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A Human-in-the-Loop Evaluation of Flow-Based Trajectory Management in Mixed Equipage Airspace

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Abstract— **The feasibility and benefits of a concept for flow-based trajectory management were tested in a mixed equipage en route environment. Aircraft were designated *equipped* or *unequipped* based on the presence or absence of a data communications (Data Comm) capability for receiving auto-loadable clearances and transfer of communication messages from the air navigation service provider. *Feasibility* issues addressed in this simulation included: (1) whether these operations were feasible for unequipped aircraft, and (2) whether they worked in a mixed equipage context. Two categories of *benefits* were also explored: (1) system performance improvements (throughput, workload) at different equipage levels, and (2) how well flow-based trajectory management could support a "best-equipped, best-served" policy of air traffic management.**

FAA facility personnel staffed six traffic management, supervisor and radar controller positions for four high altitude sectors and the surrounding airspace within a simulated facility in the central United States. Eight test scenarios presented variations of a combined convective weather and traffic load problem with either 10%, 50% or 90% equipped aircraft. Traffic management coordinators used decision support tools to identify and assess the situation, and to manage it by modifying the trajectories of one or more aircraft. Solutions were coordinated as needed with the area supervisors. Trajectory clearance requests were then sent to the controllers for review and delivery to the aircraft.

Results found trajectory clearance coordination for unequipped aircraft to be feasible and useful in a variety of contexts. Flow management operations were also effective, with traffic management coordinators achieving a good balance between demand (traffic load) and capacity (controller workload) at all three equipage levels. These operations also proved an effective means for providing priority service to the Data Comm equipped aircraft, supporting the proposed NextGen "best-equipped, best-served" policy of air traffic management.

Keywords-trajectory management; flow management; multi-sector planner; multi-sector planning; NextGen; Data Comm; datalink; mixed equipage; functional allocation; roles and responsibilities.

I. INTRODUCTION

In the Next Generation Air Transportation System (NextGen), new communication, navigation and air traffic management technologies will be introduced in the en route environment. These include air-ground data communications, satellite-based navigation, and new air traffic control and traffic management automation, all of which will support a shift from today's methods for controlling aircraft along fixed route structures towards more dynamic management of aircraft trajectories, or "trajectory-based operations" (TBO) [1, 2]. This shift should provide more flexibility in adjusting traffic flows in response to changing conditions. For example, TBO procedures could address local demand-capacity imbalances by modifying in-flight trajectories for aircraft within specific flows. This "flow-based" trajectory management (FBTM) approach could enable the air traffic system to cope more effectively with local disruptions such as weather or traffic congestion.

Effective application of FBTM operations will require new tools and methods for situation assessment, trajectory management, and clearance coordination. A mechanism will be needed to implement trajectory changes that meet objectives that are outside the sector controller's geographic and temporal field of view, without compromising the effectiveness of sector operations. These operations will also require some changes to the roles and responsibilities within the en route facility team.

The simulation described in this paper tested an FBTM concept for managing traffic flows at the local area level. It provided a framework for developing flow-based solutions to traffic situations beyond the controller's planning horizon (e.g., downstream weather, traffic complexity, or excess sector load). This involved a non-controller (traffic management) position developing flow-based trajectory changes from a strategic multi-sector perspective, and sending them as "clearance requests" for controllers to review, then deliver to the aircraft.

A. Background

This FBTM concept evolved from an earlier effort that investigated the possibility of adding a new "multi-sector planner" (MSP) position into the United States' National Airspace System (NAS) [3]. The idea of introducing this new position within en route facilities had been explored in both Europe and the United States since the mid-1990s, with the proposed roles and responsibilities for the new position varying depending on the operational context and perceived need [3-13]. A 2006 human-in-the-loop (HITL) simulation conducted at NASA Ames compared two alternative MSP concepts in terms of their ability to support sector operations. Follow-on research expanded the preferred "area flow planner" concept, where the MSP assisted with trajectory and flow management by managing complexity and flows for several sectors, acting

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within an approximate 20-60 minute planning horizon. Further development efforts clarified the MSP's roles and responsibilities in relation to existing traffic management and air traffic control positions, and a set of automation capabilities were designed to support MSP operations [14-16].

A large scale HITL simulation was conducted in 2009 to test this expanded concept, comparing operational outcomes using the new tools and procedures both with and without the addition of a dedicated MSP position. The study found that multi-sector planning operations were feasible and effective in both conditions as an on-demand resource to assist with local flow management. The idea of performing these operations by existing facility staff members made sense for an on-demand (i.e., not full-time) activity. This suggested shifting the focus from a position-centered multi-sector *planner* concept to a function-centered concept for multi-sector *planning*,, and the effort was re-named "flow-based trajectory management" (FBTM) to more accurately describe the concept and avoid confusion with ongoing multi-sector planner researcj [17-21].

B. *The Current Study*

The 2009 HITL evaluated MSP operations in a full Data Comm environment, where all aircraft were equipped for controller-pilot data communications. Three message types were used in the simulation: altitude and route clearances that pilots could "auto-load" into their flight management system, and a transfer-of-communication message that transferred Data Comm control and provided the next radio frequency when the aircraft crossed a sector boundary. These three messages and their behavior were based on today's FANS-1 systems.

