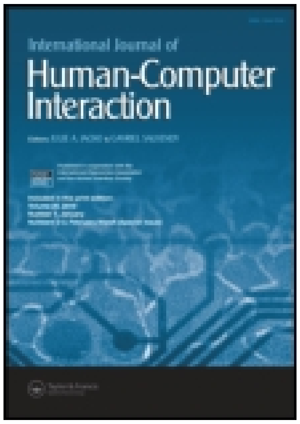

International Journal of Human-Computer Interaction
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/hihc20

Toward Automated Air Traffic Control—Investigating a Fundamental Paradigm Shift in Human/Systems Interaction

Thomas Prevot [a] , Jeffrey R. Homola [b] , Lynne H. Martin [b] , Joey S. Mercer [b] & Christopher D. Cabrall [b]

[a] NASA Ames Research Center, Moffett Field, California, USA

[b] San Jose State University/NASA Ames Research Center, Moffett Field, California, USA

Available online: 05 Jan 2012

Intl. Journal of Human–Computer Interaction, 28: 77–98, 2012
ISSN: 1044-7318 print / 1532-7590 online
DOI: 10.1080/10447318.2012.634756

Taylor & Francis
Taylor & Francis Group

Toward Automated Air Traffic Control—Investigating a Fundamental Paradigm Shift in Human/Systems Interaction

Thomas Prevot[1], Jeffrey R. Homola[2], Lynne H. Martin[2], Joey S. Mercer[2], and Christopher D. Cabrall[2]
[1]*NASA Ames Research Center, Moffett Field, California*
[2]*San Jose State University/NASA Ames Research Center, Moffett Field, California*

Predicted air traffic increases over the next 25 years may create a significant capacity problem that the United States' National Airspace System will be unable to accommodate. The concept of introducing automated separation assurance was proposed to help solve this problem. However, the introduction of such a concept involves a fundamental paradigm shift in which automation is allowed to perform safety-critical tasks that today are strictly the air traffic controllers' domain. Moving toward automated air traffic control, therefore, requires a careful and thorough investigation. As part of an ongoing series, three human-in-the-loop simulation studies were conducted at the NASA Ames Research Center with the overarching goal of determining whether the automated separation assurance concept can be integrated into air traffic control operations in an acceptable and safe manner. These studies investigated a range of issues including the proper levels of automation for given capacity targets, off-nominal operations from both air and ground perspectives, and sustained near-full mission operations with many tasks allocated to the automation in the presence of convective weather and scheduling constraints. Overall, it was found that the concept has the potential to solve the envisioned airspace capacity problem. The automation was largely effective and robust, and the function allocation of tasks between controllers and automation was generally acceptable. However, feedback and results also showed that further technological development is necessary to improve trajectory prediction and conflict detection accuracy. The need for further procedural development to govern controller/automation and air/ground interactions was also highlighted. These and other considerations are addressed as the automated separation assurance concept is further tested and pursued through subsequent studies.

1. THE NEED FOR AUTOMATION AND HUMAN–AUTOMATION OPERATIONS RESEARCH

Separating aircraft is the most important task for current-day air traffic controllers in high-density airspace, and it is one of the main components of their workload. In today's very safe system, air traffic controllers take active control over each aircraft in their airspace and issue clearances to separate each aircraft from one another. The main factor limiting en route capacity, therefore, is exactly this—controller workload associated with providing safe separation between aircraft—as this manual separation process can be performed only for a limited number of aircraft. As a consequence, each airspace sector today has a defined maximum number of aircraft that are allowed to enter. This constraint is a way of ensuring that the demands on the cognitive resources of the air traffic controller(s) working any particular sector are not exceeded (Kopardekar, Rhoades, Schwartz, Magyarits, & Willems, 2008).

The Federal Aviation Administration (FAA) currently predicts increases in instrument flight rules aircraft handled at FAA Air Route Traffic Control Centers of 25% by 2020 and more than 50% by 2030 (FAA, 2011). Demand increases like these will not be evenly distributed and could potentially increase demand, perhaps by more than 100%, in the busiest airspaces. However, separating aircraft using current-day techniques remains inherently limited by controller workload and will not be able to support the expected traffic growth (Erzberger, 2004). To illustrate the problem, Figure 1 indicates how an air traffic controller display might look if more than twice as many aircraft (right side) as compared to today (left side) were to be let into the airspace without additional modifications. Clearly, keeping track of each individual aircraft in this environment exceeds the cognitive resources of human operators.

Both the United States and Europe have programs under way that aim to update and advance their aviation systems: the Next Generation Air Transportation System (NextGen) in the United States (Joint Planning and Development Office, 2006) and the Single European Sky ATM Research Programme in Europe (SESAR Consortium, Eurocontrol, 2006). Each is promoting the investigation of a number of evolutionary concepts aimed at achieving incremental benefits over the next 10 to 20 years, including bringing new decision support technologies to the air traffic control (ATC) domain. This emphasis on introducing automation that will support, assist, and enhance ATC operators' capabilities is a characteristic that distinguishes these

Address correspondence to Thomas Prevot, NASA Ames Research Center, Moffett Field, CA 94035. E-mail: thomas.prevot@nasa.gov

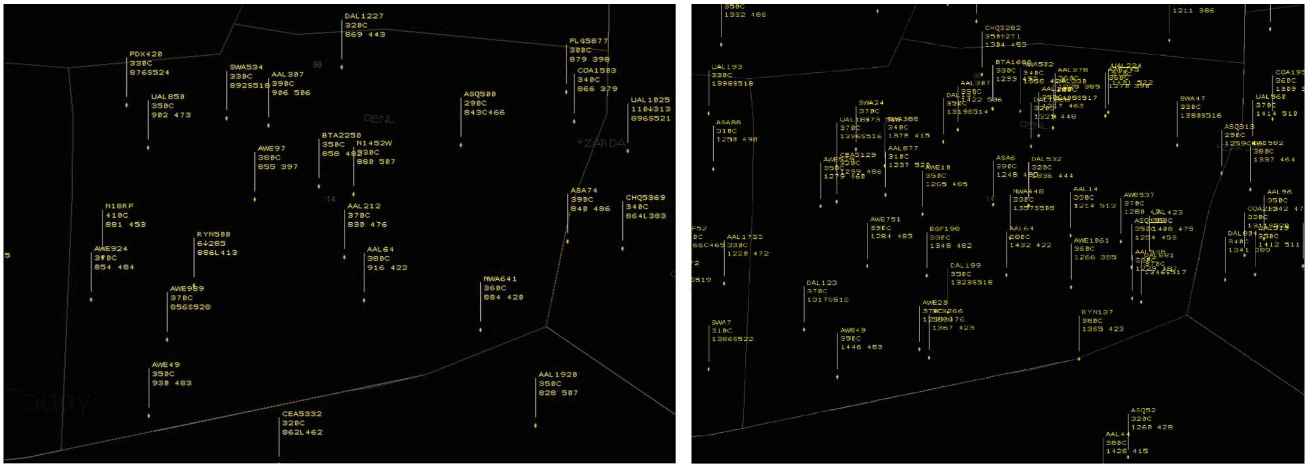

FIG. 1. Current-day controller display at current-day (left) and possible future (right) traffic density (color figure available online).

"next-generation" approaches (see, e.g., Pop, Stearman, Kazi, & Durso, 2012, Vu et al., 2012).

A key candidate function that could be enhanced by automation is separation assurance (SA), where the automation could undertake aircraft separation tasks, freeing the controller to provide service to, and complete other tasks for, a larger number of aircraft. Advances in route clearance technologies, such as trajectory-based operations and the introduction of digital communications (Data Comm) have enabled the development of concepts where separation problems could be automatically detected and resolved (Erzberger, 2001; Eurocontrol, 1999; McNally & Gong, 2006; Mueller, 2007; Prevot et al., 2005). The two primary automated SA concepts being investigated by NASA are airborne separation management (Wing, 2008) and ground-based automated SA (Erzberger, 2004, 2006). Both concepts involve new automation capabilities and new procedures for its operators, who are either pilots or controllers, respectively. The primary difference between the concepts lies in the location/distribution of the automated separation function: distributed among aircraft in the airborne concept or centralized within the ATC system in the ground-based concept.

These airborne and ground-based concepts have been developed in parallel over a number of years. Each has involved initial algorithm development and testing in fast-time, closed-loop simulations (Farley & Erzberger, 2007; Wing, 2008), and both now have matured to the point where effective human/automation cooperation frameworks can be studied in conjunction with the functioning of the automation in simulations. In 2010, the first two in a series of coordinated simulations to compare and integrate airborne and ground-based concepts were conducted (Wing et al., 2010). In addition to these collaborative efforts, there are many research questions that need to be addressed independently, and the operational research behind the ground-based concept forms the focus of this article.

Within the ground-based concept, the controller and the automation work together to enable levels of safety and efficiency equal to or greater than today in spite of much higher traffic demands. Figure 2 illustrates how the ground-based automated SA approach can impact the design of the controller display, as it presents a similar high-density traffic problem to that depicted in Figure 1. Shown in Figure 2 (right side), the automation manages most aircraft and highlights only those that require the human operators' attention. We briefly review the original concept here.

2. THE FOUNDATION FOR GROUND-BASED AUTOMATED SA—A CONCEPT

The original ground-based SA concept was developed by Erzberger (2001, 2004, 2009). The technical system incorporates two independent SA layers, each of which is designed to detect and resolve conflicts over different time ranges. In the first layer, an algorithm referred to as the Auto Resolver can be invoked to handle conflicts with times to loss of separation in the range of 2 to 20 min. This algorithm is intended to resolve nonurgent conflicts and is the mainstay of SA. The Auto Resolver aims to compute a complete trajectory that clears all traffic and weather conflicts and returns the aircraft to its original flight path. Because it takes time to communicate these trajectories to the flight deck and have them reviewed, loaded, and executed by the flight crew, the Auto Resolver is inappropriate to solve urgent traffic conflicts. Therefore, a second layer is realized through the Tactical Separation Assured Flight Environment (TSAFE), which contains an algorithm designed to handle urgent conflicts. Its main purpose is to provide a safety net for conflicts that were not detected and/or resolved by the Auto Resolver. TSAFE is designed to create an initial conflict avoidance maneuver that can be quickly communicated to and executed by the flight crew and keeps the aircraft clear of traffic for a few minutes while a trajectory-based solution is found.

The concept of ground-based automated SA utilizes technologies to shift the workload-intensive tasks of monitoring

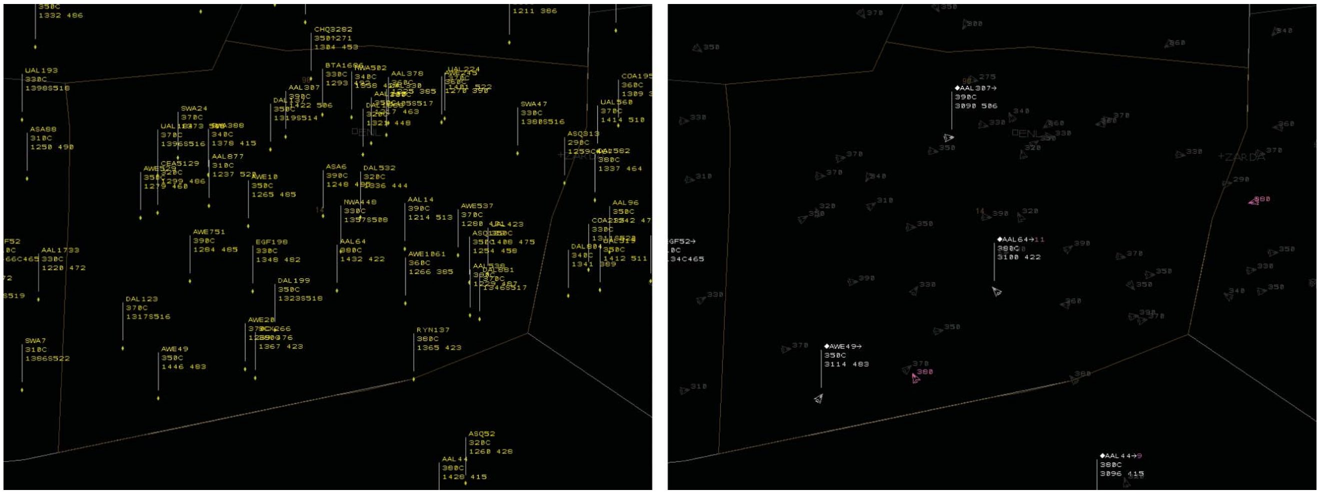

FIG. 2. High-density traffic (twice current-day demand) displayed on current-day controller display (left) and on controller display designed for advanced automation (right) (color figure available online).

and separating traffic from the controller to the automation. A critical element of this centralized concept is that the ground-side automation, not the controller, is 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 will be responsible for and will use a conventional voice link to maintain separation of unequipped aircraft and will step in to handle certain off-nominal situations. Thus, under automated SA, air traffic controllers' roles will involve providing service and performing decision-making activities in certain nominal and off-nominal situations, whereas the roles of monitoring, providing nominal separation functions, and providing back-up solutions in off-nominal situations will be allocated to the automation.

