well in select facilities but not all.
- In both the graphic and dice, the simulation ran easier at 170 kts because the closure rates on the turn indicators was slower, however, if you were ever late it was easier to recover in the 210 kt scenario.
- Of all the formats the DICE is much superior to the others.

F.6. Final Debriefing Questionnaire - Subject Evaluation and Comments

The Final Debriefing Questionnaire contains general questions about the simulation and training. The questionnaire and the total number of responses for each of the five positions along the graphic scale are included, as well as all controller comments.

1. Overall, the simulation was...

unrealistic	0	0	2	7	3	realistic

Comments

- Normally a controller will work more than depicted but for this purpose of evaluation it was fine.
- Very good as far as simulation–would be more realistic with flight progress strips but did not effect performance.
- Missed various types of a/c.
- Very sterile operation. You need to possibly put some distractions in the problem.

2. The suitability of the simulated radar display to perform the required control task was...(Please identify any deficiencies.)

seriously deficient	0	0	1	3	8	adequate

Comments

- I normally don't work with computer generated scopes and it was a pleasure having clarity of the scope.
- Controllers are used to having the capability of adjusting their scope to personal specs. - except for that it was OK.
- You could keep track of where the a/c was, but there was no beacon code slash or primary return.
- More mistakes (pilots) in real life, but all in all a good simulation.

3. Indicate how the physical environment, during the test, influenced your test performance.

degraded	0	1	8	1	2	improved

Comments

- No real distraction and the lighting was the same, no influence felt.
- Conducive to concentrating more quiet than ORF IFR radar (room).
- Ocular LIGHT a bit distracting.

4. The voice communications with the pseudo pilots were...(Please identify any deficiencies.)

unrealistic	0	4	3	1	4	realistic

Comments

- Because of the basic nature of the simulation I had no problems with them, but they could have been more attentive to respond.

- To make it more realistic once a pilot starts talking they should not stop until their transmission is complete.
- When instructions were issued to wrong aircraft...pilot didn't question instructions.
- Timing too quick not many request to repeat.
- Voice quality of the pilots sounded like martians. The pilots made very few errors and acknowledged all transmissions quickly.

5. The simulated aircraft flight paths and maneuvers were...(Please identify any deficiencies.)

unrealistic	0	2	0	4	6	realistic

Comments

- Turn to final ratio appeared slower at first, I guess due to the elevation of the terrain.
- A bit too ideal, but fine to work with.
- A DC-8 would have a tough time getting down from the SE and NE fixes. Some a/c were slowing to 110 kts 2 - 3 miles out. High performance a/c don't fly that slow that far out.
- Speeds inside marker seemed to drop off fast.

6. The traffic density in the simulation as compared to that expected in a high density, single runway terminal operation in IMC was...

not representative	0	2	2	4	4	representative

Comments

- I don't feel qualified to say, however, it was moderate to busy traffic in my opinion.
- Normally there would be a few lower performance a/c in the sequence.
- Not used to this type of traffic.
- With the exception that all a/c in the simulation were a/c without a mix of civilian smaller aircraft.
- Did not work in a facility like Denver.
- You could not run that type of traffic on a single runway with any departures to go.

7. The interaction and coordination with the feeder controller was...(Please identify any deficiencies.)

unrealistic	0	2	2	6	2	realistic

Comments

- The only thing lacking would be maybe an interphone system.
- There was very little coordination.
- Didn't use as much as would be expected.

8. The initial briefing and training on Denver airspace/procedures and the simulation interface necessary to do a representative job of controlling traffic was...(Please identify any deficiencies.)

seriously deficient	0	0	1	1	10	adequate

Comments

- No problems.
- I would like to have the ILS 26L approach plate next to me and look at the profile descent (STAR).

9. The briefing I received describing each format prior to the practice runs was...(Please indicate any deficiencies.)

seriously deficient	0	0	0	0	12	adequate

Comments

- Very informative and to the point.

10. The training I received during the format practice run before each test session was...(Please identify any deficiencies.)

seriously deficient	0	0	0	0	12	adequate

Comments

- I was comfortable after every practice run.

11. The test sessions were conducted in a controlled, serious and professional manner.

disagree	0	0	0	0	12	agree

Comments

- Very professional.
- Very professional group; it was my pleasure to be S-2.
- Everyone was amiable and professional.
- Too starchy

12. In the automated aid formats tested, the arrival aircraft's tabular sequence list presented on the right of the display was...(If useful, how was it used?)

not useful	7	2	0	1	2	useful

Comments

- The whole time I was involved in the simulation I never used it.
- I never used the tab list or felt a need to use it.
- I occasionally used it to confirm a/c sequence.
- Only necessary in maybe one - didn't use it much if at all in others.
- Annoying, distracting. I disagreed with the computer sequence at the time and it would mess up the program if I did not adhere to the computer program.
- In almost all cases the approach sequence was obvious.
- I relied on it for the sequence at all times and adjusted the pattern to comply with it.

13. List any factors not addressed above that either positively or negatively affected your performance.

- A minor detail was some background light reflecting off the radar display.
- Enjoyed!!

F.7. Researcher Topic Guide for Final Verbal Debriefing

The verbal debriefing was the final opportunity to extract the subjects thoughts and opinions in several areas including the formats, the simulation, and test procedures. The subject guide used for the verbal debriefing is as follows:

Do you have any suggestions for improvements or other comments relative to the following:

1) Centerline slot marker

2) Graphic turn advisor

3) Graphic speed reduction advisor

4) DICE time-to-turn advisor

5) DICE time-to-speed reduction advisor

6) Test procedures or test facility

Was any information missing that you think would be useful?

Did any of the information cause clutter or distractions? How about fixation? How would you suggest solving this problem (delete information, move information somewhere else, make information appear on request only)?

What is your reaction to the DICE or Graphic early warning that the automation anticipates a localizer overshoot, to maintain separation, if the current heading and speed is maintained?

Do you feel that you had enough time to develop proficiency in using the system?

Do you feel that if you were using the system daily, you might evolve a different way of using it than you did in the short period of the testing?

Did the system change the mental tasks involved in controlling traffic? How?

Do you feel that an automated advisory system will create any special problems with controller training or proficiency? If so, explain.

Do you feel that an automated aid will be beneficial to:

1) Reducing workload?

2) Spacing precision?

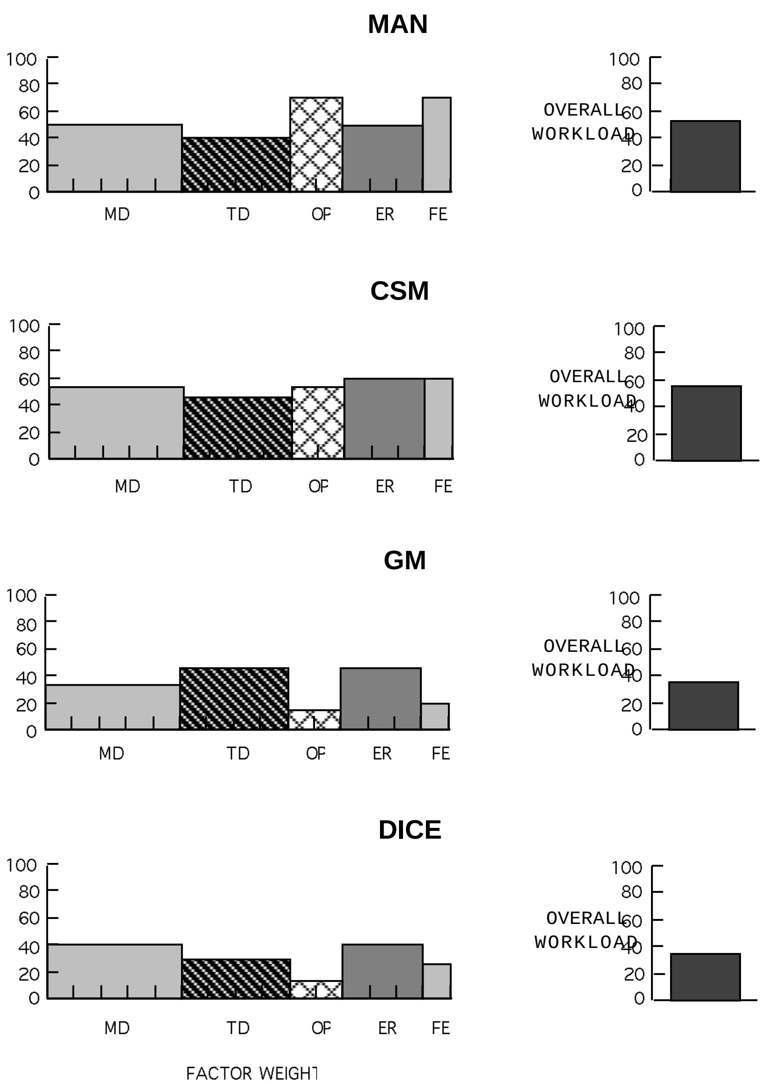
Does the reduction from 210 to 170 kts after the turn-to-final approximate the final approach procedure used at your facility? Explain.