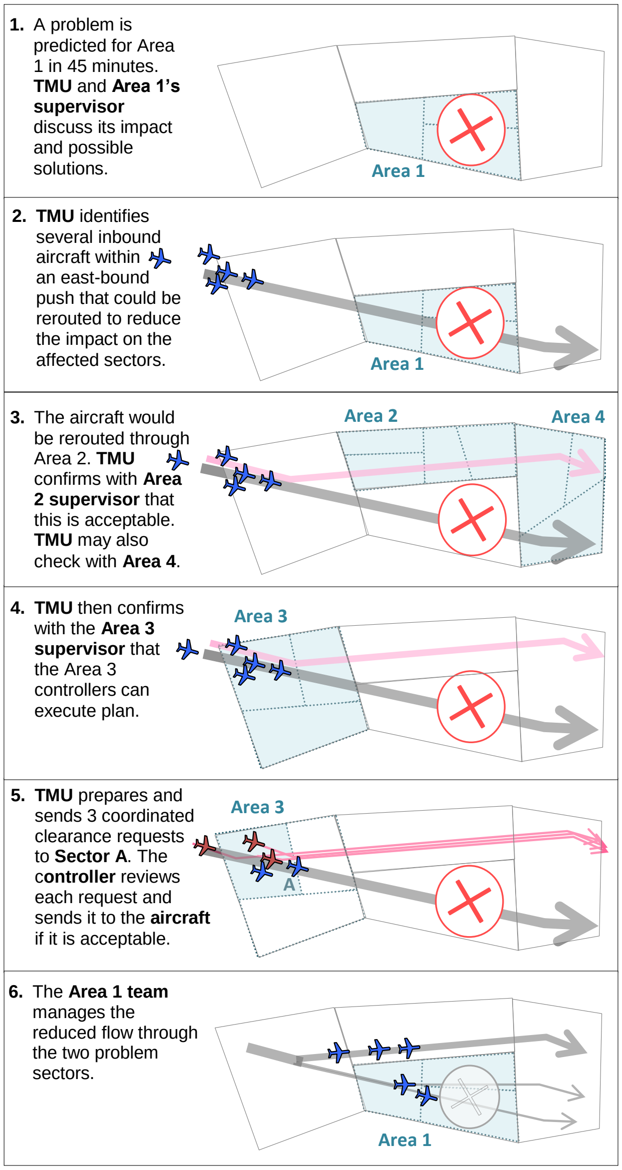
The current study was motivated by the likelihood that high Data Comm equipage levels will not be achieved by the NextGen mid-term, and so it explored the feasibility and benefits of introducing FBTM in a mixed equipage context. Aircraft were designated *equipped* or *unequipped* based on the presence or absence of the Data Comm capabilities described above. Procedures were modified to distribute FBTM responsibilities within a "planning team" comprised of traffic management and area supervisors. Controller and planner tools were adapted for unequipped aircraft and for a mixed equipage environment. Radar associate positions were added for each test sector because of workload increases with unequipped aircraft and mixed equipage operations. Simulation scenarios and procedures were developed to investigate mixed equipage operations with respect to three specific operational objectives:

- local area traffic count and complexity management
- convective weather contingency management
- ability to provide differential service for equipage

The study evaluated both feasibility and benefits of the proposed operations. The feasibility assessment addressed two related questions: (1) are FBTM operations feasible for unequipped aircraft, and (2) are they feasible in a mixed equipage context. Two categories of benefits were explored: (1) system performance improvements associated with FBTM at different equipage levels (e.g., throughput, controller workload), and (2) the possibility of providing service for equipage through FBTM operations.

C. *Flow-Based Trajectory Management Concept*

Fig. 1 presents the nominal event sequence for using flow-based trajectory management to address a local area problem (e.g., convective weather impact on two local sectors), and illustrates how it is coordinated between traffic management and the operational area teams. As shown in Fig. 1, both area supervisors and traffic management monitor local traffic to identify problems and respond to external requests. When needed, a traffic management coordinator (TMC) can develop a solution by rerouting aircraft, coordinating with area supervisors and others. Depending on the extent of the situation, the traffic management unit (TMU) team may further divide the task. For example, a supervisory TMC (STMC) may act as coordinator, and assign one or more TMCs to develop the actual trajectory reroute clearances. Proposed reroutes are sent as clearance requests to the controller for review, and execution if they are satisfactory. The area supervisor manages



1. A problem is predicted for Area 1 in 45 minutes. **TMU** and **Area 1's supervisor** discuss its impact and possible solutions.
2. **TMU** identifies several inbound aircraft within an east-bound push that could be rerouted to reduce the impact on the affected sectors.
3. The aircraft would be rerouted through Area 2. **TMU** confirms with **Area 2 supervisor** that this is acceptable. **TMU** may also check with **Area 4**.
4. **TMU** then confirms with the **Area 3 supervisor** that the Area 3 controllers can execute plan.
5. **TMU** prepares and sends 3 coordinated clearance requests to **Sector A**. The **controller** reviews each request and sends it to the **aircraft** if it is acceptable.
6. The **Area 1 team** manages the reduced flow through the two problem sectors.

Figure 1. Nominal representation of FBTM operations for local area traffic flow management.

plan execution by controllers, and may also use planning tools to develop and coordinate within-area trajectory changes.

Automation tools support FBTM operations in three areas:

- Situation assessment (SA) tools allow traffic management and area supervisors to monitor the traffic situation, identify problems, and assess the local impact of problems and their proposed solutions.
- Multi-trajectory trial planning tools, integrated with the SA tools, support development of solutions using strategic trajectory-change clearances.
- Coordination tools enable plans and clearance requests to be shared using ground-to-ground data exchange automation. These capabilities are integrated with trial planning tools to enable the receiving controllers to quickly evaluate and deliver the requested clearances.

Trajectory clearances are constructed for either Data Comm or voice delivery. Equipped aircraft trajectories may use latitude/longitude defined waypoints, but unequipped aircraft trajectories are restricted to named waypoints that can be communicated by voice. This allows more precise and efficient crafting of equipped aircraft trajectory solutions.

Data Comm support for clearance delivery and automated transfer of communication significantly reduces the controller's per-aircraft workload, thus a strategy that preferentially reroutes unequipped aircraft away from a weather- or complexity-constrained airspace can be an effective technique for sector load management. This strategy can result in fewer aircraft being rerouted overall, and has the added benefit of providing a service to the equipped aircraft in the form of access to constrained airspace. A "best-equipped, best-served" policy has been proposed for NextGen as a means to encourage airline operators to invest in equipage that will benefit the system as a whole [22]. This policy seems well-suited for FBTM, and it is already compatible with FBTM objectives.

The following sections describe the method of the study, including the airspace, tools, and experiment design, followed by the results of operational benefits and feasibility.

II. METHOD

A. Participants

Six FAA supervisory personnel were recruited to act as test participants: one from Southern California TRACON, and the others from five different en route facilities. Two area supervisors who were certified on the radar position worked as radar controllers. An area supervisor and a TRACON STMC with 9 years of prior supervisor experience staffed two supervisor positions. TMU positions were staffed by an STMC and an area supervisor with one year of prior TMC experience. The last two participants alternated roles between runs.