2.1. Challenge: Determining Requirements for Safety and Acceptability

Changing the cooperation framework under ATC human–automation operations raises many research questions. These questions range from fundamental concepts, such as safety and efficiency, through more detailed aspects of required procedural changes (e.g., what information needs to be communicated by who and to whom and at what times, etc.) to overall system performance under disturbances, such as weather or off-nominal conditions. Across all these aspects, a central tenet that motivates the human-in-the-loop (HITL) SA research is the question:

> Can SA automation be integrated into the ATC system in a safe, efficient, and acceptable way to achieve a significant airspace capacity increase?

The article reviews key findings from three SA studies designed to answer this question and to determine how best to allocate the functions between the air traffic controllers and the automation. A primary motivation for the work outlined here is the drastic change in roles and responsibilities for controllers by introducing the automated SA concept. The next section discusses the general method, followed by descriptions and key findings of a series of three progressively more complex controller-in-the-loop simulations. The article ends with a discussion about the implications of the findings for function allocation and ideas for future studies.

3. METHOD

A series of HITL simulations have been conducted over the last half decade within the highly adaptive facilities at the Airspace Operations Laboratory (AOL) at NASA Ames Research Center (Prevot, Lee, et al., 2010; Prevot et al., 2006). Progressively spanning from part-task studies to near full control room environments, the HITLs have focused on examining levels of automation, off-nominal operations, and constraints of weather and metering under advanced SA operations. Function allocation was a primary topic investigated in all studies. For all simulations, prototype technologies were implemented, and controllers, pilot participants, and confederates were exposed to operations with ground-based automated SA. Human and system performance data were recorded and analyzed, and the results were used to inform the next experiment. Next, we review the common apparatus and the commonly used metrics for the various studies.

3.1. Apparatus: AOL at NASA Ames

With its own customizable software system, the Multi Aircraft Control System (MACS; Prevot, 2002), and reconfigurable hardware and furniture components, the AOL can customize airspace, number, role, and position of participants and confederate operators as well as automation and communication technologies to provide the required test bed for multiple ongoing lines of NextGen research.

The conditions in the AOL are deliberately controlled to provide an environment for each particular set of participants that, outside of experimental aspects of interest, is as close to their anticipated specific work contexts as possible. Field-standard input and display devices are the same as those found in real-world ATC facilities. Each station has a touch-screen tablet PC-based emulation of the FAA's Voice Switching and Communication System complete with USB-based headsets, foot switches, and speakers allowing the participants to conduct realistic air–ground and ground–ground coordination via both direct and conference calling capabilities (Figure 3).

The aircraft in the traffic simulations are scripted with a start point and key parameters, like speed and route, but, once in the simulation, are worked by pseudo-pilots who monitor the flight parameters of the aircraft they control, respond to instructions given by the participant-controllers, and can create events if they are required for experimental purposes. Usually one pseudo-pilot is assigned to each controller-participant, but this ratio can vary if the traffic is particularly complex or experimental events demand.

4. METRICS

A set of five types of metrics was selected as the primary measures to describe the data from the SA studies. Other metrics were also used, where appropriate, to complement the descriptions of the data given by the five main types of metrics: throughput, efficiency, workload, safety, and acceptability.

4.1. Throughput

Across the SA studies, throughput was characterized by the computer-logged number of aircraft that flew within a sector over a period of time (e.g., in 1-min bins, over the course of an hour, or the total duration of a simulation run, etc.). An example of observed throughput for four different sectors across two different overall traffic density conditions within 30-min simulation runs is shown in Figure 4. Due to the dynamic nature of ATC simulations and depending on the run condition, the observed throughput may differ from the initially scripted load in the scenarios. Measuring throughput allowed for an assessment of how many more planes the controller and automation together were able to achieve service for in comparison to today's standards. Higher throughput reduces

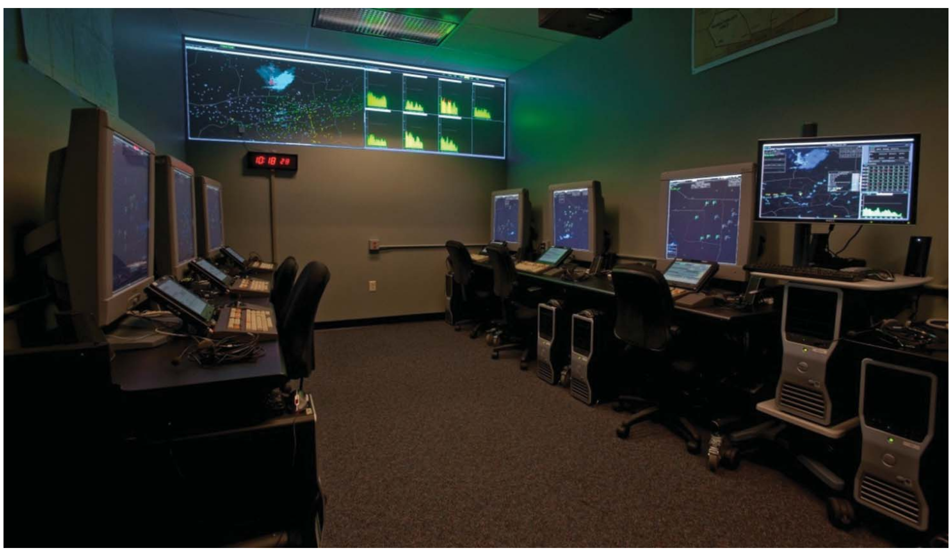

FIG. 3. En route control room configuration with controller and supervisor workstations (color figure available online).

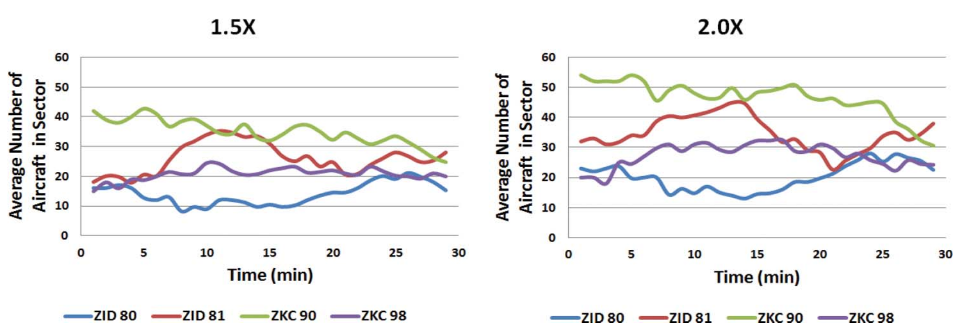

FIG. 4. Throughput metrics were captured as the number of aircraft that occupied a sector over a given amount of time (color figure available online).

the likelihood of aircraft to be delayed in the air or on the ground.

4.2. Efficiency

Flight path efficiency is the primary measure for the quality of the conflict resolutions. It was measured by both computer-logged data as well as subjective data. Differences between the originally scripted flight plan trajectories (both in time and in distance) and the trajectory the aircraft actually flew during the HITL simulations were computed as measures of efficiency. For example, a reroute around weather, as seen in Figure 5, would result in a longer trajectory than the initially filed flight plan for NWA234. In some situations, real-time arrival schedules were generated and schedule conformance (calculated as the differences between estimated time of arrival and scheduled time of arrival) were computed as another measure of efficiency. An example can be seen in Figure 6, where currently BTA501 and N165 are on-time and N413 and DAL851 are late according to the schedule. However, this sort of metric would be measured for each aircraft independently as that specific aircraft crossed the scheduled metering point (e.g., of SARGO in Figure 6). Third, efficiency was investigated through the computer logging of different kinds of clearances (i.e., route change alone, altitude alone, or route and altitude together) issued by the automation and the controller participants at key points, as each has different contextual costs to an aircraft's flight performance. Furthermore, postrun and postexperiment questions asked participants to rate perceived efficiency through, for example, asking about their modification of flight plans. Overall, efficiency metrics characterized how well planes were handled under the investigated allocation of functions. Flight path efficiency can be used to estimate the impact of the simulated air traffic operations in terms of fuel burn and environmental impact, and schedule conformance provides insights into an aircraft operator's ability to maintain their schedule and the likelihood for passengers to be delayed.

4.3. Workload

Workload metrics were collected in two different ways. The first workload measurement was administered in real-time during a simulation run based on the ATWIT technique developed by Stein (1985). At preset intervals (e.g., every 5 min) a chime would sound and a digital workload assessment keypad would appear in the top border of a participant controller's screen as a scale from 1 to 6 (Figure 7). Responses were made by directly clicking on a number in the scale or by pressing an associatively mapped function key on their Display System Replacement (DSR) keyboards. The second kind of workload metric was assessed through postrun questionnaires. Modified NASA-TLX (Hart & Staveland, 1988) workload questions

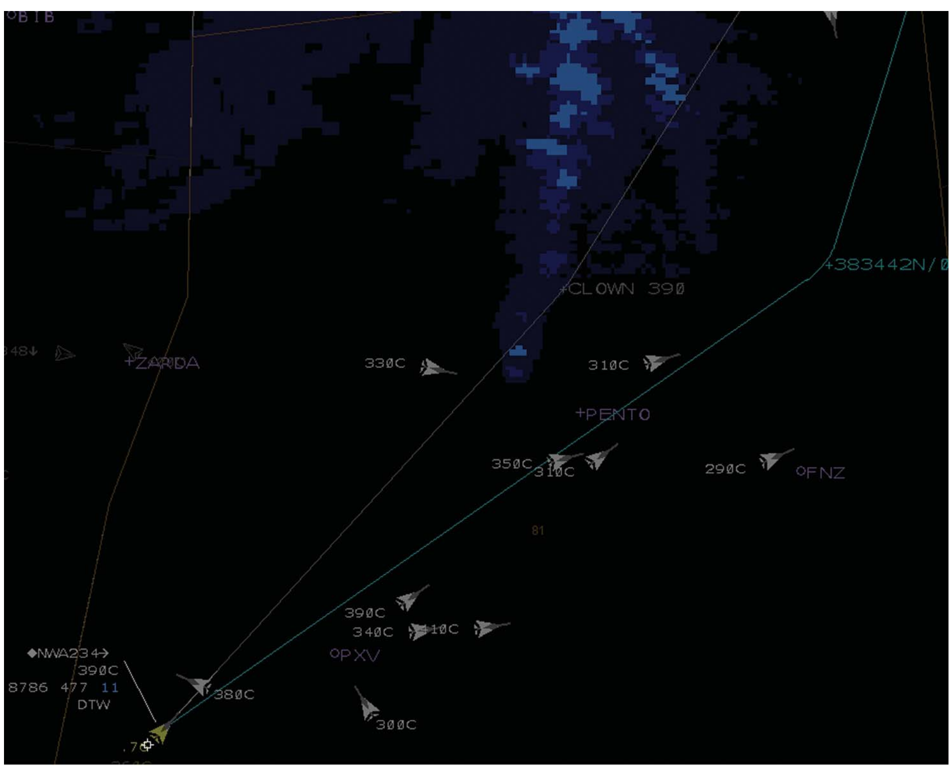

FIG. 5. Reroutes were measured as a form of efficiency by comparing them to original flight plans. Here, the aircraft's current route is displayed in gray and the proposed reroute around weather in cyan (color figure available online).

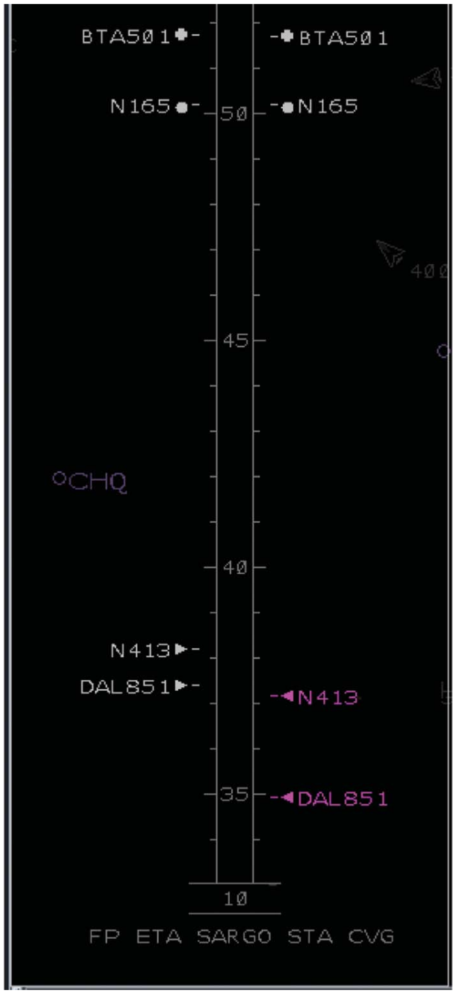

FIG. 6. Differences in estimated time of arrival (ETA) versus scheduled time of arrival (STA) were taken as an efficiency metric of achieved schedule conformance (color figure available online).

probed participants to assess their levels of mental activity, success, time pressure, and frustration on scales from 1 to 7.

