FUNCTION ALLOCATION WITH AIRBORNE SELF-SEPARATION EVALUATED IN A PILOTED SIMULATION

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Abstract

A human-in-the-loop simulation experiment was designed and conducted to evaluate an airborne self-separation concept. The activity supports the National Aeronautics and Space Administration's (NASA) research focus on function allocation for separation assurance. The objectives of the experiment were twofold: (1) use experiment design features in common with a companion study of ground-based automated separation assurance to promote comparability, and (2) assess agility of self-separation operations in managing trajectory-changing events in high traffic density, en-route operations with arrival time constraints. This paper describes the experiment and presents initial results associated with subjective workload ratings and group discussion feedback obtained from the experiment's commercial transport pilot participants.

1 Introduction

In current Air Traffic Control (ATC) operations, the traffic separation function resides with air traffic controllers, not with controller automation or with aircraft. The controller visually monitors the position of traffic within a sector at all times, makes predictions on when and where aircraft might lose separation, determines resolutions to these conflicts, and issues instructions for rerouting or maneuvering to pilots by voice radio. Using primarily a radar display and a computer repository of flight plan information, the controller provides separation in a mostly manual way, with minimal reliance on tools designed and intended to support the function [1].[1]

Aircraft today also contribute little to the function of traffic separation. Though many commercial aircraft are equipped with a Flight Management System (FMS) and thus capable of high-performance navigation, the flight crew's ability to use this capability to provide separation from traffic on their own is essentially nonexistent. Without onboard traffic surveillance, they cannot detect conflicts or make trajectory modifications safely with respect to traffic beyond visual range. Therefore, today's air traffic controllers remain solely responsible for separation of traffic operating under Instrument Flight Rules (IFR).

Air traffic controllers expertly provide safe operations at current traffic levels, but the method restricts the ability to indefinitely accommodate expected levels of traffic growth [2]. The limiting factor is controller workload, which governs the number of aircraft and the configuration of traffic flows that can be monitored and controlled simultaneously within a sector [3]. Traffic capacity is limited primarily by the human perception of traffic flow complexity and the controller's ability to maintain complexity at a manageable level. In addition, the ability to respond with agility to dynamic conditions is restricted by the requirement for serial communications in which controllers issue relatively tactical instructions

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[1] ATC has some automation systems they use, such as Short Term Conflict Alert (STCA) and Minimum Safe Altitude Warning (MSAW), that are rudimentary and used as a backup to the controller.

to one aircraft at a time. These procedures slow down the process of traffic management and therefore impede growth in air traffic volume.

New technologies, such as airborne and ground-based separation automation tools and airborne surveillance, provide potential means for overcoming these restrictions by exploiting a reallocation of functions between humans and automation and between ATC and aircraft. The current separation function is weighted toward a human-centered, ground-based allocation. Through application of advanced computer automation, aircraft trajectories can be modeled with much greater precision and monitored automatically for traffic conflicts.[2] Resolutions[3] can be rapidly computed and sent in full form to the aircraft's FMS for execution by the flight crew. In a ground-based application of this concept currently under study [4][5], the separation function resides in the ATC facility but is largely automated, and trajectory revisions are sent automatically to aircraft via data link. Controllers monitor the operation and provide services when needed, typically on an exception basis.

Emerging airborne surveillance technology enables a further allocation of the separation function from the ground to the aircraft [6]. Automatic Dependent Surveillance Broadcast (ADS-B) provides the means for an aircraft to directly receive position and trajectory information from broadcasting aircraft. This information, supplemented by uplinked radar data of non-ADS-B-equipped aircraft, allows receiving aircraft to host the automation functions that predict trajectories, detect conflicts, and compute resolutions. Thus, the aircraft can theoretically provide the separation service directly for themselves. The concept is referred to as self-separation and is also under study [7][8]. Self-separation does not require ground-based automation for separation or the infrastructure for uplinking trajectories into the FMS.[4] The onboard automation system can be integrated directly into the avionics system to provide more accurate trajectory prediction and more resolution alternatives to the flight crew.

A human-in-the-loop (HITL) simulation of self-separation was recently conducted in support of the NASA research focus on function allocation for separation assurance. The objectives of the experiment were twofold: (1) use experiment design features in common with a companion study of the ground-based automated separation concept to promote comparability, and (2) assess agility of self-separation operations in managing trajectory-changing events in high traffic density, en-route operations with arrival time constraints. This paper describes the experiment and presents initial subjective response data. Section 2 summarizes the self-separation operational concept as presented to the experiment's commercial transport pilot participants. Sections 3 through 6 present the experiment objectives, scenarios, simulation platform, and experiment design. Section 7 presents initial results associated with subjective workload ratings and group discussion feedback provided by 46 subject pilots.

