IN-04-TM

7970

NASA-TM-111255

AIAA-95-3367

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AIAA Guidance, Navigation, and Control Conference

August 7-10, 1995 / Baltimore, MD

EFFECTS OF ATC AUTOMATION ON PRECISION APPROACHES TO CLOSELY SPACED PARALLEL RUNWAYS

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Abstract

Improved navigational technology (such as the Microwave Landing System and the Global Positioning System) installed in modern aircraft will enable air traffic controllers to better utilize available airspace. Consequently, arrival traffic can fly approaches to parallel runways separated by smaller distances than are currently allowed. Previous simulation studies of advanced navigation approaches have found that controller workload is increased when there is a combination of aircraft that are capable of following advanced navigation routes and aircraft that are not. Research into Air Traffic Control automation at Ames Research Center has led to the development of the Center-TRACON Automation System (CTAS). The Final Approach Spacing Tool (FAST) is the component of CTAS used in the TRACON area. The work in this paper examines, via simulation, the effects of FAST used for aircraft landing on closely spaced parallel runways. The simulation contained various combinations of aircraft, equipped and unequipped with advanced navigation systems. A set of simulations was run both manually and with an augmented set of FAST advisories to sequence aircraft, assign runways, and avoid conflicts. The results of the simulations are analyzed, measuring the airport throughput, aircraft delay, loss of separation, and controller workload.

Nomenclature

ASL	=	Above sea level
AQN	=	Acton gate
BPR	=	Bridgeport gate
BUJ	=	Blueridge gate
CAS	=	Calibrated Airspeed
Center	=	Air Route Traffic Control Center
CTAS	=	Center-TRACON Automation System
DFW	=	Dallas-Fort Worth airport
FAST	=	Final Approach Spacing Tool
IFR	=	Instrument Flight Rules
ILS	=	Instrument Landing System
nmi	=	nautical miles
NTZ	=	Non-Transgression Zone
SCY	=	Scurry gate
TCAS	=	Tactical Collision Avoidance System
TRACON	=	Terminal Radar Approach Control
VFR	=	Visual Flight Rules

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I. Introduction

Improved navigational technology (such as the Microwave Landing System and the Global Positioning System) installed in modern aircraft will enable the air traffic controller to better utilize available airspace. Consequently, arrival traffic can fly approaches to parallel runways separated by smaller distances than are currently allowed. After new navigation systems are approved by the Federal Aviation Administration, they are slowly adopted by the aircraft fleet. Thus, for the next few decades, the number of aircraft equipped with advanced navigation technology will gradually increase. Previous simulation studies of advanced navigation approaches[1] have found that controller workload is higher when there is a combination of aircraft that are capable of following advanced navigation routes and aircraft that are not, than when all aircraft are equipped with the same navigation technology. Automated air traffic control tools are thus desirable to help reduce controller workload in such a situation.

Research into Air Traffic Control automation at Ames Research Center has led to the development of the Center-TRACON Automation System (CTAS) [2]. CTAS is designed to help air traffic controllers manage arrival traffic to an airport. The Final Approach Spacing Tool (FAST) is the component of CTAS used in the TRACON area. Information describing the design and evaluation of FAST may be found in Reference 3 and

Reference 4. Active FAST advisories consist of the runway assignment, the sequence of aircraft at the runway, and the turns and speeds calculated by FAST to cause the aircraft to meet the sequence. Passive FAST, which is scheduled to be tested in the field at Dallas-Fort Worth (DFW) in 1995, consists of runway assignments and sequences only. Passive FAST was augmented with conflict advisories for this simulation, to compensate for the closer runways.

The work in this paper examines, via simulation, the effects of this augmented passive FAST when used for aircraft landing on closely spaced parallel runways. A set of simulations was run both manually and with the augmented set of passive FAST advisories. The simulation contained various combinations of aircraft, equipped and unequipped with advanced navigation systems. The purpose of this paper is to describe the experiment used to examine the closely spaced parallel runway problem, and to present simulation results comparing a strictly manual simulation with a simulation using passive FAST automation. The airspace organization is described in section II, followed by the definition in section III of the scenarios that comprise the simulations. Section IV describes the advisories presented for both simulations. The data that was recorded and the variables that were analyzed are described in section V. Finally the results of the two simulations and conclusions are presented in sections VI and VII. This paper compares the technical data for these simulations while Reference 5 examines the controller coordination and controller-reported workload.