If the allocation of functions between controller and automation were not properly balanced, controllers may become over- or underworked and will likely not be able to perform their duties most effectively and/or be dissatisfied with their work environment. In general, the goals for workload aimed for balanced midscale "in-the-groove" participant responses.

4.4. Safety

Safety metrics were centered around aspects of how close planes were predicted to come and actually came together; and in conditions with weather, how well aircraft were able to avoid the weather. These included computer-logged measurements of weather penetrations, conflict detections, conflict resolutions (automated or manual), and losses of separation, which were categorized as Proximity Events when horizontal separation was between 4.5 to 5 nautical miles and vertical separation was less than 800 ft, or as Operational Errors when horizontal separation was less than 4.5 nautical miles and vertical separation was less than 800 ft (Figure 8). Furthermore, subjective responses to questions of safety were collected from participants via postrun and postexperiment questionnaires. The number of conflict detections and resolutions provides insights into the severity and complexity of the SA problem and how the automation and operators performed these tasks. The selected function allocation concept aimed to present a manageable problem to the controllers by using automation for many functions in order to reduce and/or eliminate weather penetrations and prevent losses of separation. Therefore, these metrics are important in understanding the safety implications of the investigated function allocation.

4.5. Acceptability

Acceptability was measured with postrun and postexperiment questionnaires, primarily following the Controller Acceptance Rating Scale developed by Lee, Kerns, Bone, and Nickelson (2001) as closely as possible. Additional acceptability questions asked participants to rate various aspects of the concept's operations and tools along scales of usefulness and usability (e.g., Figures 9 and 10). For example, although the information of a particular decision support tool might be highly valuable and applicable for a particular situation (high usefulness), it might not be presented in a manner in which it can be effectively used (low usability). Although other metrics might show the functional allocation concept to be beneficial, these metrics solicited feedback from controllers to voice their personal and expert opinions on specific concept components that might otherwise have been overlooked. The function allocation concept needs to be highly acceptable, so that controllers will be comfortable in their work environment, like their job, perform at their peak and recruiting future controllers will not be a problem.

5. LEVELS OF AUTOMATION: THE FIRST HITL SIMULATION FOR SA

Although research has consistently shown that current operations cannot accommodate significant traffic growth, it was unclear how much automation would be required to accommodate certain levels of traffic growth. Joint Planning and Development Office (2011) documents indicate that NextGen should be designed to accommodate a traffic demand ranging from a 30% increase to as much as three times the current demand. To gain initial insights into the automation requirements for this range of potential demand increase, the first simulation was conducted to examine the following question:

> What level of automation is required/appropriate to meet specific capacity targets?

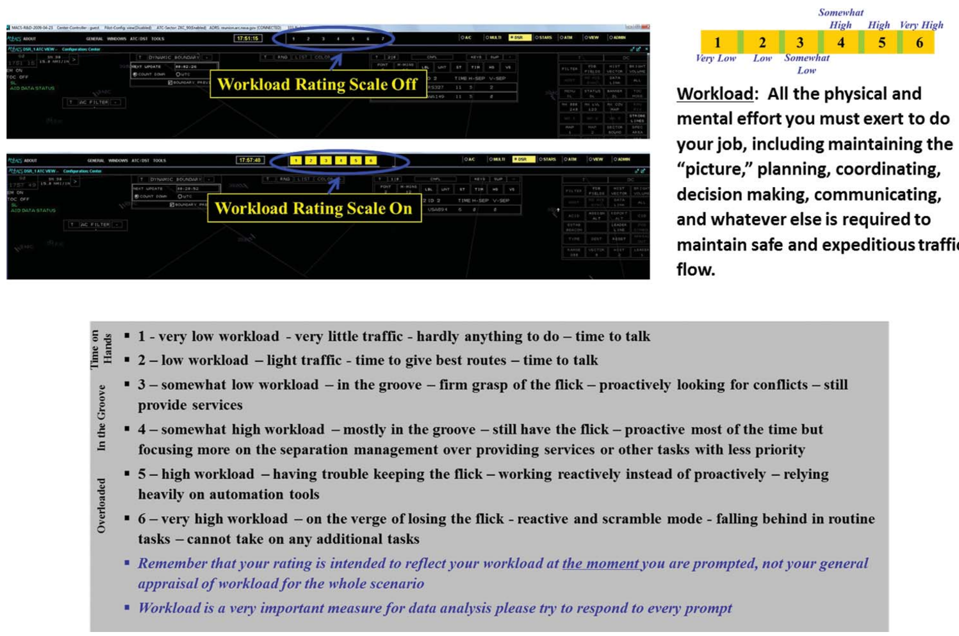

FIG. 7. Digital workload assessment keypads ranged from 1 to 6 and were integrated at the top of controller participant screens. *Note.* Interpretations of the numbers were briefed during the training session prior to the start of data collection (color figure available online).

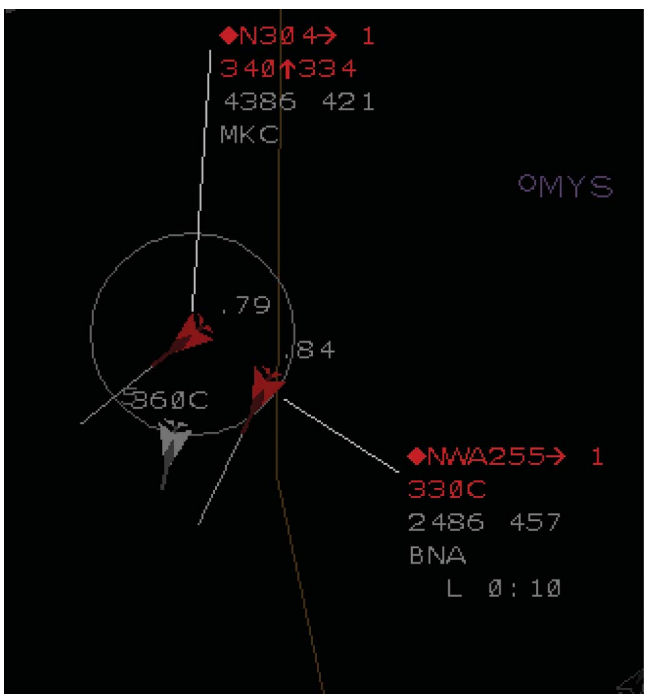

FIG. 8. Losses of separation were logged and characterized by how close the aircraft involved came together both vertically and laterally. *Note.* The circle around aircraft N304 represents a J-ring of 5 nmi radius (color figure available online).

5.1. Strategic Conflict Detection and Resolution Automation

The first study (SA1) was a part-task, HITL simulation conducted in 2007 (Homola, 2008; Prevot, Homola, & Mercer, 2008), which focused on the first, strategic layer of the SA system, the trajectory-based conflict detection and resolution layer. The study was a 3 × 3 repeated measures design that allocated conflict resolution functions under three levels of automation (manual, interactive, and fully automated) over three traffic densities (1x, 2x, and 3x). The *Manual* conflict resolution mode required participants to create their own conflict resolutions through MACS's graphical trajectory trial planning tool, without the aid of automated algorithm support. Resolutions were sent directly to the aircraft via data communications. In addition to the tools available in the Manual mode, the *Interactive* mode provided on-demand resolution suggestions that were provided by the automation. The resolutions were sent to the aircraft unchanged, modified according to the participant's strategy, or rejected by the participant. The *Fully Automated* mode allocated all conflict resolution functions to the automation and did not involve any human interaction in this process; no controllers were on-position. In this condition, the automation detected conflicts, generated resolutions, and sent them to the aircraft for clearance execution.

In the Manual and Interactive modes, for each traffic density, one controller was assigned the airspace equivalent of two of today's sectors, with about 15 aircraft per sector in the 1x conditions, about 30 aircraft per sector in the 2x conditions, and about 45 aircraft per sector in the 3x conditions. Each participant, therefore, managed an average of 30, 60, and 90 aircraft in the 1x, 2x, and 3x conditions, respectively.

As discussed in the introduction of this article and depicted in Figures 1 and 2, displaying higher levels of traffic density than today would unacceptably clutter current controller displays, rendering them inappropriate for the ATC task. Therefore a

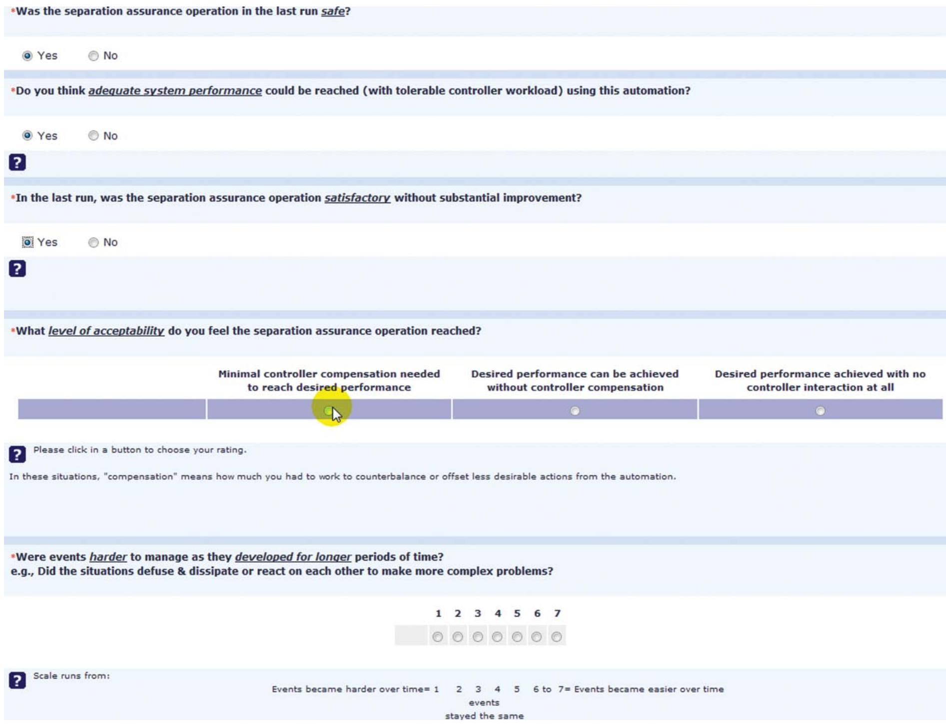

FIG. 9. Acceptability and safety example questions from postrun questionnaires (color figure available online).

FIG. 10. Tools and operations usefulness/usability acceptability questions from postrun questionnaires (color figure available online).

concept designed to enable 2x and 3x densities demanded a new display design. The display in the first study was designed for general situation awareness and management by exception and was tailored toward the conflict resolution task. Management by exception aims to free controllers from being involved in routine control events for every aircraft and moves toward having controllers focus on traffic management—primarily traffic monitoring—and stepping in to control individual aircraft only to resolve exceptional situations. Conflict detection was automated, and aircraft in conflict were highlighted according to their time to predicted loss of separation (LOS; Figure 11). Aircraft not in conflict were low lighted and essentially operated in the background. Nominally, aircraft were displayed as chevrons with altitudes, a design originally developed for cockpit displays of traffic information (Johnson et al., 1997). All functions for conflict detection and resolution, trajectory planning, and routine operations were directly accessible from the controller display. The participants' responsibilities were isolated to resolving detected conflicts in accordance with the levels of automated resolution support available in a given condition.

To enable traffic responses to controllers' actions, nine pseudo-pilots worked the aircraft. The operations in SA1 assumed that pilots would comply with all Data Comm messages and did not include any negotiations with pilots. So, the pseudo-pilots were asked to always execute the clearances given.

5.2. Key Findings

An analysis of the flight path efficiency indicated that as the traffic levels increased to the 2x and 3x levels, the Interactive and Fully Automated modes consistently resulted in less average delay imposed by conflict resolutions than the Manual mode (see Figure 12). This indicated that allocating some or all conflict resolution tasks to automation had a positive effect under the conditions of this study.

There were other effects as the traffic count increased. There was an increase in the use of automated resolution requests and a decrease in the modification of those resolutions by controllers indicating higher traffic levels required higher levels of automation to manage efficiently. Controllers were able to generate slightly better solutions when they had more time, but the automated resolutions were found to be acceptable and necessary when under the time pressure experienced at the 2x and 3x levels of traffic.