2 Operational Concept

In NASA's self-separation concept, an aircraft operating under self-separation is said to be operating under 'Autonomous Flight Rules' (AFR). AFR operations would occur primarily in the en-route phase of flight but could also include segments of the departure and arrival phases. They may occur in homogeneous airspace or mixed-operations airspace, i.e., AFR and ground-managed aircraft sharing the airspace without segregation.

AFR can be considered by operators as an additional flight filing option to Visual Flight Rules (VFR) and IFR. AFR operations would resemble VFR operations in that responsibility for separation from traffic lies with the pilot, not

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[2] A conflict is a predicted loss of separation (LOS) with another aircraft. LOS is typically defined by a lateral and vertical standard, e.g., five nautical miles (nmi) laterally and 1000 feet (ft) vertically.

[3] A resolution is an FMS trajectory revision or a tactical maneuver that eliminates a conflict. Resolutions may be in the lateral, vertical, or speed dimensions.

[4] Ground-based services would still be required by these aircraft for other purposes, for example managing their insertion into the schedule of converging arrivals to high-demand terminal airspace.

the controller. AFR operations would resemble IFR operations in that they may be conducted in Class A airspace in any meteorological conditions, and that appropriate standards for separation would apply unless aircraft are visually acquired. An AFR pilot has complete authority to manage and revise the aircraft's trajectory and is therefore free to choose a flight path and altitude, provided that traffic separation requirements are met. The pilot works with an onboard AFR tool (i.e., automation) to accomplish the task.[5]

2.1 AFR Rules for Pilots

The operational concept evaluated in this experiment included four AFR 'rules' presented here in priority order. The functionality of the AFR tool that supports the pilot in adhering to these rules is presented in Section 5.2.

AFR Rule #1: The pilot is to resolve traffic conflicts without delay when notified. The pilot does not scan a traffic display for conflicts, but rather relies on the AFR tool for conflict detection. When notified of a conflict by the AFR tool, the pilot is expected to select from a set of tool-provided resolutions and is expected to execute the selected resolution in a timely fashion. Fig. 1 shows an example of a conflict (yellow segment and aircraft) and a resolution (blue line).

AFR Rule #2: The pilot is to use the AFR tool to check trajectory changes for conflicts before executing the change. Trajectory changes are made for many reasons besides conflict resolution, such as turbulence, unexpected headwinds, weather hazards, fuel efficiency, and absorbing arrival delays. Any time the pilot intends to initiate a flight profile change, the new route or maneuver must first be probed for traffic conflicts. AFR Rule #2 prohibits a trajectory change that would create a 'Level 2' conflict alert for any aircraft, including their own. This notification level indicates greater urgency to resolve, because of reduced time to LOS. Less urgent 'Level 1' conflicts may be temporarily created but must then be resolved according to AFR Rule #1.

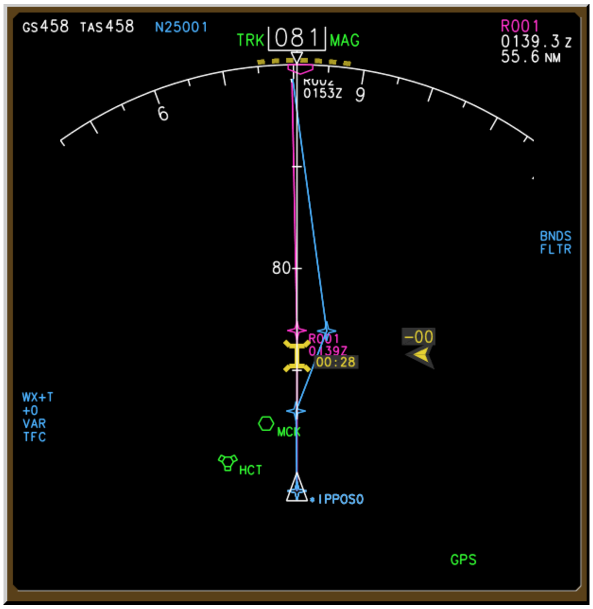

Fig. 1 Navigation display showing a conflict (yellow) and a resolution (blue).

AFR Rule #3: The pilot is to ensure that the aircraft's trajectory will conform to ATC constraints, should any be in effect. ATC constraints are sometimes necessary to protect special use airspace or to manage the traffic flow rate into capacity-constrained areas such as terminal airspace. In this latter case, ATC may assign crossing times at an arrival metering fix to inbound aircraft, the pilots of which then enter into the FMS their 'required time of arrival' (RTA) constraint at that fix. Any changes to the trajectory must ultimately support RTA conformance, otherwise ATC must be notified if the constraint becomes unachievable.