Given the traffic rate during the test runs, was a 210 kts pattern speed with speed reduction to 170 after the final turn acceptable to manage the final traffic?

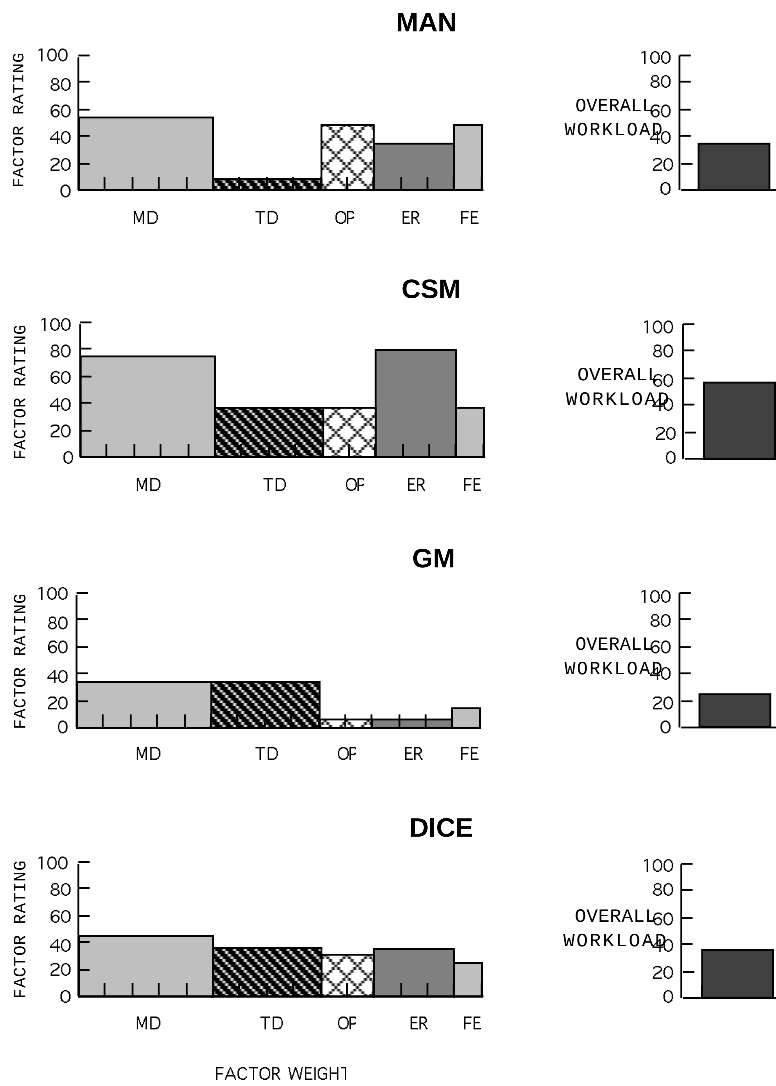
Do you have any thoughts, opinions, or suggestions that were not previously covered?