As may be predicted, given the increased reliance on automation to cope with traffic load, participant workload when measured in real-time (Stein, 1985) was found to increase significantly as the traffic levels increased (Figure 13). Although this increase was observed in both Manual and Interactive conditions, it was found that the Manual mode resulted in higher peak workload at the 3x traffic level than the Interactive mode, confirming the workload benefits of automated conflict resolution support.

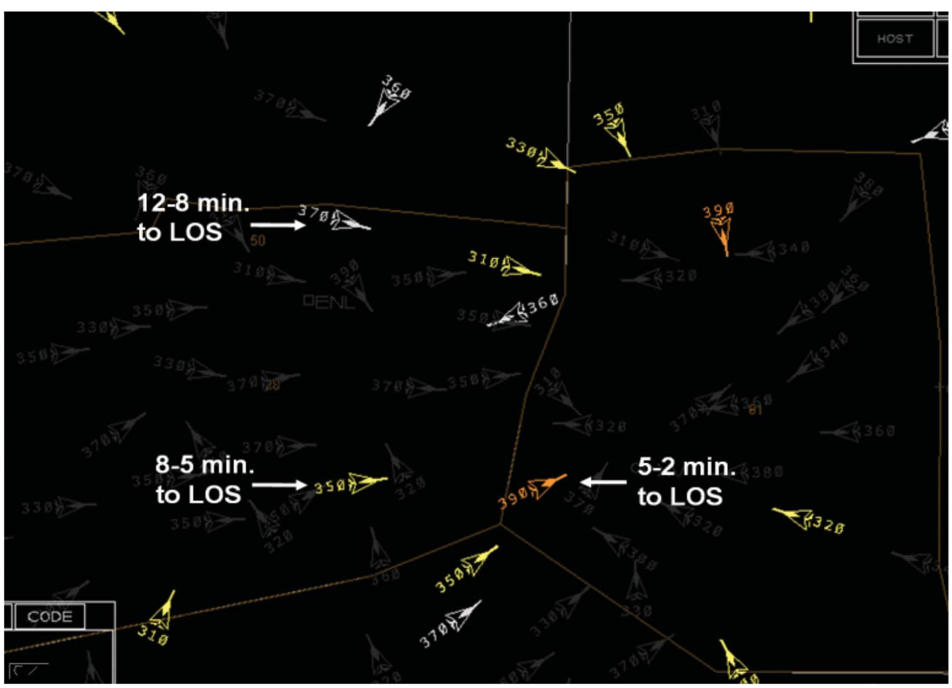

FIG. 11. Display design used in SA1. Note the differentiation in target symbol colors based on time to predicted loss of separation (LOS) (color figure available online).

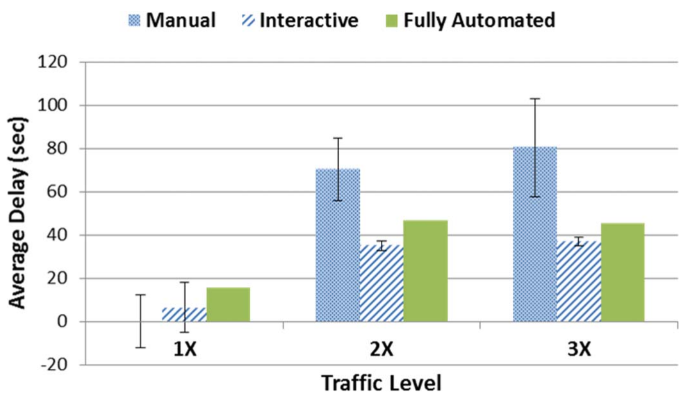

FIG. 12. Average delay imposed by conflict resolutions per level of automation across traffic levels. Note that standard error values did not apply to the Fully Automated condition (color figure available online).

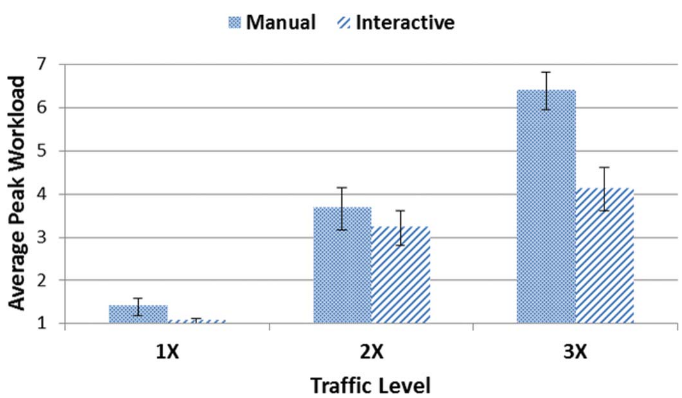

FIG. 13. Average peak workload ratings for the Manual and Interactive conditions across traffic levels (color figure available online).

The most dramatic impact of the automation, however, was apparent in the primary safety measure, the loss of separation events. As shown in Figure 14, there was a significant increase in the number of LOS events as the level of traffic increased. In addition, the Manual resolution mode resulted in significantly higher numbers of LOS events than the Interactive mode.

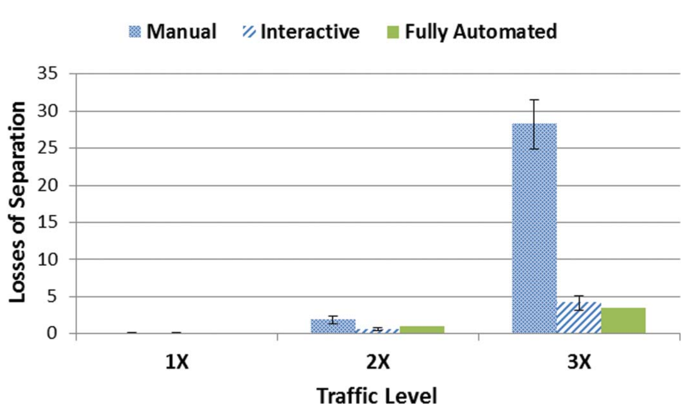

FIG. 14. Average number of loss of separation (LOS) events per condition (color figure available online).

In this study, the participants' role was dictated by the automation available, where the conflict resolution function was allocated to the automation in the Interactive mode but not in the Manual mode. While proving that the automation was necessary under higher traffic loads, the efficiency results from SA1 (Figure 12) also showed that controllers were able to improve on the solutions suggested by automation, given the time to properly consider problems. Thus, the participants did take on some of the decision-making role within the problems, sharing this function with the automation.

The resolutions provided by the automation were rated as generally acceptable by participants. The mean acceptability ratings of the conflict resolutions suggested by the algorithm were generally high across the three levels of traffic density. However, there was a trend that as the levels of traffic increased, the acceptability of the resolutions decreased such that the 3x level of traffic resulted in significantly lower acceptability ratings than those for 1x and 2x traffic levels. However, it is not entirely clear whether the difficulty of the 3x problems influenced the final ratings of acceptability.

In summary, the results from this first study showed that allocating some controller SA functions to an automated conflict resolution algorithm had a positive impact on safety, efficiency, and workload, particularly at the higher levels of traffic, and that the acceptability of the provided resolutions was generally high (for more details, see Homola, 2008). The Interactive mode, where both controllers and automation worked the traffic, resulted in fewer delays and LOS under 2x traffic than the Fully Automated mode, demonstrating that the awareness of the controller was supported by the strength of the automation and together they were more effective than either alone. However, a number of LOS events continued to occur even with such support. This was no surprise, because this first study included only the first, trajectory-based, SA layer and not the second, tactical layer. The results of this study underlined the importance of a safety layer and highlighted that further research needed to include this tactical component to protect against late or missed conflict detections and other off-nominal events.

6. OFF-NOMINAL PROCEDURES: THE SECOND HITL SIMULATION

The concept of ground-based automated SA shifts the role of the controller to one that supervises the automation and manages by exception. A common concern with this management by exception approach is the risk of a reduction in traffic awareness (Dekker & Woods, 1999; Endsley & Rodgers, 1996). This is a valid concern when one imagines a highly automated system operating in its nominal state, and suddenly a time-critical situation needs to be dealt with urgently by the operator. To examine this, off-nominal events were carefully scripted to cause short-term conflicts, simulate emergency situations, or require trajectory negotiations. Dealing with these events involved controllers trying to gain situation awareness immediately and engage in quick decision making.

Any new concept and technology needs to be designed to handle the off-nominal situations seen in today's air traffic system, such as medical emergencies, technical defects, severe weather, and so on, either by providing federal regulations or by certain strict technology requirements. Regulations can be instantiated as procedures for pilots and controllers that clearly define the tasks to keep aircraft properly separated while the off-nominal situation occurs. An example would be the clearly defined procedures for lost radio communication in today's environment. On the other hand, strict technology requirements are necessary whenever a technology degradation would result in an unmanageable situation. If the concept of automated SA assumes that conflict detection automation allows significantly more aircraft into an airspace sector than the operator can handle without the automation, then this technology needs to meet strict requirements about the probability and duration of any potential failures.

Because the first study's focus was to investigate the task of conflict resolutions in high-traffic densities, its part-task nature necessarily limited the role of the aircraft such that the flight crews accepted 100% of the uplinked trajectories. Including more realistic flight deck operations, where pilots could initiate route requests, be unable to comply with clearances, and so on, became an additional objective of the second simulation. Therefore, evolving the concept into one that addressed off-nominal situations as well as the role of the flight deck and the issues associated with a richer environment of air–ground operations steered the research question to the following:

> Can off-nominal operations be handled in an automated SA environment?

6.1. Enhancements Added to the Concept of Operations

The second study (SA2; Prevot, Homola, Mercer, Mainini, & Cabrall, 2009) was conducted in 2008 and focused on air–ground operations with off-nominal events. A key focus was the tactical safety layer and resolution mode to handle short-term conflicts. The first study confirmed that the strategic conflict detection and resolution algorithm was not able to reliably handle conflicts that were detected with short look-ahead times (i.e., less than 3 min from initial LOS). Therefore, in accordance with Erzberger's concept design, the TSAFE was added to the simulation prototype. TSAFE is a separate automation component designed to detect close-in conflict situations and automatically uplink heading changes to one or both of the conflicting aircraft (Erzberger & Heere, 2008).

To investigate the impact of the addition of the TSAFE automation, off-nominal events, and controller–pilot interactions: the roles, responsibilities, and procedures were evolved from the first study to create a more complete picture of the concept of operations. Both the Fully Automated and Interactive modes from the first study were utilized at the same time such that nominal operations were delegated to the automation system (i.e., they became fully automated), whereas exceptional circumstances were managed by the controller supported by graphical trial-planning and interactive conflict resolution tools.

More specifically, upon detecting a medium-term conflict (between 3 and 15 min before initial LOS), the automation sent trajectory constraints directly into aircraft FMS without controller involvement. When the automation detected a conflict with less than 3 min before initial LOS, TSAFE generated a heading change for one of the conflicting aircraft. These resolution heading changes were then sent to the appropriate aircraft's flight deck via a separate high-priority Data Comm channel (e.g., Mode-S). On the flight deck, this information was relayed to the flight crew through a graphical display and via speech synthesis for urgency. When an aircraft turned for a TSAFE instruction, the ground system's conformance monitoring function detected the off-trajectory status of the aircraft. For aircraft in this state, the conflict probe switched to an off-trajectory mode that was limited to only looking ahead 5 min along the aircraft's current velocity vector, which increased the potential for false alerts and required more attention from the controller. To return an aircraft to its desired trajectory, (i.e., nominal operations) the controller used the graphical trial-planning tools and uplinked a new trajectory to the aircraft, at which point the automation would again assume responsibility for managing the separation of the aircraft.

The role of the flight deck was expanded so that flight crews could downlink trajectory change requests at any time. The ground automation then probed the request for conflicts and automatically uplinked an approval message if found to be conflict free, without involving the controller. If the request could not be approved by the automation, the controller was alerted that there was a trajectory request that needed review.

6.2. Tactical Safety Layer

The study used a 2×2 repeated measures design that varied two tactical resolution modes (TSAFE, No TSAFE), across two progressively higher levels of traffic density: 2x and 3x. It challenged the concept of ground-based automated SA with the scripted insertion of routine and off-nominal events that created difficult short-term conflicts. Examples of events used to create off-nominal situations included but were not limited to loss of voice/data link communications, pilot declarations of medical emergencies, cabin depressurization, early/late descents, and trajectory nonconformance. To test the acceptability of air–ground trajectory exchange procedures, in addition to the controller participants, pilot participants were also included in the simulation, reviewing uplinked trajectories and initiating downlink requests.

In the No TSAFE condition, the controller participants had access to all strategic automated conflict detection and alerting support tools, trajectory trial planning tools, and data communications capabilities, but had to resolve short-term conflicts using their own judgment and voice communications.