AFR Rule #4: The pilot is to have the auto-flight system remain FMS-coupled as much as possible. This lowest priority rule, perhaps better described as a guideline, is intended to maximize the proportion of aircraft on a 4D trajectory, i.e., 'strategic' flight, while providing the pilot with the flexibility to operate in 'tactical' flight when necessary, i.e., using just Mode Control Panel (MCP) guidance. Aircraft flown using FMS guidance are anticipated to have more predictable and stable trajectories,

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[5] This automation tool is specific to the separation function. Separate tools, such as the Traffic Alerting and Collision Avoidance System (TCAS), remain focused on their designed function of providing collision escape maneuvers.

thereby benefitting all operators and controllers using that airspace. AFR pilots are therefore encouraged to fly with the FMS engaged to the greatest extent reasonably achievable. Specifically in conflict situations, aircraft in strategic flight are given higher priority over aircraft in tactical flight.

2.2 Coordination and System Optimization

Although the concept of self-separation may seem very vehicle-centric, inter-aircraft coordination and system optimization also play central roles. Coordination is applied implicitly through, for example, right-of-way rules. In every conflict, a common rule set defines one aircraft as having priority and the other as the 'give way' vessel (following in the original nautical tradition). In AFR, this priority is manifested in the timing of notifications such that the 'give way' aircraft crew is notified first and generally resolves the conflict by itself. If time passes without resolution, the priority aircraft crew is then notified, providing a valuable system redundancy and safety benefit. Right-of-way rules would generally be based on conflict geometry, but may also be designed to incorporate a variety of additional system-level optimization objectives, such as giving arrival traffic flows priority over crossing traffic. Since the rules are encoded directly in the automation and do not rely on human memory or interpretation, the rule set may be as complex and extensive as needed to provide the desired system-level balance of equity and efficiency.

Additional means for system optimization are also present, although in a manner different than in centralized systems. For instance, overall operations cost is minimized by the flight crew directly through their trajectory authority, as this is nearly always one of their principal objectives. Contention for airspace and other resources is minimized through the application of ATC constraints such as RTAs. System predictability is enhanced by AFR aircraft receiving elevated priority when using FMS guidance. Although total system behavior of AFR operations is still under study, these elements of the concept are expected to be beneficial at the system level.

3 Experiment Objectives

This AFR experiment was designed to meet two objectives. The first objective was to determine the degree of comparability that could be achieved between experiments in separate HITL laboratories that were conducted to study different approaches to separation assurance under 'four-dimensional trajectory-based operations' (4D TBO). This objective was derived from a NASA programmatic goal to investigate issues of air/ground function allocation between the airborne and ground-based 4D TBO concepts developed and matured by NASA to a medium-to-high level of fidelity by different research teams using different laboratory facilities. Two experiments were therefore designed, one in each laboratory, with subject pilots in the airborne self-separation experiment and subject controllers in the ground-based automated separation experiment. The experiment designers took the initial steps toward comparability by using common experiment design matrices, identical initial traffic scenarios, and jointly defined metrics. While these steps do not guarantee truly comparable results, the exercise was expected to shed light on issues of comparing significantly different operational concepts in dissimilar simulation platforms with different human subject populations (i.e., commercial transport pilots vs. air traffic controllers). The resulting comparability assessment is not the subject of this paper but was a significant factor in the experiment design presented here.

The second objective of the AFR experiment was to assess agility of self-separation operations under high traffic density conditions. As traffic levels rise, it remains important that a trajectory management system be able to react nimbly to events requiring many aircraft to change trajectories nearly simultaneously. In the self-separation concept, the trajectory management system is *distributed* among the aircraft, and it is expected that the timing of trajectory-change events would not have an impact on performance, whether these events be dispersed in time or synchronous.[6]

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[6] The same might not be true for a controller, who must issue trajectory change instructions in a serial fashion.

The experiment sought to create an operationally realistic event (to both pilots and controllers) requiring a trajectory change to be made by a large number of aircraft and to control the timing of that event. The event chosen was notification of an arrival delay necessitating a maneuver to lengthen or stretch an aircraft's flight path to absorb the delay. RTA change notifications were sent as data link messages. Timing was controlled by scheduling the messages to be synchronous among aircraft in some scenarios and dispersed in others.

4 Scenario Description

The airspace modeled was a rectangular region defined by the corner points 36.5N 94W and 40.5N 86W. This area, approximately 376 nmi by 240 nmi, includes the eastern region of Kansas City Center and the western region of Indianapolis Center, and it is roughly centered over St. Louis, Missouri. The size accommodated 30-minute flights for the subject pilots (and controllers), and the location provided a mix of crossing and transitioning traffic. Vertically, the experiment airspace extended from Flight Level (FL) 290 to FL 400, although climbing and descending aircraft were permitted below the floor. City pair routing was roughly similar to today, including the use of existing waypoints and standard terminal arrival routes. Although all aircraft were initiated at regular 1000 ft altitudes (FL340, FL350, etc.), aircraft were permitted under AFR rules to change to any altitude during the scenario (e.g., FL362). Similarly, changes to routing were permitted and expected. The simulated winds were westerly from 30 to 50 knots with small variations in magnitude and direction by altitude but no variation laterally or with time. Wind forecasting errors were not modeled.