II. Airspace Organization

The DFW TRACON airspace was used for the simulations as an example of an airport with close parallel runways. The TRACON is an approximately circular region around the airport with a radius of about 45 nmi. The general arrangement of the DFW TRACON is shown in Figure 1. Arrival traffic to DFW enters through four gates, each near the TRACON boundary. The gates are Blueridge (BUJ) in the northeast, Scurry (SCY) in the southeast, Bridgeport (BPR) in the northwest, and Acton (AQN) in the southwest. Traffic was landing from the north. The runways that were used are 18R and 18L where 18R is on the west side of the airport. The airspace was divided into four sectors, each controlled by a single controller: east feeder, west feeder, 18R final, and 18L final. Each controller spoke to a pseudo-pilot, who "flew" all the aircraft in that sector. The east feeder controller controls traffic coming from the two east gates, BUJ and SCY, until about 20 nmi from the runway threshold. The west feeder controller controls the equivalent airspace on the west side of the airport. The two final controllers handle traffic on the east or west side of the runways from about 20 nmi to the outer marker. From the outer marker to touchdown, aircraft are controlled by the tower. The control of the aircraft in the final sectors is based strictly on airspace, not runway assignment. If an aircraft comes from the northeast and must land on runway 18R, it will be controlled by the 18L final controller. The 18L final controller would coordinate with the 18R final controller to provide an arrival slot.

The 18R and 18L runways are 1100 feet apart. In actual DFW operations these two runways are not both used for landings at the same time. The runway approaches used for the simulations are shown in Figure 2 (not to scale). The normal Instrument Landing System (ILS) approach was followed for runway 18R, and an offset parallel approach was followed for 18L. The offset approach could only be flown by aircraft equipped with advanced navigation equipment. All aircraft could fly the ILS approach and land on runway 18R. The two approaches are shown as the solid vertical lines in the figure. Aircraft enter from the top of the figure and land on the runways at the bottom. The current minimum required separation for independent ILS approaches is 4300 ft for most airports and 3400 ft for airports equipped with advanced radar equipment. For this study, the ILS approach to runway 18R and the advanced navigation approach to 18L were 3400 feet apart, which would be allowable with advanced radar.

Between the two approaches is the Non-Transgression Zone (NTZ). The NTZ is a buffer between the two approaches, 2000 ft across, that is restricted to avoid conflicts between landing aircraft. If an aircraft from 18L enters the NTZ when there is another aircraft on the 18R approach, the aircraft on the 18R approach must be directed away from its approach. Operational TRACONs have a separate controller whose job is to monitor the NTZ and can override either the final or tower controller's instructions in the event of a conflict. An NTZ controller was not used in the simulation, so an unrealistic number of conflicts may have occurred.

At approximately 3 nmi from the threshold and 1600 to 1700 ft above sea level (ASL), the advanced navigation aircraft transitioned to Visual Flight Rules (VFR) and moved over to the runway. This procedure is similar to an approach procedure used at San Francisco airport, but differs because the two approaches at San Francisco are both defined by ILS equipment. The advantage of an offset approach is that aircraft can fly under Instrument Flight Rules (IFR) to two runways that are too close for joint ILS approaches until they drop below a low (1900 ft ASL) cloud ceiling. A normal VFR approach to the two runways requires the aircraft to be visible when they turn onto the final approach at 3000 or 4000 feet. Restrictions on IFR approaches reduce the traffic throughput of the airport (one runway instead of two when the clouds are below 4000 ft). The main disadvantage to an offset approach is that the pilot workload is increased near touchdown.

