

Pilot and Controller Evaluations of Separation Function Allocation in Air Traffic Management

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Abstract—Two human-in-the-loop simulation experiments were conducted in coordinated fashion to investigate the allocation of separation assurance functions between ground and air and between humans and automation. The experiments modeled a mixed-operations concept in which aircraft receiving ground-based separation services shared the airspace with aircraft providing their own separation service (i.e., self-separation). Ground-based separation was provided by air traffic controllers without automation tools, with tools, or by ground-based automation with controllers in a managing role. Airborne self-separation was provided by airline pilots using self-separation automation enabled by airborne surveillance technology.

The two experiments, one pilot-focused and the other controller-focused, addressed selected key issues of mixed operations, assuming the starting point of current-day operations and modeling an emergence of NextGen technologies and procedures. In the controller-focused experiment, the impact of mixed operations on controller performance was assessed at four stages of NextGen implementation. In the pilot-focused experiment, the limits to which pilots with automation tools could take full responsibility for separation from ground-controlled aircraft were tested.

Results indicate that the presence of self-separating aircraft had little impact on the controllers' ability to provide separation services for ground-controlled aircraft. Overall performance was best in the most automated environment in which all aircraft were data communications equipped, ground-based separation was highly automated, and self-separating aircraft had access to trajectory intent information for all aircraft. In this environment, safe, efficient, and highly acceptable operations could be achieved for twice today's peak airspace throughput. In less automated environments, reduced trajectory intent exchange and manual air traffic control limited the safely achievable airspace throughput and negatively impacted the maneuver efficiency of self-separating aircraft through high-density airspace. In a test of scripted conflicts with ground-managed aircraft, flight crews of self-separating aircraft prevented separation loss in all conflicts with detection time greater than one minute. In debrief, pilots indicated a preference for at least five minute's alerting notice and trajectory intent information on all aircraft. When intent information on ground-managed aircraft was available, self-separating aircraft benefited from fewer conflict alerts and fewer required deviations from trajectory-based operations.

Keywords – air traffic management, function allocation, separation assurance, automation, self-separation, air/ground integration

I. INTRODUCTION

An essential part of developing the Next Generation Air Transportation System (NextGen) is the exploration of new technologies, procedures, and human roles in providing services and functions for the safe and expeditious passage of aircraft. Separation assurance is a key function of Air Traffic Control (ATC) and a core responsibility of air traffic controllers in current-day operations. Due to the safety criticality of separation assurance, a complex system of airspace and route structures, surveillance and communication technologies, and operational controls on aircraft trajectories has evolved to enable a separation assurance environment in which controllers, using voice communication with pilots, can sustain safe operations with manageable workload.

This evolved, complex system is reaching its limits in accommodating new demand and satisfying operator needs for efficiency. A significant constraining factor is the controller's workload in communicating with and separating aircraft. Currently, the controller is responsible for nearly all separation-related functions. Ground automation plays an ancillary role in enhancing controller situation awareness, and the aircraft (i.e., the flight crew and airborne automation) has a passive role with respect to separation, simply obeying trajectory instructions (except in collision avoidance situations where an active role is taken). Given that human workload capacity cannot be substantially increased, other means will be needed to stretch beyond the current limits.

The Concepts and Technology Development Project of the NASA Airspace Systems Program is exploring fundamental changes to separation assurance that reduce or eliminate human workload as a limiting factor. Through this "function allocation" research thrust, NASA researchers are testing separation concepts that leverage the extensive use of automation and the untapped, distributed resource of aircraft systems and crews. Concepts for ground-based and airborne separation developed and researched over the last decade and beyond are brought together into a "mixed operations" environment where the maximum use of all resources for separation can be explored.

The focus of this mixed-operations research activity is non-segregated airspace where airborne and ground-based separation capabilities coexist. If it can be made sufficiently safe, integrated mixed operations provides more flexibility to

aircraft operators than homogeneous or segregated operations. It allows the aircraft operators to choose the method of trajectory management, ground-based or airborne, that is the most cost-effective for each flight without compromising their access to the most efficient routes and altitudes. Having this flexibility is economically valuable to the operator community, given the large variations in operator business models, aircraft equipment, stage lengths, and flight-optimization objectives. Even though ground-based and airborne concepts have each shown potential for scaling and efficiency, a multi-option concept provides more opportunity for achieving these goals and less implementation risk. By developing mixed-operations concepts, NASA's goal is to provide the largest range of viable solutions for the aviation community.

Several key questions were identified in the context of enabling mixed operations (those for which separation of traffic in shared airspace is managed through multiple function-allocation means). These questions form the basis of the two coordinated simulation experiments (pilot-focused and controller-focused).

A. How does the presence of self-separating aircraft affect the performance of the ground-based separation system?

Since any new separation system will not be built from scratch but rather will build upon the existing, complex system of skilled controllers and well-established procedures, it is important that the performance of the existing system not be compromised in the process of achieving the system with newly allocated separation functions. To address this question, the controller-focused experiment was designed to assess ground-based separation performance in traffic environments with and without self-separating aircraft.

B. What are the limits of ability of self-separating aircraft to shoulder the burden of mixed operations?

The complexity of the existing ground-based system may preclude making significant changes to accommodate the introduction of new operations such as self-separation. Therefore, the most feasible approach to implementation is for the self-separating aircraft to give way to ground-controlled aircraft (at least in the early stages of implementation) and to avoid placing new operational restrictions on the ground-based control of traffic. In practical terms, the controller should be free to focus almost exclusively on ground-controlled traffic, while self-separating aircraft must be capable of resolving all conflicts with ground-controlled aircraft (in addition to conflicts with other self-separating aircraft), regardless of warning time or encounter geometry. There will be limits to this ability, and thus the pilot-focused experiment was designed to assess self-separation performance in a variety of (primarily short-notice) conflicts with ground-managed aircraft.

