Trajectory Negotiation via Data Link: Evaluation of Human-in-the-loop Simulation

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ABSTRACT

A simulation evaluation of Distributed Air Ground-Traffic Management (DAG-TM) concepts for distributing flight information and decision-making authority among pilots and controllers was completed at NASA Ames. A procedure for en route trajectory negotiation was tested, with air-ground communication method (voice vs. data link) and level of automation technology varied in four experimental conditions: Baseline, Uplink, Uplink/Downlink, and Uplink/Downlink with conflict detection and resolution (CD&R). Data link was used for transfer of communication (TOC) in all conditions. The results suggest that pilot-initiated requests and simple controller response to the requests was as an efficient method of trajectory negotiation. However, the pilot and controller interfaces could provide better cues for the requests and the traffic situation. The data linked route requests were most likely to be accepted by the controllers when the routes were conflict-probed by the flight deck CD&R, showing potential benefits of conflict-probed paths. In addition, controllers highly endorsed the transfer of communication through data link as a workload saving mechanism.

Keywords

trajectory negotiation, air-ground integration, data link, transfer of communication, user preferred trajectories

INTRODUCTION

Distributed Air Ground Traffic Management (DAG-TM) is a proposed set of solutions that target specific problems identified in today's National Airspace System (NAS). DAG-TM is based on the premise that new human-centered tools and procedures can enable NAS participants to share information and collaborate at all levels of traffic management decision-making. Individual DAG-TM "concept elements" describe how these innovations can alter user and air traffic service provider (ATSP) roles and responsibilities to allow more user-preferred routing, increase flexibility, increase system capacity, and improve operational efficiency. DAG-TM research is part of the Advanced Air Transportation Technologies (AATT) project under the National Aeronautics and Space Administration's (NASA's) Airspace Systems program.

Researchers at NASA Ames Research Center recently conducted an integrated air-ground human-in-the-loop (HITL) simulation to investigate the feasibility of a concept element for en route Trajectory Negotiation (referred to as CE 6). The objectives of CE 6 are to reduce inefficient ATSP-issued route deviations, reduce controller workload, and facilitate trajectory change requests by integrating ATSP and user automation with data link [1]. Improving the ATSP trajectory prediction capability with user-supplied data on key flight parameters can help reduce the inefficient route deviations used in today's operations. In addition, providing the flight deck the capability to construct conflict-free user-preferred trajectories that conform to traffic flow management (TFM) constraints should facilitate trajectory change requests and reduce controller workload associated with separation assurance and TFM conformance.

A series of prior simulations at NASA Ames Research Center explored CE 6. The most recent of these earlier simulations was a HITL experiment conducted in September 2002 [2]. Participants were five certified professional controllers and eight commercial pilots who operated in scenarios that simulated arrival and overflight traffic in the en route airspace northwest of Dallas/Fort Worth International Airport (DFW). One purpose of this study was to explore the viability and potential benefits of flight deck-initiated trajectory changes. The results demonstrated that CE 6 might provide improvements in efficiency and capacity without compromising safety or significantly increasing workload. In the CE 6 condition, aircraft were able to fly more efficient paths at higher altitudes over a shorter period of time. In addition, aircraft were delivered to the TRACON meter fix more accurately and with better spacing than in the Baseline condition. Subjective feedback from participants further indicated the acceptability of the concepts in terms of mental workload, temporal demand, and situation awareness, as compared to current day operations [2].

METHODS

The current study was completed in November 2003. This simulation focused more closely on the importance of air and ground technology enhancements to support en route trajectory negotiation for user-preferred routing. Three different implementations of CE 6 were compared to a baseline condition to evaluate the importance of different concept-enabling capabilities such as the uplink and downlink of four-dimensional (4D) trajectory plans and integration of data link with air and ground Decision Support Tools (DSTs) for CD&R and time-based metering.

Equipment

ATSP Automation

Controller DSTs included an automated scheduler to support time-based metering to the TRACON boundary, a timeline representation of this meter fix schedule, and controller-pilot data link communication (CPDLC) support for TOC. The three CE 6 conditions added a trajectory-based conflict probe (Figure 1), speed advisories to support time-based metering, and a trajectory trial planning capability, all integrated into a CDPLC clearance uplink capability. The ground-side CPDLC system and interface were modeled on the CPDLC Build 1 implementation currently used at Miami Center (ZMA) [3]. The conflict probe presentation was loosely based on the design developed for the Center TRACON Automation System's Direct-To interface [4].

