GROUND-SIDE PERSPECTIVE ON MIXED OPERATIONS WITH SELF-SEPARATING AND CONTROLLER-MANAGED AIRCRAFT

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Abstract

An anticipated increase in future traffic demand has propelled an investigation of numerous concepts aimed at improving efficiency and gaining capacity by reducing controller workload. NASA Ames and NASA Langley Research Centers have recently conducted a joint simulation to test the En Route Free Maneuvering concept element of Distributed Air-Ground Traffic Management (DAG-TM), which integrated advanced air and ground decision support tools (DSTs) with Controller-Pilot Data Link Communication (CPDLC). In this concept, controller "managed" aircraft flying under Instrument Flight Rules (IFR) were mixed with self separating "autonomous" aircraft flying under Autonomous Flight Rules (AFR). The overall results showed a significant potential for capacity gains and controller workload reduction, provided that safety concerns raised by the controllers can be addressed. The overall results are summarized in [1]. This paper describes the ground-side automation prototyped for DAG-TM operations and presents results on sector capacity, controller workload, traffic constraint compliance and safety. Controller feedback on the overall concept and the provided DSTs is discussed in detail. Results presented here also indicate that integrated ground-side DSTs can increase capacity even before concepts like airborne self separation are ready for operational implementation.

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Introduction

The objective of Distributed Air/Ground Traffic Management (DAG-TM) was to develop operational concepts, procedures, and decision support technologies to meet the future demands of air travel. Its goal is to enhance user flexibility and efficiency and increase system capacity without adversely affecting system safety [2].

One concept element within DAG-TM is En Route Free Maneuvering, which delegates the separation responsibilities to the flight crews of properly equipped aircraft. By distributing both the tasks and the responsibilities from controllers to flight crews, the concept aims at gaining significant en route capacity and improving efficiency without compromising safety. By eliminating the controller workload as a limiting factor to total aircraft capacity, the upper limit of capacity can potentially be much higher, perhaps up to the physical airspace capacity limit. By allowing the flight crews to fly preferred routes and altitudes, they may fly routes optimal for fuel efficiency. En Route Free Maneuvering – like many other future air traffic concepts proposed by NASA, RTCA, Eurocontrol, etc. – proposes to distribute tasks and responsibilities using well integrated air-ground decision support tools (DSTs) [2-5].

Air-ground communication enhancements and DSTs enable exploring the potential benefits and feasibility of delegating responsibility for maintaining separation to flight crews of properly equipped aircraft. Pilots and controllers use DSTs that process all information to develop conflict-free flight path changes that comply with Traffic Flow Management (TFM). During the DAG-TM research, new Autonomous Flight Rules (AFR) operations were defined for free maneuvering aircraft. These operations essentially stated that pilots can choose their own routes, speeds, and altitudes without the controller's approval, as long as they do not create short-term conflicts and assume responsibility for separation from other self separating and managed traffic. The controller is still responsible for separation between managed aircraft complying with standard Instrument Flight Rules (IFR) operations.

In 2004, a joint human-in-the-loop experiment was conducted at the NASA Ames and Langley Research Center to investigate the feasibility and operational benefits of this concept. The experiment addressed two primary issues: the feasibility of conducting operations with autonomous and managed aircraft in the same airspace and the ability of en route capacity to scale the traffic by increasing the autonomous portion of the air traffic without adversely effecting controller workload.

Simulation of En Route Free Maneuvering Concept

Participants

The experiment included 22 commercial airline pilots and 5 certified professional air traffic controllers. Four controllers, located at Ames staffed four radar positions (three high altitude sectors and one low altitude sector). One additional controller served as a tracker supporting the radar controllers during peak workload periods. Twenty one aircraft simulators were flown by participant pilots at NASA Ames and NASA Langley. All remaining aircraft in the simulation were flown by pseudo-pilots with autonomous agent support at Ames and Langley.

Airspace

The simulation airspace included portions of Albuquerque Center (ZAB), Fort Worth Center (ZFW) and Dallas-Fort Worth TRACON (DFW) (Figure 1). Controller participants worked four test sectors in the northwest arrival corridor: three high altitude sectors (Amarillo in ZAB, Wichita Falls and Ardmore in ZFW), and one ZFW low altitude sector (Bowie). Three retired controllers worked Ghost North, Ghost South and a TRACON position to handle the surrounding traffic.