C. How will the implementation and maturation of NextGen affect the ability to operate with mixed operations?

Envisioned as part of NextGen are new technologies such as air/ground data communications (data comm.) and decision-support automation for controllers and pilots. As NextGen matures, the number of data comm. equipped aircraft is expected to grow, enabling greater controller reliance on automation for managing trajectories (and therefore managing

separation). NextGen technologies will also support greater air/ground sharing of trajectory intent information. The question to be addressed is whether the concept for mixed operations (i.e., the means by which self-separating and ground-managed aircraft share the airspace) is compatible with the expected emergence of NextGen. To address this question, the controller-focused experiment tested mixed operations at different stages of the NextGen evolution of ground-based automation (i.e., over a range of minimum to maximum envisioned capabilities), and the pilot-focused experiment tested NextGen self-separation operations with and without access to the trajectory intent of ground-managed aircraft.

The two human-in-the-loop simulation experiments were designed and conducted in a coordinated effort to explore these questions that arise in function allocation of separation assurance. This mixed operations research builds upon a recent separate comparison study of each concept operating separately [1]. Of the preceding set of key questions, Question A was addressed in a controller-focused experiment conducted in the Airspace Operations Lab (AOL) at NASA Ames Research Center. Question B was addressed in a pilot-focused experiment conducted in the Air Traffic Operations Lab (ATOL) at NASA Langley Research Center. Different elements of Question C were addressed in both experiments. This paper presents a summary of these experiments and their top-level results. Section II describes separation assurance concepts (airborne and ground-based) and their mixed-operations integration. Sections III and IV respectively describe the controller-focused and pilot-focused experiments and present initial results. Section V gives conclusions.

II. SEPARATION FUNCTION ALLOCATION CONCEPTS

A. Airborne Separation Concept

The airborne separation concept leverages the attributes of both distribution and automation in its approach to function allocation. In this approach, separation functions for individual aircraft are performed onboard the aircraft (i.e., the "ownship") to provide separation from all traffic the ownship encounters. The aircraft (rather than the controller) manages its own trajectory during en route flight, and it "self-separates" from all traffic by detecting conflicts and adjusting its trajectory as needed. With multiple self-separating aircraft in the airspace, the separation "service" is distributed among them and resident onboard each equipped aircraft. Separation automation onboard the aircraft is heavily leveraged to avoid the flight crew having to provide such capability manually.

Aircraft that manage their own trajectory and separation are referred to as flying under Autonomous Flight Rules (AFR). AFR distinguishes these aircraft from IFR aircraft, which are managed by and receive separation services from ATC. While AFR aircraft optimize their own trajectory through airspace shared with IFR traffic, the mixed operations concept tested in these experiments requires AFR aircraft to yield right-of-way to IFR aircraft in all conflict encounters and to take responsibility for ensuring the separation standard is met. To meet this responsibility, the flight crew uses onboard automation that processes data from ownship avionics and airborne surveillance (Automatic Dependent Surveillance Broadcast, ADS-B) to probe for conflicts and compute

resolution maneuvers, and possibly several acceptable alternatives. The crew chooses the desired maneuver and executes it directly. Because the separation function is performed onboard, no ATC approval is needed to maneuver. AFR intent information is electronically available to controllers, but they bear no responsibility for separation between AFR and IFR aircraft. Coordination between AFR pilots and controllers, if needed, is conducted by voice communication.

NASA has developed and investigated the AFR concept for over a decade, designing prototype flight-deck automation and conducting numerous analyses, batch simulations, and human-in-the-loop experiments. A more thorough description of the AFR concept is provided in [2].

B. Ground-Based Separation Concept

Separation assurance in the National Airspace System today is ground-based, manual, and limited by how many aircraft the air traffic controller can keep under positive control. Emergent technologies are intended to support air traffic controllers in detecting conflicts and generating solutions and will reduce some of the coordination and communication workload. The current near- and mid-term NextGen plans foresee the introduction of additional decision support tools to improve operations, but under the current paradigm the human operator remains responsible for providing separation between all aircraft. [3]

In 2000 Erzberger [4] introduced the automated airspace concept, which was conceptualized as a completely automated ground-based separation assurance concept with two layers: a trajectory-based layer providing efficient resolutions for non-urgent conflicts to be communicated to the flight deck's flight management system via data communication, and a tactical layer providing short term conflict avoidance maneuvers to keep aircraft separated in case the trajectory-based layer failed. Human-Systems Integration research at NASA Ames has taken components of this fully automated concept, integrated them into transitional stages and developed a ground-based concept in which humans and automation collaborate to substantially increase airspace capacity while retaining acceptable operations for the operators. [5]

This concept of ground-based automated separation assurance utilizes technologies to shift the workload-intensive tasks of monitoring and separating traffic from the controller to the automation. A critical element of this centralized concept makes the ground-side automation, not the controller responsible for conflict detection. The automation is also responsible for monitoring the compliance status of all aircraft relative to their reference trajectory. In many cases, the automation, not the controller, is responsible for resolving conflicts as well. However, the controller is responsible for maintaining separation of unequipped aircraft using a conventional voice link and steps in to handle certain off-nominal situations. Thus, under automated separation assurance, air traffic controllers' roles involve providing services and performing decision-making activities, while the roles of monitoring, providing nominal separation, and back-up solutions in off-nominal situations are allocated to the automation.

III. CONTROLLER-FOCUSED EXPERIMENT

The controller-focused experiment addressed the impact of self-separating aircraft on ground-based separation assurance services in different stages of NextGen. Conducted at the Ames AOL, the experiment compared the air traffic controllers' ability to provide separation services in increasingly advanced operational environments with and without the presence of self-separating aircraft. The primary questions with regard to mixed operations were (1) whether the self-separating aircraft would impact the controller's (and ground-based automation's) ability to separate conventional aircraft (Question A in Section I) and (2) how these operations would unfold under different emergent stages of NextGen (Question C in Section I).

In order to investigate the first question, multiple stages of NextGen were run in both IFR-only and mixed IFR/AFR scenarios. The only difference between the IFR-only and the mixed-operations scenarios was that eight selected aircraft, operating according to IFR rules in one case, were operated under AFR rules in the corresponding mixed-operations case. The remaining aircraft were all operating under IFR rules.

In order to investigate the second research question, four different NextGen stages were run. The first stage, "Baseline", was designed to provide data approximating current day operations with the addition of ADS-B out surveillance data. The mixed-operations runs were designed to indicate what would happen if aircraft conducted self-separation in a very near-term environment that is characterized by voice communication and manual control. Controllers had to verbally issue frequency changes to the AFR aircraft but had no separation responsibility for them. AFR aircraft and controllers had access to ADS-B state data for all traffic, but no ADS-B intent information. The traffic levels were selected to be representative of current day peak traffic levels with a Monitor Alert Parameter (MAP) value of 18 aircraft per sector.