In the TSAFE condition, the controller participants had the same complement of tools available as in the No TSAFE condition, but they were also supported by automation-computed tactical heading changes that could resolve short-term conflicts. The heading changes were computed for one or both aircraft in a conflict pair that were detected with a predicted time to LOS of less than 90 s and were uplinked via a high-priority data communications channel to the aircraft without controller involvement. However, the controller was free to complement the TSAFE maneuver with one of their own to ensure separation.

To support these tactical conflict resolutions, displays were modified to show full data tags whenever two aircraft were in a short-term conflict. In the TSAFE condition, heading changes were indicated in the fourth line of the data tag (Figure 15).

6.3. Key Findings

This section provides a few key findings; for a more comprehensive description and analysis of this study, see Homola, Prevot, Mercer, Mainini, and Cabrall (2009) and Prevot et al. (2009). By and large, the concept of automated tactical conflict resolutions was found to be appropriate, feasible, and generally acceptable. In the simulation, various situations were designed to result in late conflict detections and separation losses without a tactical safety layer. Although it did not avoid all LOS events, the TSAFE automation showed promise to resolve many of those short-term conflicts. However, function allocation procedures between the automation and operator in short-term conflicts needed to be further refined.

Because this was the first HITL simulation that tested operations with TSAFE automation, issues related to the human–systems integration and how controllers worked with the automation were of interest. Analysis showed that in the TSAFE condition, participants often provided additional, complementary maneuvers that supplemented the tactical vector issued by TSAFE. There was also a greater tendency to use both aircraft in a conflict pair in an attempt to provide greater separation. Participants stated that they wanted to have final authority over the issuance of TSAFE maneuvers. Participants also called attention to the importance of having an awareness of the immediate traffic situation in making effective and safe time-critical decisions. All of these findings indicate that although the automation was able to handle off-nominal operations that were allocated to it, participants preferred to work interactively with the automation to resolve close-in conflicts.

In SA2, the participants' role was again dictated by the automation, which now included TSAFE. As was found in SA1 with the Auto Resolver, participants finessed the solutions offered by the TSAFE automation where they could, such as providing additional, complementary maneuvers that supplemented the tactical TSAFE vector. Task allocation feedback from the participants emphasized that, because they had a role in making time-critical decisions, it was important for them to build and maintain an awareness of the traffic situation. They also began to define the functions that should be carved out for them, such as having the final authority over the issuance of TSAFE maneuvers rather than the automation.

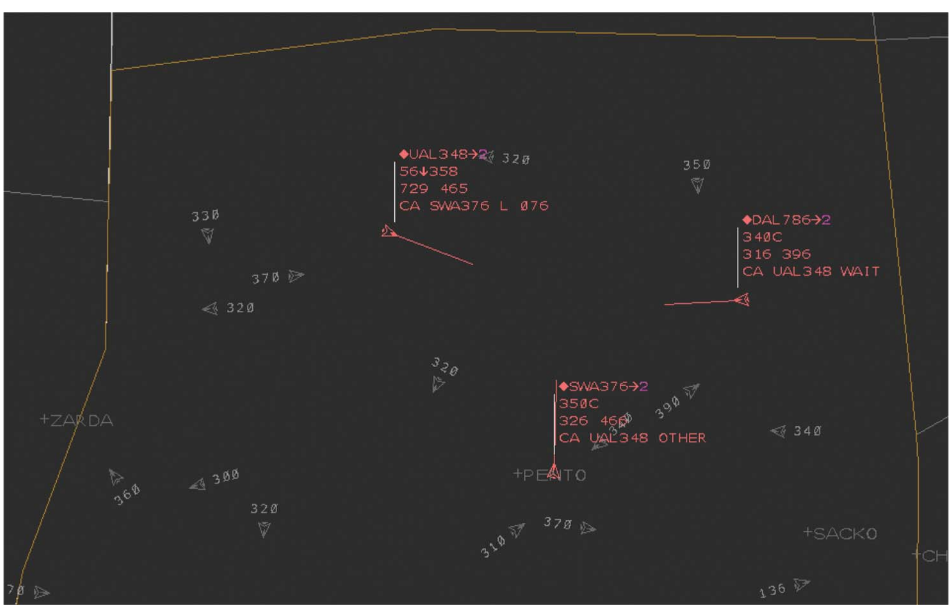

FIG. 15. Tactical Separation Assured Flight Environment (TSAFE) indication in the data tag (color figure available online).

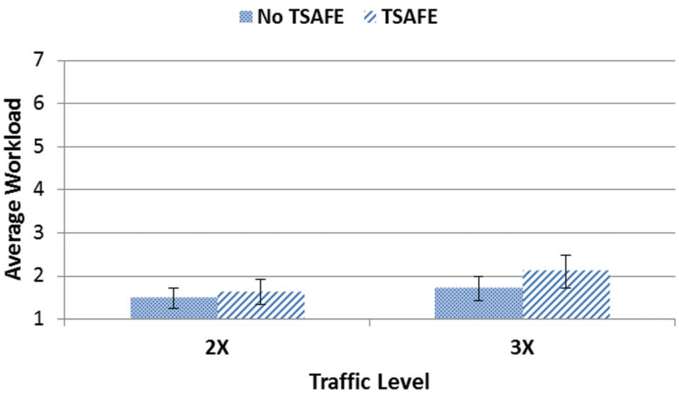

FIG. 16. Average workload ratings across traffic levels and resolution modes. TSAFE = Tactical Separation Assured Flight Environment (color figure available online).

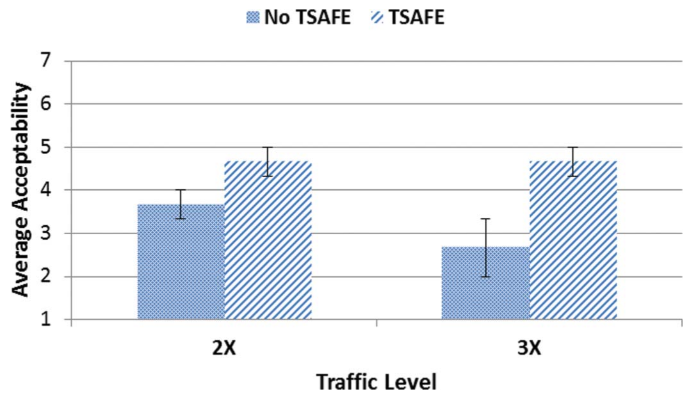

FIG. 18. Overall concept acceptability ratings by the controller participants. TSAFE = Tactical Separation Assured Flight Environment (color figure available online).

One of the objectives of this simulation was to examine the effectiveness of the concept in removing the controller workload constraint that has been cited as a limiting factor to airspace capacity increases. Workload ratings were obtained in real time (Stein, 1985) at 5-min intervals throughout the course of each run. Figure 16 presents the workload results across traffic levels and resolution modes, where it can be seen that workload was low regardless of traffic levels. Although workload was slightly higher for the TSAFE condition, the difference was minimal.

Safety analyses focused around conflict resolution success rates and LOS events. The number of successful conflict resolutions was converted to a success rate based upon the overall number of conflicts and LOS events (Figure 17). Although the success rate decreased as the traffic density increased from 2x to 3x, results showed that the TSAFE condition consistently provided improvements relative to the No TSAFE condition. Despite the decrease observed at 3x, the lowest success rate for the No TSAFE condition was still high at 98.13% of conflicts successfully resolved.

These safety ratings are supported by the participants' reported acceptability for the concept. Controllers' acceptability ratings of the overall concept were gathered from a postrun question that simply asked, "How acceptable/feasible was the overall concept?" Ratings were on a scale from 1 to 7 in increasing increments of acceptability. Figure 18 indicates that the TSAFE condition was rated as more acceptable than the No TSAFE condition across traffic density levels and that the concept was equally acceptable in the TSAFE condition at both 2x and 3x levels of traffic. The relatively low mean acceptability rating of only 4.5 even in the TSAFE condition was influenced by having the controllers exposed to off-nominal situations and scripted failures at a much higher rate than could operationally be expected. However, it also reflects the reservations that the controllers had with the tested prototype system as well as the function allocation for dealing with short-term conflicts: Both would have to be further improved. Extensive postsimulation questionnaires probed the pilot participants as well, and similarly, one major consensus was that conditions with TSAFE were ranked as more acceptable than conditions without TSAFE for both the 2x and 3x traffic densities.

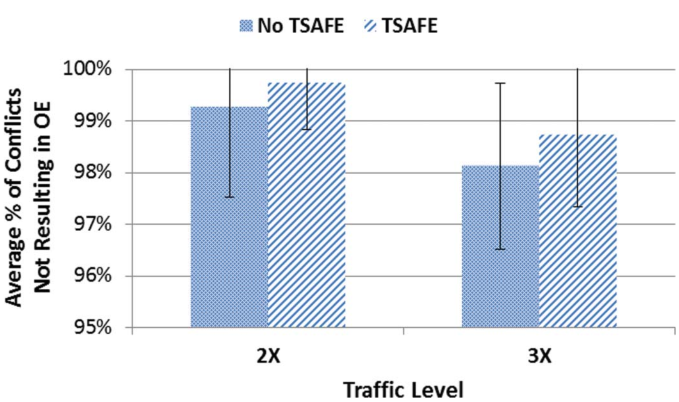

FIG. 17. Average rate of successful conflict resolutions. TSAFE = Tactical Separation Assured Flight Environment (color figure available online).

In this second simulation, participants operated in an environment that was an even further functional shift away from the current control paradigm in that all nominal separation and routine tasks were allocated to the automation. The integration of TSAFE automation as a tactical safety layer was shown to provide benefits in terms of safety and overall concept acceptability. Although LOS events still occurred and issues related to the interaction with the automation were raised, the overall results from this study indicated that the ground-based automated SA concept showed promise and highlighted the need for pursuing it further.

7. CONTROL ROOM OPERATIONS WITH WEATHER AND TIME CONSTRAINTS: THE THIRD HITL SIMULATION

The first and second studies showed that the concept of ground-based automated SA was a valid and promising approach. However, the testing was limited, in a sense, to addressing specific aspects of the concept in isolation. The next step in our exploration into automated SA was to determine whether operations that integrate the technological and procedural advancements tested in the previous studies could be applied in a sustained, day-to-day setting under typical constraints, such as heavy convective weather and metering requirements. The question, then, that guided this effort was as follows:

> Can automated SA be a standard operating mode in the control room even with heavy weather and metering constraints?

This third and most recent study (SA3; Homola et al., 2010; Prevot, Mercer, Martin, Homola, & Cabrall, 2010; Prevot, Homola, Martin, Mercer, & Cabrall, 2011) was conducted in 2010 and expanded the complexity of operations to include a greater number of staffed control positions spanning adjacent and supervised Air Route Traffic Control Center areas of specialization. Unlike the prior studies, SA3 was focused not on a single piece of technology and its integration but on the interplay of all pieces within the larger context of the ATC system. The experiment was designed as an exploratory study rather than a formal evaluation. Controllers operated in a comprehensive work environment that required them to perform a wide range of ATC tasks and work with automation that performed other control tasks. The operator stations, tools, and function allocation remained constant throughout all runs. Three parameters were varied: (a) traffic demand on the airspace, (b) traffic demand on the metering fixes, and (c) convective weather situation.

Three-hour-long runs allowed the observation of operational aspects not yet represented in the typical short simulations of an hour or less, such as shift changes, stress, boredom, and fatigue. The study looked to push the envelope past the shorter duration and single-sector part-task studies and explore a high-fidelity simulation environment that incorporated both meter fix-scheduling and weather constraints. In this scaled-up context, eight different radar controller positions and two supervisor positions were staffed across two different areas in adjacent central U.S. Air Route Traffic Control Centers: from the eastern part of Kansas City Center (ZKC) and the western part of Indianapolis Center (ZID), where the previous and shorter studies had used subportions of this same airspace (see Figure 19). Figure 20 shows a scene from the study as it was displayed on an overhead projector in the ZID control room during the simulation. Each colored symbol on the traffic situation display on top represents one active aircraft within the scenario. The gray area in the middle represents weather impacting the center of the test airspace. The displayed weather looped from 30 min prior to the current time to 30 min into the future, indicating the predicted weather. Underneath the traffic situation display are load graphs for the four ZID sectors 81, 80, 89, and 82. Indicated in red are predicted sector loads of more than 45 aircraft for a given sector. These sectors have current-day Monitor Alert Parameters of maximum 18 aircraft. During the study, controllers could look up to this display, which was driven by the area supervisor, and gauge their current and future load as well as the overall traffic situation.

7.1. Further Evolutions in the Concept of Operations

The required tasks of the controller in this study's environment were, necessarily, a significant departure from the way they are today. In terms of SA, the controllers managed by exception, dealing only with conflicts that were either deferred by the automation or aircraft that needed to be placed back on to their trajectories following a tactical vector. The controllers were also required to avoid convective weather as well as to manage arrival metering to various airports.