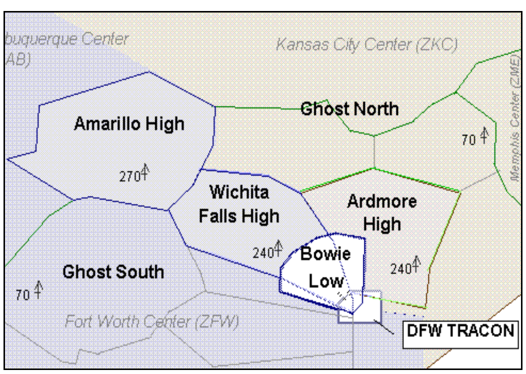

Figure 1. Simulated airspace

Arrivals transitioned Amarillo high and Wichita Falls high from the northwest and Ardmore high from the north. The two main streams of arrivals merged at the BAMBE meter fix in the Bowie low sector before entering the TRACON. Once AFR aircraft passed the meter fix and were under TRACON control, their status switched to IFR automatically. The traffic mix in Amarillo consisted of arrivals and overflights in level flight. Wichita Falls had a significant portion of the arrivals in level flight and descent, mixed in with overflights and some departures. Ardmore had arrivals, departures,, as well as a significant number of overflights.

Experimental Conditions

The experiment consisted of four experimental conditions, incorporating a within-subjects design (Figure 2). Each condition was run five times, four of which were used in subsequent analyses. Conditions C1 and C2 were conducted at slightly above current day maximum traffic levels (Level 1), the former consisting of entirely managed aircraft and the latter having a mix of autonomous (~25%) and managed (~75%) aircraft.

Level 1 traffic levels were established for the three high altitude sectors through an informal study prior to the final simulation. This informal "traffic load test" determined the maximum traffic levels for each of the high altitude sectors. The maximum manageable traffic levels came out higher than the current day Monitor Alert Parameters (MAPs), even with only one controller per sector, because the advanced DSTs alone offload the controller workload significantly. Level 1 traffic levels were then picked to be slightly lower than the maximum traffic count, resulting in traffic levels similar to current day MAPs (18 in each high altitude sector).

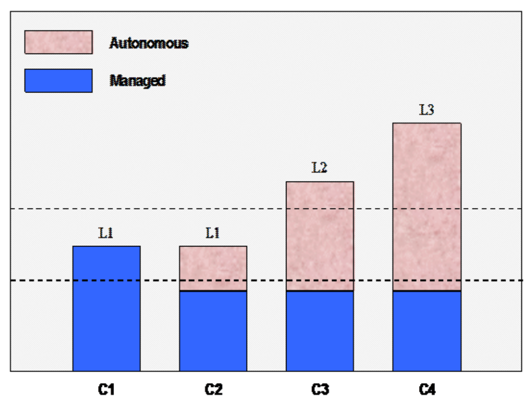

Figure 2: Experimental conditions

Conditions C3 and C4 included the same number of managed aircraft as Condition C2, but added increasing numbers of AFR aircraft. Varying traffic volume between scenarios was accomplished by only altering the number of overflights. The traffic volume increase was greater for Amarillo and Ardmore than for Wichita Falls. The sector geometry of Wichita Falls prevented a significant increase in total aircraft count without also significantly increasing traffic complexity. The arrival problem, while demanding, remained relatively constant throughout all scenarios. Accordingly, Bowie sector, which had arrival traffic only, maintained a relatively constant traffic volume across conditions.

Separation Responsibilities

To achieve scalability, free maneuvering aircraft needed to have little or no impact on controller workload. A key concept designed to achieve this goal was that the pilot flying under AFR was responsible for separating their aircraft from all other aircraft, including controller-managed IFR aircraft. The controller was responsible for separation assurance of IFR aircraft only when the conflict was with another IFR aircraft.

To minimize the interactions between AFR and IFR aircraft, pilots of AFR aircraft were expected to resolve all conflicts for which they were responsible at least 2 minutes before loss of separation (LOS). Conflicts between AFR and IFR aircraft were announced to the controllers only when the pilot did not resolve the conflict by 3 minutes before LOS, i.e. one minute before the pilot was required to resolve the conflict. Controllers could contact the pilot to coordinate a resolution, ask for pilot's intent, etc., but they were not required to do so. In addition, pilots and controllers could not make flight path changes that caused a predicted LOS of less than 4 minutes. The minimum separation distance was 5 NM laterally and 1,000 ft vertically (reduced vertical separation minimum).

Ground Capabilities

The controller decision support tools have been integrated into a high fidelity emulation of the Display System Replacement (DSR) controller workstation (Figure 3). This DSR emulator is highly configurable to mimic both DSR workstations in the field today and future DSRs with advanced decision support tools.

To maximize the benefits of advanced air and ground-side DSTs, they were integrated with Controller Pilot Data Link Communication (CPDLC) and the Flight Management System (FMS). This integration allows the controllers and the pilots to exchange 4-D trajectory information quickly and with low workload. Much of the capabilities described below, e.g. speed advisories, altitude and route trial plan, etc., were integrated with CPDLC to be able to uplink them to the flight crews as a clearance.