The second stage, labeled "Minimum NextGen", introduced limited data communication between the ground-side and 25% of the simulated aircraft. This data communication enabled an automatic transfer of communication of aircraft from one sector to the next. This eased the controller workload in handling those aircraft, which included the AFR aircraft under mixed operations. It was expected that controllers could potentially ignore the AFR aircraft, because they had no routine duties with regard to them. This stage also introduced more decision support capabilities for the controllers, none of which were integrated with data comm. So, all control instructions still had to be communicated via voice. It was hoped that the new technologies could enable a capacity increase of 20%, and the MAP value was set to 22 aircraft per sector for the "Minimum NextGen".

In the third stage, entitled "Moderate NextGen", the controller planning tools and the flight management systems on-board the aircraft were integrated with data comm., and 50% of the aircraft were assumed data comm. equipped. Unlike the previous two stages, AFR aircraft in this condition had access to trajectory intent of up to four trajectory change points for all other aircraft. Controllers were able to issue trajectory change instructions to equipped aircraft via data comm. Based upon earlier research, it was hypothesized that this environment

could enable a capacity increase of 50% over the Baseline and therefore the MAP value was set to 27 for this stage.

In the final NextGen stage, referred to as “Maximum NextGen”, the responsibility for conflict detection among IFR aircraft was assigned to the ground automation and all aircraft were data comm. equipped. When conflicts were detected, ground automation computed trajectory-based resolutions and issued those directly to the flight deck, as long as the computed resolutions did not violate preset tolerances. Otherwise, the conflict was flagged to the controller for resolution. Prior research had indicated the scalability of this approach, and therefore the traffic levels were selected at 100% over the Baseline with a MAP value of 36 aircraft per sector.

A. Experiment Design

The experiment used a within-subjects design with two air/ground function allocation concepts (IFR-only and mixed IFR/AFR) over four stages of NextGen, resulting in eight experimental conditions. Prior tests had shown that the complex nature of changes between the NextGen stages made it impossible for participants to operate within the different environments in a randomized or counter-balanced order. Therefore, the conditions were run in order of their maturation/automation level: first Baseline, then Minimum, then Moderate, and finally Maximum NextGen. In each stage, the pilots and controllers were briefed and trained for one day on the operational environment, tools, and procedures, followed by one day of data collection in which they ran a total of six scenarios alternating between IFR and mixed IFR/AFR operations. The test matrix is shown in Table 1.

The test airspace consisted of five simulated high altitude sectors in Cleveland Center (ZOB) that were combined into two air traffic control areas (north and south), controlling all traffic at FL 320 and above (Fig. 1). Six current and one very recently retired Federal Aviation Administration (FAA) front line managers served as primary participants, five as radar controllers and two as area supervisors. Five retired controllers operated radar associate positions in the test airspace, and three retired controllers controlled the traffic in the “ghost” sector outside the test airspace. Ten airline pilots operated eight mid-fidelity, single-aircraft flight simulators, and ten general aviation/corporate pilots operated multi-aircraft stations.

B. Facility and Test Scenario Description

For the experiment, the AOL at Ames [6] was configured with two air traffic control rooms hosting the five test sectors.

TABLE 1: TEST MATRIX FOR CONTROLLER FOCUSED EXPERIMENT

		Tue, We	Th, Fr	Mo, Tu	We, Th
Air/ground function allocation	Mixed IFR/AFR				
	Ground IFR				
		Baseline	Minimum NextGen	Moderate NextGen	Maximum NextGen
Human/automation function allocation NextGen Maturation Level of automation increases →					

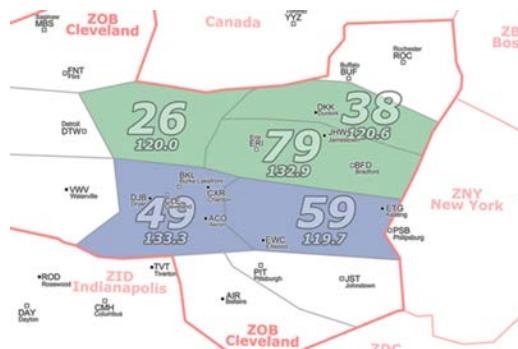


Figure 1. Test airspace for controller focused experiment.

Each sector was configured with a radar display and a nearly identical radar associate display (Fig. 2). A supervisor participant managed each room and brought radar associates on position when needed. The air traffic control environment, controller workstations, and majority of IFR aircraft were simulated using the Multi Aircraft Control System (MACS) developed at Ames.

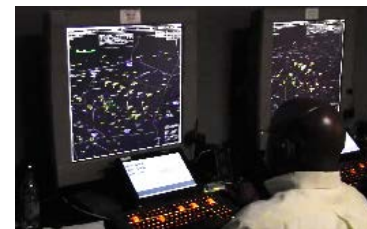


Figure 2. AOL sector position.

The AFR aircraft in the mixed-operations conditions and their respective IFR counterparts in the IFR-only conditions were simulated using the higher fidelity ASTOR desktop flight simulators developed at Langley and operated by type-rated airline pilots. The ASTORs and their capabilities are discussed in more detail in the description of the pilot-focused experiment. Traffic scenarios consisted of overflights, departures, and arrivals into nearby airports originally based on actual ZOB traffic flows, but modified for the higher traffic densities used in the simulations.

C. Results of Controller-Focused Experiment

1) Separation Assurance Performance

Separation assurance performance was initially analyzed by comparing the loss of separation (LOS) events between the IFR-only and the mixed IFR/AFR conditions for the different stages of NextGen. Table 2 shows a summary of the conditions and the combined number of LOS events as well as the number of ASTORs involved in these LOS events after discounting simulation artifacts, pseudo pilot, and ghost controller errors. Each of the data points represents 120 minutes of simulation time across five test sectors.