III. Definition of the Scenarios

Each simulation was composed of one of four traffic scenarios, using two flow rates. Each traffic scenario contained traffic entering the TRACON over the course of an hour. There were two scenarios at the lower flow rate of 45 aircraft per hour. The first, called the medium scenario, had 30 ILS equipped aircraft (67%) and 15 advanced navigation aircraft in an hour. The second, called the west scenario, had 15 ILS aircraft (33%) and 30 advanced navigation aircraft. In the west scenario, two thirds of the ILS traffic and half the advanced navigation traffic came through the west gates. There were two scenarios at the higher flow rate of 57 aircraft per hour. The first, called the heavy scenario, had 30 ILS aircraft (53%) and 27 advanced navigation aircraft. The second, called the future scenario, was the same as the heavy except that all the aircraft were equipped with advanced navigation. For all the cases, except the west, the ILS equipped and advanced navigation equipped aircraft were equally divided among the four gates. The scenarios are summarized in Table 1, starting with the smallest percentage of advanced navigation equipped aircraft and ending with all aircraft being equipped. The scenarios were created by assigning the creation times of the aircraft randomly within an hour, and assigning the aircraft types and airlines in the same percentages as a reference recording of actual DFW traffic over a five-hour period.

	Med	Heav	West	Fut
Flow Rate (ac/hr)	45	57	45	57
ILS%	67	53	33	0
Adv. Nav%	33	47	67	100
Comment	1/4 each gate	1/4 each gate	2/3 ILS west	same as Heav

TABLE 1. List of Scenarios

Each of the four scenarios was run at least twice, under staggered and simultaneous approach conditions. A simultaneous approach is used for runways that are far enough apart that the wake vortex of an aircraft on one runway will not interfere with an aircraft on the other runway. Controllers only need to maintain the required in-trail separation between aircraft landing on the same runway and, of course, the required general separation between aircraft. A simultaneous approach requires less coordination by controllers, and therefore lower workload, than a staggered approach[6]. A staggered approach assumes that the aircraft landing on different runways must have a diagonal separation of at least 2 nmi. A staggered approach is currently required for parallel runway approaches less than 3400 ft apart at airports with special radar. Both approaches were simulated on the routes shown in Figure 2, though a staggered approach would only be necessary if the runway approaches had been closer together. Staggered approaches reduce the maximum possible throughput of the airport compared to a simultaneous approaches, increasing delay, for the same traffic level.

IV. Advisory Definition

Two simulations were performed using the same four scenarios under both simultaneous and staggered approaches: a baseline simulation was conducted without CTAS advisories; and a second simulation including passive FAST advisories. For the baseline simulation, the controller's display was similar to actual controllers' displays at DFW except for the equipment type (ILS or advanced) being indicated on the aircraft tag and the use of color. The equipment type was shown after the aircraft call sign in yellow (where the rest of the tag was in green) to make it immediately obvious. All decisions (e.g., routes, speeds, altitudes, headings, runway assignments) were made by the controller, with the restriction that only advanced navigation equipped aircraft were allowed to land on 18L.

The passive FAST simulation had the same equipment type display plus passive FAST advisories and several advisories designed for the close parallel runway simulation. Passive FAST advisories are runway assignments and sequence numbers. The runways were assigned by FAST and presented to the controller about 40 nmi from the threshold. Sequence numbers showed the order of the aircraft landing on a particular runway. Besides the passive FAST advisories, two new advisories were created for the close parallel runway simulation to help the controller avoid conflicts, which were assumed to be more likely with the closer approaches.

The conflict advisories were conflict alert and NTZ violations. Conflict alert is a function that uses the current speed, altitude and heading of all aircraft to project ahead, checking to see if any aircraft will come within the required separation, 3 nmi horizontally and

1000 ft vertically. The look-ahead time can be set by the controller between one and thirty seconds. The controllers in the simulation chose a look-ahead time of one second. Longer times caused too many false alarms. When two aircraft were predicted to lose separation, the tags of both aircraft turned red, giving the controller(s) notice of the problem and allowing them to resolve it. This advisory was not applicable when both aircraft were on final approach, since the final approaches were only 0.6 nmi apart.