Subject 1

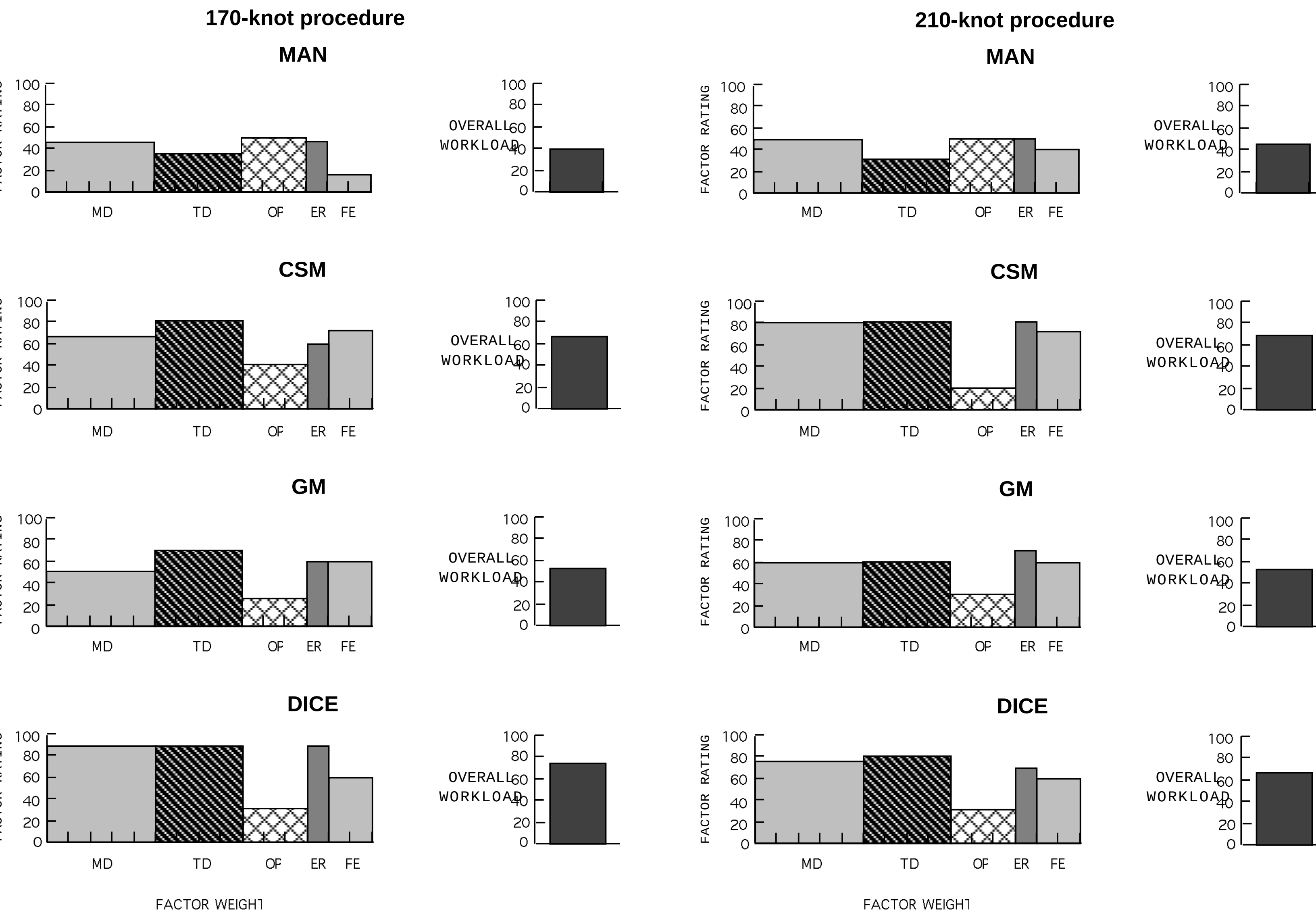
170-knot procedure



210-knot procedure

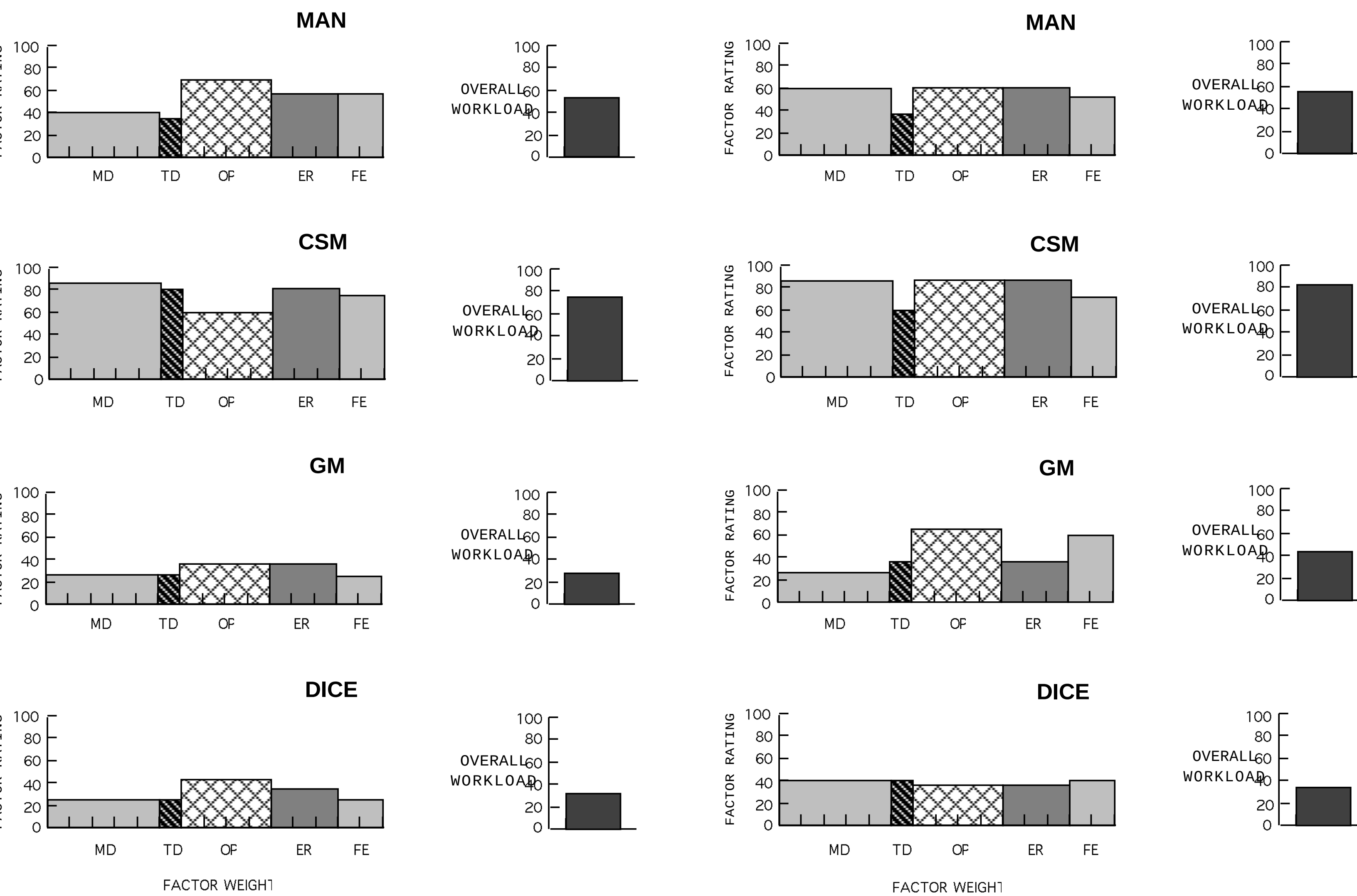


Subject 2


170-knot procedure
210-knot procedure
MAN
CSM
GM
DICE
FACTOR RATING
OVERALL
WORKLOAD
100
80
60
40
20
0
MD
TD
OP
ER
FE
FACTOR WEIGHT

Subject 3

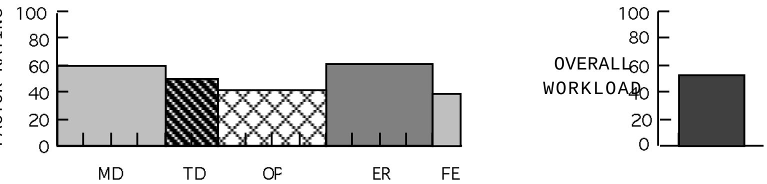
170-knot procedure **210-knot procedure**