Approximately half of all the LOS events could be traced to automation failures, causing late conflict detections, and the other half to operator/automation interaction failures, e.g.,

TABLE 2: LOS EVENTS INVOLVING ALL AIRCRAFT AND ASTORS ONLY

	Traffic level	MAP	Data comm eq.	LOS IFR-only all (ASTORs)	LOS Mixed IFR/AFR all (ASTORs)
Baseline	1x	18	0%	1 (1)	1 (0)
Minimum	1.2x	22	25%	3 (0)	3 (2)
Moderate	1.5x	27	50%	10 (1)	5 (0)
Maximum	2.0x	36	100%	0 (0)	2 (0)

ignoring a conflict warning or failing to probe a trajectory change before issuing it to the aircraft. There were no significant differences between IFR only and mixed operations within each NextGen stage. The ASTORs were involved in four LOS events, two as IFR in the IFR-only conditions and two as AFR in the mixed conditions.

Clearly, there were differences between the various stages of NextGen. The Minimum and especially the Moderate NextGen condition resulted at times in unacceptable separation assurance performance, because the traffic levels were increased beyond the complexities/levels that the operational environment could handle. Worst performance overall was observed in the Moderate IFR-only condition. Identifying the exact factors that made the scenarios unworkable will be the subject of further analysis and future publications. Remarkably, the Maximum NextGen condition performed very well at twice current traffic levels. The subjective data mirror the separation assurance performance very well.

2) Controller Workload

Every three minutes during a run, participants were asked to rate their subjective workload experience in real-time on a 1-6 scale from 'very low' to 'very high'. Participants rated their workload between 1 and 6 for all but the Maximum condition, in which their rating did not exceed 3. Mean ratings and standard errors are shown in Fig. 3. On average, participants' rated their workload at just over 3 ("moderate"), except in the Maximum condition, where participants' mean workload rating was just below 2 ("low"), i.e., participants reported their workload dropped in the Maximum condition significantly. However, there was no significant difference in workload between IFR/AFR and IFR-only conditions within any of the four NextGen conditions. Controllers' workload experience was also verified through post-hoc ratings. The results closely reflect the real time workload ratings and will be published separately.

3) Acceptability

Once for each condition, controllers were asked a series of six questions that form the Controller Acceptability Rating Scale (CARS) [7]. The CARS scale is comprised of four ratings, where participants indicate the safety, controllability, and satisfactoriness of the separation assurance operations and then rate its acceptability. Comparing the CARS ratings over the eight conditions, most of the controllers (84%) rated the full set of separation assurance operations as "acceptable", with only 16% giving a less than acceptable rating. Fig. 4 shows the

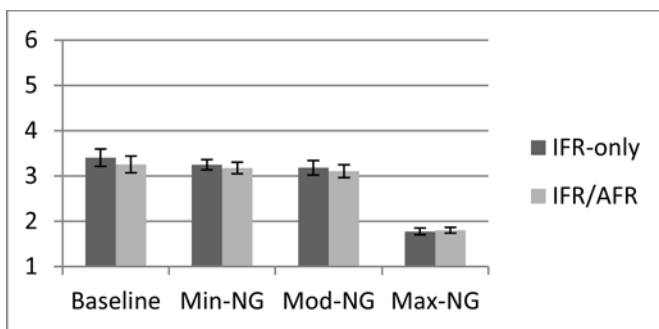


Figure 3. Mean real-time workload and standard error for all controllers under the 8 study conditions

means for each study condition when these ratings are combined. The mean ratings emphasize that the controllers rated the SA operations as safe and controllable with some amount of compensation on their part to make the operations run smoothly, as all the mean ratings fall between 6 "considerable compensation" and 10 "desired performance reached". Although the mean CARS for mixed IFR/AFR and IFR-only conditions within each NextGen condition are very similar, whenever there is a difference, the mixed IFR/AFR rating is slightly higher than the IFR-only rating. The main variation in mean ratings occurs between NextGen conditions.

While the average CARS rating was high for the Baseline, Minimum, and Maximum NextGen conditions at around 9 "minimal controller compensation" (a little lower for the Baseline-IFR condition), it was noticeably lower for the two Moderate conditions at 6.75. Although the averages mask it, this lower mean is not due to slightly lower ratings from all controllers but stems from two participants rating the operations as "unsafe". Their reasons for the unsafe ratings were mainly that they were not alerted to conflicts: "close vicinity descents were not alerting until after separation would have been lost". And secondly, they indicated that they were put in positions where they couldn't control the traffic in time, e.g., "no control over several situations in which aircraft were already in dangerous proximity to each other".

4) Situation awareness

An impression of how much controllers felt they understood about the new separation assurance automation and operations was targeted by using the Situation Awareness Rating Tool (SART) [8]. The SART is comprised of 3 subscales that participants rate on a 7-point scale. These ratings are then combined to generate an overall situation awareness (SA) rating for each participant in each run. With 7-point sub-scales, the SART scores range from -5 "very low SA" to 13 "very high SA"; a score of 4 is "medium SA".

Fig. 5 shows that, on average, in the Baseline and Moderate NextGen conditions, participants rated their awareness at just above "medium SA" (4). Ratings in the Minimum NextGen condition were slightly higher, and in the Maximum NextGen condition, participants' scores were above 10, indicating they felt they had "high" awareness. This is complementary to the workload ratings and indicates that controllers perceived the Maximum NextGen condition differently. SART scores were compared between mixed IFR/AFR and IFR-only conditions in