When on the final approach, the NTZ was used to keep aircraft apart laterally on final, while the controller maintained the required in-trail separation. NTZ violations turned the tag of an aircraft blue if it was illegally in the NTZ. An illegal entry was defined as the aircraft entering the NTZ from the direction of the assigned runway. Aircraft from the northeast which crossed the NTZ to land on runway 18R did not cause an NTZ violation unless the controller overshot the runway. The NTZ violation occurred even if there was no aircraft on the other runway to cause an actual conflict. It was just a warning that the controller was in danger of causing a violation.

An example of aircraft tags showing passive FAST advisories (not separation violations, which require color) is shown in Figure 3. The aircraft position is shown as a letter (H for the 18R final sector and M for the 18L final sector) connected to the aircraft tag (text) by a line. The top line of each tag is the aircraft call sign followed by the equipment type. The call sign is made up of the airline (UAL is United Airlines) and the flight number. The equipment type 'A' is an ILS equipped aircraft, and 'G' is an advanced navigation aircraft. All aircraft landing on 18L must be advanced navigation ('G') aircraft. UAL134, an advanced navigation aircraft, was assigned to runway 18R by FAST, to reduce either delay or workload. The second line alternately displays the assigned runway on the left and the aircraft type on the right or the aircraft altitude on the left (in 100's of feet) and speed (in 10's of knots) on the right. The third line shows the sequence number. In Figure 3, UAL001 is first to runway 18R, and UAL12 is the first aircraft to runway 18L. UAL001 is followed by UAL134 and UAL12 by UAL1422.

V. Data and Analysis

During each scenario there were four types of data recorded: the CTAS recorded file, the pseudo-pilot recorded files, human factors observations, and technical observations. The CTAS recorded file contained aircraft state information, plus a record of the advisories issued to the aircraft. The pseudo-pilot recorded files contained every command issued by the controllers and carried out by the aircraft. The human factors observations were: written notes taken by the human factors observers, surveys completed by the controllers to measure their perception of workload, and audio tape recordings of voice communication between the two final controllers. Technical observations were written notes taken by the technical observer, including runway assignment and causes of errors.

There were four areas of interest in analyzing the simulations: conflicts, delay, throughput, and workload. Conflicts included loss of separation away from the runway or errors during turn on to the runway (both considered conflict alert), NTZ violations, in-trail separation errors, and stagger separation errors. Conflict alert and NTZ violation data were recorded in the CTAS recorded file during simulations. A conflict violation (away from and turn-on to the runway) was defined by the duration of the conflict in seconds. Thus a single one-minute conflict would be rated equal to 60 one-second conflicts. The NTZ violations were all of fairly consistent durations, so the number of NTZ violations per simulation was used. The in-trail and stagger separations were calculated as $(d_{REQ} - d_{actual})/d_{REQ}$ where d_{REQ} is the required separation and d_{actual} is the actual separation. The required stagger separation is 2 nmi, and the required in-trail separation is given in Table 2.

		Size of aircraft behind			
		Heavy	Large	Small	757
ahead	Heavy	4	5	6	5
	Large	3	3	4	3
	Small	3	3	3	3
	757	4	4	5	4

TABLE 2. Required in-trail separation (nmi)

The delay of interest was the delay in the TRACON, which was measured by taking the original estimated time of arrival when the aircraft was at the gate, and comparing it to the actual landing time. The estimated time of arrival was always calculated from the shortest IFR route, using the fastest speeds. Therefore, the estimated time of arrival was the CTAS-calculated minimum time for the aircraft to get to the runway from its current position. The landing times and actual landing runways were extracted from the CTAS files, by finding the final recorded aircraft state. Throughput was measured as the number of aircraft per hour that landed at the airport.

The workload of the controllers was found objectively from the number of commands issued to the pseudo-pilot by the controller and subjectively by Task Load Index (TLX)[7] surveys filled out by the controller. The surveys asked separate questions about the elements that make up workload (mental demand, temporal demand, performance support, effort, and frustration). The questions were each rated on a scale of 1-5 with 5 being the heaviest workload and were combined to produce an overall workload rating.