Retired controllers from Oakland Center staffed the remaining controller and traffic management positions. Positions staffed by participants or retired controllers are shown in Fig. 2 and Fig. 3, with participants labeled in white and retired controllers in black. All of the simulated aircraft were flown by simulation-pilots, who are active commercial pilots or students from the Aviation Department at San Jose State University.

B. Airspace

The simulation airspace included four high altitude test sectors in Kansas City Center (ZKC) and the surrounding airspace (Fig. 2, 3). Test sectors were divided into two areas: ZKC-North (sectors 94 and 98) and ZKC-South (sectors 29 and 90). The ZKC traffic management team coordinated with the surrounding facilities and managed inbound and outbound flows to address problems within ZKC and the adjacent facilities. The altitude floor of the simulation airspace was FL290.

The supervisory and traffic management positions, collectively comprising the planning team, are shown in Fig. 2. The ZKC traffic management team included two TMCs and one STMC. ZKC-North and ZKC-South each had an area supervisor and shared a "supervisor's assistant."

Controller positions are shown in Fig. 3. Test sectors were staffed by a 2-person team consisting of a radar controller (R-Side) and a radar associate (D-Side). One TMC and three controllers managed the ghost airspace.

C. Experiment Design

The experimental test scenarios combined 2 convective

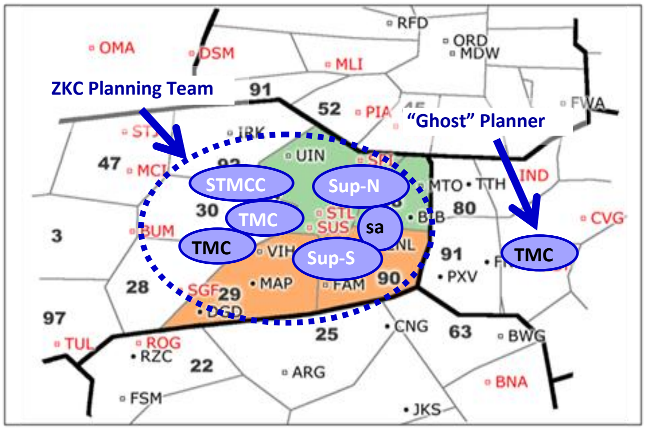


Figure 2. "Planning" positions: traffic management (STMC and TMC) and area supervisors (Sup-N, Sup-S and "supervisor assistant" (sa)).

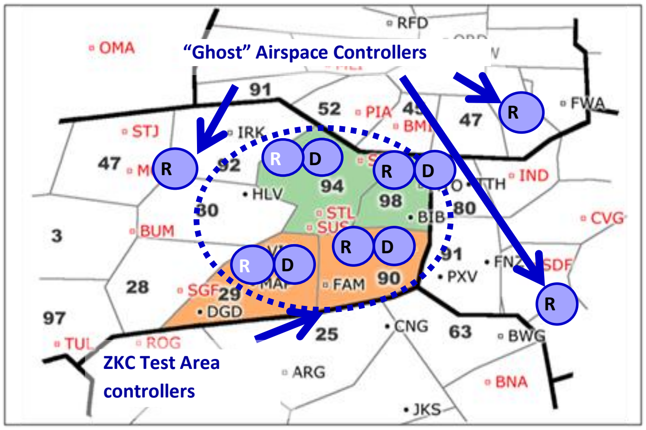


Figure 3. R-side and D-side Controller positions.

weather patterns (W1 and W2), 2 traffic patterns (Traffic Set 1 and Traffic Set 2), and 2 scenario variants (A and B), for a total of 8 unique traffic - weather combinations (Table 1).

Weather patterns W1 and W2 included convective weather within the ZKC test sectors and in the upstream or downstream ghost airspace (Chicago or Indianapolis Centers). Traffic Sets 1 and 2 were designed to present different traffic configurations that included interacting traffic flows, and some periods of excessive sector complexity, with similar traffic volumes. Each set also saw a different ratio of (Data Comm) equipped to unequipped aircraft in the test sectors, with Set 2 presenting an approximate 50/50 mix, and Set 1 an unequal mix with an approximate 10/90 between-category ratio. Scenario variants A and B swapped aircraft equipage assignments within a given traffic set: the equipped aircraft in variant A became the unequipped aircraft in variant B, and vice versa. Combining traffic sets with scenario variants resulted in three different equipage levels, with 10%, 50% or 90% equipped aircraft.

With the exception of equipage assignment, aircraft attributes within each of the paired A-B sets (1A and 1B, 2A and 2B) were identical. Swapping equipage assignments presented markedly different problems for the planning team however, since their strategies for handling equipped and unequipped aircraft were different. Swapping equipage for Traffic Set 1, the 10/90 mix, resulted in two different equipage levels, and allowed investigation of the impact of high vs. low equipage levels on feasibility and performance. Swapping equipage within Traffic Set 2 enabled analysis of service for equipage outcomes, since the equipage level remained the same but each aircraft's equipage assignment was changed.

D. *Simulation Environment*

The simulation was conducted in the Airspace Operations Laboratory (AOL) at NASA Ames Research Center [21]. FBTM (MSP) tools and procedures that were developed for the 2009 simulation were modified for the 2010 mixed equipage simulation in two areas:

- Planning team and controller tools were adapted for unequipped aircraft and mixed equipage traffic.
- Controller tools and procedures were modified so that a radar associate could assist with sector operations.

1) *FBTM Tools for Mixed Equipage Operations*

Automation on the planning workstations included decision support tools for situation assessment, trial planning and ground-to-ground coordination (Fig. 4). The FBTM tool set is described below, with a focus on enhancements that were made to support mixed equipage operations.