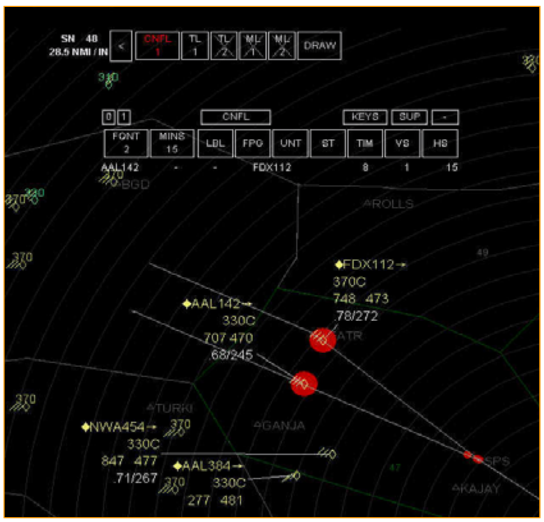

Figure 1: Trajectory-based conflict prediction

Transfer of Communications (TOC)

A CPDLC-supported method for TOC was used by pilots and controllers in all conditions. TOC is 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 either automatically sent to the aircraft (TOC "AUTO") or automatically created and "held" in the data link Status List (TOC "MANUAL"). When ready, the transferring controller uplinks the held message. The pilot receives the uplink message, tunes the new frequency, and responds via CPDLC. CPDLC eligibility transfers to the receiving sector as soon as the downlinked "WILCO" is received.

Flight Deck Automation

All aircraft in the simulation had CPDLC, a flight management system (FMS) and automatic dependent surveillance-broadcast (ADS-B) in all experimental conditions. The subject pilot's flight deck also included a cockpit display of traffic information (CDTI) that provided a view of proximal traffic based on state and, if available, intent information. The CDTI displays traffic location relative to ownship, relative and absolute altitude, vertical trajectory, and speed. Four dimensional flight plans with waypoints and altitude changes could be viewed for traffic within the broadcast range and altitude surveillance band of the CDTI. For aircraft broadcasting a flight plan, a pulse predictor indicated the future position over time, as it travels along the planned flight path according to the commanded FMS speeds. The CDTI has an optional 3D view-mode that enabled the pilot to rotate the traffic display 360° (Figure 2). A Route Assessment Tool (RAT) for constructing trajectory change requests that could be downlinked to the controller was available in two conditions. The most advanced condition integrated CD&R capability with the RAT.

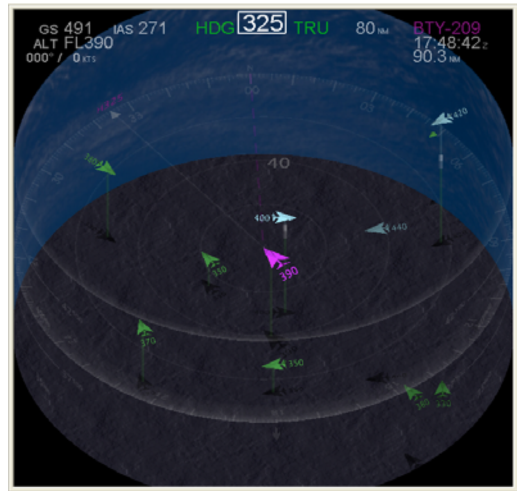

Figure 2: CDTI showing optional 3D traffic presentation

Airspace and Scenarios

The simulation airspace included portions of Fort Worth Center (ZFW) and DFW TRACON (see Figure 3). Controller participants worked 4 test sectors in ZFW's northwest arrival corridor: three high altitude sectors (Amarillo in Albuquerque Center, Wichita Falls and Ardmore in ZFW) and one ZFW low altitude sector (Bowie). Three retired controllers worked the airspace adjacent to these sectors.

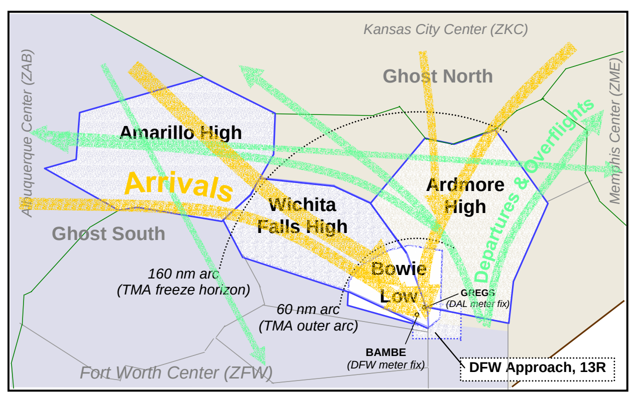

Figure 3. Simulated Airspace

Scenarios were approximately 70 minutes long, at a moderate traffic level. Approximately half of the aircraft were overflights/departures and half were arrivals converging to the ZFW northwest cornerpost. Amarillo and Wichita Falls sectors worked the main arrival flow into Bowie while the Ardmore sector provided a secondary arrival flow. The Ardmore sector handled most of the departure traffic, and

Amarillo and Ardmore sectors handled the majority of overflight traffic. Subject pilots flew both as arrivals and overflights.