VI. Results

Three assumptions were made before the simulations were performed. (1) The new conflict advisories in the simulation which included passive FAST advisories would reduce the duration of the conflicts by causing the controllers to notice the conflicts earlier than in the baseline simulation. (2) The throughput of the simulation with passive FAST would be higher than the baseline simulation, causing a corresponding reduction in delay. The greatest advantage for situations with more accurate position requirements, such as described in this paper, is expected to be gained with active FAST. Giving the turns and speeds required to meet the schedule exactly would lead to better precision for the aircraft. Simulations using passive FAST[8] have shown about a 20% increase in throughput for normal operations at DFW. This increase due to passive FAST is mostly caused by improved runway allocation. Due to the restrictive nature of the runway assignment allowed in this experiment, it was assumed, before the simulations occurred, that the improvements would be less than 20%. (3) The workload of the controllers using passive FAST would be reduced over manual operations. This result has been noticed by DFW controllers in simulations with passive FAST[8]. As it turned out, the only one of these assumptions to be supported by the simulations was the third. Conflicts were not reduced nor throughput increased with augmented passive FAST advisories, but workload was decreased.

The results for the simulations are shown in two tables. Table 3 shows the values from the baseline simulation, and Table 4 shows the results when passive FAST was used. The simulation results were combined in two different ways, producing four sets of data. The west and medium scenarios were averaged to produce data for a flow rate of 45 aircraft per hour, and the heavy and future scenarios were averaged for a flow rate of 57 aircraft per hour. Staggered approach scenarios were combined, and simultaneous approach scenarios were combined. For variables which are defined per aircraft and the TLX rating, which was not associated with aircraft, the numbers were averaged. For variables defined per scenario as an aggregate of all aircraft, the numbers were weighted by dividing by the number of aircraft in the scenario and multiplying by 51 (i.e., (45+57)/2). The mean and standard deviations are listed across the rows. The variables examined are listed down the columns. The conflict variables examined were the loss of separation away from the runway (Conflicts), errors during turn on to the runway (Turn-on errors), NTZ violations (NTZ), in-trail separation errors (In-trail error), and stagger separation errors (Stagger error). Airport throughput and delay per aircraft were the next two variables examined. The workload variables were the TLX rating (Workload-TLX), and number of commands per aircraft during a simulation (Commands/ac).

Contrary to the original assumption, there was no statistically significant difference for any of the conflict variables between the passive FAST and baseline simulations. The conflict advisories did not make a significant difference in either the number or duration of conflicts. The conflict variables are characterized by very large standard deviations. Even when there seems to be a difference between the two simulations (such as stagger separation), the large deviations make it not statistically significant. There are several possible reasons for this result. The conflict variables examined cause a statistical problem because they are created by discrete events, and are not continuous variables. Even if the statistics were valid, the advisories might have occurred at nearly the same time as a controller would naturally spot the conflict, or the controllers may have ignored the advisories. During training simulations, the controllers felt that the conflict alert advisory occurred too frequently when the situation had already been corrected, leading to the reduction of the look-ahead time to only one second for the passive FAST simulation. This experience may have led the controllers to consider the conflict alert function inaccurate and ignore it. The NTZ violation, having been designed only as a warning, might also have been ignored. The stagger and in-trail separation errors were not addressed by any passive FAST advisories and were only considered to see if the workload reduction, shown by passive FAST, could give the controllers time to be more careful on final. Like the other conflict information, there was no difference between the two simulations.

Examining the throughput and delay, there was again no statistically significant difference between the two simulations. The throughput for the stagger simulations shows an increase of about 8%. The simultaneous scenarios show no improvement which causes the 45 and 57 aircraft per hour data to average to an insignificant improvement. The lack of improvement in the simultaneous scenarios is due to the larger percentage of aircraft being assigned to runway 18R by passive FAST than by the controllers. Passive FAST uses the minimum required separation at the runway to decide whether to assign the aircraft to runway 18L. Since the controllers in the test generally produced a larger separation, the throughput was reduced from that planned by FAST, making the runway plan invalid. For a stagger scenario, the minimum separation at the runway was effectively increased to a value which the controllers met. The delay also seems to be slightly smaller for all of the combinations except the simultaneous scenarios, but due to the size of the standard deviations, none of the differences were statistically significant. The standard deviations for the delay were generally smaller for the passive FAST simulation (except simultaneous scenario). The delay and throughput may not show a significant improvement because they are nearly the best values that the controller pool was capable of producing without further advisories. The constraints on runway balancing, due to the experimental design, also limited the possible throughput and delay improvements with passive FAST. Another limiting factor may be that the number of samples was too small. Each scenario took about an hour and a half to run, so the number of scenarios that could be performed was limited by resources.