In every scenario run, each subject pilot's aircraft was initialized in a level cruise condition near the FMS-computed optimum altitude and approximately 25-30 minutes from the top-of-descent point, i.e., close enough to the destination to realistically expect an RTA assignment for arrival metering. Initial RTA assignments were set to be approximately equal to the aircraft's estimated time of arrival, with adjustments made only as necessary to avoid bunching or overscheduling the arrival flow (for subject controller realism in the companion ground-based experiment). Initial RTAs and RTA changes, when they were used, were sent to selected aircraft at the appropriate time via a data link.

5 Experiment Environment

The self-separation experiment was conducted in the Air Traffic Operations Lab (ATOL) at the NASA Langley Research Center, in Hampton, Virginia. This facility specializes in simulation-based research and development of advanced operational concepts employing ADS-B, but is suitable for a variety of operations research. For conducting batch and HITL experiments, it has over 300 computers, including 12 desktop pilot workstations, four of which are shown in Fig. 2.

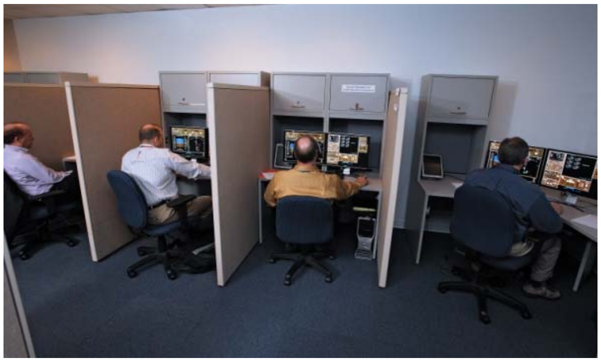

Fig. 2 Desktop pilot workstations in the NASA Langley Air Traffic Operations Lab.

5.1 Simulation Platform

The ATOL computing network hosts the Airspace and Traffic Operations Simulation (ATOS) simulation platform [9]. ATOS provides a medium fidelity setting for studying the interactions of aircraft in a realistic ADS-B environment. ATOS uses an implementation of High Level Architecture (HLA) to network together multiple individual Aircraft Simulations for Traffic Operations Research (ASTORs) and a background traffic generator, Traffic Manager Executable (TMX) [10]. ATOS supports the exchange of industry standard ADS-B reports (i.e., state vector, mode status, air referenced velocity, target state, and trajectory change reports) with standard message content and broadcast frequency [11]. For this experiment, frequency interference modeling was disabled, transmission range was fixed at 120 nmi, broadcast rate of key reports was established at 1 Hz, and trajectory intent was broadcast up to 12 trajectory change points (i.e., effectively full trajectory intent).

The traffic aircraft in the experiment scenarios were provided by 12 HITL ASTOR computers, 63 batch ASTOR computers, and up to 557 lower fidelity aircraft modeled by a single TMX computer. Since the experiment was designed to model homogeneous operations, all aircraft operated under AFR. The function of the hundreds of TMX aircraft was to create the required traffic density and to provide ADS-B message broadcasts of aircraft performing AFR procedures. For this purpose, TMX aircraft included capabilities for conflict detection and resolution; however, their separation performance was not the subject of this experiment.

Each ASTOR computer simulates one aircraft at medium fidelity. ASTOR has realistic displays and controls representative of a Boeing 777 and a six degree-of-freedom flight performance model representative of a medium-sized twin-engine transport aircraft. For the functions required in this experiment, the auto-flight system and FMS were fully functional. Its avionics bus emulates ARINC 429 specifications for realistic internal and external communications [12]. ASTOR supports trajectory uplink and auto-load, a capability in this experiment used for loading RTAs. In HITL mode, ASTOR is controlled by subject pilots using a desktop computer mouse. In batch mode, a pilot model automatically operates ASTOR controls according to standard AFR procedures.

5.2 AFR Tool

ASTOR contains a research-prototype AFR tool for the pilot called the Autonomous Operations Planner (AOP) [13]. AOP supplied the self-separation automation functions necessary for the pilot to meet the aforementioned four AFR rules: (1) resolve conflicts when notified, (2) check and clear all trajectory changes for conflicts before executing, (3) conform to ATC constraints, and (4) remain FMS-coupled whenever possible. The method of AOP support for each rule follows.