Realizing such operations was enabled by incorporating the strategic and tactical components from the two previous studies. For weather avoidance, a weather probe function was used to probe aircraft trajectories for predicted weather penetration. In the event that an aircraft was predicted to penetrate, feedback was provided regarding the time until penetration. The controller could then use the trial planning functionality for rerouting aircraft appropriately around the weather. For metering constraints, the controllers had access to interactive timelines that presented each metered aircraft's estimated time of arrival in relation to its scheduled time of arrival. If the two times deviated away from one another beyond a defined threshold, the controller could activate an automated function that computed the necessary trajectory (i.e., route, altitude, and/or speed adjustments) to bring the estimated time of arrival and scheduled time of arrival within tolerances while ensuring that the resulting maneuver was conflict free and weather free.

For this third study, the controller workstation was further developed as depicted in Figure 21.

As shown in Figure 21, aircraft that were managed by the automation within the controller's sector had a brighter icon than the aircraft outside that area, which were dimmed. Additional information in data tags and colors were used to draw the controller's attention to a specific problem. Similar to Figure 2, the sector displayed in Figure 21 contained approximately 3 times as many aircraft as can be controlled within this sector in current-day operations. As in SA2, all functions for conflict detection and resolution, trajectory planning, and routine operations were directly accessible from the controller display. Transfer of control and communication between sectors was conducted by the automation. Traffic conflict information, hazard penetration, and metering information was presented where applicable. Full data tags were displayed only in short-term conflict situations, or when the controller selected them manually. Time-based metering was supported via interactive timelines, which showed aircrafts' estimated and scheduled arrival times at specific fixes, usually meter fixes into congested airports.

Traffic demand on airspace and metering fixes was varied within and between runs, with two basic traffic scenarios: (a) a

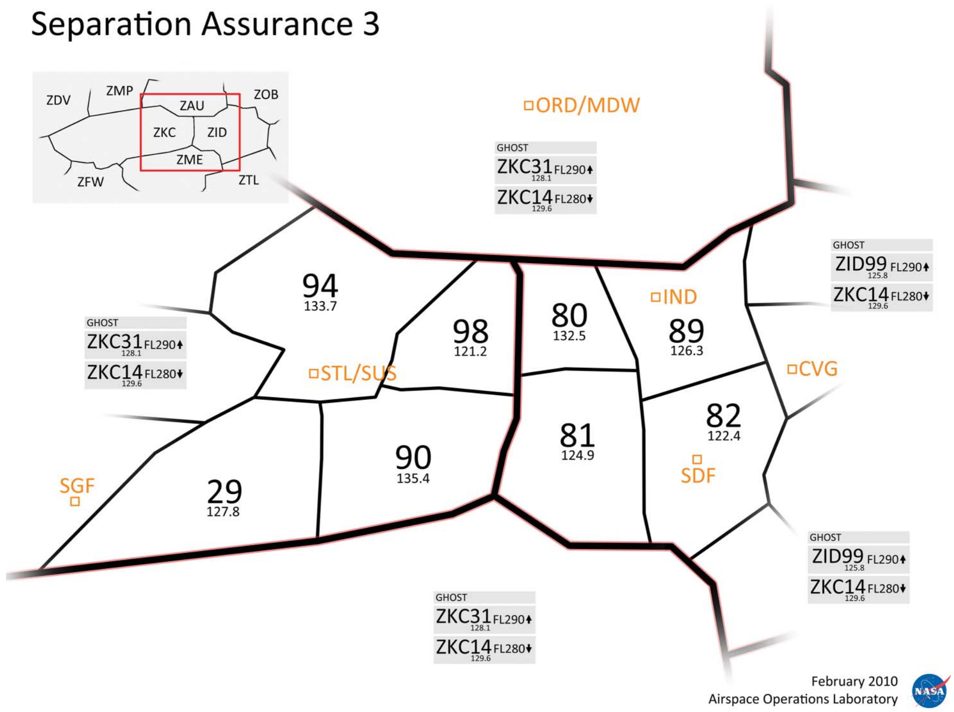

FIG. 19. Expanded airspace for simulation study (color figure available online).

FIG. 20. Scene from simulation as displayed on an overhead projector (color figure available online).

Light Metering scenario with 2,216 aircraft, moderate arrival flows with little meter delay, and (b) a Heavy Metering scenario with 3,060 aircraft, dense arrival flows often requiring more than 5 min of meter delays to be absorbed. Two different weather scenarios were used, where the convective weather was growing or decaying within half of each scenario and absent during the other half. This resulted in four different and challenging traffic, weather, and metering problems designed to stimulate a wide range of controller activities related to ATC and coordination. Each scenario lasted for 3 hr and, for analysis purposes, can be divided into three consecutive 1-hr-long phases. Each phase was a combination of a light or heavy metering situation and the presence or absence of growing or decaying weather.

7.2. Participants and Experimental Procedure

For this study, the AOL was configured with two participant control rooms, each hosting the four ATC sector positions and one supervisor position in ZID and ZKC, respectively. Refer to

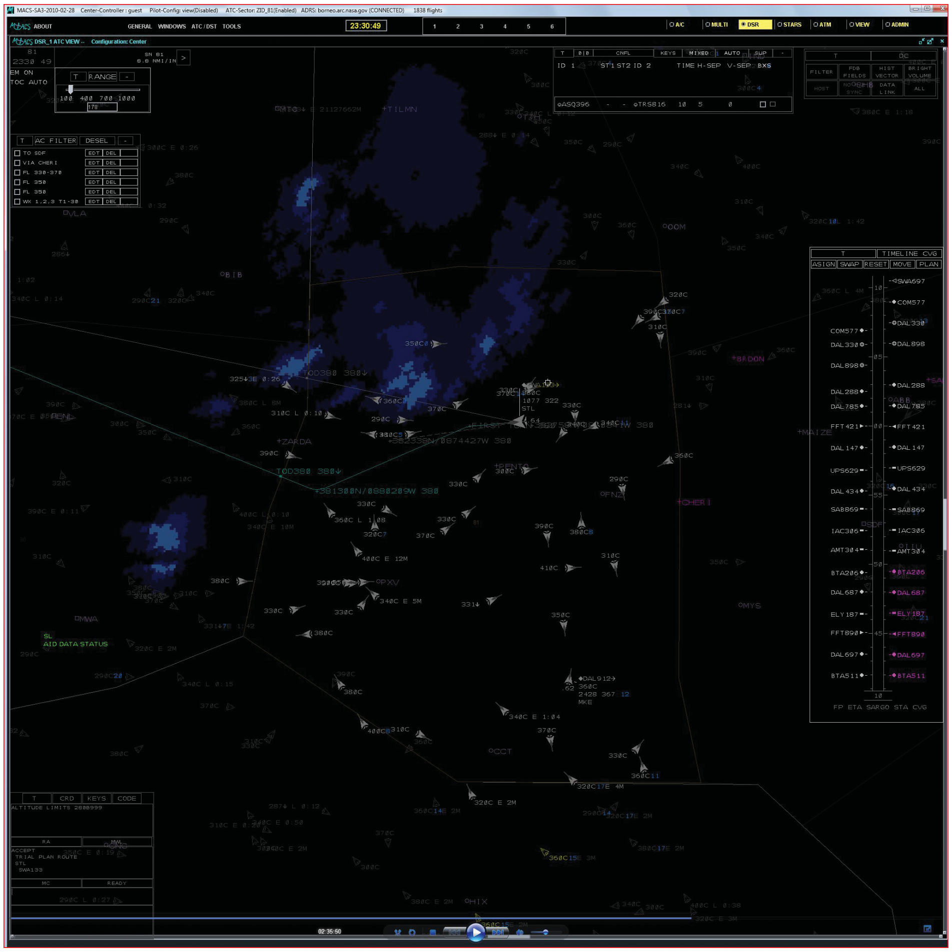

FIG. 21. Controller display designed for automated separation assurance (color figure available online).

Figure 3 earlier in this article for a layout of the ATC rooms with four radar positions and the supervisor workstation. Each workstation displayed one sector that was worked by a single radar controller. Six active FAA front-line managers certified as current on the radar position were complemented by six recently retired air traffic controllers and one supervisor from Oakland Center. Together, they staffed the eight ATC and two area supervisor positions in the two ATC rooms. Three additional confederate controllers worked the traffic flows into and out of the test sectors, and 10 general aviation pilots served as pseudo-pilots, who operated the simulated traffic.

After 3 days of training, the 3-hr-long scenarios were conducted for 4 consecutive days/afternoons. In each run, four teams of three controllers rotated through two neighboring sectors, so that each of the teams' three controllers worked both of their Center's sectors for 1 hr each. The rotation was scheduled such that a controller had a 30-min break after each shift and was therefore never on position for longer than 1 hr. Shift changes were scheduled and posted in the control room and the break room. During each shift change, the outgoing controller briefed the incoming controller, who then signed into the workstation.

System data as well as user inputs were recorded with the MACS data collection system. At 3-min intervals throughout each run, participants were prompted visually and audibly to rate their perceived workload. At the end of shifts in the first two phases of each afternoon, the outgoing participants responded to a short questionnaire in the break room. After each run, all participants completed a more comprehensive postrun questionnaire, which included items on function allocation. All questionnaires (postshift, postrun, and postsimulation) were posted electronically.

7.3. Key Findings

Conditions within this study provided the highest fidelity test yet of ground-based automated SA operations over extended durations and numbers of positions, and continued to show the concept's feasibility during routine operations even with constraints of weather and metering. Within the concept, weather and metering were evidenced to have larger impact on controller workload than aircraft count alone. In general, the function allocation between controller and automation was feasible but needed to be balanced with proper levels of controller engagement, development of suitable short-term human automation interaction procedures, and increased refinement of safety-critical automated conflict detection and resolution algorithms.

The operations demonstrated that aircraft count alone is not directly detrimental to safety performance. On the contrary, by respecting the appropriate levels of complexities (e.g., through the support of well-designed tools and procedures), the controllers and automation together were able to safely manage levels of traffic far beyond those of today. Figure 22 illustrates this high traffic load. It shows the peak aircraft counts in the test areas during a Heavy Metering run, which peaked at just over 60 in the ZID Center (Phase 3, Figure 22) and at just over 50 in the ZKC Center (Phase 1). As a reference point, today the peak aircraft count for these sectors is not supposed to exceed the Monitor Alert Parameter of 18 aircraft.

Workload was also found to increase with more severe weather and metering conditions. This was not surprising given that these conditions required a greater number of tasks to be performed to maintain safety and scheduling requirements. However, the raw aircraft count did not appear to have an effect on the workload. Figure 23 presents the mean workload reported by the ZKC controllers overlaid on the mean aircraft counts for the Heavy Metering runs. Phase 1 of the Growing Weather run (upper portion of Figure 23) did not involve any weather cells, and the mean workload was relatively low despite high levels of traffic. In contrast, the workload reported for Phase 1 in the Decaying Weather run (lower portion of Figure 23) was much higher despite nearly identical aircraft counts. The only difference was that Phase 1 of the Decaying Weather run started with weather cells affecting the test airspace, whereas weather affected later phases in the Growing Weather run.

In the 12 hr of simulation, 1,450 loss of separation events were scripted to occur, and the participants were able to avoid all but 42 of these. Figure 24 presents the distribution of events across conditions and according to the phase of occurrence. As a testament to the approach of the concept, neither the aircraft count nor amount of weather present within a sector at the time of a LOS appeared to affect the probability of a LOS occurrence. Interestingly, it initially appears that time factors might have contributed to LOS events. Regardless of the specific run condition, the majority occurred in Phase 3 (20 LOS events) compared to Phase 2 (12) and Phase 1 (10). In addition, with respect to the controller rotation, 31% took place within either the first 10 min or last 3 min of a controller's shift.

From the pattern of these occurrences within specific localized arrival/departure flow interactions, candidates for improvement in the automation logic have been identified that would improve the conflict detection of climbing and descending aircraft and also allow TSAFE to send altitude in addition to heading changes. With these improvements, and further development of human–automation short-term responsibility procedures that would allow controllers to temporarily deactivate TSAFE for a given conflict, these losses of separation can be largely addressed and avoided in future operational refinements of the concept.