The controller data link interface was modeled after CPDLC Build I used in Miami Center (ZMA). Its features include data block symbology, automated transfer-of-communication (TOC), and a status list. The CPDLC-based TOC was modeled after the process used in ZMA and proceeds as follows. Sector handoff is initiated by the transferring controller. When the handoff is accepted, a frequency change uplink message is automatically sent to the aircraft. The pilots then accept the CPDLC message and change the radio frequency to the appropriate channel. This TOC mode is called "TOC AUTO", which was the preferred mode by the controllers in a previous study [6].

One of the key capabilities of the implemented decision support tools is the integration of trajectory-oriented tools with CPDLC. Trajectory-oriented metering has shown potential benefits in efficiency and workload in handling arrivals. Based on earlier research an initial set of DSTs was recommended [7]. One of those capabilities is an interactive timeline that provides a graphical representation of the meter fix scheduler that is modeled after the Center TRACON Automation Systems (CTAS) Traffic Management Advisor (TMA). The timeline in Figure 3 shows the expected time of arrivals (ETAs) on the left side and scheduled time of arrivals (STAs) on the right. The STA at the meter fix was automatically assigned once an aircraft was within 160 nm of BAMBE meter fix. Even after the schedule was frozen, a controller could change the STA of an aircraft using an "ASSIGN" function or swap STAs of a pair of aircraft using a "SWAP" function.

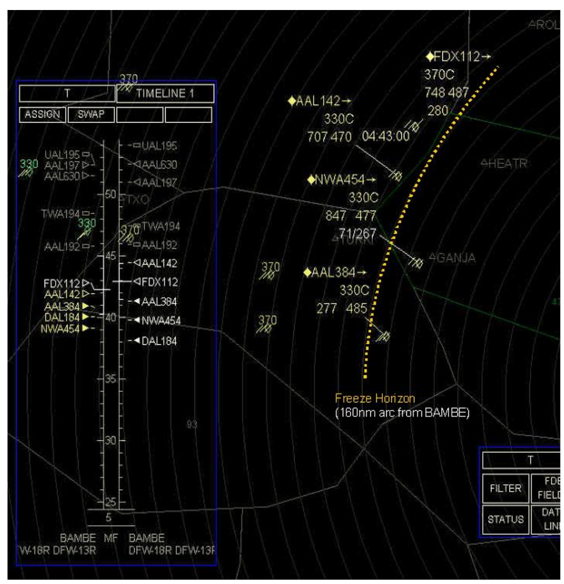

Figure 3: DSR emulation with timeline showing arrival schedule

Another trajectory-oriented metering tool is a speed advisory. Speed advisories are computed along an aircraft's current route to deliver it to the meter fix on the STA. In Figure 4, for example, the fourth line in the data block shows a speed advisory of .81 Mach in cruise and 312 knots in descent. The controller may uplink this advisory to the flight deck as a loadable data link clearance. If a speed change alone cannot deliver the plane on its STA, the controller can modify the 4-D flight path using trial plan capabilities to either stretch or shortcut the path or change the aircraft's cruise altitude. During trial planning, the ETA on the timeline is updated dynamically to reflect the ETA changes resulting from the proposed path change. The trial plan capability is accessed by clicking on a trial planning portal (right arrow) on the data block (Figure 4).

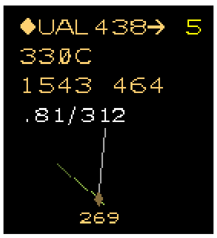

Figure 4: Prototype DSR data tag with trial planning portal (arrow), speed advisory, and predicted conflict in 5 minutes

Graphically, the ground-side CD&R automation indicates a potential LOS in two ways. First, trajectory based conflict-probe (CP) alerts are displayed as minutes to LOS in the first line of the data block. Clicking on the time to LOS highlights the aircraft targets with filled J-rings and displays the flight paths and the predicted conflict location (Figure 5).

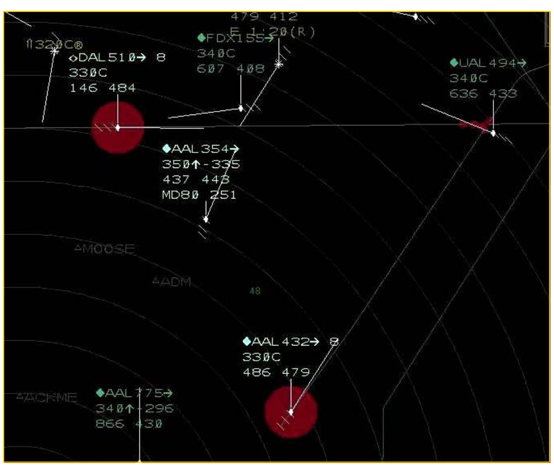

Figure 5: Conflict probe display

The second alert representing the current day conflict alert (CA) uses an independent state-based logic and triggers data block flashing. Trajectory-based conflict predictions can also be presented in a conflict list with the aircraft pairs, predicted time, vertical/lateral separations at the LOS. Once a conflict is identified, trial planning can be used to create a new lateral route, a new altitude, or both. The ground-side CD&R automation is active for the trial planned route/altitude as well as the current route, so the controller can create a conflict-free path before sending it as a clearance via CPDLC. The trial plan portal and the time to conflict indicators are both modeled after initial CTAS Direct To prototypes [8].