Supporting AFR Rule #1, AOP automated the process of conflict detection and crew notification by making trajectory predictions of the ownship and all traffic aircraft within ADS-B reception range, and by probing these trajectories for predicted loss of separation (LOS). A nominal look-ahead horizon of 10 minutes was used for detection, and the trajectory predictions were refreshed at least every 10 seconds. Volumetric uncertainty bounds were applied to all trajectory segments to encompass prediction errors and minimize missed alerts [14]. AOP notified the pilot of conflicts using textual, aural, and graphical methods, and at a time and notification level appropriate to the ownship aircraft's right-of-way and the conflict's level of urgency. Fig. 3 shows the staggered notification scheme used to provide implicit coordination and minimize simultaneous resolution actions by both aircraft.

Time to Loss of Separation (minutes)	Right-of–Way	
	Give Way Aircraft	Priority Aircraft
10 to 7	Level 1 "Traffic Conflict"	No alert
7 to 6		Level 1 "Traffic Conflict"
6 to 5	Level 2 "Traffic Alert"	
5 to 0		Level 2 "Traffic Alert"

Fig. 3 Conflict notification based on right-of-way to reduce simultaneous resolutions.

Also for AFR Rule #1, AOP automated the process of computing acceptable resolutions to a conflict. Two methods were available to the pilot: strategic [15] and tactical [16]. A strategic resolution is a modification of the FMS route, and in most situations, AOP will present both lateral and vertical alternatives.[7] For each of these alternatives, a pattern-based genetic algorithm determined the fuel-optimal solution,

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[7] Speed resolutions were not employed in this experiment.

and the pilot could upload either option to the FMS for execution. Fig. 1 shows a Level 2 "traffic alert" and an AOP-computed lateral strategic resolution that is ready for upload and execution in the FMS. To execute a vertical resolution, the pilot must also reset the MCP altitude window appropriately for the new altitude. A tactical resolution is a non-FMS maneuver activated by the pilot typically through MCP 'track select' or 'flight level change' commands. Again, AOP will typically offer both alternatives, computed by sweeping through possible track, altitude, and vertical speed changes until a conflict-free maneuver is found. At five or four minutes to LOS for the give-way and priority aircraft, respectively, AOP will enter 'tactical override' mode and offer only tactical resolutions, given the short time remaining to resolve the conflict.

To help pilots meet AFR Rule #2 (i.e., clear all trajectory changes before executing), AOP probed 'provisional' (i.e., "what if…") trajectories or maneuvers prior to execution. 'Planning' conflict symbology was displayed that indicated whether the proposed change would create a conflict and at what notification level. With this capability, pilots could safely investigate both FMS strategic trajectory changes and MCP tactical maneuvers before acting. In addition, AOP displayed yellow bands on the flight displays to indicate ranges of tracks and vertical speeds that should not be selected since their selection would result in a Level 2 conflict for themselves or another aircraft. Fig. 1 shows such a 'maneuver restriction band' on the compass rose of the navigation display.

AFR Rule #3 (i.e., conform to ATC constraints) was supported with a combination of FMS and AOP capabilities. The FMS evaluated any required waypoint constraints, such as an RTA, and notified the pilot if the aircraft could not meet a given constraint with speed changes alone, e.g. too much delay to absorb by simply slowing down. AOP then provided the capability to 'resolve' this 'unable RTA' situation with path changes using the same strategic resolution capability for resolving traffic conflicts. In this experiment, only lateral 'Resolve RTA' solutions were enabled. AOP will also resolve conflicts with airspace regions defined by polygons; however no such regions were included in this experiment.

AOP supported the pilot with adherence to AFR Rule #4 (i.e., remain FMS-coupled whenever possible) by providing a 'strategic reconnect' capability. This function was to be used following an MCP tactical maneuver that took the aircraft off its FMS path or cruise altitude. AOP would construct a nominal reconnect path and probe it for conflicts, providing as well the capability to resolve them. AOP would also provide the pilot with guidance regarding the MCP settings required to again become 'fully coupled' to FMS guidance.

Finally, since all aircraft in this experiment were AFR, and no aircraft entered terminal airspace during the simulation runs, no *active* ATC simulation component was required to accomplish the experiment objectives. Though ATC would normally assign RTAs dynamically, the RTAs were predetermined for this experiment and sent as scripted data link messages at scheduled times during the appropriate scenarios. Each scenario contained 63 aircraft with destination airports in common with the 12 subject pilot ASTORs. These 63 aircraft were modeled by batch ASTORs flown by the pilot model, which enabled them to exercise AOP's 'Resolve RTA' capability when the situation called for it.