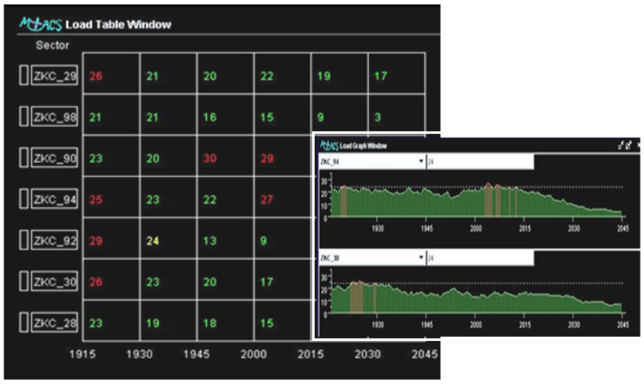
Situation assessment tools. A Traffic Situation Display (TSD) showed current traffic, with color-coded flows and an animated weather loop depicting recent and projected weather. A weather penetration probe identified aircraft that were predicted to penetrate convective weather at three intensity levels. An interactive radar display showed an FBTM view of current traffic, and a set of dynamic, interactive filters enabled the planner to highlight data blocks for subsets of this traffic. These filters allowed sets of aircraft to be identified by flight level, departure or arrival airport, waypoint, equipage type or predicted weather penetration.

TABLE I. 8 TRAFFIC + WEATHER COMBINATIONS

	Traffic Set 1: 10/90 Mix		Traffic Set 2: 50/50 Mix	
	10% EQ	*90% EQ*	*50% EQ*	*50% EQ*
W1	1A	1B	2A	2B
W2	1A	1B	2A	2B

Figure 4. FBTM Planning Tools

The planner station also had an interactive sector load table and load graphs (Fig. 5). The load table displayed predicted values for individual sectors (complexity, aircraft count, weather penetration events and other measures) in 15 minute increments. The load graphs showed predicted sector values in 1-minute increments. These displays could be used to actively filter the presentation on the DSR display. Clicking on a load table entry or time slice in the load graph highlighted the set of aircraft that contributed to that value. The complexity values were calculated by weighting and combining key workload contributors in this environment, such as aircraft equipage, aircraft count, number of weather-penetrating aircraft, and the sector size. In the mixed equipage environment with convective weather, the raw aircraft count did not properly represent the



MACS Load Table Window

Sector

ZKC_29	26	21	20	22	19	17
ZKC_98	21	21	16	15	9	3
ZKC_90	23	20	30	29		
ZKC_94	25	23	22	27		
ZKC_92	29	24	13	9		
ZKC_30	26	23	20	17		
ZKC_28	23	19	18	15		

1915 1930 1945 2000 2015 2030 2045

Figure 5. Sector Load Table (left), and Sector Load Graphs (right)

associated controller workload. Therefore participants used the complexity values instead as a “modified aircraft count.”

Multi-aircraft trial planning tools. The planning station also had multi-trajectory trial planning automation that supported the development of clearances and trajectory changes for one or several aircraft at a time. Filters could be used to highlight aircraft of interest. Routes could be developed using a trial planning tool that graphically generated routes to meet flow management objectives, e.g., weather avoidance, sector load redistribution, or complexity reduction.

Trajectories for Data Comm equipped aircraft were constructed by graphically creating user-defined waypoints at precise locations using lat/long coordinates. A new function was added to support the development of trajectory clearances suitable for the unequipped aircraft. This “snap-to” function found a named waypoint close to the desired trajectory change point, and then used that waypoint to construct a modified route that could be issued as a voice clearance.

Ground-to-ground coordination. Plan coordination and clearance requests were accomplished using radio and digital ground-to-ground data exchange. Ground-to-ground data exchange functionality was integrated such that a coordinated plan could send one or multiple trajectory trial plans to sender-specified TMCs or area supervisors for review and discussion. Proposed clearance requests could then be sent from the planning station to the sector that currently controlled that aircraft for the controller to review and execute.

2) *Controller Tools for Mixed Equipage Operations*

The controller station (Fig. 6) combined a current radar controller’s DSR display with additional automation tools that have been prototyped in the AOL simulation environment. The clearance request function was fully integrated with the controller’s trial planning, conflict probe, and Data Comm automation, all of which supported the sender in developing acceptable clearances, and the receiver in quickly evaluating their operational suitability and issuing the requested clearance. This functional integration was critical to the operational feasibility of FBTM operations. A controller D-Side station that had the same automation tools as the R-Side was also used in this simulation. Some D and R behaviors could be selectively coupled between stations (e.g., data block movement). The configuration of the stations and the role of the radar associate were decided by the radar controller.

Ground-to-ground coordination in a mixed equipage environment. Elements of the controller’s tools were modified to support mixed equipage operations, including equipage-based flight data block differences (color, symbols, and content) and features of the trial plan and clearance request interface (Fig. 7). Flight data blocks for equipped and unequipped aircraft were assigned different colors to facilitate quick recognition of aircraft equipage type. In order to support TBO for both equipped and unequipped aircraft, controllers were asked to try to keep unequipped aircraft on assigned trajectories rather than using vectors for lateral clearances. The target symbols were enlarged to a large chevron when an aircraft was out of conformance with its assigned trajectory, or “free-track”, which assisted controllers in monitoring aircraft status during this period.

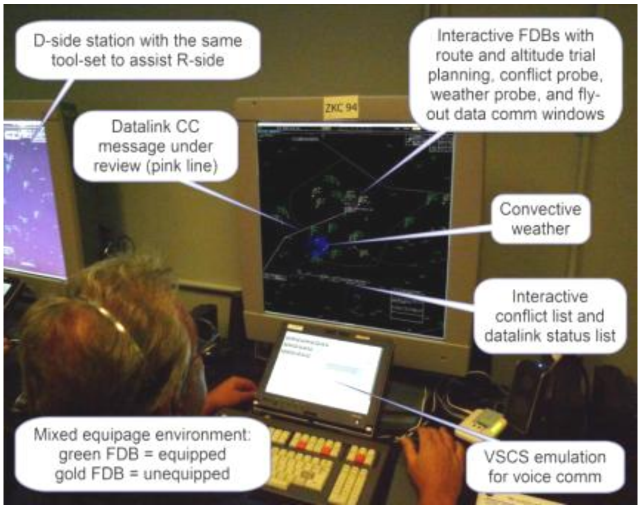


Figure 6. Controller station

Fig. 7 (top) illustrates the clearance requests that were received by the controller for an equipped aircraft (right) and an unequipped aircraft (left). Incoming requests were indicated by a pink box around the trial plan portal (arrow symbol). The controller clicked on the portal to show the pink trajectory for the request. Trajectory clearances for equipped aircraft were defined with lat/long coordinates, while unequipped aircraft trajectories used named waypoints, with new waypoints shown in the fourth line of the full data block.