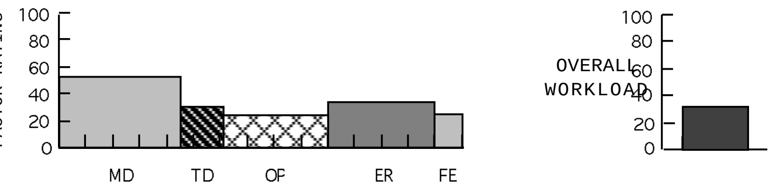
Subject 4

170-knot procedure

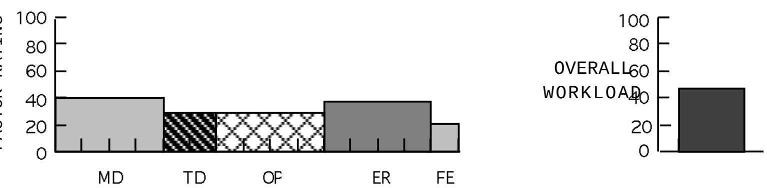
MAN



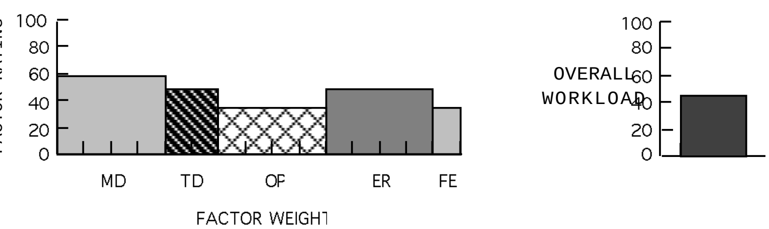
CSM



GM

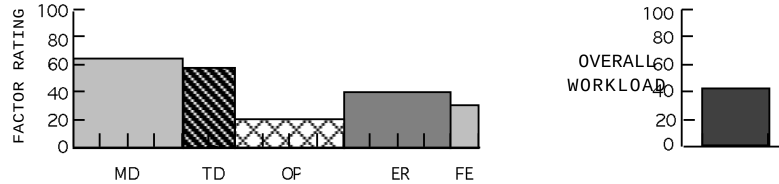


DICE

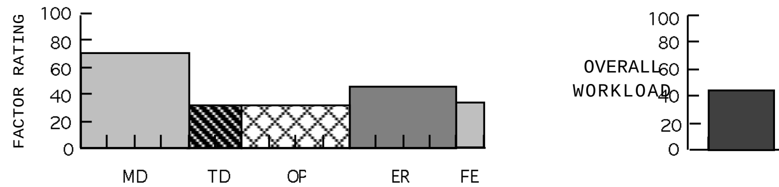


210-knot procedure

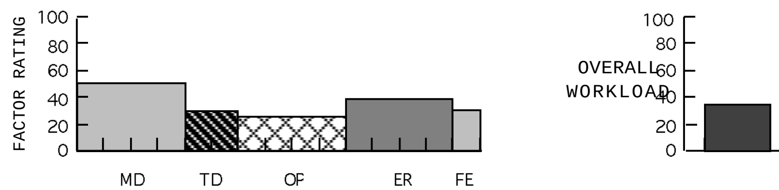
MAN



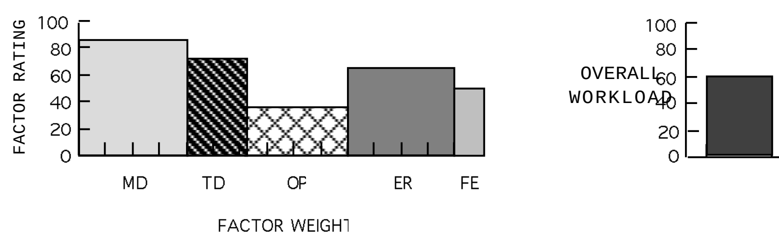
CSM



GM



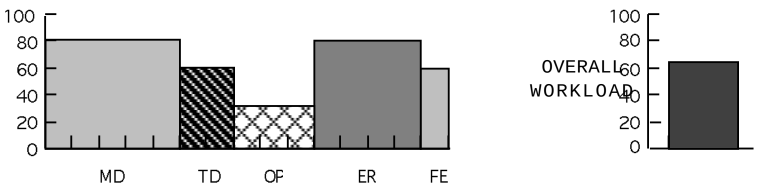
DICE



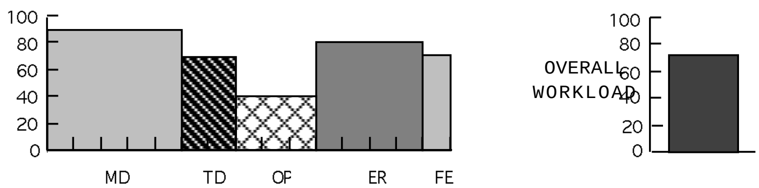
Subject 5

170-knot procedure

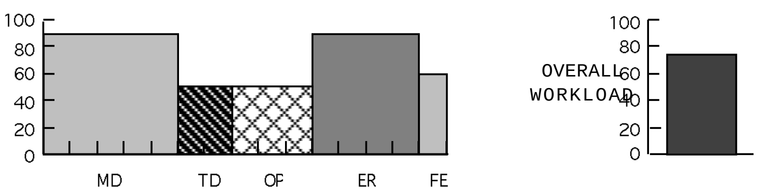