6 Experiment Participants, Design, and Procedure

6.1 Pilot Participants

Forty-eight commercial transport pilots participated in the NASA Langley HITL experiment. However, since two of these pilots had not flown a transport category aircraft within the last year, data collected from these pilots are not included in data analyses. The remaining 46 pilot participants consisted of 38 commercial transport pilots employed by U.S. air carriers or aircraft manufacturers and eight commercial transport pilots employed by European air carriers. The participation of

European as well as American pilots was desired to support a global perspective on ATM research.

All of the pilots were male and ranged in age between 38 and 62 years. Twenty-two of the participants were captains, and the other 24 were first officers. On average, the pilots had 19 years of airline experience and over 10,000 hours of airline flying experience. At the time of the study, 33 of the participants served as Boeing 777 pilots, nine served as 747 pilots, one served as a 757/767 pilot, one served as a 737NG pilot, one served as a 737-300 pilot, and one served as an A330 pilot. Pilot recruitment favored those having recent experience with glass cockpit technology since their experience facilitated their training and use of the ASTORs.

6.2 Experiment Design

6.2.1 Independent Variables

Common experiment design matrices were used to collect data from pilot participants within the NASA Langley ATOL and from controller participants within the NASA Ames Airspace Operations Lab. A 2x2 within-subject design (Fig. 4) was used to collect data during four moderate duration ("M" series) 30-minute experiment scenarios. The 30-minute scenarios involved either the presence (*Yes*) or absence (*No*) of scheduling assignments (i.e., RTAs) provided to aircraft operating within an airspace having a sustained traffic density level either 1.5 times (*1.5x*) or 2 times (*2.0x*) greater than current day capacity.[8]

		Scheduling Assignment	
		No	*Yes*
Traffic Density	*1.5x*	30-minute Scenario "M1"	30-minute Scenario "M4"
	2.0x	30-minute Scenario "M2"	30-minute Scenario "M3"

Fig. 4 Experiment design matrix for 30-minute scenarios.

A separate 3x1 within-subject design (Fig. 5) was used to collect data during three short duration ("S" series) 15-minute experiment scenarios. During the 15-minute scenarios, aircraft operated within an airspace having a 2.0x traffic density level, and, in two of the three 15-minute scenarios, scripted events that manipulated the timing of aircraft trajectory changes were introduced. The event was a new RTA indicating that a delay maneuver was required. The timing was either *Dispersed*, i.e., sent to all 75 ASTOR aircraft at various (dispersed) times throughout a scenario, or *Synchronous*, i.e., sent to selected aircraft at the same time during a scenario.

	Timing of Trajectory Change Event		
	No Scripted Trajectory Changes	*Dispersed Trajectory Changes*	*Synchronous Trajectory Changes*
2.0x Traffic Density	15-minute Scenario "S1"	15-minute Scenario "S2"	15-minute Scenario "S3"

Fig. 5 Experiment design matrix for 15-minute scenarios.

6.2.2 Dependent Measures

During each scenario, the following quantitative data were recorded: the 4D flight path history of every aircraft, all conflicts and LOS events and their associated timelines and details, the auto-flight mode changes (e.g., switching from FMS to MCP guidance), and all control actions and button pushes by the pilots. Data analyses will address both safety and efficiency metrics, and results will be reported in subsequent papers. When considering safety, the primary metric is LOS,[9] and each event involving a subject pilot will undergo detailed causal analysis for contributing factors, including possible pilot errors, modeling/simulation anomalies, and design issues in AOP and pilot procedures. Additional safety metrics of interest include pilot response time to conflict alerts [17], the proportion of tactical to strategic conflict

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[8] A simplified assumption was made for current day capacity. '1.0x' was defined as 18 aircraft per 10,000 nmi^2, or approximately 164 aircraft in the airspace region.

[9] Loss of separation or 'operational error' was defined to be a lateral closest point of approach (CPA) within 4.5 nmi while within 800 ft vertically. A CPA of 4.5 to 5.0 nmi, while within 800 ft vertically, was considered a 'proximity event' and tracked separately from LOS.

resolution maneuvers, and a general assessment of pilot procedural errors. When considering efficiency, metrics of interest include the extent of deviation from the nominal trajectory, the effect of fuel burn, the predicted RTA compliance at scenario completion, and the time proportion spent in tactical flight (i.e., not 'FMS-coupled').

Subjective response data were collected from pilots via paper-and-pencil questionnaires. Following each scenario, the pilots were asked to rate the level of workload they experienced during the scenario they had just completed using the Modified Cooper-Harper (MCH) Subjective Workload Rating Scale [18][10], and they were asked to characterize the acceptability of the airborne self-separation procedures and automation tool (i.e., the AOP) for that scenario. At the conclusion of the experiment, the pilots were asked to provide feedback regarding the ASTORs and flight scenarios, the experiment's training methods and materials, the AFR operational concept, the airborne self-separation procedures, and the AOP tool. Finally, the pilots participated in an interactive verbal group debrief session with the research team.