In mixed operations, the look-ahead time filter for IFR-IFR conflicts was set to a maximum of 15 minutes, whereas the setting for AFR–IFR conflicts was only 3 minutes and AFR-AFR conflicts were not shown at all. The short look-ahead time for AFR-IFR conflicts was so that these conflicts would have minimal impact on the controller workload unless the impending conflict was not resolved until the last moment. Although controllers were not responsible for resolving AFR-IFR conflicts, this short-term conflict information was provided as a safety back-up.

In addition, AFR aircraft were presented to the controllers as limited datablocks – with callsign, datalink status, and current altitude – in order to further limit their impact on workload. Finally, colors were added judiciously on the DSR displays to enhance the ability to monitor the traffic and to allow similar functions to be visually grouped together. In particular, different colors were used for the datablocks of arrivals and overflights/departures which was determined effective in past studies [7].

In order to support the concept, all aircraft were equipped with CPDLC, FMS, and automatic dependent surveillance-broadcast (ADS-B). The aircraft flown by the commercial pilot participants also had conflict detection & resolution (CD&R) as well as advanced required time of arrival (RTA) capabilities.

Selected Ground-side Results

Some key ground-focused results will be discussed here. The overall air and ground results presented in [1] suggest that the En Route Free Maneuvering concept element has great potential to increase en route and transition airspace capacity, provided that safety concerns raised by controllers can be addressed. Meter fix conformance was equally good for mixed operations and managed operations, suggesting that time-based traffic management constraints are an effective way to coordinate managed and autonomous flights from mixed into managed airspace. The following section will discuss the details of potential capacity gains and safety issues.

Impact of Traffic Volume on Workload

A primary anticipated benefit of the concept is the ability of en route airspace to accommodate substantial increases in traffic volume through the increase of AFR aircraft. In order to test this hypothesis, the traffic scenarios gradually increased traffic to its maximum during the first twenty minutes of the simulation and maintained this traffic level during the next 30-35 minutes before tapering off for the last 5-10 minutes. Figure 6 illustrates the traffic pattern for Amarillo sector across four conditions. The graph shows average total aircraft count (i.e. both AFR and IFR) every 5 minutes for the four conditions, as well as the average IFR aircraft count for the mixed equipage conditions C2-C4.

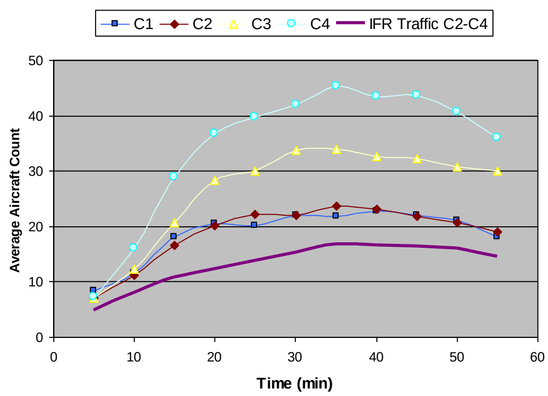

Figure 6: Average aircraft count over time across four experimental conditions

The targeted traffic levels for Amarillo were 20, 20, 30, and 40 for C1, C2, C3, and C4, respectively; for Ardmore, they were 18, 18, 30, and 40; and for Wichita Falls, they were 16, 16, 20, and 24. The Bowie sector did not have a targeted traffic count as it only handled arrivals to the meter fix, but the arrival rate was set to 84 seconds which allowed 8-10 aircraft to be in sequence. A cursory look at Figure 6 shows that the targeted traffic levels were exceeded in the study. Figure 7 summarizes the maximum aircraft count in each sector across conditions. For the Amarillo sector, maximum count was 26, 26, 35, and 44 for C1-C4; for Ardmore, 22, 22, 32, and 43; for Wichita Falls, 21, 19, 25, and 27; and for Bowie, 9, 9, 8, and 9. For C2-C4 conditions, the IFR portion of the aircraft count was approximately 70% of the IFR count in the all managed condition (C1) and it remained constant across the three mixed equipage conditions. The peak total traffic occurred on the average at 35 – 45 minutes into the scenario.