MAN



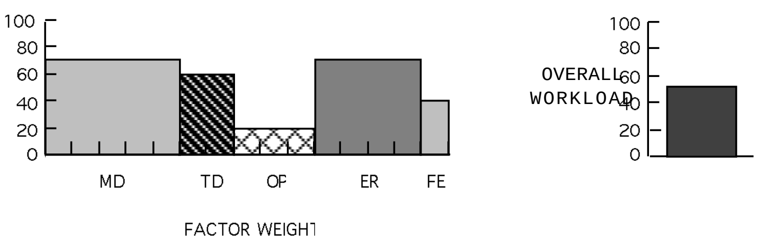
CSM



GM

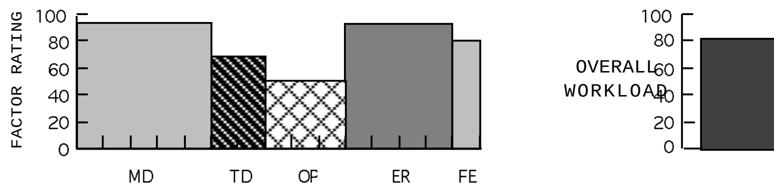


DICE

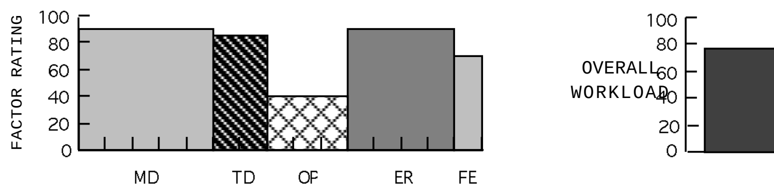


210-knot procedure

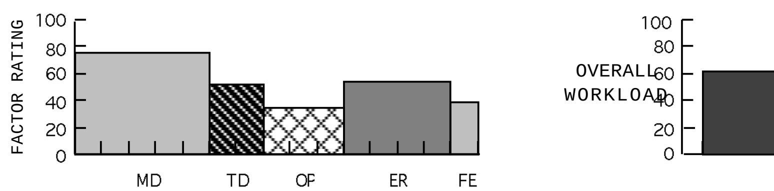
MAN



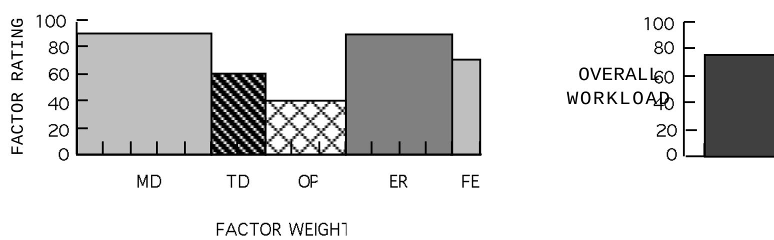
CSM



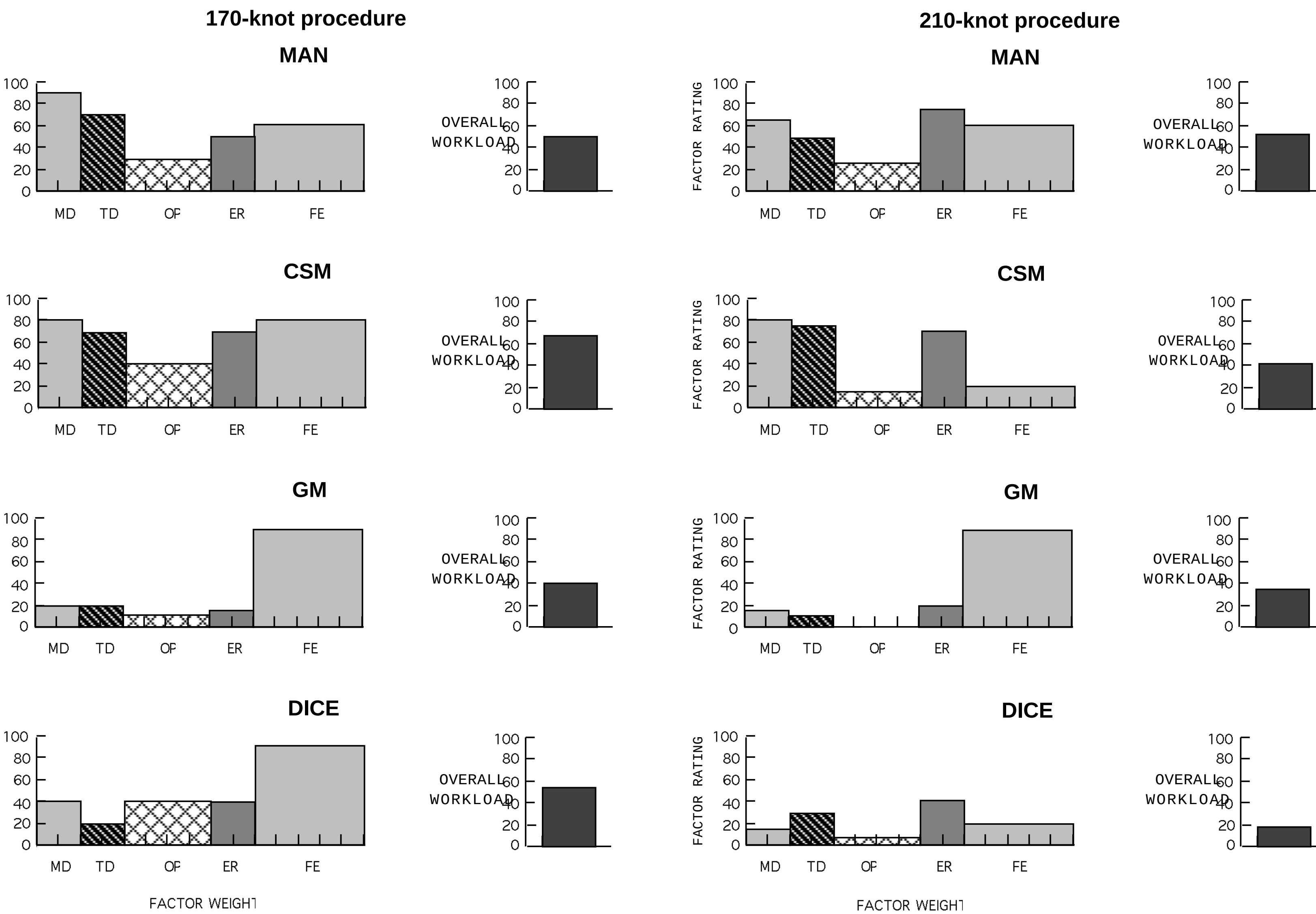
GM



DICE

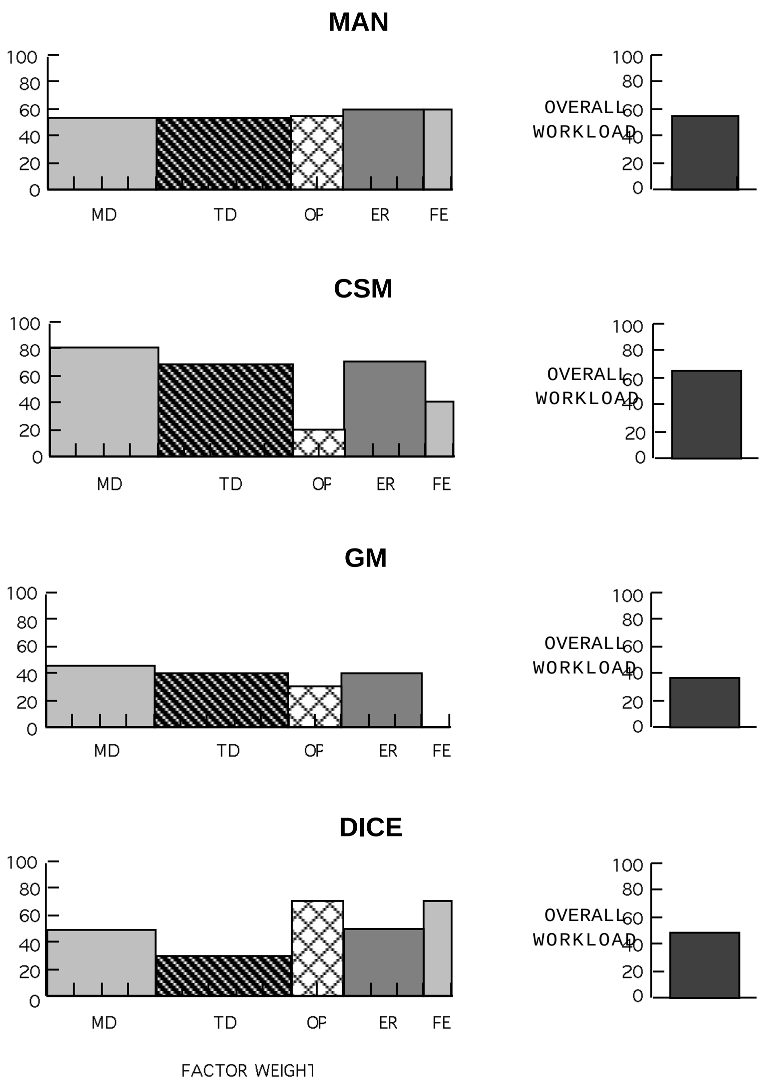


Subject 6

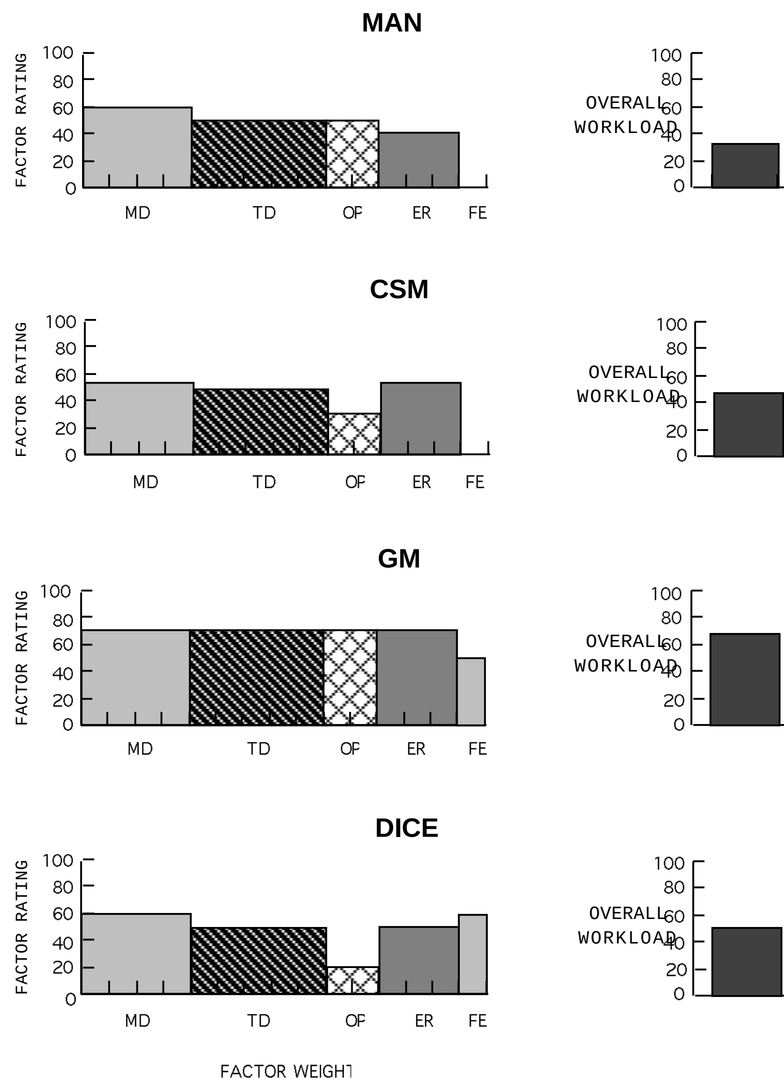

170-knot procedure
210-knot procedure
MAN
CSM
GM
DICE
FACTOR RATING
OVERALL WORKLOAD
MD
TD
OP
ER
FE
FACTOR WEIGHT