6.3 Experiment Procedure

The 48 subject pilots participated as groups of 12 in four separate three-day experiment sessions conducted in March 2010. Each experiment session consisted of a series of training exercises involving classroom instruction and hands-on simulated flight, 14 data collection scenarios, questionnaires following each scenario, a final 'post-experiment' questionnaire, and a final debrief session involving all 12 pilots and members of the research team. During Day 1, the pilots completed approximately 5-1/2 hours of training. During Day 2, pilots completed the four 30-minute scenarios twice in random order. During Day 3, pilots completed the three 15-minute scenarios twice in random order, completed the post-experiment questionnaire, and participated in the group debrief session.

7 Initial Results and Discussion

Future reports will present quantitative safety and efficiency metrics, as these analyses were not yet complete at the time of this writing. Similarly, the analyses of pilot acceptability ratings of the AFR procedures and tool will be subsequently published. This paper presents initial results regarding the pilots' subjective rating of workload. It also summarizes some of the primary discussion points shared during the post-experiment group debrief sessions.

7.1 Workload Ratings

Pilots used the MCH scale to provide a workload assessment after each of the experiment's 14 flight scenarios. Descriptive statistics associated with these data are shown in Table 1.

Table 1 Descriptive statistics for MCH workload ratings

	30-minute scenarios	15-minute scenarios
Mean (*M*)	2.41	2.14
Standard Deviation (*SD*)	1.80	1.33
Minimum (*Min*)	1	1
Maximum (*Max*)	10	8
Sample Size (*N*)[11]	340	253

Mean workload ratings associated with the 10-point MCH scale indicate that pilots found the tasks performed during the scenarios to have a difficulty level of "fair" or "mild" and that they felt an acceptable level of mental effort was required to attain adequate performance. Specific events will be analyzed and described in subsequent papers to elucidate why, at times,

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[10] Use of the MCH scale yields an overall workload rating ranging from "1" (indicating that the instructed task was very easy and/or highly desirable; operator mental effort was minimal; and desired performance was easily attainable) to "10" (indicating that the instructed task was impossible and could not be accomplished reliably).

[11] Sample sizes of 368 and 276, respectively, were anticipated since each of the 46 pilots was asked to provide a MCH workload rating after completing each scenario. Four pilots did not complete the MCH scale as requested, however, resulting in an absence of data.

pilots provided high ratings of workload. For example, the research team will examine 30-minute scenarios having ratings of "10" (which indicate that the instructed task was impossible and could not be accomplished reliably) and 15-minute scenarios having ratings of "8" (which indicate that maximum operator mental effort was required to avoid large or numerous errors).

It was not the intent of the researchers to compare the workload ratings of the 30-minute scenarios with those of the 15-minute scenarios. Therefore, analyses of the 30-minute and 15-minute scenarios' workload ratings are presented separately.

7.1.1 30-minute scenarios

Descriptive statistics associated with the four 30-minute scenarios' workload ratings are shown in Table 2.

Table 2 Descriptive statistics for the four 30-minute scenarios' MCH workload ratings

	M1	M2	M3	M4
M	2.18	2.33	2.73	2.41
SD	1.83	1.65	2.18	1.41
Min	1	1	1	1
Max	9	10	10	8
N[12]	85	85	85	85

Statistical analysis was performed using the Wilcoxon Test, a nonparametric within-subject test appropriate for analyzing two related samples of ordinal data [19]. A series of Wilcoxon Tests revealed a statistically significant difference between pilots' workload ratings for scenario M1 as compared to M3 (p[13] = 0.0341). Pilots found that the combination of higher traffic density and an RTA constraint increased workload, whereas either effect separately did not. It should be noted that the pilots were not told the traffic density of each scenario or that the density was changing between scenarios.

When workload ratings were averaged across the levels of Scheduling Assignment, a Wilcoxon Test revealed no statistically significant difference in workload between the 1.5x traffic density level (represented in scenarios M1 and M4)[14] and the 2.0x traffic density level (represented in scenarios M2 and M3)[15] ($p = 0.2666$). When workload ratings were averaged across the levels of Traffic Density, a Wilcoxon Test revealed that the pilots provided a statistically significant lower mean workload rating for scenarios flown without RTAs (M1 and M2)[16] when compared with scenarios flown with RTAs (M3 and M4)[17] ($p = 0.0306$). This RTA effect may be related to the extra effort required to comprehend the RTA data link message, load the RTA in the FMS, and execute the change.

7.1.2 15-minute scenarios

Descriptive statistics associated with the three 15-minute scenarios' workload ratings are shown in Table 3.