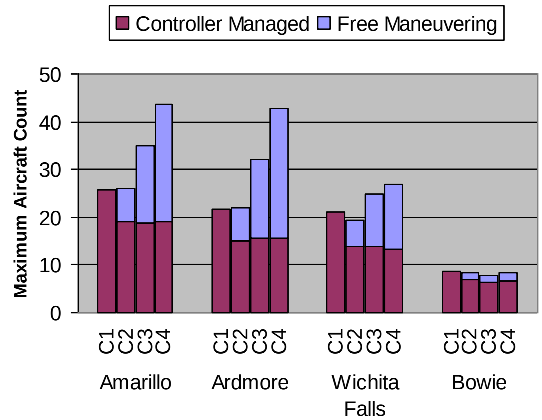

Figure 7: Maximum aircraft count in each condition per sector

The fact that the controllers could control the traffic at all with a total aircraft count exceeding the current day MAP values by far demonstrates the potential en route capacity gains in mixed equipage situations. Moreover, controller workload appears to correlate primarily to the number of managed aircraft, whereas the number of autonomous aircraft in the airspace has little impact on controller workload. Figure 8 shows average workload ratings per sector across the four conditions, which shows a similar pattern as that of IFR aircraft in Figure 7.

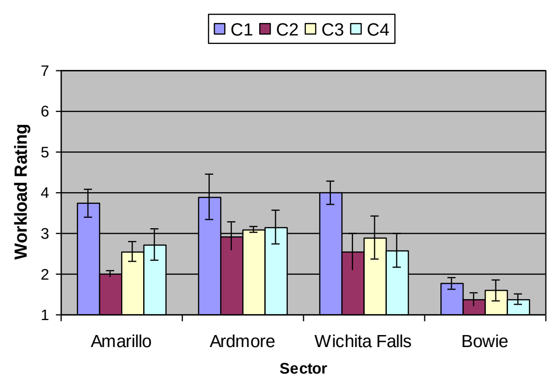

Figure 8: Controller workload (ATWIT) ratings

Subjective workload assessments were collected from controllers using the Air Traffic Workload Input Technique (ATWIT) [9]. Controllers were required to rate their workload on a scale of 1 to 7, at 5-minute intervals throughout each simulation run. The workload ratings showed higher workload for C1 than those for C2-C4, suggesting that mixed traffic posed no significant workload. Furthermore, the workload was relatively flat for C2-C4 despite a significant increase in AFR traffic, suggesting that AFR aircraft did not create a significant amount of workload.

Traffic Complexity and Safety

Based on the workload data, one might erroneously conclude that increasing the AFR aircraft count in C3 and C4 did not result in increased workload because they added no traffic complexity to the controllers. On the contrary, post-run ratings on traffic complexity reveal that the controllers increasingly rated the traffic to be more complex from C2 to C4 (Figure 9). The data suggest that the controllers were able to dissociate traffic complexity from workload and used workload ratings to indicate only the amount of "activity" that they were engaged in.

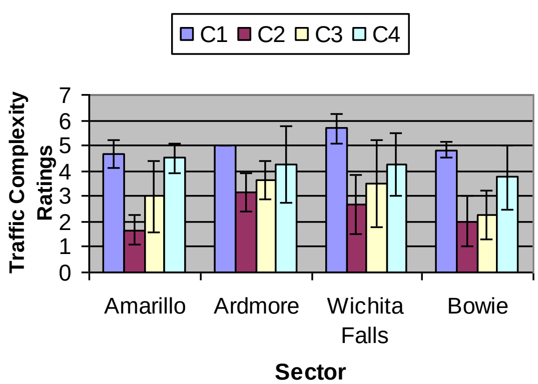

Figure 9: Traffic Complexity Ratings

A likely source of increased traffic complexity in C4 vs. C2 is the reduced maneuver space for controller-managed IFR aircraft due to the sheer volume of AFR aircraft at the C4 traffic level. In the high altitude sectors in C4, AFR aircraft often blocked the potential delay paths for IFR aircraft, especially during the descent phase of the arrivals. Another source of increased complexity is added display clutter of limited datablocks for AFR aircraft. At the relatively low AFR traffic volume in C2, the limited AFR datablocks provided peripheral traffic awareness without cluttering the display. However, at the high C4 traffic level, the sheer volume of AFR aircraft created enough clutter on the display that controllers had some difficulty accessing IFR datablocks.

A third significant source of increased complexity was an increase in AFR-IFR conflicts in higher traffic levels. The ground side tools provided controllers with CP alerts whenever AFR-IFR conflicts were unresolved with less than 3 minutes to LOS. Table 1 tabulates the AFR-IFR conflicts that were alerted to the controllers. The increases in unresolved AFR-IFR conflicts were mainly due to pseudo-pilot AFR flights, which had greater difficulty in resolving conflicts as the traffic volume increased. The participant pilots, who flew single-piloted AFR aircraft simulators, seemed to be less affected by the traffic increase. The volume of impending AFR-IFR conflicts that the controllers observed in the high traffic conditions – caused mostly by the limitations in the pseudo-pilot stations or autonomous agent pilots – led to their safety concerns. The ability to resolve AFR-IFR conflicts well before they are presented to the controllers (e.g. 3 minutes) will be critical to future success of mixed operations.