If the controller approved the request, he or she issued the clearance to the aircraft. Equipped aircraft clearances could be sent to the aircraft and entered into the ATC computer system at the same time using the “UC” command in the Communication fly-out menu. Clearances were issued to unequipped aircraft by voice, and the route was amended in the ATC computer with the “QC” command (Fig. 7 bottom).

Some of these capabilities – conflict resolution advisories, route and altitude trial planning, Data Comm, R and D stations with similar functionality – are present in today’s operational systems, or will be available in planned system upgrades.

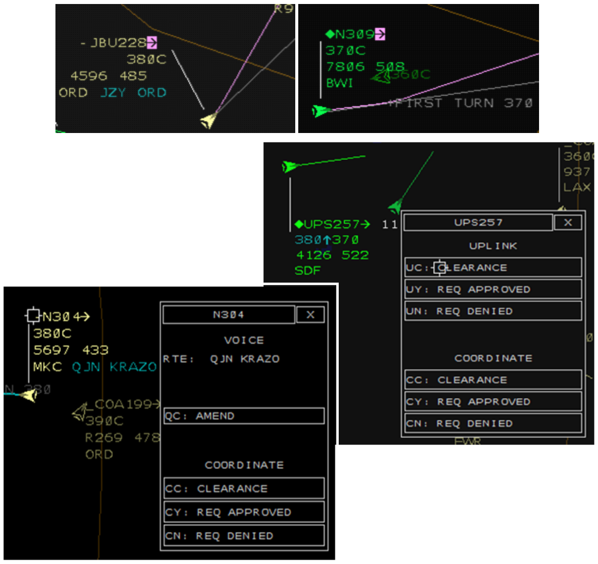


Figure 7. Pink coordinated clearances and Communication Fly-out Menu: unequipped aircraft (left), equipped aircraft (right)

Others, such as trajectory-based weather probes and resolution advisories, color-coded data blocks, integrated automation for ground-to-ground trajectory clearance request coordination – are either not planned, or are in early development [23].

E. *Experimental Procedures*

The study consisted of one day of concept briefing and training, followed by two days of data collection. In order to minimize training time, participants were sought who were familiar with the tools from earlier AOL simulations. Data collection runs began at the end of the first day and continued until the afternoon of the third day, followed by questionnaires and a debrief discussion.

The two ZKC areas (North and South) and the ZKC TMU were situated in three separate rooms. Pseudo-pilots and ghost positions were located in a fourth room. The two ZKC TMU participants alternated between STMC and TMC positions between consecutive runs. All other positions (supervisors North and South; radar controllers for sectors 29 and 94) worked the same positions throughout the simulation.

Each run began with a traffic management teleconference between the ZKC TMU, Command Center, and adjacent facilities. A confederate acting as a Command Center representative led a discussion about the status of current playbook routes, convective weather and other concerns, and provided a high level plan for modifying traffic flows to deal with the current situation. The STMC then organized the response within ZKC. The TMCs' activities were coordinated by assigning each a subset of the traffic problem: e.g., internal or external weather avoidance, northern or southern flows, different altitude strata. The STMC also briefed the area supervisors about the plan, including particular reroutes that their controllers might be asked to implement.

TMCs developed specific reroutes to accomplish their assigned tasks and to maintain sector complexity at manageable levels. Local problems were solved by developing reroutes that could occur within the test sectors or in the upstream ghost airspace. Downstream problems in a different facility might also involve rerouting aircraft in the test sectors. TMCs were told to move the unequipped aircraft first to provide better service to the equipped aircraft, but they could vary their responses based on the traffic situation.

The STMC monitored task execution, airspace status, and occasionally visited the operational area to insure that the plan was working out. The area supervisor briefed his controllers about what to expect, monitored their task load and the developing situation, and kept the TMU informed as needed about the area status. Finally, the radar controller determined the within-sector distribution of tasks with his D-Side, a split that might vary with weather and equipage level. The R-side and D-side worked side-by-side to closely collaborate on sector management. Controllers were instructed to provide better service to the equipped aircraft *when able*, by keeping equipped aircraft on their trajectories and rerouting the unequipped aircraft, particularly when solving "mixed equipage" conflicts.

III. RESULTS

Simulation results were analyzed for *benefits* in terms of system efficiency (test sector throughput), flight efficiency (flight distance), and service to equipped aircraft (higher throughput, shorter routes). *Feasibility* metrics included usage and outcome of clearance requests, workload, operational acceptability, and participant feedback on tools and procedures.

A. *Test Sector Throughput*

Sector throughput was defined as the number of unique aircraft that were observed in a test sector during each 60 minute run. Although the scripted test sector throughput was the same for paired sets of runs (1A and 1B; 2A and 2B), and similar by design between Traffic Set 1 and Traffic Set 2, observed throughput varied as the planning team routed aircraft around the test airspace to manage sector load and complexity.

Observed changes in mean test sector throughput as a function of equipage level are shown in Fig. 8. Total sector throughput increased when more aircraft were equipped. A one-way ANOVA performed on the mean sector throughput for the four ZKC test sectors revealed a significant difference by condition ($F(2,5) = 45.93$, $p < 0.01$), and post hoc tests revealed that mean sector throughput in the 10% equipage condition was significantly lower than in either the 50% or the 90% conditions (Tukey's HSD $p < 0.05$). The observed difference between the 50% and 90% conditions did not reach significance (Tukey's HSD $p > 0.05$).

Summed across all eight scenarios, exactly the same number of equipped and unequipped aircraft were scripted to pass through the test airspace. Observed differences can be attributed to selective rerouting by the planning team. The cumulative throughput of the four test sectors was significantly higher for equipped than for unequipped aircraft ($\chi21 = 17.24$, $p < 0.001$). Combined across all eight runs, 250 more equipped than unequipped aircraft flew through the test sectors (Fig. 9).