Two methods were used to examine workload: the TLX survey given to the controllers and the average number of commands executed by each aircraft. The survey results, which were a measure of controller perception of workload, were slightly higher for the baseline simulation, but were not statistically significant. This may be due to the controller pool used in this study. These controllers have become familiar with the FAST system over several years and may be less aware of the workload benefits. Calculating workload from the average number of commands given per aircraft, the baseline simulation numbers were 5 to 20% higher than the passive FAST simulation. The 45 aircraft per hour and the stagger combinations were statistically significant, and the simultaneous combination was nearly statistically significant. The 45 aircraft per hour had about 15% less commands issued, and the stagger scenarios had about 20%.

VII. Conclusions

This experiment assumed that improved navigational technology on aircraft will enable air traffic controllers to land arrival traffic on parallel runways separated by smaller distances. This problem was studied in two simulations consisting of at least eight scenarios performed by air traffic controllers and pseudo-pilots. The scenarios consisted of two different flow rates, two approaches, and various combinations of equipped and unequipped aircraft. The simulations were run with and without augmented passive FAST advisories. Due to the more regulated runway assignments, the ability of automation to increase airport throughput was reduced. The benefits of ATC automation were to reduce conflicts, which could be increased in the smaller airspace, and to reduce controller workload by planning for the aircraft further in advance. The results of these simulations, although statistically not significant, showed slight increases in throughput and decreases in delay with passive FAST advisories, except for a simultaneous approach. There was also no reduction in number or duration of conflicts, leading to the conclusion that the conflict advisories used were not helpful. A statistically significant workload reduction of 15 to 20%, measured in number of commands issued to the aircraft, was produced by the lower flow rate and stagger scenario with passive FAST advisories. Reduced workload has previously been shown in passive FAST simulations along standard arrival routes. This measurement of controller workload should also correspond to a reduction in pilot workload.

Several issues should be examined in future work. Significant throughput increases for this experiment should occur with active FAST advisories (speeds and turns) to help the controllers meet the computer-generated schedules. Active FAST, producing advisories based on conflict-free trajectories, should also cause a reduction in the number of conflicts. Further work could be performed on improving conflict advisories to be more helpful to the controller. The simulations could also be performed with controllers less familiar with FAST for a more accurate measurement of perceived workload.

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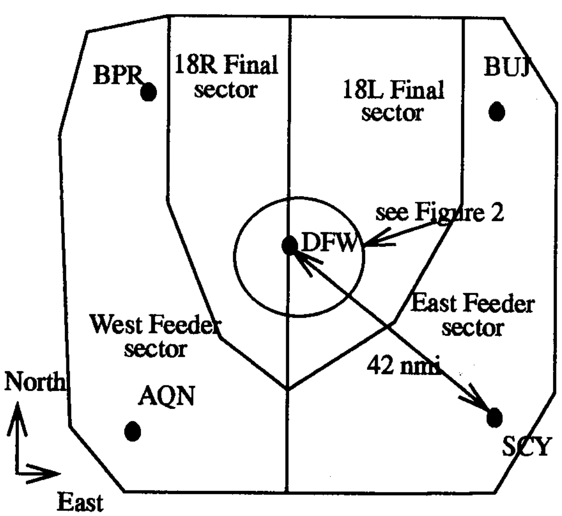