Table 1. AFR-IFR conflicts with LOS within 3 minutes[1]

Conflict Type	**C2**	**C3**	**C4**	**Total**
Pseudo-piloted AFR aircraft	13	35	71	119
Single-piloted AFR aircraft	15	19	17	51
Total	28	54	88	170

Approximately 80% - 90% of the last-minute AFR-IFR conflicts were resolved before resulting in separation violations. Overall, there were 3, 4, 5, and 7 separation violations for C1–C4, respectively. The data only pertains to aircraft that were controlled by participant pilots or controllers (i.e., AFR flights flown by pseudo-pilots/autonomous agents were excluded). Although the number of violations increased gradually from C1–C4, it is difficult to generalize the results from the number of violations because each violation resulted from a unique circumstance. For example, in-depth analyses of IFR-IFR violations – i.e. violations in which controllers were responsible – revealed that all but one violation was due to support staff and/or simulation system error. Similarly, separations violations by participant pilots were mainly attributable to software errors and procedural lapses [1]. The number of IFR-IFR violations remained constant with increasing AFR traffic levels, suggesting that the increasing traffic

[1] *Due to data logging problems, the analysis includes data from runs 5–16 only.*

levels of AFR aircraft did not negatively impact controllers' ability to separate IFR aircraft.

Meter Fix Conformance

One challenge for controllers under mixed operations was to manage the STA for all IFR arrivals in the presence of AFR aircraft. Controllers did not have many problems delivering aircraft within ±15 seconds of their STA. The number of IFR flights that deviated from the STA was quite small – less than 3%. AFR pilots also had little difficulty in conforming to the schedule. Arrival conformance varied little regardless of whether the subject-piloted aircraft was AFR or IFR. Similarly, complying with the TRACON crossing restriction of 11,000 (±300) feet and 250 (±10) knots was not a particular problem for controllers or AFR pilots. IFR aircraft were equally likely to conform to the crossing restriction in the mixed as well as the all managed condition.

Concept Acceptability – Controller Perspective

At the end of the simulation, controllers were asked to rate the acceptability of different aspects of the free maneuvering concept. Their overall impression of the concept was somewhat positive (M = 3.5; 1 = much less efficient, 5 = much more efficient) in terms of efficiency and somewhat negative in terms of safety (M = 2.25; 1 = much less safe; 5 = much safer). They thought that it was somewhat more difficult to cope with unplanned events during mixed operations than during all managed operations (M = 3.75; 1 = much less difficult, 5 = much more difficult). However, they thought that it was only slightly more difficult to detect non-conforming aircraft (M = 3.25) and to maintain/monitor separation (M = 3.25) under mixed operations compared to all managed operations. Concerning time-based metering, they thought that it was just as easy to sequence planes in mixed as in managed operations (M = 3.0). They stated that it was easy to deliver IFR aircraft on schedule during mixed operations (M =2; 1 = very easy, 5 = very difficult).

Regarding traffic conflicts, controllers felt that always burdening AFR aircraft to resolve AFR-IFR conflicts was marginally acceptable (*M* = 2.9; 1 = completely unacceptable, 5 = completely acceptable). When an AFR-IFR conflict was imminent, controllers thought that the procedures and phraseology for resolving the conflict was somewhat unacceptable (*M* = 2.3). However, the phraseology for requesting pilot intent was rated somewhat acceptable (*M* = 3.8).

The controllers elaborated further when asked about the acceptability of the concept during debrief discussions. In general, controllers' comments highlighted four significant issues regarding concept acceptability: automation dependency, situation awareness of AFR aircraft, traffic density, and near-term AFR-IFR conflicts.

One of their concerns was that if the conflict detection automation "misses" an AFR-IFR conflict, the conflict may not be independently detected by the controller because they are discouraged from monitoring autonomous aircraft. A related issue is situational awareness of AFR aircraft. In order for AFR flights to add no workload for the controllers, they need to be near invisible to the controllers (e.g., limited depiction on the controller's display, no controller responsibility, little interaction with AFR aircraft). However, if information about AFR traffic is suppressed, the controller is less prepared to provide service for exceptional cases, such as unresolved near-term conflicts and RTA revisions. In summary, less awareness leads to inability for the controllers to deal with emergency situations but more awareness undermines the scalability premise.

Another interesting point raised by the controllers was that the current day rules and procedures have excess buffers built in to absorb errors by the controllers and/or by the system. It might not be good idea to strip away all of the safety buffers by dramatically increasing the traffic density. They were concerned that increased traffic density reduced options for maneuvering IFR aircraft out of critical situations. One controller commented that "...resolution was always more difficult in high mixed environment because AFR aircraft are in the way of IFR aircraft." In general, they were not sure how one determines what capacity increases can be achieved without compromising safety. One controller commented that "our reality is people <u>fly</u> planes, people <u>work</u> planes, and people <u>get on</u> planes", so safety should be valued higher than efficiency because people's lives are at stake.