Subjective findings suggest that the selected allocation of functions was generally acceptable to the participants. Questions and debriefs probed for how adequate participants thought the function allocation was and what should be changed. Participants were asked to identify the agent that should perform different functions, as shown in Figure 25. The functions or activities included in the questionnaire fell into two categories: routine and housekeeping tasks, or decision-making tasks. The majority of the participants' responses allocated the

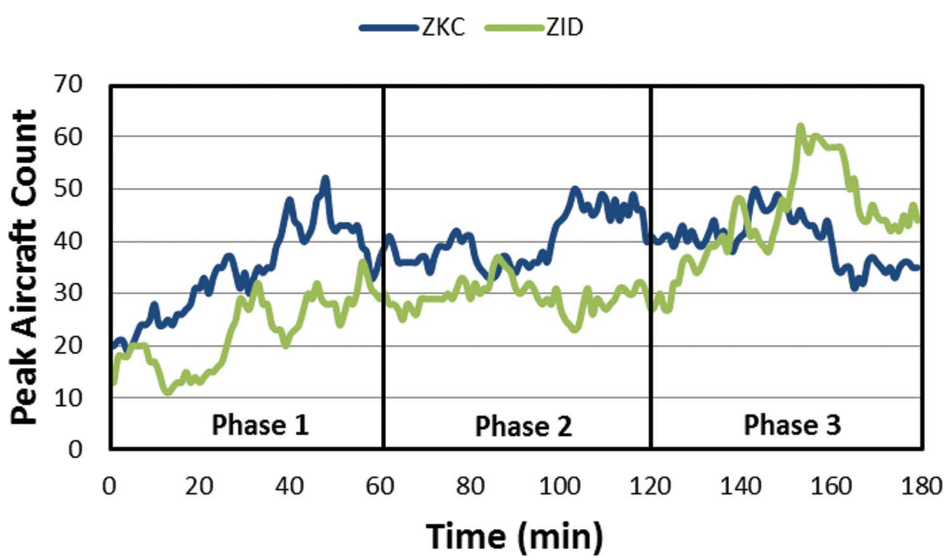

FIG. 22. Peak aircraft count for peak sectors in SA3 study (color figure available online).

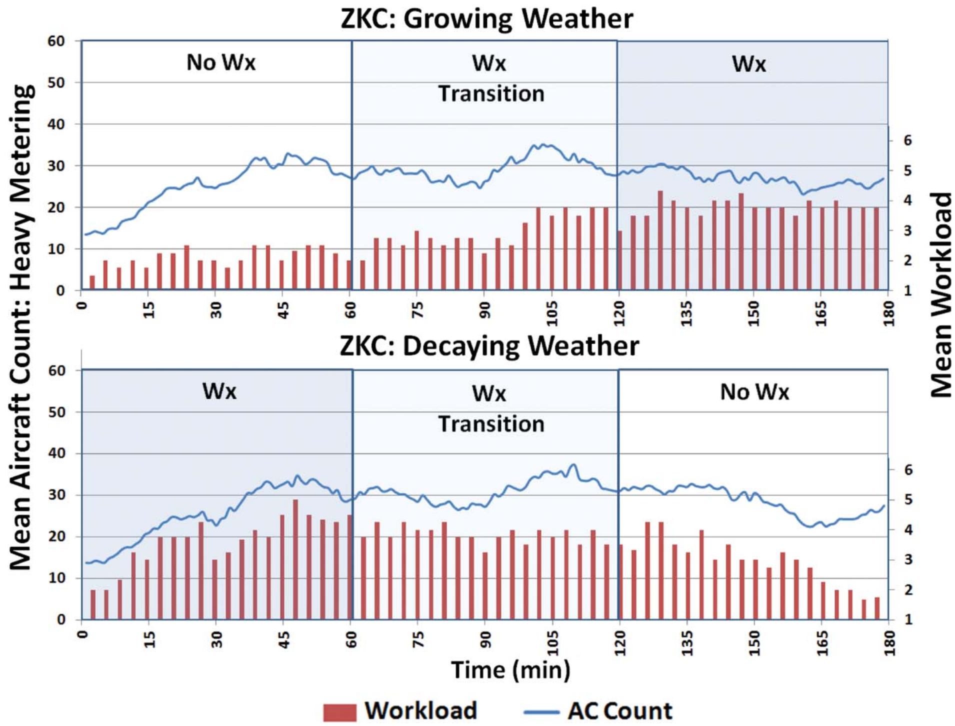

FIG. 23. Workload versus aircraft count in SA3 study (color figure available online).

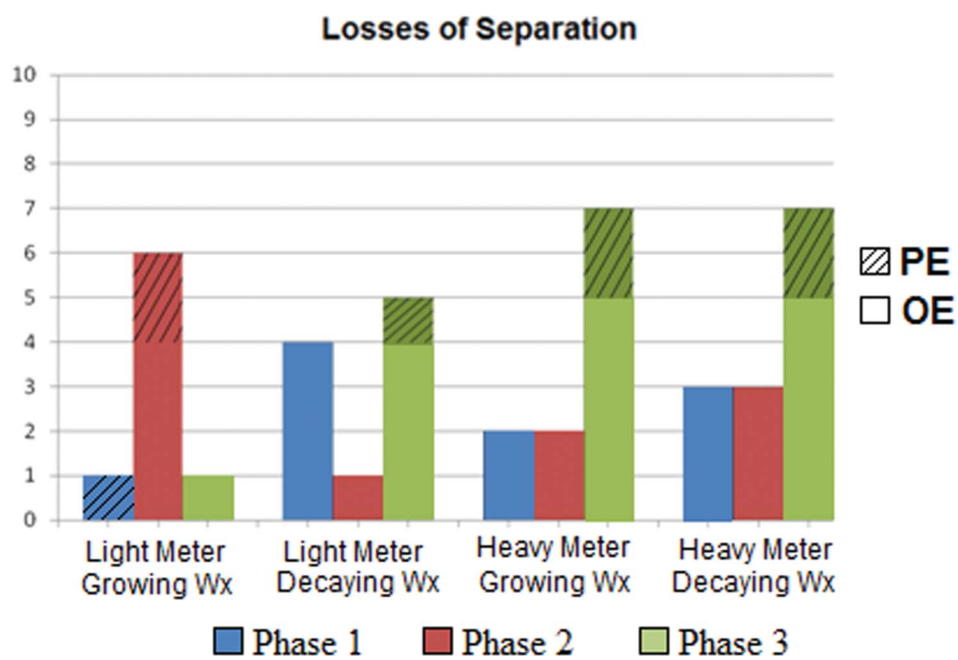

FIG. 24. Total number of loss of separation (LOS) events by condition and phase of run, categorized by proximity events and operational errors (color figure available online).

individual routine tasks either to themselves (e.g., display range changes) or the automation (e.g., handoffs), but for the decision-making tasks, their preferred response was to share the task, displaying a desire to work with the automation on those tasks.

However, specific comments in questionnaires highlighted that the tested allocation needs refinement particularly in the area where the controller and the automation are both working on a problem. At this point, the efforts of controllers and

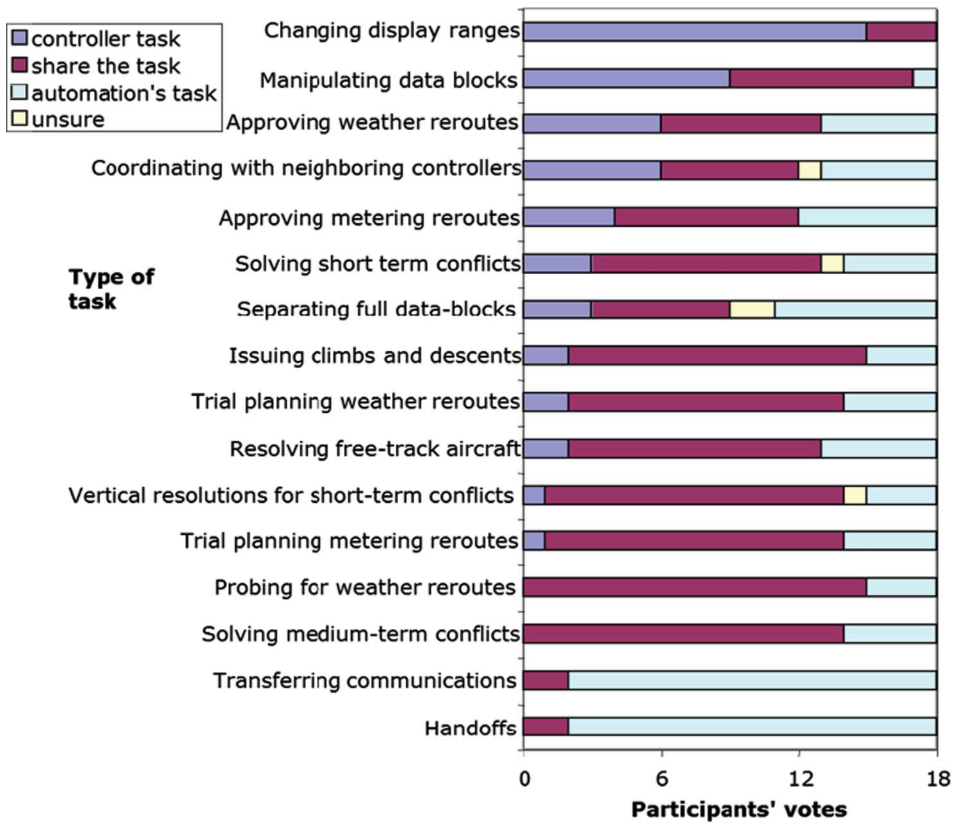

FIG. 25. Participants' allocation of tasks between the automation and themselves (color figure available online).

automation have to be complementary rather than antagonistic. For example, one participant thought that the "controller and automation fought against each other at times to resolve conflicts." Participants suggested earlier detection but later resolution of short-term conflicts from the automation to give them time to work the problem.

The acceptability ratings from the questionnaire were compared over the three phases of each run. On average participants found the SA operations slightly less acceptable as a run progressed, that is, the highest mean acceptability score was reported in Phase 1 ($M = 7.15$, "Moderate compensation required to maintain adequate performance") and the lowest mean Controller Acceptance Rating Scale (Lee et al., 2001) was in Phase 3 ($M = 6.56$, "Considerable compensation required to maintain adequate performance"). This is due to operations being consistently rated as more acceptable in the first phase than in the third.

SA3 again showed great promise for the operational feasibility of the concept, as did the prior SA studies. Workload, acceptability, and function allocation ratings were very positive and have proven informative for the tested operations. Real-time subjective workload ratings by and large were below the midpoint of the scale, and means were within a very workable range. Although acceptability ratings in the previous SA studies have been generally very high, the longer and higher fidelity runs in SA3 have evidenced negative implications of their extended use, in the present developmental state of the automation and controller procedures. Specific areas for improvement have been highlighted from the function allocation analyses.

8. DISCUSSION

Most concept developers are trying to answer the question of whether their concept will work under known real-world constraints and conditions. The ground-based automated SA concept is no exception, with the general question asked of it being:

> Can SA automation be integrated into the ATC system in a safe, efficient, and acceptable way to achieve a significant airspace capacity increase?

This question has been addressed through a series of three ground-based SA studies that have taken progressively more complex approaches and were designed to address four aspects of this central question: required/appropriate level of automation to meet capacity targets, handling off nominal events, automated SA as standard operations even with airspace and time limitations, and allocation of functions between operators and automation. The results pertaining to each of these four aspects—discussed next—have shaped the advancement of the concept and its future directions.

Required/appropriate level of automation to meet capacity targets. As traffic levels increase, SA1 showed that the automated conflict resolution algorithms became more important to maintaining desired levels of safety, efficiency, and workload. The resolutions provided by the automation were highly acceptable for the most part, although SA1 showed that losses of separation were a problematic area that merited focused study. In this study, the function allocation differences were determined by the research conditions.

Handling off-nominal events. With SA1 confirming that an SA concept sited in sectors with dense traffic requires a layer of automation at the tactical level to handle short-term conflicts, SA2 investigated how such a layer of tactical automation should work. TSAFE functioned at an acceptable level, providing safety benefits and supporting the concept in general. LOS still occurred, but under more specific conditions in which the conflicts were detected too late. Through this study, issues of function allocation began to come to the fore as participants asserted the functions they felt they should be responsible for—such as final decisions on the resolutions to short-term conflicts—and how the automation would have to develop to support this. To this point, the emphasis in SA1 and SA2 was on the ability of the automation to perform at desired levels. However, these findings from SA2 shifted the perspective of SA3 and beyond to investigate the roles of the controllers and their performance under day-to-day operations and typical real-world constraints.

Automated SA as a standard operating mode in the control room even with heavy weather and metering. The results of SA3 showed that sustained high capacity is achievable, even in the presence of convective weather and with heavy metering constraints. In addition, the results corroborate the findings from the earlier studies indicating that, unlike today, aircraft count is no longer the primary limiting factor for ATC. However, safety remains an issue, highlighting the importance of robust and reliable automation. Although some of the LOS data seem to suggest valid challenges for human operators (e.g., greater numbers in the last phase of any day and near shift transitions), the majority of LOS events were associated with the problematic complexity that comes with dense departure and arrival flows and fundamentally automation, rather than human, issues.