B. *Flight Distance*

The lateral path length difference between an aircraft's scripted trajectory and its actual flown trajectory was used as a measure of user efficiency. Mean path length differences were computed for all aircraft that flew in the simulation at FL290 and above. Most aircraft in the simulation saw no change in path length (observed changes less than 1 nmi), while path length was increased for 21% and reduced for 9% of flights. Averaged over all aircraft, path length was increased, with the average per-aircraft increase greater for unequipped aircraft

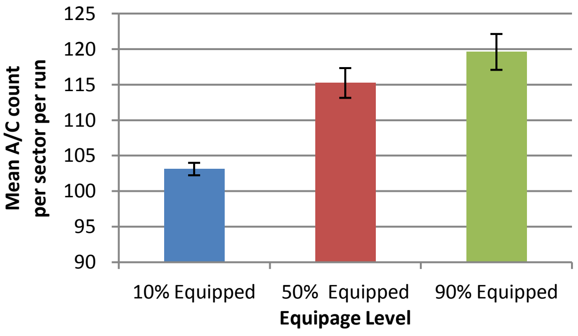


Figure 8. Average sector throughput per run, by equipage level.

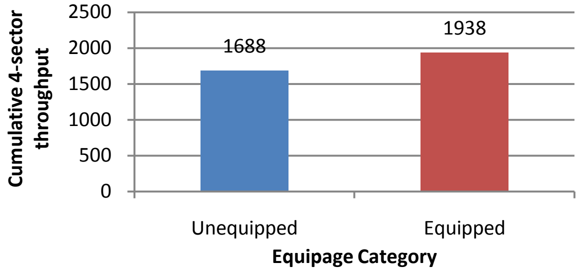


Figure 9. Cumulative throughput across all test sectors and all runs, by equipage type.

than for equipped aircraft ($M_{unequipped}$ = 1.91 nmi; $M_{equipped}$ = 0.69nmi; F(1,7963) = 22.09, $p < 0.001$). This difference was consistent with the hypotheses that the equipped aircraft received priority service (i.e. shorter flight distance) and that more unequipped aircraft were routed away from the congested airspace.

A comparison of mean path length changes for aircraft that transited the test sectors showed a similar advantage for equipped aircraft across all equipage levels (Fig. 10). A repeated measures ANOVA with the within-run variable "equipage type" (unequipped or equipped) and the between-run variable "equipage level" (10%, 50%, or 90%) confirmed a main effect of equipage type (F(1,5) = 7.16, $p < 0.05$), but no main or interaction effects of equipage level (F(2,5) = 0.02, $p > 0.05$ and F(2,5) = 0.00, $p > 0.05$), suggesting that the equipped aircraft advantage is independent of equipage level.

Path length changes inside and outside test sectors. Reroutes outside the test sectors could only have been initiated by the planners, while aircraft that entered the test sectors might have been rerouted by either controller or planner actions. An examination of these two categories of aircraft was used to provide insight into the impact of planners vs. controllers on the path length of rerouted aircraft.

Aircraft were first sorted into two sets: those that transited the test sectors and those that did not. Aircraft within each set were further sorted according to whether their path length was increased, decreased or unchanged, and the mean increases or decreases were calculated for equipped and unequipped aircraft. Results are shown in Table II, along with the ratio of unequipped to equipped changes.

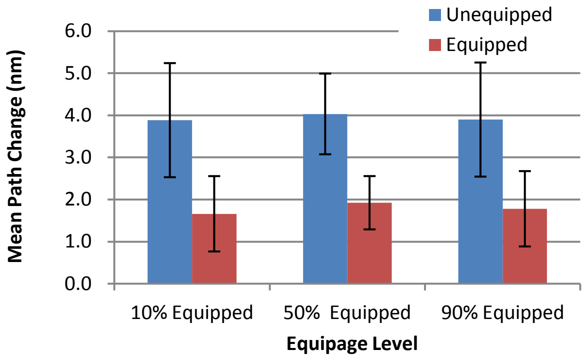


Figure 10. Mean path length change (final – original path length) per aircraft by equipage level, for aircraft that transited the test airspace.

TABLE II. MEAN PATH LENGTH INCREASE OR DECREASE, FOR AIRCRAFT WITH CHANGE MAGNITUDE GREATER THAN 1 NAUTICAL MILE

	aircraft that transited test airspace			**aircraft that did not transit test airspace**		
	mean decrease (n)	***mean increase (n)***	***(no change)***	***mean decrease (n)***	***mean increase (n)***	***(no change)***
uneq.	-12.4 (185)	18.8 (344)	(647)	-16.5 (205)	21 (328)	(2341)
eq.	-10.7 (182)	10.9 (387)	(572)	-14 (172)	12.3 (234)	(2364)
ratio	*1.16*	*1.72*		*1.18*	*1.71*	

When comparing the mean values for the aircraft that did and did not pass through the test sectors, three things stand out:

- Path length increases of *unequipped* aircraft were approximately 70% longer than those of *equipped* aircraft both inside and outside of the test airspace. This suggests that the planners were primarily responsible for the between-equipage path differences in both sets, and that the controllers main impact was to maintain the shorter reroutes for the equipped aircraft as they flew through the test airspace.
- Unequipped aircraft path length decreases were approximately 17% greater (i.e., saw greater reduction) than equipped aircraft decreases for both sets. One explanation for this would be that the adjustments for equipped aircraft could be more precisely crafted using lat/long waypoints closer to the original route, with the cruder resolutions for unequipped aircraft sometimes resulting in a shorter flight path that deviated further from the original route.
- Flight path changes for all categories in Table II were smaller for aircraft that flew through the test sectors. This is probably because more drastic maneuvers were needed to route aircraft completely out of the test sectors.

C. *Maneuvered Aircraft Type in Conflict Resolution*

Radar controllers and associates were asked to give priority service, when able, to equipped aircraft in mixed equipage conflicts by maneuvering the unequipped aircraft and leaving the equipped aircraft on their trajectories. In the vast majority of cases (108 out of 132) the test controllers' resolution maneuvers conformed with this guideline and moved the unequipped aircraft. Most of the cases where the controller chose to move the equipped aircraft occurred when the unequipped aircraft was either off the radar scope or not "owned" by the controller resolving the conflict, or when the equipped aircraft was changing or about to change altitude.