Subject 7

170-knot procedure



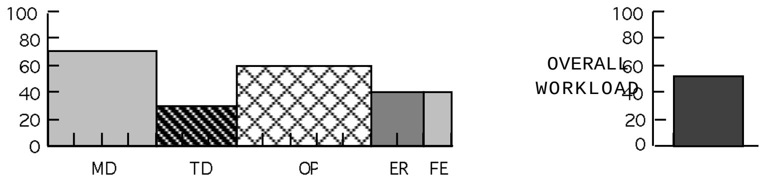
210-knot procedure



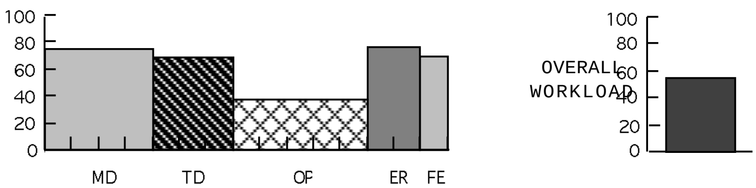
Subject 8

170-knot procedure

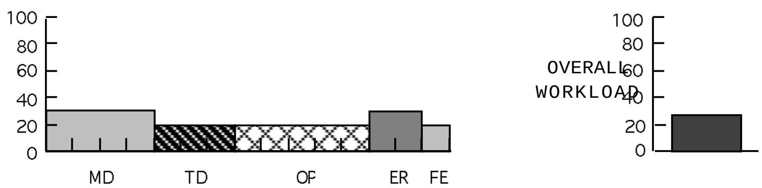
MAN



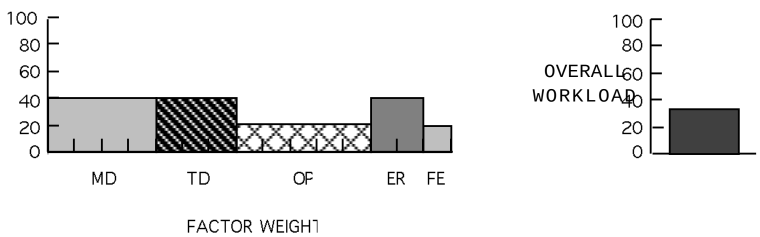
CSM



GM

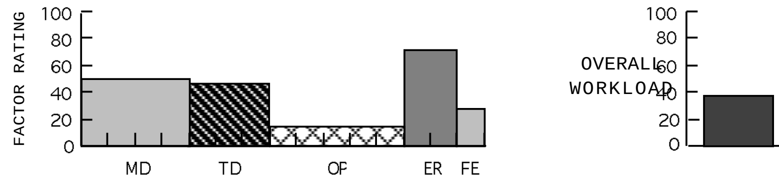


DICE

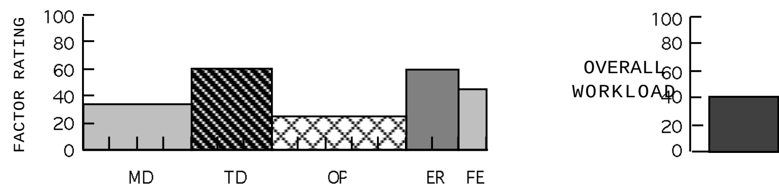


210-knot procedure

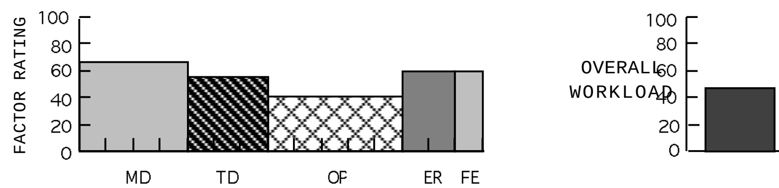
MAN



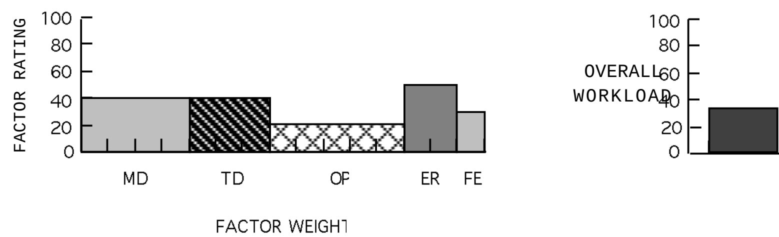
CSM



GM



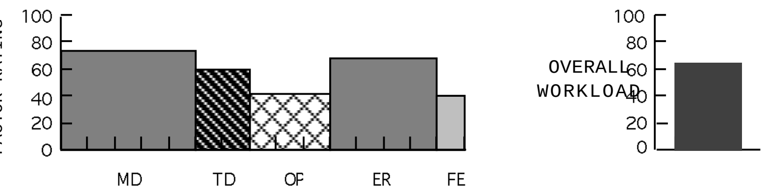
DICE



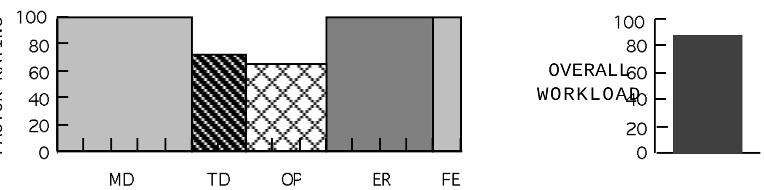
Subject 9

170-knot procedure

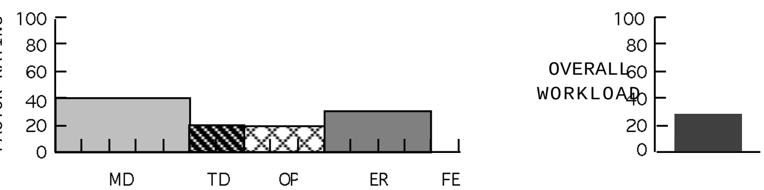
MAN



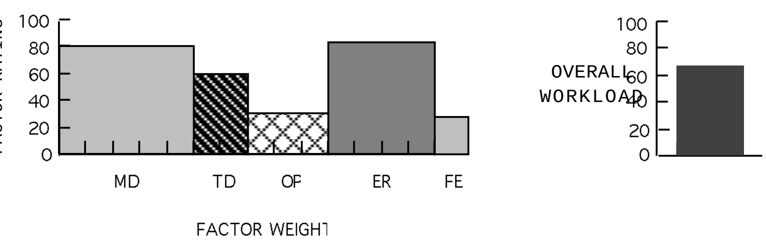
CSM



GM

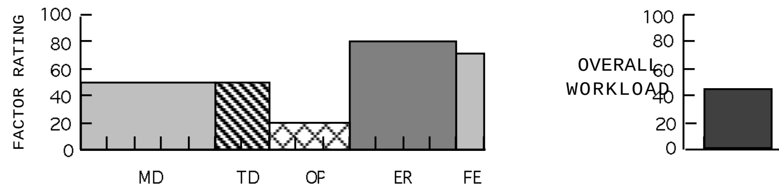


DICE

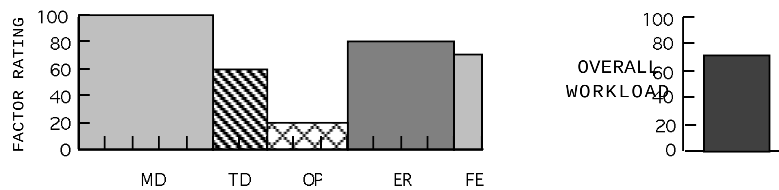