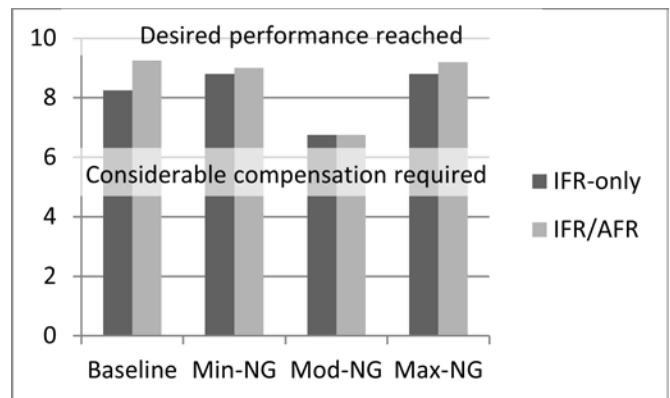


Figure 4. Mean CARS rating for each study condition

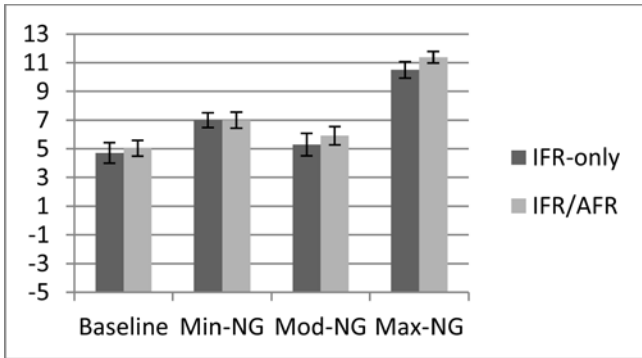


Figure 5. Mean Situation Awareness and standard error reported by controllers under the 8 study conditions

each of the four NextGen conditions using a Wilcoxon signed rank test, but none of the differences between the mixed IFR/AFR and IFR-only conditions were significant.

The SART subcategory ratings indicated that in the Maximum conditions controllers said there was very low demand in the mixed IFR/AFR condition and low demand in the IFR-only condition. Correspondingly, controllers rated that they had more spare capacity and slightly higher understanding in the Maximum NextGen conditions.

5) Flight-path efficiency

In order to gather additional insight into the effectiveness of mixed operations under the various stages of NextGen, the flight paths of the ASTOR aircraft flying under AFR rules were compared to their counterparts flying under IFR rules for all NextGen conditions. Since AFR aircraft had to avoid all other IFR traffic, they were expected to maneuver more frequently than IFR traffic. In order to get a first impression on this potential impact of additional resolution maneuvers and how NextGen environment differences might affect flight-path efficiency in dense air traffic environments, the progress the ASTORS made towards their destination was computed as the distance to the destination at the beginning of a scenario minus the distance after 20 minutes of flight time (chosen because some ASTORS exited the test airspace shortly after 20 minutes). As shown in Fig. 6, for the three NextGen conditions excluding Maximum NextGen, aircraft operating under AFR exhibited delayed mean progress toward destination relative to operating under IFR on the same initial routes, likely a reflection of additional flight miles flown. In part, the behavior is expected because AFR aircraft always gave way to IFR aircraft, whereas under IFR, the aircraft had a 50-50 chance of not being selected by ATC to maneuver for conflict resolution.

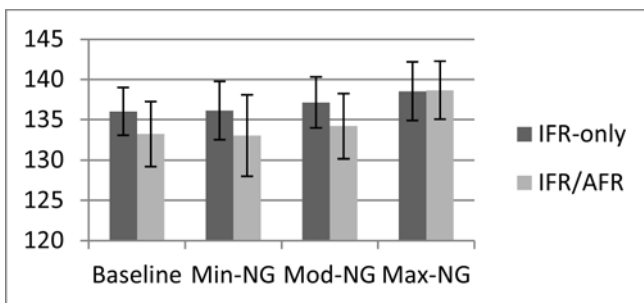


Figure 6. Progress towards destination after 20 minutes flight time (mean and standard error).

However, NextGen equipment and information assumptions were likely contributing factors as well. In the Baseline and Minimum NextGen conditions, AFR aircraft were not given access to IFR intent information. In addition, the Baseline to Moderate NextGen conditions included some voice-only aircraft for which intent information (available in the Moderate NextGen condition) was less reliable. The lack of intent information may have resulted in additional or prolonged tactical maneuvering by AFR aircraft, which can be less efficient. In the Maximum NextGen condition, aircraft progressed toward their destination equally well under AFR and IFR rules, indicating that in a truly trajectory-based environment, where intent information is ubiquitously available and reliable, both types of operations may have similar operating efficiency.

IV. PILOT-FOCUSED EXPERIMENT

The companion experiment in this coordinated research study addressed the perspective of the AFR pilot in mixed operations. Conducted at the Langley ATOL, the experiment focused on two issues: the ability of AFR aircraft to shoulder the burden of detecting and resolving conflicts with ground-controlled IFR aircraft, and the value of AFR aircraft having access to IFR intent information. The experiment was organized in two parts, a set of “primary” runs to examine the first issue and a set of “exploratory” runs for the second issue.

The primary portion of the pilot-focused experiment was designed to identify the limits under which AFR aircraft can ensure separation from IFR aircraft in normal operations. The parameters of interest included amount of alerting time and conflict geometry. It was hypothesized that achieving adequate separation performance requires some minimum amount of alerting time for pilots, and that conflict geometry does not have an interaction effect with this alerting time. To ensure AFR aircraft can shoulder the separation burden of mixed operations, it will be important that this minimum required alerting time be guaranteed through a combination of ATC restrictions on IFR maneuvers, IFR intent information sharing, and AFR automation design and parameter settings. An example of the latter is the use of extra separation buffers beyond the minimum required separation standard, a technique initially explored in this experiment. To test the effects of alerting time and conflict geometry, a series of scripted conflicts with a range of carefully controlled IFR maneuver timing and encounter orientation were created for AFR flight crews to resolve using automation tools. Controllers did not participate in these runs.

The exploratory portion of the experiment addressed the value of AFR aircraft having access to trajectory intent information from IFR aircraft. Currently, the ADS-B mandate does not require broadcast of intent, either trajectory change points or target state information (e.g., target headings and altitudes). The absence of this intent information may cause conflicts to “pop-up” with shorter notice, as planned IFR maneuvers are executed without forewarning. Pop-up conflicts can also occur when controllers turn, climb, or descend IFR aircraft in previously unplanned maneuvers in proximity to AFR aircraft, e.g., to resolve conflicts between IFR aircraft. These events can be mitigated through ATC-to-AFR voice

coordination or through ATC restrictions on IFR maneuvering near AFR aircraft, but the parameters of these elements need to be defined. To explore the issues surrounding intent information exchange, AFR flight crews flew a series of scenarios representing normal en route operations with and without automatic data transmission of IFR intent information. Confederate controllers and IFR aircraft pilots participated in these runs to provide for normal interactions.