A repeated measures ANOVA using within-run variable of maneuvered aircraft equipage type (unequipped or equipped) and between-run variable of airspace equipage level (10%, 50%, or 90%) revealed main effects of both equipage type and equipage level (F(1,5) = 22.13, $p < 0.01$ and F(2,5) = 58.79, $p < 0.001$, respectively), which were qualified by a significant equipage type by equipage level interaction (F(2,5) = 10.08, $p < 0.05$). An inspection of the means revealed that unequipped aircraft were moved more often than equipped aircraft. This difference was more pronounced with 50% equipage (Fig. 11).

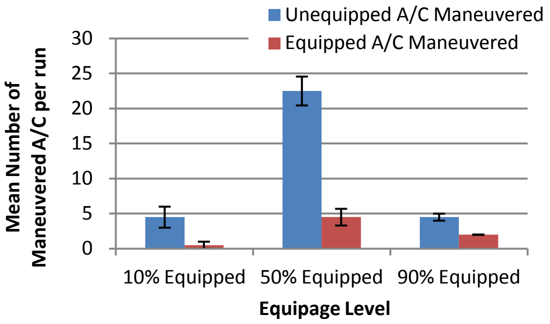


Figure 11. Mean number of unequipped and equipped aircraft maneuvered to resolve mixed equipage conflicts, per run.

D. *Clearance Requests*

A total of 1595 clearance requests were recorded across all 8 runs: 625 sent from a ZKC TMC or area supervisor, 235 from a ZKC test sector, and 735 from the Ghost TMC. 229 of these requests were sent to one of the four test sectors, and 1366 to the ghost airspace (Table III).

There were nearly twice as many requests sent for unequipped aircraft as there were for equipped aircraft ($T_{unequipped} = 1026$, $T_{equipped} = 569$), reflecting the planners' strategy for preferentially moving unequipped aircraft. This high number also indicates that participants found the tools satisfactory for planning trajectory modifications for unequipped aircraft.

Most clearance requests received by the ghost sectors were sent from a planning station (1297 out of 1366). Most requests received by test sector controllers were sent by another controller (166 out of 229), either for within-sector (D to R) coordination of trajectory clearances for unequipped aircraft, or for between-sector coordination of conflict resolution or weather avoidance maneuvers. Unlike planners, controllers had other options for within and between sector clearance coordination, so their use of this function, particularly for within-sector coordination, suggests that they found it both useful and usable.

Controllers accepted 218 of the 229 clearance requests that were sent to the test sectors. 10 requests were rejected, and 1 (sent shortly before the end of a run) was ignored. Nine of the rejected requests were sent by the associate to his/her own radar controller. These were canceled by R-side and D-side controllers, either because the problem went away or because he or she wanted to use a different clearance.

E. *Workload*

Instantaneous workload ratings, on a scale from 1 (lowest) to 6 (highest), were recorded every five minutes throughout each run. Workload was obtained from all test positions.

The mean workload for radar controllers and radar associates decreased as equipage level increased (Fig. 12). A repeated measures ANOVA confirmed a significant difference between conditions ($F(2,14) = 12.91$, $p < 0.01$) and follow-up planned contrast tests revealed mean workload was significantly lower in the 50% condition than in the 10% condition, and significantly lower in the 90% condition than in the 50% condition ($F(1,7) = 6.04$ and 17.16, $p < 0.05$ and 0.01, respectively).

TABLE III. NUMBER OF REQUESTS SENT TO TEST SECTORS AND GHOST SECTORS, BY EQUIPAGE TYPE.

Recipient	Unequipped	Equipped	Total
ZKC test sector	202	27	229
Ghost sector	824	542	1366
TOTAL	1026	569	1595

Mean workload of area supervisors and the three ZKC TMU participants was lower in the 90% condition, but did not differ between the 10 and 50% conditions. A repeated measures ANOVA revealed a significant difference between conditions ($F(2,8) = 21.84$, $p < 0.01$) and follow-up planned contrast tests revealed that workload was significantly lower in the 90% condition than in the 50% condition, but did not differ between the 50 and 10% conditions ($F(1,4) = 31.36$ and 0.02, $p < 0.01$ and > 0.05, respectively).

After each run, each of the six participants responded to a modified version of the NASA-Task Load Index (NASA-TLX), rating each of the six factors, (performance success, effort, frustration, and mental, physical, and temporal demand) based on their peak workload during the run [24]. Each factor was rated on a seven point scale ranging from very low to very high. Average ratings were computed for each position-equipage level combination. These followed the same pattern as the workload data, with the 10% and 50% conditions tending to be more similar to each other than to the 90% condition.

One TLX sub-factor, "frustration," was consistently higher across all positions in the 50% runs. In post-run questionnaires participants also reported experiencing more confusion during the 50% runs. R-side and D-side controllers also reported task coordination to be somewhat more difficult at 50% equipage.

F. *Operational Acceptability*

Participants completed a modified version of the Controller Acceptance Rating Scale (CARS) [25]. Phraseology was adapted for the planner and controller positions. After each run, the CARS questionnaire was presented by computer, with answers to the following questions leading conditionally to either the subsequent question or a choice of rating statements:

1) "Were the [radar controller] operations safe and manageable?" (if "no" rating = 1)

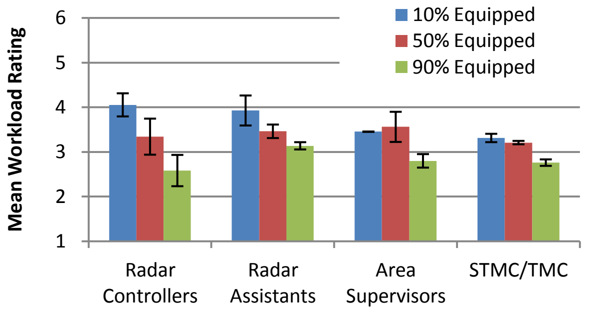


Figure 12. Mean workload rating per position and equipage level.