Finally, controllers commented extensively on the near term AFR-IFR conflicts. Controllers felt in general that waiting until an IFR-AFR conflict is within 2-3 minutes seems too late to start critical decisions. They also felt that there was the potential for ambiguous information because it was not always clear if the AFR aircraft was taking action to resolve the conflict that it was responsible for. The general feeling of "not knowing" what the AFR aircraft was doing caused additional concern and even when they knew the aircraft intent, they weren't always sure if the intended action was appropriate. One of the key lessons learned from the study was the importance of clear and unambiguous procedures for both pilots and controllers when handling short-term AFR-IFR conflicts. If the resolution responsibility is to be shared between the pilot and controller under these situations, then some level of air and ground system compatibility may be required. Alternatively, if the responsibility is to remain solely with the AFR pilot, then the decision to alert the controller to these conflicts should be re-visited.

Decision Support Tools and Display

Controllers rated the usability and usefulness of the ground-side DSTs (Table 2). Overall controllers felt the tools assisted them in making more efficient decisions. Also, they felt CPDLC route uplinks and TOC reduced workload and frequency congestion, which gave them the extra time to use other tools.

Table 2. Controller rating of usability and usefulness of displays and tools

Tool Feature	Useful	Usable
Speed advisories	5	4
Trial-planning tool	5	5
CPDLC interface for TOC	4.8	4.5
CPDLC interface for clearances and requests	4.8	4.3
Graphical display of trial plan conflicts	4.8	4.5
Arrival timelines	4.6	4.3
STA assignment/swap functions	4.5	3.5
Graphical display of conflict alerts (i.e. flashing data blocks)	4.5	4
DSR emulation of existing functions	4.5	4.3
Color coding of information	4.5	4.5
Data link status list	4	3.5
Graphical display of active IFR conflicts	4	4
Conflict list	3.8	3.3
Graphical display of AFR-IFR conflicts	3.5	3
Graphical display of AFR aircraft (i.e. limited data block)	3.5	3.8

Average usefulness ratings ranged from 3.5–5.0 (1 = Not useful, 5 = Very useful). Speed advisories, trial-planning tool, CPDLC interface for TOC, CPDLC interface for clearances and requests, and graphical display of trial plan conflicts all were rated very high. The usefulness rating for the conflict list increased noticeably from the 2002 simulation [7] (2004 usefulness rating = 3.8, 2002 usefulness rating = 2.8). The conflict list was redesigned to use time-to-LOS as the main determinant for both the color (i.e. red = less than 2 minutes to LOS, yellow = 2 -5 minutes, white = greater than 5 minutes) and the location on the list (e.g. impending conflict near the top of the list). The conflict list in the 2002 simulation used two dimensions: time-to-LOS and likelihood of LOS, which was found to be confusing to the controllers. Also false alerts were much less frequent due to a redesign of the conflict logic which allowed the controllers to trust it much more.

Average usability ratings ranged from 3.0–5.0 (1 = Very difficult to use, 5 = Very easy to use). The trial-planning tool, CPDLC interface for TOC, graphical display of trial plan conflicts, and color coding of information were the features that received the highest ratings. The trial-planning tool received a considerably higher usability rating than in the 2002 simulation (2004 usability rating = 5.0, 2002 usability rating = 3.0) [7]. The redesigned highly responsive trial planning tool integrated with the R-side display provided immediate conflict feedback. Full CPDLC integration for easy uplink of trial plans allowed the controllers to work the traffic without issuing many vectoring instructions.

The lowest combined usability and usefulness rating was for the graphical display of AFR-IFR conflicts (M = 3.0, M = 3.5, respectively). Controllers commented that frequent AFR-IFR conflict alerts lead to display clutter, partly because the alerting method involved displaying the AFR aircraft's expanded data blocks.

In addition, controllers rated that data link clearances greatly reduced their workload (M = 4.67; 1 = greatly increased, 5 = greatly reduced). They also thought that trial plan route and altitude amendments were much more effective than vectoring and altitude changes in current day operations (4.75 and 4.25, respectively; 1 = much less effective, 5 = much more effective). One controller commented that tools allowed controllers to plan and make more efficient decisions. CPDLC's reduction of frequency congestion was a very useful workload reduction tool. Another controller commented that uplinking route and altitude changes reduced his workload greatly. However, a third controller thought that actual aircraft may not comply with speed restrictions at the meter fix in the real environment as well as they have done in the simulation, which would be a huge factor in the success of the concept in the field.

The questionnaire also asked about the preferred display location of the following information: delay absorption information on the timeline, datablock, or both; conflict information on the list, datablock, or both; and data link status information on the list, datablock, or both. All controllers agreed that delay information should be on both the timeline and the datablock, but 3 out of 4 controllers thought that conflict information should only be on the datablock and half thought that data link information should only be on the datablock. No one thought that any of the information should be in the lists alone. In general they thought that lists added to display clutter and were often ignored when busy. Although too much information on the datablock could have been a problem, none voiced any issues with the IFR datablocks in the simulation, which were designed to minimize display clutter and maximize readability.