A. Experiment Design

1) Primary Matrix

To test the ability of AFR pilots to resolve conflicts of varying timing and geometry, a test matrix of conflict scenarios was generated using a fractional $4 \times [2 \times 2 \times 2]$ between-subjects design with four categorical factors, shown in Table 3. The first factor was *Time to Buffer Loss* (TBL), the amount of alerting time given to pilots prior to reaching a buffered protected zone around the IFR aircraft (8 nmi lateral separation, 1000 ft vertical separation). Alerting times within each bin were assumed identical for analysis purpose. The quantity of data points planned for the first four bins was 12, 12, 18, and 24, respectively, emphasizing the shorter alerting times of greater research interest. An additional bin for alerting times less than 20 seconds included only vertical encounters, due to the difficulty in creating such short-notice lateral encounters. This bin contained six data points and was generally not combined with the other bins for statistical analysis.

The $2 \times 2 \times 2$ portion of the design represented three elements of conflict geometry: *encounter angle*, *maneuver dimension*, and *passage orientation*. The first element, *encounter angle*, was divided into convergence angle bins with the two aircraft either roughly aligned (“acute”) or roughly opposed (“obtuse”). *Maneuver dimension* refers to the IFR aircraft approach direction being either “lateral” (same altitude and level with the AFR aircraft) or “vertical” (climbing or descending into separation loss, with the AFR aircraft always level). *Passage orientation* refers to whether the IFR aircraft in the encounter would “pass in front” of the AFR aircraft or “pass behind” if the conflict were left unresolved.

A total of 34 airline pilots participated as 17 flight crews, with each crew flying 12 scenarios in the primary matrix. Each flight crew saw 12 scripted conflicts, but not the same 12 conflicts. A between-subjects design with blocking by groups of 3 crews was used to provide balanced coverage of the fractional test matrix, where not every geometry combination could be tested at every TBL condition. A complete description of the primary matrix experiment design and conditions tested is presented in [9].

TABLE 3. FACTORS INCLUDED IN PRIMARY MATRIX.

Factors	Values				
	Time to Buffer Loss	10-4 min.	4-2 min.	2-1 min.	60-20 sec.
Encounter Angle	Acute (0-50 deg.)			Obtuse (130-180 deg.)	
Maneuver Dimension	Lateral			Vertical	
Passage Orientation	Pass in front			Pass behind	

† Analyzed separately

2) Exploratory Matrix

To explore the value of IFR intent information in the context of normal mixed-operations procedures, a 2×1 within-subjects design was employed, with the one categorical factor of IFR intent information availability. With IFR Intent On, AFR aircraft received up to four trajectory change points for IFR aircraft, whereas with IFR Intent Off, only state information was received. Twelve flight crews participated in the exploratory runs in groups of six across two weeks. Over two weekly sessions, a total of 72 flights were accomplished, split evenly between IFR Intent On and IFR Intent Off (i.e., 12 flight crews each flying three scenarios in each of the two intent conditions). The flight duration was 30 minutes. Traffic density matched the Moderate NextGen condition (MAP = 27 aircraft per sector) in the controller-focused experiment, with all aircraft flying as IFR except the six subject AFR aircraft. Each run included one scripted conflict (TBL > 9 min.) near the beginning and additional conflicts occurring naturally following the initial resolution maneuver.

B. Facility and Test Scenario Description

The Langley ATOL was configured with six “team pilot” stations that permitted a flight crew to share a desktop simulator. Referred to as an ASTOR, the desktop simulator provides the displays and controls of a modern Boeing-style widebody jet aircraft. Integrated with the avionics system is an automation tool designed to support the flight crew in self-separation operations. The Autonomous Operations Planner (AOP) [10] provides a full suite of conflict detection, resolution, and prevention tools, using information obtained from ownship systems (aircraft state, autoflight settings, active strategic route, pilot-specified tactical flight targets) and ADS-B (traffic aircraft states, intent information if available), among other sources of information. AOP supports both “strategic” trajectory-based operations, i.e., fully coupled to the Flight Management System (FMS), as well as “tactical” operations using pilot-specified flight targets set on the Mode Control Panel (MCP). The flight crew is alerted to conflicts detected by AOP on a textual display, as well as by audible alerting and graphical depiction on the Navigation Display. Fig. 7 shows an example AOP display for a “tactical urgent” conflict.

In addition to the six ASTOR stations serving as AFR aircraft, the ATOL was configured with six MACS stations: two sector controller stations for the test sectors, one ghost controller station for the surrounding airspace, and three “pseudo-pilot” stations from which the IFR aircraft were flown. The MACS controller stations were configured in the Moderate NextGen mode (as described earlier for the controller-based experiment) with the corresponding



Figure 7. Example AOP display of a tactical-urgent conflict.

advanced suite of controller automation tools, IFR trajectory data comm., and auto-handoff capability for all aircraft. These stations were staffed in the exploratory runs. The scripted primary runs required no human controllers or pseudo-pilots.

The primary runs used the same Cleveland Center sectors tested in the controller-based study (Fig. 1), and the exploratory runs used a two-sector subset. The traffic files and densities matched the Moderate NextGen condition. The durations of the primary and exploratory runs were 10 and 30 minutes, respectively. The short primary runs were sufficient for detecting and resolving a single conflict, whereas the longer exploratory runs permitted operations to unfold naturally and produce more extensive interactions. Each pilot completed a survey after each primary and exploratory run. Additional pilot comments were captured during group debrief sessions.

C. Results of Pilot-Focused Experiment

1) Separation Assurance Performance (Primary Runs)

The purpose of the primary test matrix was to determine the limits of ability of self-separating aircraft to ensure separation from ground-managed IFR aircraft as functions of alerting time and conflict geometry. A total of 188 of 204 conflict scenarios were analyzed, excluding 16 scenarios where flight crews maneuvered preemptively and disrupted the scripted conflict.

Table 4 presents the LOS results. The separation standard for analysis was 5 nmi and 800 ft. All conflicts with alerting times greater than one minute were resolved without LOS. In the 20-60 sec. bin, 11 LOS events occurred out of 62 runs, excluding three borderline cases. A two-sided Fisher’s Exact Test [11] indicated the difference in proportions of LOS was significant between the top four bins ($p = 0.016$) and between the top three combined bins and the 20-60 sec. bin ($p = 0.001$). Thus, the data show that with at least one minute alerting, the flight crews using AOP tools and procedures were effective in ensuring separation from ground-controlled aircraft. However, many pilots indicated in their debrief comments that alerting of five or more minutes would likely be necessary for operational acceptability.