2) "Was adequate performance attainable with tolerable workload?" (if "no" choose from rating statements 2-4)

3) "Were operations satisfactory without improvement [Was the radar controller's role satisfactory]?" (if "no" choose from rating statements 5-7, if "yes" indicate effectiveness / desirability from 8-10)

Most of the eight runs received high scores from all participants, with 41 out of the 48 CARS data points clustered in the 8-10 range. All of the lower ratings were distributed between the 10% and 50% runs, with the 10% equipage level receiving a rating of "4" from one controller and one TMC, and one "6" from a supervisor; and the 50% equipage level receiving a "2" rating from one controller and a "6" and two "7s" from area supervisors. When asked to explain, participants attributed their low post-run ratings to excessive workload or complexity associated with convective weather, traffic volume, or the number of unequipped aircraft. Mixed equipage and service for equipage operations did not appear to be contributing factors.

G. Participant Feedback

1) Tools

Usage data suggest the prototype tools were effective and satisfactory for mixed equipage operations. Both TMCs and controllers developed the majority of their coordinated clearances for unequipped aircraft, and the vast majority of these were accepted and executed via voice by controllers.

Subjective feedback from post-simulation questionnaires and a debrief discussion confirmed this observation. When asked to rate the usefulness and usability of simulation tools, TMCs and supervisors gave generally high ratings to solution planning, situation awareness and coordination tools. Controllers also rated the trial planning and coordination tools highly. However, both TMCs and controllers reported that the sparse distribution of named waypoints made it difficult to construct efficient routes for unequipped aircraft [17, 23].

2) Service for Equipage in Flow Planning Operations

Area supervisors and traffic management coordinators reported that, whether moving traffic for sector load or weather, they were able to provide better service to the equipped aircraft across all equipage levels. They did this by rerouting unequipped aircraft first and allowing equipped aircraft to fly their original, or close to their original, trajectory. For weather, that meant unequipped aircraft were rerouted and equipped aircraft were allowed to just "skirt" the weather. One supervisor commented that the service for equipage policy was a "win-win," since moving an unequipped aircraft out of a sector lightens that sector controller's workload more than moving an equipped aircraft, and at the same time rewards equipped aircraft with better service. Traffic management coordinators indicated that a strategy of focusing on the unequipped aircraft, and leaving the equipped aircraft untouched helped them resist the inclination to move the equipped first simply because it was operationally easier to do so. When able, the TMU left it to the controller to move an equipped aircraft, if necessary.

TMCs also pointed out that the varying equipage levels did not change their general strategy for providing better service to equipped aircraft. They said that if they noticed a sector "going red" (i.e., about to exceed its maximum aircraft count), they would "let it ride," if it was equipped aircraft pushing it over the limit, since these were "not a big deal" for controllers.

3) Service for Equipage in Sector Operations

Across equipage levels, controllers responded that they gave equipped aircraft priority access to constrained airspace, and made unequipped aircraft yield to equipped aircraft in mixed equipage conflicts. In a post-simulation questionnaire, the difficulty of these two tasks was rated 2 or less for all three equipage levels on a 1 ("not at all") to 7 ("very difficult") scale. However some participants questioned whether it was necessary or suitable for controllers to favor equipped aircraft, particularly since the FBTM operations were so effective.

IV. DISCUSSION

Feasibility. Overall, results suggested that FBTM operations were feasible in a mixed equipage environment and that the tools were effective with both equipped and unequipped aircraft. Using the FBTM tools, traffic management coordinators were able to effectively balance throughput with complexity and task load at each equipage level. Also across equipage levels, mean reported task load and workload remained tolerable, and operational acceptability was reported to be satisfactory. Although reported frustration was comparatively higher at the 50% equipage level, the 50% mix was still reported to be workable based on both the ratings and participant feedback. On a more tactical level, controllers also found the trajectory tools useful and effective for trial planning and coordinating clearances for both equipage categories within their own sector team and with other sectors.

Benefits. Benefits were observed both in terms of system performance and operational support for a "best-equipped, best-served" approach to traffic management and air traffic control. As equipage level increased, throughput increased, even as controller workload decreased. FBTM operations effectively supported priority service for equipped aircraft. When flow adjustments were needed, more equipped than unequipped aircraft transited the test airspace, and unequipped aircraft received a greater increase in flight path length.

Roles and Responsibilities. Other operational procedures established throughout the simulation suggested that the bulk of area flow planning – trial planning and clearance coordination – can be effectively carried out from the TMU with operational area supervisors performing these functions far less often. Task division within the TMU can vary depending on the situation: the STMC divided flow management responsibilities between TMCs based on altitude strata, geographic area, or airspace problem (e.g., weather constraint or traffic volume). Other than voice communication with aircraft, which was always performed by the radar controller, the division of tasks and responsibilities between radar controllers and associates varied by sector team and by equipage level.

Service for Equipage. The procedures and tools designed to support a "best-equipped, best-served" policy within FBTM and controller operations were both feasible and effective. Planners and controllers agreed that this was a suitable objective for traffic management and one that could be very effectively met using FBTM operations. Solving local area demand/capacity imbalances by moving unequipped aircraft away from the affected airspace is a flow planning strategy that can maintain higher system throughput while rewarding operators of equipped fleets. Planners were quick to adopt this strategy in the simulation, and found it highly effective, with no apparent downside.

In contrast, feedback was somewhat divided about whether controllers should provide priority service for equipped aircraft, although controllers reported that it was possible, and that the added workload was reasonable. Participants suggested that the benefit that could be provided to equipped aircraft at the sector level would be small compared to FBTM operations.

V. CONCLUSIONS

In summary, a concept for flow-based trajectory management was prototyped and tested in this simulation. This concept appears both feasible and beneficial for supporting local area traffic flow management in a mixed equipage environment.

The simulation demonstrated that a TMU practice of providing Data Comm equipped aircraft priority access to constrained airspace represented a “best-equipped, best-served” policy that also equated to good airspace management and improved system efficiency. Results indicate that service for equipage practices at the sector level were also feasible, and might be acceptable if implemented at the controller’s discretion, with good tool support.

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