210-knot procedure

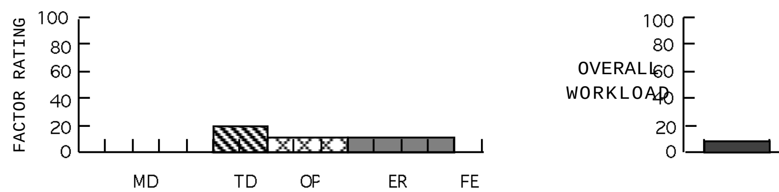
MAN



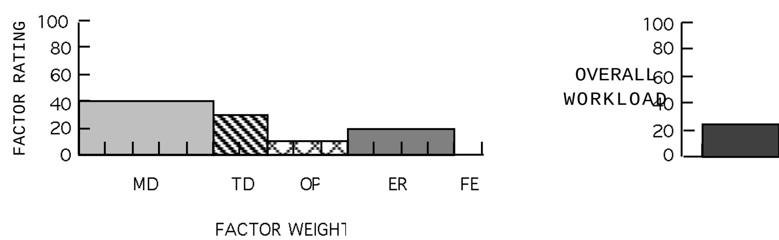
CSM



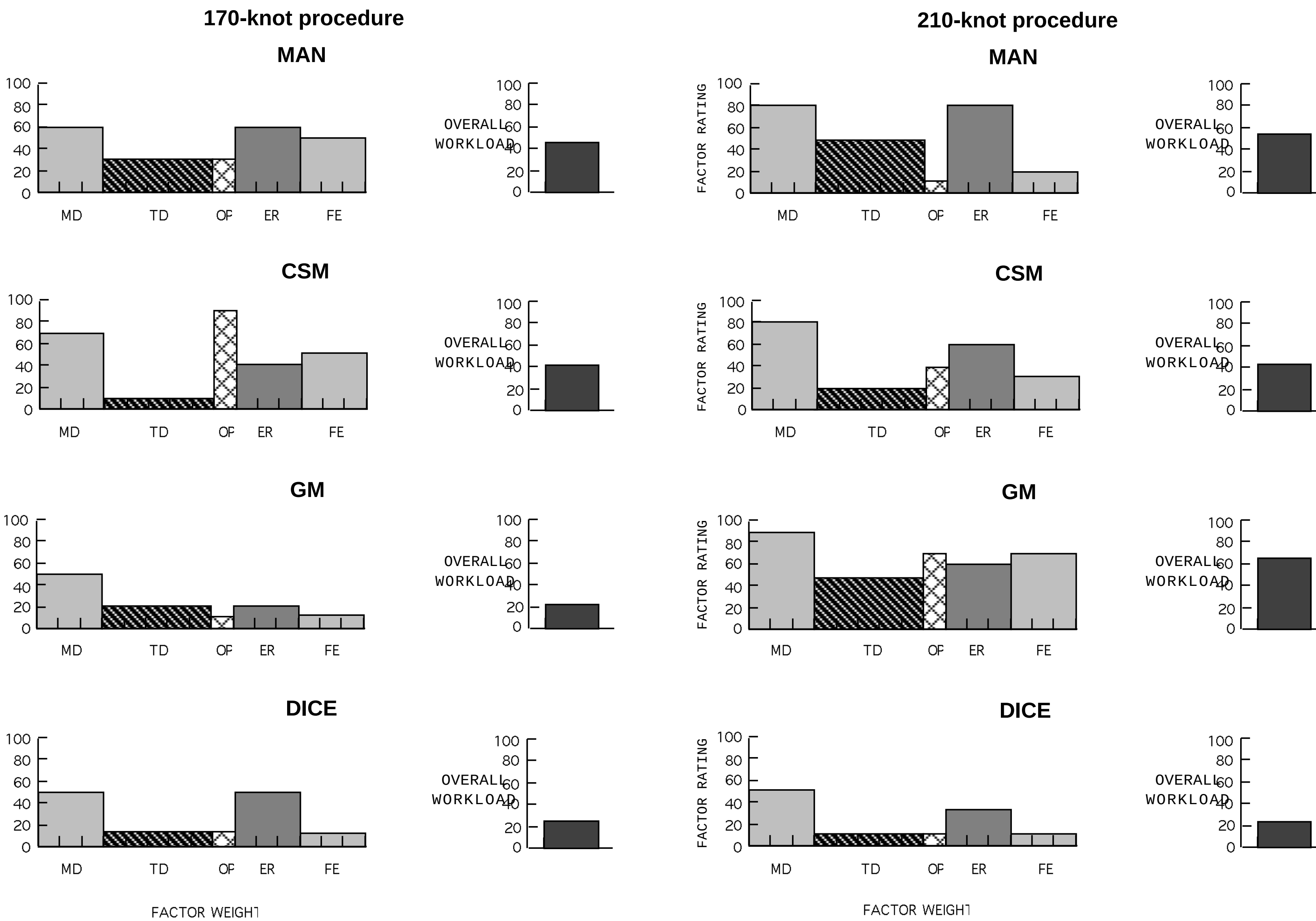
GM



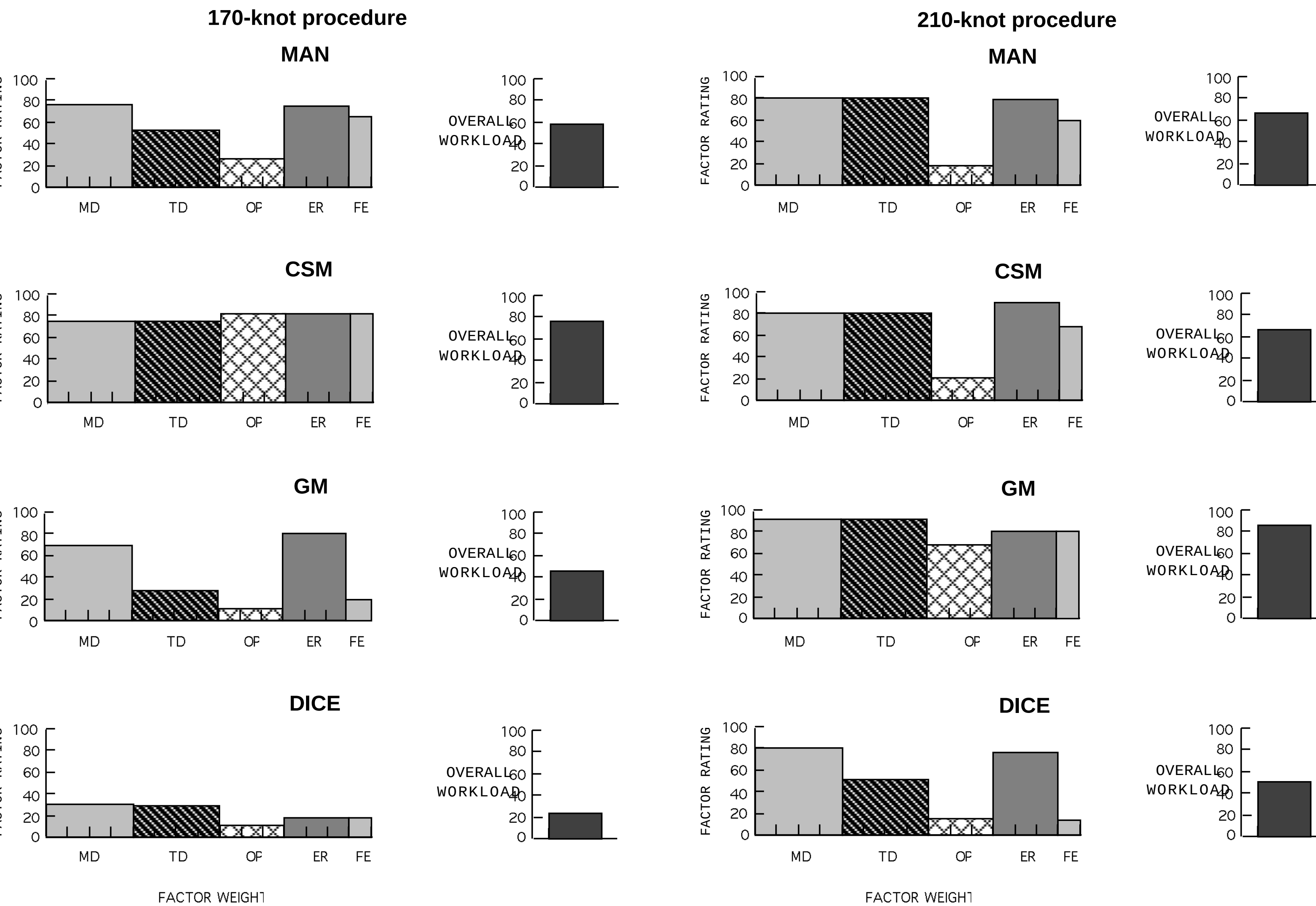
DICE



Subject 10


170-knot procedure
210-knot procedure
MAN
CSM
GM
DICE
MD
TD
OP
ER
FE
OVERALL
WORKLOAD
FACTOR RATING
FACTOR WEIGHT
0
20
40
60
80
100

Subject 11


170-knot procedure
210-knot procedure
MAN
CSM
GM
DICE
FACTOR RATING
OVERALL WORKLOAD
MD
TD
OP
ER
FE
0
20
40
60
80
100
FACTOR WEIGHT

Subject 12

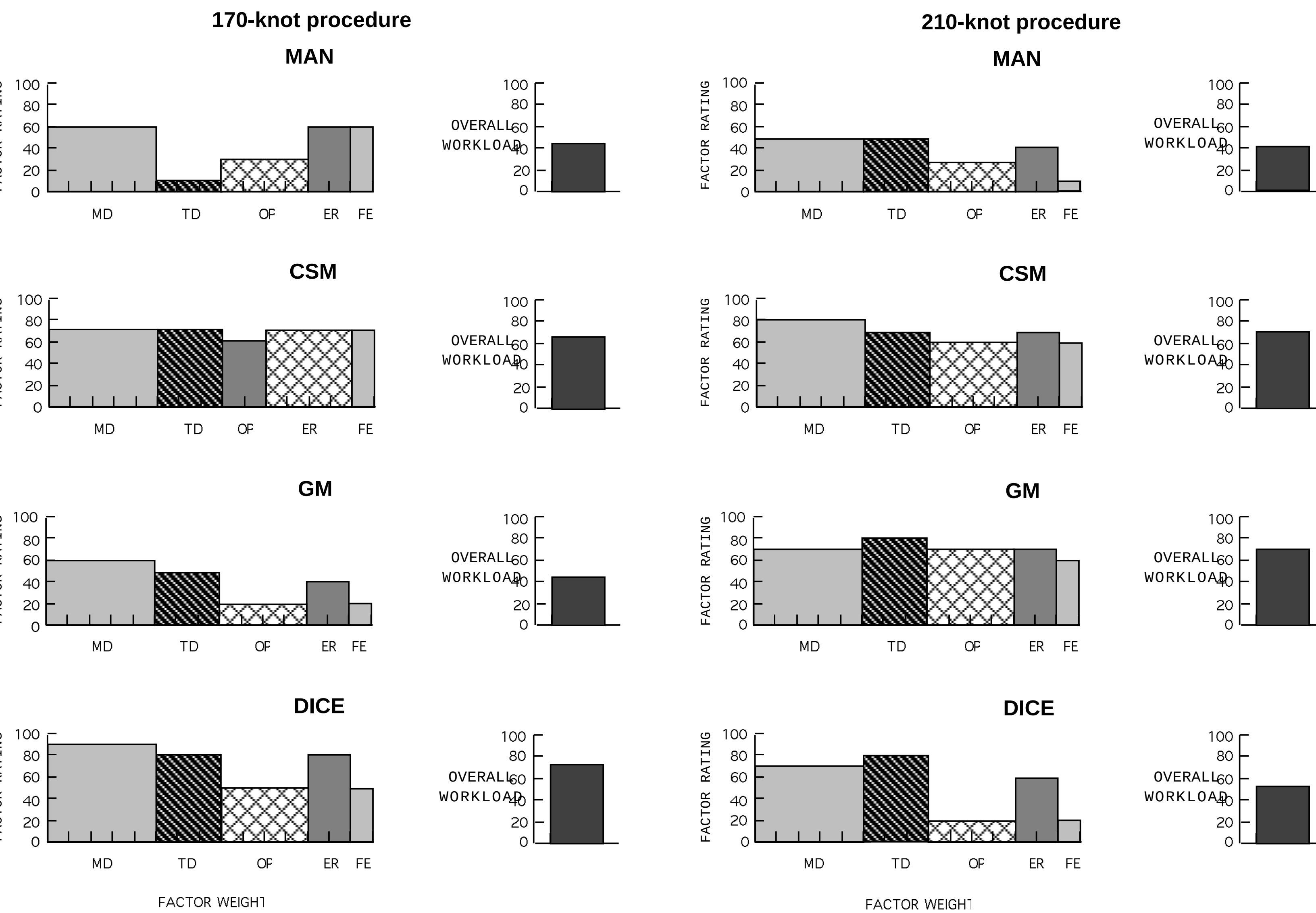

170-knot procedure
210-knot procedure
MAN
CSM
GM
DICE
FACTOR RATING
OVERALL WORKLOAD
MD
TD
OP
ER
FE
FACTOR WEIGHT

Table 1. Approximate Schedule for Subject Controller

[Asterisk and bold run number denote data run (1 hr and 10 min)]