En Route Sector Capacity in 100% Managed Condition

The results from this simulation demonstrated potential capacity benefits with the free maneuvering concept. A critical requirement of the concept, i.e. full integration of air and ground systems via CPDLC, in itself suggested substantial capacity benefits, even without self-separating aircraft. With only one controller managing each position, high altitude controllers were able to work traffic levels well beyond current day MAPs. Figure 8 shows maximum owned aircraft at each 5-minute time block for the four test sectors in the all managed condition.

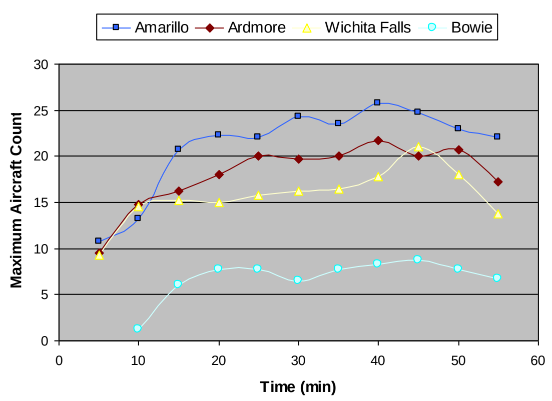

Figure 8: Maximum aircraft count over time in all managed condition

The relationship between sector count (Figure 8) and workload (Figure 9) provides evidence that these peak counts sustained over approximately 30 minutes resulted in moderately high but manageable workload. It is likely that without the integrated decision support tools, the manageable peak aircraft count would be substantially lower, although further research is needed to confirm this hypothesis. Overall, controllers thought that it was relatively easy to monitor and maintain separation during the all managed condition (M = 2.0; 1 = very easy, 5 = very difficult) and that it was easy to deliver aircraft on schedule during the all managed condition (M = 1.5).

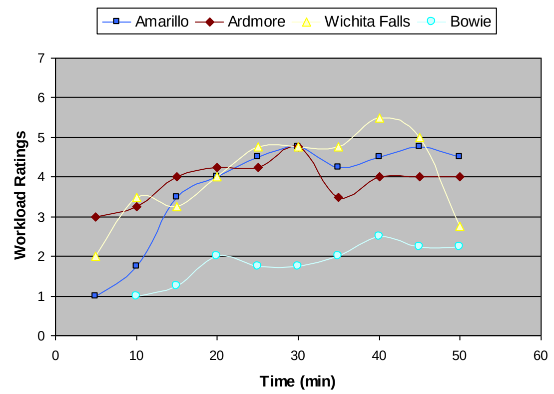

Figure 9: Workload (ATWIT) rating over time in all managed condition

Conclusion

The joint Ames/Langley simulation study of the DAG-TM En Route Free Maneuvering concept element demonstrated potential en route capacity benefits. When the majority of the aircraft were free maneuvering, the total aircraft count far exceeded the current day MAPs in the high altitude sectors. In these high traffic situations, controller workload remained manageable and was actually lower than those of managed operations with more IFR but fewer total aircraft. The data suggest that workload is correlated primarily with the managed portion of the traffic, validating one of the key assumptions that AFR aircraft has minimal workload impact on the controllers.

Despite reporting manageable workload with high traffic levels of mixed traffic, controllers reported increasing traffic complexity imposed by the additional AFR aircraft. At the highest traffic level, AFR aircraft limited the potential maneuver space for IFR aircraft and caused display clutter even though they were shown as limited datablocks that took little display space. Increased AFR traffic also increased the number of AFR-IFR conflicts – mostly due to limitations of multi-aircraft stations and/or autonomous agent pilots. These conflicts were main contributors to safety concerns by the controllers.

Mixed operations would not have been feasible without a well integrated air/ground system that connects Flight Management Systems, airborne decision support tools, traffic flow management systems with tools for scheduling and trajectory planning, ground-based decision support tools, integrated CDPLC/DSTs, and broadcast of up-to-date state and short-term intent information. In this paper, we focus on the impact of the ground-based DSTs on the success of the overall concept. The ground DSTs have been significantly re-designed from our past studies to improve the responsiveness and accuracy of the tools. The design of individual display components has also been significantly improved. The integrated air/ground system and the corresponding decision support tools described here are a key component to excite maximal benefits in many of the future concepts that are discussed today. Therefore, the tools, procedures, results, and lessons learned from this study and simulation architecture should provide us with a solid foundation to test different concepts in the future.

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Keywords

distributed air ground traffic management, free flight, cockpit display of traffic information, trajectory oriented metering, conflict probe, scalability, mixed equipage, capacity, workload, decision support tools, automation, CPDLC.

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