Table 3 Descriptive statistics for the three 15-minute scenarios' MCH workload ratings

	S1	S2	S3
M	1.83	2.30	2.27
SD	1.16	1.27	1.50
Min	1	1	1
Max	8	6	8
N[12]	84	85	84

Wilcoxon Tests revealed that pilots provided a statistically significant lower mean workload rating associated for scenario S1 than for either scenario S2 ($p = 0.0021$) or scenario S3 ($p = 0.0088$). However, no statistically significant difference was indicated between the ratings provided for scenarios S2 and S3 ($p = 0.9820$). Therefore, the inclusion of a second RTA event affected pilot workload, but the relative timing of this event among the 75 aircraft did not affect pilot workload. In the self-separation concept, the trajectory management system is distributed among the aircraft, and it was expected that the timing of trajectory-change events would not have an

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[12] A sample size of 92 was anticipated; however, four pilots failed to complete the MCH scale as requested, resulting in an absence of data.

[13] A p-value ≤ 0.05 indicates a statistically significant difference between sample means.

[14] $M = 2.29$, $SD = 1.63$, $Min = 1$, $Max = 9$, $N = 170$

[15] $M = 2.53$, $SD = 1.94$, $Min = 1$, $Max = 10$, $N = 170$

[16] $M = 2.25$, $SD = 1.74$, $Min = 1$, $Max = 10$, $N = 170$

[17] $M = 2.57$, $SD = 1.84$, $Min = 1$, $Max = 10$, $N = 170$

impact on performance, whether these events are dispersed in time or synchronous. The workload analysis results are consistent with this expectation and provide evidence of the agility of the AFR concept.

7.2 Pilots' Group Comments Regarding the AFR Concept

The group-debrief sessions produced lively discussion on several common themes regarding the AFR concept in general and its implementation in this experiment. Overall, a generally positive view of the concept was shared, along with some cautionary remarks on various aspects. In some cases, these cautionary remarks reflected situations in which some pilots felt they lost situation awareness, e.g., a conflict alert given later than usual. These late alerts are being reviewed, and preliminary analysis indicates that modeling errors may have caused late alerts in certain situations. Other cautionary remarks were projections by the pilots into areas beyond the experiment scope but of relevance to the general concept of operations. For example, a general consensus was expressed on the opportunity for gaming (i.e., acting in a manner to gain advantage or put others at a disadvantage), and that some type of monitoring and enforcement may be needed to ensure the AFR rules are dutifully followed by all flights.

It was noted that the concept would be well suited for near-term use in many parts of the world where robust ATC services are lacking, provided that international standard operating procedures are used. Application in the domestic U.S. airspace was considered feasible above 18000 ft, but concerns were expressed regarding viability in flight phases already high in crew workload such as the descent phase and approaching the arrival metering fix. In this experiment, the pilots were not tasked with performing these arrival procedures.

The positive value of a modified Mode Control Panel design to suit AFR operations was raised, given that the current design reflects functionality associated with current-day ATC-based operations, such as the altitude clearance limit set in the MCP altitude window. It was also noted that the single-pilot testing of the concept in this experiment precluded the opportunity for crew cross-checks of conflict resolutions and other trajectory changes, which would be paramount for safety.

Overall, the research team found the group-debrief comments from the pilots to be highly constructive. Their input will be used to refine the AFR operational concept, tools, procedures, and training for future experiments.

8 Conclusions

A human-in-the-loop simulation experiment evaluating airborne self-separation was designed with two objectives: (1) use experiment design features in common with a companion study of ground-based automated separation assurance to promote comparability, and (2) assess agility of self-separation operations in managing trajectory-changing events in high traffic density, en-route operations with arrival time constraints. The experiment addressed the comparability objective by using common experiment design matrices, identical initial traffic scenarios, and jointly defined metrics. While these steps do not guarantee truly comparable results, the exercise highlights many issues concerning the comparison of significantly different operational concepts in dissimilar simulation platforms with different human subjects (i.e., commercial transport pilots vs. air traffic controllers). The comparability assessment is reported in a joint paper dedicated to this topic [20].

Self-separation, due to its distributed nature and the use of automation, was found to support highly dynamic 4D trajectory-based operations while maintaining a low mean level of pilot-reported workload. Agility was indicated by a workload analysis showing no significant difference in pilot-reported workload between simultaneous vs. dispersed trajectory change events.

As with any significant operational change, implementation of an AFR concept can be expected to include fundamental changes in procedures and equipment, including many specific examples suggested by the pilots during the debrief sessions. New responsibilities will also require a change in the operational mindset of both pilots and controllers, as the context of today's human-centered, ground-based air traffic management system evolves toward more automation and distribution of critical functions like traffic separation.

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