Statistical tests were unable to detect an effect of the three geometry variables (*encounter angle*, *maneuver dimension*, *passage orientation*) on the LOS results. Analysis of individual LOS scenario recordings confirmed that the primary factor in most cases was lack of sufficient time to initiate and complete a maneuver. Additional factors in some scenarios included crew response delay, desktop simulation control issues (mouse vs. real knobs and switches), and a simulation bug (uncommanded auto-flight mode switch). Two of the 11 LOS cases were Operational Errors with lateral separation less

than 4.5 nmi. The minimum separation for the smaller of these was 3.97 nmi.

To provide an extra safety margin in AFR-to-IFR separation, the primary conflict-detection logic employed a 3 nmi lateral buffer. Thus, AOP alerted conflicts if the distance to the IFR aircraft at the closest point of approach (CPA) was predicted to be less than 8 nmi rather than 5 nmi, and the primary “intent-based” conflict resolution algorithms computed maneuvers to remain at least 8 nmi from the IFR aircraft. If TBL decreased below one minute, the automation switched to a “state-based” conflict detection and resolution algorithm that used the minimum required 5 nmi separation standard (i.e., the 3 nmi buffer was ignored). Thus, the total system attempted to remain outside the buffer but ultimately acted to prevent LOS or, in the event of LOS, to establish divergence from the conflict aircraft to quickly restore separation.

The effectiveness of the buffer approach is a question of interest, as it is intended to provide additional time and airspace to maneuver for separation. The number of buffer losses, excluding actual and borderline LOS, is presented in Table 5.

As the time of first alerting was reduced (by design of each scripted conflict), the frequency of buffer loss increased, i.e., the buffered airspace was put to increasing use for maneuvering to avoid actual LOS. Statistical analysis using the two-sided Fisher’s Exact Test indicated significant effects of TBL between the top two bins combined and the third bin ($p = 0.001$), and between the third and fourth bins ($p = 0.001$). Additional testing determined that *passage orientation* geometry significantly affected the buffer loss frequency ($p = 0.004$). Taking all TBL cases together, the 3 nmi buffer was a more effective tool in ensuring separation when the intruding aircraft would pass behind the AFR aircraft than pass in front. In further testing of geometric effects, the mean actual CPA was 6.18 nmi (s.d. = 0.81 nmi) for acute-angle conflicts and 5.48 nmi (s.d. = 0.33 nmi) for obtuse-angle conflicts. A two-sample t-Test confirmed the *encounter angle* effect was significant ($p < 0.001$), indicating that the 3 nmi buffer was entered more frequently when aircraft converged with similar headings (rather than opposed headings). These results indicate that *non-circular* buffers may be equally effective at achieving the required separation performance while using up less airspace. Ultimately, in all of these buffer loss cases, the required minimum separation was preserved, a basic indicator of buffer effectiveness.

2) Effect of Shared Intent (Exploratory Runs)

The purpose of the exploratory runs was to compare operations where the trajectory intent of ground-managed IFR

TABLE 4. LOSS OF SEPARATION RESULTS BY INITIAL ALERT TIME.

Initial Alert Time	Losses of Separation	Number of Runs
4 – 10 minutes	0	33
2 – 4 minutes	0	32
1 – 2 minutes	0	46
20-60 seconds †	11	62
< 20 seconds	0	15
Total	11	188

† Excludes 3 runs in this bin with borderline loss < 0.04 nmi

TABLE 5. BUFFER LOSS RESULTS BY INITIAL ALERT TIME.

Initial Alert Time	Buffer Losses ‡	Number of Runs
4 – 10 minutes	0	33
2 – 4 minutes	3	32
1 – 2 minutes	13	46
20-60 seconds	37	48
< 20 seconds	10	15
Total	63	174

‡ Excludes actual and borderline LOS

aircraft was available to those where it was not. Other than an initial scripted conflict to ensure some maneuvering occurred during the run, conflicts occurred naturally in the complex airspace of Cleveland Center.

No LOS events occurred between AFR and IFR aircraft throughout the exploratory runs. The frequency of conflicts detected by AFR aircraft during the exploratory runs is presented in Fig. 8. The histogram indicates, for example, that 6 AFR flights detected exactly three conflicts during runs with IFR Intent Off, and 8 AFR flights detected exactly three conflicts during runs with IFR Intent On. Overall, runs with IFR Intent Off resulted in 207 conflicts, whereas runs with IFR Intent On resulted in 170 conflicts, an 18 percent reduction. A binomial test could not confirm significance of the reduction. As shown in the box plot, the distribution's tail was somewhat reduced with IFR intent information available, indicating fewer cases of high-frequency detection per flight, in addition to overall fewer conflicts. Since each conflict alert prompts an AFR trajectory change to resolve it, making IFR trajectory intent information available to AFR aircraft promotes greater stability and efficiency of trajectories in the airspace.

Out of 377 total detected conflicts, 111 were detected as "pop-up conflicts" with less than 4 minutes notice. Of these, 62 were detected with IFR Intent Off, and 49 were detected with IFR Intent On, a 21 percent reduction and improvement. The frequency of pop-up conflicts detected per flight is presented in Fig. 9. Although higher-frequency detections were not substantially affected by the availability of IFR intent information, flights with only one pop-up conflict decreased and the flights with zero pop-up conflicts increased. In this study, conflicts detected with sufficient notice (e.g., 4-10 min.) could be resolved with a "strategic" FMS route modification or cruise altitude change. Conflicts with less notice required a "tactical" response using open-loop maneuvering, a deviation from trajectory-based operations. The flight crew procedure for resolving conflicts with less than four minutes time available was to disengage FMS guidance and maneuver without delay using AOP's tactical resolution advisories. A total of 122 such mode switches were made, with 73 occurring

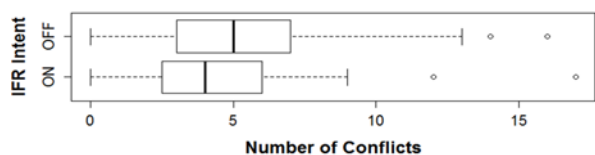
in IFR Intent Off runs and 49 occurring in IFR Intent On runs, a 33 percent reduction. The number of strategic-to-tactical mode switches made by the flight crews is presented in Fig. 10. These data show that frequent switches to tactical mode were reduced when intent information was available.