Tuesday—170 (or 210) knots	
7:45	Conference room briefing (airspace, procedures, etc.)
8:30	Equipment introduction, discussion, and oculometer calibration
9:15	Manual practice run (run 1)
10:15	Break
*10:35	Manual baseline data run **(run 2)**
11:45	Session questionnaire
12:00	Lunch
12:50	Graphic, centerline slot marker, or DICE format explanation, familiarization run (run 3)
1:50	Break
*2:10	Graphic, centerline slot marker, or DICE format data run **(run 4)**
3:20	Session quesionnaire
Wednesday—170 (or 210) knots	
8:15	Centerline slot marker, DICE, or graphic format explanation, familiarization run (run 5)
9:15	Break
*9:30	Centerline slot marker, DICE, or graphic format data run **(run 6)**
10:40	Session questionnaire
11:00	Lunch
12:00	DICE, graphic, or centerline slot marker format explanation, familiarization run (run 7)
*1:00	Break
1:15	DICE, graphic, or centerline slot marker format data run **(run 8)**
*2:25	Session questionnaire
2:45	170- or 210-knot questionnaire
Thursday—210 (or 170) knots	
8:15	Manual practice run (run 9)
9:15	Break
*9:30	Manual baseline data run **(run 10)**
10:40	Session questionnaire
11:00	Lunch
12:00	Graphic, centerline slot marker, or DICE format explanation, familiarization run (run 11)
1:00	Break
*1:15	Graphic, centerline slot marker, or DICE format data run **(run 12)**
2:25	Session questionnaire
Friday—210 (or 170) knots	
8:15	Centerline slot marker, DICE, or graphic format explanation, familiarization run (run 13)
9:15	Break
*9:30	Centerline slot marker, DICE, or graphice format data run **(run 14)**
10:40	Session questionnaire
11:00	Lunch
12:00	DICE, graphic, or centerline slot marker format explanation, familiarization run (run 15)
1:00	Break
*1:15	DICE, graphic, or centerline slot marker format data run **(run 16)**
2:25	Session questionnaire
2:45	210- or 170-knot questionnaire
3:15	Final questionnaire, discussion, and debriefing
5:00	Conclusion

Table 2. FASA Format Traffice Samples

(a) 170-knot pattern-speed procedure

Run type	Record[a]	Sample	Start time, sec	Stop time, sec	Duration
Practice	17-8	423EHR	5 416	9 016	1 hr
Data	17-2	421GHR	3 632	7 832	1 hr 10 min
Data	17-3	422FHR	3 632	7 832	1 hr 10 min
Data	17-4	421GHR	7 284	11 484	1 hr 10 min
Data	17-5	422FHR	7 236	11 436	1 hr 10 min
Data	17-6	421GHR	10 868	15 068	1 hr 10 min
Data	17-7	422FHR	10 820	15 020	1 hr 10 min

[a]In record number, 17 indicates 170 knots.

(b) 210-knot pattern-speed procedure

Run type	Record[a]	Sample	Start time, sec	Stop time, sec	Duration
Practice	21-8	3E	5 242	9 024	1 hr
Data	21-2	1G	3 620	7 820	1 hr 10 min
Data	21-3	2F	3 644	7 844	1 hr 10 min
Data	21-4	1G	7 224	11 424	1 hr 10 min
Data	21-5	2F	7 284	11 484	1 hr 10 min
Data	21-6	1G	10 836	15 036	1 hr 10 min
Data	21-7	2F	10 816	15 016	1 hr 10 min

[a]In record number, 21 indicates 210 knots.

Table 3. FASA Format Study Test Sequence

[Subject numbers are in original test order and do not correspond to subject numbers used to indicate subject performance; even run numbers denote experimental data runs, whereas odd numbers (not shown denote controller practice run; in record numbers, 17 and 21 denote 170- and 210-knot pattern-speed procedures; respectively.]

Subject	170 (or 210) knots				210 (or 170) knots			
	Run 2	Run 4	Run 6	Run 8	Run 10	Run 12	Run 14	Run 16
1	MAN, R17-2	GM, R17-3	DICE, R17-4	CSM, R17-5	MAN, R21-2	DICE, R21-3	CSM, R21-4	GM, R21-5
2	MAN, R21-3	CSM, R21-4	DICE, R21-5	GM, R21-6	MAN, R17-3	DICE, R17-4	GM, R17-5	CSM, R17-6
3	MAN, R21-4	CSM, R21-5	GM, R21-6	DICE, R21-7	MAN, R17-4	GM, R17-5	CSM, R17-6	DICE, R17-7

References

1. Erzberger, Heinz: *CTAS: Computer Intelligence for Air Traffic Control in the Terminal Area.* NASA TM-103959, 1992.

2. Erzberger, Heinz; and Nedell, William: *Design of Automated System for Management of Arrival Traffic.* NASA TM-102201, 1989.

3. Davis, Thomas J.; Erzberger, Heinz; and Bergeron, Hugh: *Design of a Final Approach Spacing Tool for TRACON Air Traffic Control.* NASA TM-102229, 1989.

4. Mundra, Anand D.: *New Display Aid for Controllers Could Improve Airport Traffic Capacity. A New Automation Aid to Air Traffic Controllers for Improving Airport Capacity.* ICAO Bulletin, vol. 44, Sept. 1989, pp. 37–38.

5. Holland, F. C.; and Garceau, T. V.: *Genealogy of Terminal ATC Automation.* M70-9, Revis. 2, MITRE Corp., Mar. 1974.

6. Credeur, Leonard; and Capron, William R.: *Simulation Evaluation of TIMER, a Time-Based, Terminal Air Traffic, Flow-Management Concept.* NASA TP-2870, 1989.

7. Benoît, André; Swierstra, Sip; and De Wispelaere, René: Next Generation of Control Techniques in Advanced TMA. *Efficient Conduct of Individual Flights and Air Traffic or Optimum Utilization of Modern Technology for the Overall Benefit of Civil and Military Airspace Users*, AGARD-CP-410, Dec. 1986, pp. 55E-1–55E-15.

8. Völckers, U.: Computer Assisted Arrival Sequencing and Scheduling With the COMPAS System. *Efficient Conduct of Individual Flights and Air Traffic or Optimum Utilization of Modern Technology for the Overall Benefit of Civil and Military Airspace Users*, AGARD-CP-410, Dec. 1986, pp. 54-1–54-11.

9. Völckers, Uwe; and Schenk, Hans-Dieter: Operational Experience With the Computer Oriented Metering Planning and Advisory System (COMPAS) at Frankfurt, Germany. AIAA-89-3627, 1989.

10. Andrews, John W.; and Welch, Jerry D.: The Challenge of Terminal Air Traffic Control Automation. *34th Annual Air Traffic Control Association Conference Proceedings—Fall 1989*, 1989, pp. 226–232.

11. Credeur, Leonard; Houck, Jacob A.; Capron, William R.; and Lohr, Gary W.: *Delivery Performance of Conventional Aircraft by Terminal-Area, Time-Based Air Traffic Control—A Real-Time Simulation Evaluation.* NASA TP-2978, 1990.

12. Chi, Zhihang: *An Adaptive Final Approach Spacing Advisory System: Modeling, Analysis and Simulation.* Flight Transp. Lab. Rep. R 91-3, MIT, May 1991.

13. Petre, Eric: *Time Based Air Traffic Control in an Extended Terminal Area—A Survey of Such Systems.* EUROCONTROL Div. E1 Doc. 912009, June 1991.

14. Wilkinson, E. T.: *Proof of Concept Trial of the Predictive Approach Control Tactical Advisor System (PACTAS).* Project PBB 2.13.2, AD4 Memo. 91/02/01, British R. Signals & Radar Est., July 1991.

15. Davis, Thomas J.; Erzberger, Heinz; Green, Steven M.; and Nedell, William: Design and Evaluation of an Air Traffic Control Final Approach Spacing Tool. *J. Guid., Control & Dyn.*, vol. 14, no. 4, July–Aug. 1991, pp. 848–854.

16. Anderson, Robert H.: Upgrading the New York Tracon Automation System. *34th Annual Air Traffic Control Association Conference Proceedings—Fall 1989*, 1989, pp. 429–435.

17. Kaylor, Jack T.; Simmons, Harold I.; Naftel, Patricia B.; Houck, Jacob A.; and Grove, Randall D.: *The Mission Oriented Terminal Area Simulation Facility.* NASA TM-87621, 1985.

18. Harris, Randall L., Sr.; Glover, Bobby J.; and Spady, Amos A., Jr. (Appendix A by Daniel W. Burdette): *Analytical Techniques of Pilot Scanning Behavior and Their Application.* NASA TP-2525, 1986.

19. *Air Traffic Control.* 7110.65F, FAA, Sept. 1989.

20. Winer, B. J.; Brown, Donald R.; and Michels, Kenneth M.: *Statistical Principles in Experimental Design*, Third ed. McGraw-Hill, Inc., 1991.

21. Hart, Sandra G.; and Staveland, Lowell E.: Development of NASA-TLX (Task Loading Index): Results of Empirical and Theoretical Research. *Human Mental Workload*, Peter A. Hancock and Najmedin Meshkati, eds., North Holland Press, 1988, pp. 239–250.

22. Crawford, D. J.; Burdette, D. W.; and Capron, W. R.: *Techniques Used for the Analysis of Oculometer Eye-Scanning Data Obtained from an Air Traffic Control Display.* NASA CR-191559, 1993.