Allocation of functions between operators and automation. The reallocation of functions from the controller to the SA automation is arguably the most transformative aspect of this ground-based automated SA concept. At the core of all of the questions that have been discussed earlier in this article lies the question of function allocation. If higher levels of automation are needed, it has to be determined which functions should be allocated to the operator and which functions to the automation; this was the basic function allocation query addressed in SA1. Function allocation questions in SA2 centered around who should handle off-nominal situations: the controllers, pilots, or the automation? That is, should off-nominal events be addressed procedurally or technologically, or both? The concern in SA3 was to look at the problem of keeping controllers appropriately engaged, but not overworked, which speaks directly to the issue of function allocation. A common thread to all three studies was as follows:

How are functions allocated between operators and automation?

Layering the findings from the three studies begins to build up a picture of the direction in which the concept's function allocation is developing: allocating routine conflict avoidance to the automation, unusual situations to the controller, and providing information about short-term conflicts that gives the controller a larger window of opportunity during which they can intervene in a solution. The focus on function allocation in SA3 also highlighted issues that had been revealed in SA1 and SA2. Recognizing these, SA3 began the process of identifying the proper balance between the roles of humans and automation in this concept to maintain a consistent and appropriate level of engagement for the controllers. Controllers were comfortable with automation dealing with several routine tasks without their involvement but wanted decision-making authority and support in maintaining an overall awareness. The three studies have also served to shed light on specific tasks where the allocation of function was less clear, such as handling short-term problems.

On a broader level, although the concept development to date has addressed function allocation to ensure that the workload never exceeds the cognitive capabilities of the controller(s), an issue that remains is selecting those tasks to ensure that the air traffic controller is, at the same time, always engaged. This involves a balance not only in the *amount* of tasks that controllers have to complete but also the *substance* (complexity) of those tasks. One reason that the participants to date have found this concept acceptable could be that they were still involved with decision-making tasks and could, to an extent, choose to become more or less involved in the problems that occurred in their sector. However, many human–automation interaction issues remain and more were revealed by the study, with particular regard to short-term conflicts.

The research thus far has shown that SA automation can be integrated into the ATC system in a safe, efficient, and acceptable manner. This is a critical step toward achieving the capacity increases envisioned as part of NextGen. This step, however, is one of many that are necessary for realizing the full potential of the ground-based automated SA concept and understanding the challenges inherent in such a highly complex system. Continued research in this area is vital and will be undertaken through the continuing efforts planned in the Airspace Operations Laboratory.

9. FUTURE WORK

Future work will continue on many levels. The prototype automation will be improved to address the conflict detection/resolution deficiencies uncovered in SA3 and to provide the additional functionality requested by the controllers. Although these studies have provided a first look at some of the pertinent issues, questions still remain regarding procedures, controller interaction, the impact of the environment (e.g., weather), and automation performance under different situations. The changes in allocation of functions between controllers and automation, which will shift ATC operations into a new paradigm, require further shaping. Research, technology, and procedure development will continue to tie into this effort to improve the function allocation between air and ground and automation and controllers. Mixed equipage operations and off-nominal situations will also be studied, along with the continuing collaborative work to examine the ground-based SA concept with the airborne concept. As the concept matures, the process of phasing these new technologies and procedures into the current operating paradigm of manual control will be necessary. A gradual paradigm shift toward more automated operations can occur once the technology and procedures have been further refined in research and operations.

10. CONCLUSIONS

This ground-based SA concept shows great promise in solving en route airspace capacity problems for the foreseeable future. However, building its technologies is not enough. Making the technologies usable is a human–systems integration problem that requires HITL research and design iterations. Our investigations identified controller acceptability and reliance on strategic automated conflict detection and resolution under elevated traffic densities. Short-term conflicts emerged as problematic cases, tactical automation algorithms were tested, and improvements in timing and maneuvers were evidenced from real-time usage. Increased simulation fidelity in terms of extended duration and real-world constraints further informed operational feasibility. The function allocation of human–automation operations progressively developed across the studies into an effective and acceptable balance with the routine being addressed by the automation, the unusual by the controller and enough information/control provided for human engagement when appropriate. With the right research and integration approach, even this fundamental paradigm shift seems achievable. There is still a long way to go, but we believe this to be a promising path that ultimately can increase the efficiency of the air traffic system dramatically.

REFERENCES

Dekker, S. W. A., & Woods, D. D. (1999). To intervene or not to intervene: The dilemma of management by exception. *Cognition Technology and Work*, *1*, 86–96.

Endsley, M., & Rodgers, M. D. (1996). Attention distribution and situation awareness in air traffic control. *Proceedings of the 40th Annual Meeting of the Human Factors and Ergonomics Society*, 82–85.

Erzberger, H. (2001, December). The automated airspace concept. *Proceedings of the Fourth USA/Europe Air Traffic Management R&D Seminar*.

Erzberger, H. (2004). Transforming the NAS: The Next Generation Air Traffic Control System. *Proceedings of the 24th International Congress of the Aeronautical Sciences*.

Erzberger, H. (2006). Automated conflict resolution for air traffic control. *Proceedings of the 25th International Congress of the Aeronautical Sciences*.

Erzberger, H. (2009). Separation assurance in the future air traffic system. *Proceedings of the ENRI International Workshop on ATM/CNS*.

Erzberger, H., & Heere, K. (2008) Algorithm and operational concept for solving short range conflicts. *Proceedings of the International Congress of the Aeronautical Sciences 2008-8.7.5*.

Eurocontrol. (1999). *PHARE final report*. Available from the Eurocontrol website: http://www.eurocontrol.int/

Farley, T., & Erzberger, H. (2007). Fast-time simulation evaluation of a conflict resolution algorithm under high air traffic demand. *Proceedings of the 7th FAA/Eurocontrol R&D Seminar*.

Federal Aviation Administration. (2011). *FAA aerospace forecasts fiscal years 2011–2025*. Retrieved from http://www.faa.gov/

Hart, S., & Staveland, L. (1988). Development of the National Aeronautics and Space Administration (NASA) Task Load Index (TLX): Results of empirical and theoretical research, In P. Hancock & N. Meshkati (Eds), *Human mental workload* (pp. 139–183). Amsterdam, the Netherlands: North Holland.

Homola, J. (2008). *Analysis of human and automated conflict resolution capabilities at varying levels of traffic density* (Master's thesis). San Jose State University, San Jose, CA.

Homola, J., Prevot, T., Mercer, J., Brasil, C., Martin, L., & Cabrall, C. (2010). A controller-in-the-loop simulation of ground-based automated separation assurance in a NextGen environment. *Proceedings of the ENRI International Workshop on ATM/CNS (EIWAC 2010)*.

Homola, J., Prevot, T., Mercer, J., Mainini, M., & Cabrall, C. (2009). Human/automation response strategies in tactical conflict situations. *Proceedings of the Digital Avionics Systems Conference*.

Johnson, W., Battiste, V., Delzell, S., Holland, S., Belcher, S., & Jordan, K. (1997). Development and demonstration of a prototype free flight CDTI. *Proceedings of the SAE/AIAA World Aviation Congress*.

Joint Planning and Development Office. (2006, July 24). Concept of operations for the Next Generation Air Transportation System [Draft version 0.2].

Joint Planning and Development Office. (2011). *Vision 100—Century of Aviation Reauthorization Act* (Pub. Law No. 108–176). Retrieved from http://www.jpdo.gov/vision_100_law.asp

Kopardekar, P., Rhoades, J., Schwartz, A., Magyarits, S., & Willems, B. (2008, September). *Relationship of maximum manageable air traffic control complexity and sector capacity* (AIAA-ATIO-2008–8885). Paper presented at the 26th International Congress of the Aeronautical Sciences, Anchorage, AK.

Lee, K., Kerns, K., Bone, R., & Nickelson, M. (2001). Development and validation of the Controller Acceptance Rating Scale (CARS): Results of empirical research. *Proceedings of the 4th USA/Europe Air Traffic Management R&D Seminar*.

McNally, D., & Gong, C. (2006). Concept and laboratory analysis of trajectory-based automation for separation assurance (AIAA 2006–6600). *Proceedings of the AIAA Guidance, Navigation, and Control Conference and Exhibit*.

Mueller, E. (2007). Experimental evaluation of an integrated datalink and automation-based strategic trajectory concept. *Proceedings of the 7th AIAA Aviation Technology, Integration, and Operations (ATIO) International Conference*.

Pop, V., Stearman, E., Sadaf, K., & Durso, F. T. (2012). Using engagement to negate vigilance decrements in the NextGen environment. *International Journal of Human-Computer Interaction*, *28*(1), 99–106.

Prevot, T. (2002). Exploring the many perspectives of distributed air traffic management: The Multi-Aircraft Control System MACS. In S. Chatty, J. Hansman, & G. Boy (Eds.), *HCI-Aero 2002* (pp. 149–154). Menlo Park, CA: AIAA Press.

Prevot, T., Battiste, V., Callantine, T., Kopardekar, P., Lee, P., Mercer, J., . . . Smith N. (2005). Integrated air/ground system: Trajectory-oriented air traffic operations, data link communication, and airborne separation assistance. *Air Traffic Control Quarterly*, *13*, 201–229.

Prevot, T., Homola, J., & Mercer, J. (2008). Human-in-the-loop evaluation of ground-based automated separation assurance for NextGen (AIAA-ATIO-2008–8885). *Proceedings of the 26th International Congress of the Aeronautical Sciences*.

Prevot, T., Homola, J., Martin, L., Mercer, J., & Cabrall, C. (2011). Automated air traffic control operations with weather and time-constraints. *Proceedings of the 9th FAA/Eurocontrol R&D Seminar*.

Prevot, T., Homola, J., Mercer, J., Mainini, M., & Cabrall. C. (2009). Initial evaluation of NextGen air/ground operations with ground-based automated separation assurance. *Proceedings of the 8th FAA/Eurocontrol R&D Seminar*.

Prevot, T., Lee, P., Callantine, T., Mercer, J., Homola, J., Smith, N., & Palmer, E. A. (2010). Human-in-the-loop evaluation of NextGen concepts in the Airspace Operations Laboratory. *Proceedings of the AIAA Modeling and Simulation Technologies (MST) Conference*.

Prevot, T., Mercer, J., Martin, L., Homola, J., & Cabrall, C. (2010). Function allocation for ground-based automated separation assurance in NextGen. *Proceedings of the International Conference on Human-Computer Interaction in Aerospace*.

Prevot, T., Smith, N., Palmer, E., Mercer, J., Lee, P., Homola, J., & Callantine, T. (2006). The Airspace Operations Laboratory (AOL) at NASA Ames Research Center (AIAA-2006–6112). Reston, VA: AAIA.

SESAR Consortium, Eurocontrol. (2006, December). *Air Transport Framework, The Performance Targets D2*. Brussels, Belgium: Eurocontrol. Retrieved from http://www.eurocontrol.int/

Stein, E. S. (1985). *Air traffic controller workload: An examination of workload probe* (DOTIFAA/ CT-TN84124). Atlantic City International Airport, NJ: Federal Aviation Administration Technical Center.

Vu, K.-P. L., Strybel, T. Z., Battiste, V., Lachter, J., Dao, A.-Q. V. Brandt, S. Ligda, S., & Johnson, W. (2012). Pilot Performance in Trajectory-Based Operations under Concepts of Operation that Vary Separation Responsibility Across Pilots, Air Traffic Controllers, and Automation. *International Journal of Human-Computer Interaction*, *28*(1), 107–118.

Wing, D. (2008). Performance basis for airborne separation. *Proceedings of the 26th International Congress of the Aeronautical Sciences*.

Wing, D., Prevot, T., Murdoch, J., Cabrall, C., Homola, J., Martin, L., . . . Palmer, M. (2010, September). *Comparison of ground-based and airborne function allocation concepts for NextGen using human-in-the-loop simulations*. Paper presented at the 10th AIAA Aviation Technology, Integration, and Operations Conference, Fort Worth, TX.

ABOUT THE AUTHORS

Dr. Thomas Prevot is a principal investigator in the Human Systems Integration Division at NASA Ames. He received his doctorate in aerospace engineering from the Munich German Armed Forces University in 1995. Tom's research is aimed at developing and evaluating concepts and technologies for the future air transportation system.

Jeffrey R. Homola received his B.S. in Cognitive Science from UCLA and M.S. in Human Factors and Ergonomics from SJSU. He is a senior research associate in the Airspace Operations Laboratory where he has focused much of his research efforts on separation assurance and function allocation.

Lynne H. Martin works for the San Jose State University at NASA Ames Research Center, primarily researching human factors issues in future air traffic control system design and evaluation projects. She received her doctorate in Social Psychology on team decision making from the University of Surrey in England.

Joey S. Mercer is a Senior Research Associate for San Jose State University, working at NASA Ames Research Center. He earned an M.S. in human factors from San Jose State University, and for the past several years has been investigating human factors issues related to advanced air traffic management concepts.

Christopher D. Cabrall earned his B.A. in Psychology and Linguistics with a minor in Computer Science from Northeastern University in 2007 and a M.S. in Human Factors and Ergonomics from SJSU in 2010. He has been with the AOL for the last 3 years.