Of the 207 conflicts detected with IFR Intent Off, only 15 eventually involved a buffer loss. For IFR Intent On, only six of the 170 conflicts involved buffer loss. This indicates the buffer airspace was rarely entered in the "normal" operations tested in the exploratory runs. Reducing buffer size may therefore be feasible, allowing more efficient use of airspace without reducing safety.

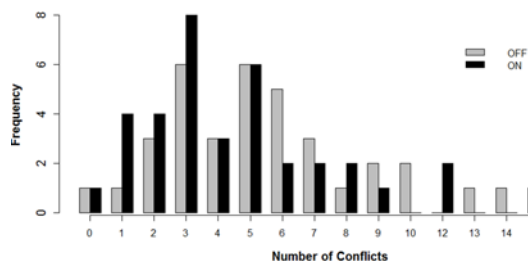
During group debrief sessions, the subject pilots had the opportunity to share and discuss their impressions of AFR operations and the issues tested in this experiment. Several pilots expressed a strong need for IFR intent information, specifically descent points and turns. Although opinions were varied, pilots generally agreed that a minimum conflict warning time of two minutes is required, with 5-10 minutes preferred for acceptability. It was also noted that ATC would not normally turn an IFR aircraft into conflict with an AFR aircraft, which will naturally limit the occurrence of late conflict detections. Because late detections often resulted in large trajectory changes and inefficient routes, it was noted that improvements are needed in the automation's tactical resolution logic to allow more efficient maneuvers. There was general agreement that the AFR procedures were easy and that the crew coordination was effective.

V. CONCLUSIONS

Two human-in-the-loop simulation experiments were designed and conducted in a coordinated effort to explore function allocation of separation assurance through a mixed-operations concept. The en route concept included ground-separated aircraft and self-separating aircraft in shared airspace,



(a) Box plot



(b) Histogram

Figure 8. Conflicts detected for conditions of IFR Intent On and Off.

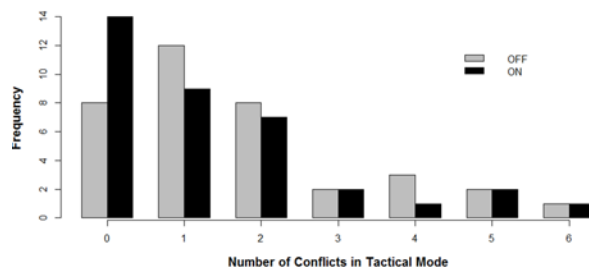


Figure 9. Conflicts detected for conditions of IFR Intent On and Off with initial alerting times less than 4 minutes.

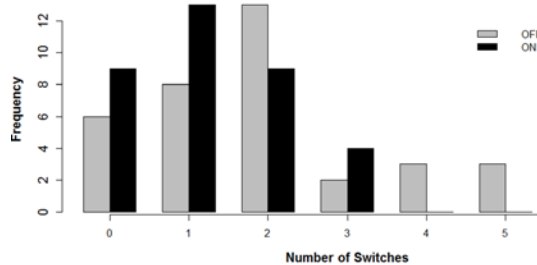


Figure 10. Number of switches from strategic to tactical mode for conditions of IFR Intent On and Off.

as well as varying levels of function allocations between humans and automation systems as NextGen technologies emerge. Simulation platforms incorporating advanced ground and aircraft automation tools were integrated and instantiated at two NASA research labs to test pilot-focused and controller-focused perspectives of the mixed-operations concept. Conclusions from the coordinated experiments are drawn with respect to three principal research questions.

How does the presence of self-separating aircraft affect the performance of the ground-based separation system?

To assess the impact of AFR aircraft on the performance of the ground-based separation assurance system, the results from IFR-only runs were compared to the results from mixed IFR/AFR runs in the controller-focused study. There were no significant differences between these types of operations in terms of separation violations, controller workload, acceptability, and situation awareness. Given that only a small subset of aircraft were conducting AFR operations, it can be concluded that the presence of a few self-separating aircraft does not impact the performance of the ground-based separation system.

What are the limits of ability of self-separating aircraft to shoulder the burden of mixed operations?

To determine the conditions within which self-separating aircraft could ensure separation from ground-controlled aircraft, flight crews tested a variety of conflicts with scripted alert timings and geometries. Using airborne automation tools and procedures, flight crews provided separation in all cases where at least one minute warning was given, regardless of encounter geometry. Pilots expressed a preference for at least five minutes notice. Two principal elements were identified to ensure such notice is normally available, thereby increasing safety, efficiency, and acceptability of mixed operations. The first element is airborne access to trajectory-intent information on planned maneuvers of traffic aircraft, either through ADS-B messaging or uplink from ground information systems. The second element is coordination between controllers and self-separating pilots on unplanned maneuvers of ground-controlled aircraft. The use of separation buffers to minimize the need for such coordination was effective but resulted in somewhat inefficient use of airspace.

How will the implementation and maturation of NextGen affect the ability to operate with mixed operations?

This question was addressed in the controller focused study by conducting IFR-only and mixed IFR/AFR operations in four different stages of NextGen. Overall, the Maximum NextGen stage outperformed all others by providing the same level of safety as the Baseline at twice the throughput and a lot less controller workload. In addition, only the Maximum stage enabled flight crews to provide their own separation from all other traffic with as little maneuver delay as the ground-based system, while all other stages required extra maneuvering.

As advancements continue to be made in airborne and ground-based computing platforms, automation tools, and data-exchange capabilities, a variety of methods of managing aircraft trajectories will emerge naturally. This research effort

has focused on determining whether multiple emerging function-allocation schemes for separation assurance can coexist in the same airspace. The approach emphasizes making effective use of all resources – human, automation, airborne, and ground-based – to achieve the most flexible and effective air transportation system possible to serve a highly diverse community of aircraft operators.

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