Figure 1 Dallas-Fort Worth TRACON used for Simulations

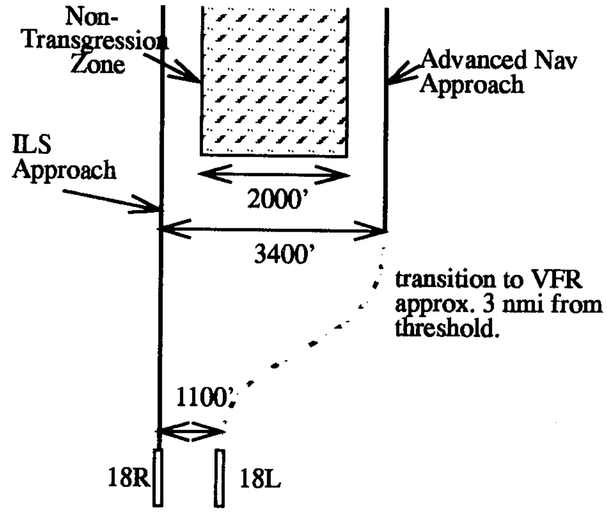

Figure 2 Runway Layout

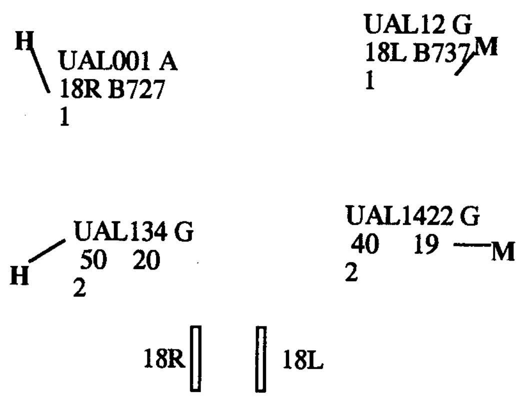

Figure 3 Passive FAST Advisory Example

	all 45/hr		all 57/hr		stagger		simultaneous	
	ave	σ	ave	σ	ave	σ	ave	σ
Conflicts (sec/ac)	0.435	0.49	0.531	0.44	0.498	0.46	0.467	0.47
Turn-on err. (sec/ac)	6.01	3.9	4.22	4.1	1.94	2.1	8.29	1.8
NTZ (#/ac * 10)	5.44	0.98	5.51	0.67	5.17	0.92	5.78	0.57
In-trail err (nmi/ac * 100)	5.19	1.8	3.82	1.4	5.49	1.5	3.51	1.3
Stagger err (nmi/ac * 100)	6.71	2.0	3.91	0.42	5.31	2.0	0	0
Throughput (ac/hr)	41.6	3.2	50.6	4.0	43.7	3.0	48.7	1.9
Delay (sec)	1017	123	1026	146	1126	189	945.2	124
Workload-TLX	11.1	1.8	11.9	2.3	11.9	2.4	11.4	2.2
Commands/ac (#/ac)	9.7	0.77	10.1	1.5	10.8	0.79	8.98	0.29

TABLE 3. Baseline simulation - baseline data

	all 45/hr		all 57/hr		stagger		simultaneous	
	ave	σ	ave	σ	ave	σ	ave	σ
Conflicts (sec/ac)	0.905	1.0	0.748	0.93	0.354	0.5	1.299	1.0
Turn-on err. (sec/ac)	2.13	1.4	6.91	5.1	3.23	2.8	5.81	5.5
NTZ (#/ac * 10)	6.44	1.0	5.46	0.85	6.25	1.1	5.65	0.94
In-trail err (nmi/ac * 100)	5.55	0.79	3.79	0.87	4.96	1.32	4.38	1.21
Stagger err (nmi/ac * 100)	10.0	2.7	5.21	4.2	7.63	4.0	0	0
Throughput (ac/hr)	43.3	1.6	52.7	3.3	47.6	3.5	48.6	1.4
Delay (sec)	948.4	9.5	988.6	96	1008	97	951.1	141
Workload-TLX	9.5	2.1	10.7	1.5	9.4	2.1	11.0	1.5
Commands/ac (#/ac)	8.25	0.74	8.99	0.41	8.78	0.94	8.47	0.38

TABLE 4. Passive FAST Simulation - advisory data