Participants

Subject participants consisted of six certified professional controllers and ten licensed pilots. The four en route controller participants were from Oakland, Fort Worth, Atlanta, and Memphis Centers. The number of years of experience for these controllers ranged from 19 to 27 years (mean = 22.2 years).

Ten air transport-rated pilots participated in the study, all of whom had previous experience with the DAG-TM concepts. The pilots ranged in age from 29 to 61years, with a mean of 42 years. Total number of flight hours for each pilot ranged from 3,330 to 23,000, with a mean of approximately 8,710 hours.

All ten pilots had glass cockpit experience ranging from 100 to 8,000 hours, with a group mean of approximately 3,200 total hours. One pilot team (first and second officer) flew the Advanced Concepts Flight Simulator (ACFS) and the eight other subject pilots individually flew Multi Aircraft Control System (MACS) desktop flight deck stations. Seven private pilots flew all remaining aircraft in the simulation from MACS workstations [5].

Experiment Conditions

This study compared four en route modes of operation that represent a continuum of increasing levels of automation and procedural support for trajectory negotiation:

- Baseline – roughly approximates year 2015 operations, with CPDLC-supported TOC, time-based metering, and ADS-B. Pilot requests and controller replies were exclusively voice communications.
- Uplink – includes all functions supported in the Baseline condition with the addition of an "uplink" clearance capability from the ground-side to the cockpit. This capability was fully integrated with ground-side DSTs, including a 4D trajectory trial planner, meter fix scheduler, and speed advisories. In this condition, pilots made their requests by voice, and the controller could approve the request by voice or by sending a CPDLC uplink clearance that meets the request.
- Uplink/Downlink – provides all of the capabilities and functionality described in the previous two conditions with the addition of flight deck downlink and route planning automation. This mode of operation allowed the flight crew to use the CDTI's RAT to construct trajectory changes and downlink them to the controller as a request. The controller then used ground automation tools to review the downlink request, then accept or reject the requested route by data link.
- Uplink/Downlink with CD&R – provides all the capabilities and functionality described in the previous three conditions with the addition of strategic conflict detection and resolution functionality. Under Uplink/Downlink operations with CD&R, the RAT could be used to create nominally conflict-free trajectory modifications.

Eight data collection runs were completed, testing each of these four conditions twice.

Trajectory Negotiation

Trajectory changes requested by the flight deck were made either by voice or by CPDLC, depending on the experimental condition. The controller could respond to the request by voice or CPDLC, as appropriate. The pilot request by CPDLC was presented to the controller in two ways: a down arrow symbol in the datablock that is clickable to view the requested route and a message in the data link status list with a "REQ" marker to indicate that it is a pilot request. Both the down arrow symbol and "REQ" in the status list were highlighted in magenta so that the requests were highly salient. The request can be accepted or rejected either by voice or by CPDLC, but if the request was rejected, a radio communication explaining the reason for rejecting the request was required, providing the opportunity for the pilot to reformulate a more acceptable request, or for the controller to determine flight crew intent and offer an alternative solution.

In each run, subject pilots were given scripted scenarios to "probe" the trajectory negotiation process. These probes provided pilots with a reason for requesting a route modification, the description of the modification, and the general time frame for making the request. Two examples of probe-related route changes include 1) an arrival in the Amarillo sector is requested to absorb an en route delay and 2) an overflight flying northwest through the Ardmore sector requests a shorter route that cuts through the arrival stream in Wichita Falls and Amarillo sectors.

RESULTS AND DISCUSSION

Pilot-initiated Trajectory Requests

The simulation design planned for 38 pilot-initiated requests. Table 1 summarizes the result of these negotiations between pilots and controllers across the four conditions. In the baseline and the Uplink condition, the negotiation was done by voice, and in the Uplink/Downlink conditions, it was done through CPDLC with voice as a backup channel for conveying pilot and controller intent.

Negotiation	Condition				Total
	Baseline	Uplink	Uplink/ Downlink	Up./Down. w/ CD&R	
Approved on 1st request	7	6	5	8	26
Rejected on the 1st request; uplinked a similar route before the 2nd request	0	0	2	1	3
Rejected on 1st request; approved on later request	3	2	0	1	6
Rejected Completely	0	1	2	0	3

Table 1. Scripted Pilot-Initiated Negotiation Results

En route controllers approved 26 of the 38 pilot requests when they were first made. Nine of the 12 requests that controllers initially rejected were subsequently approved. According to pilot comments collected following rejected negotiations, requests were often not approved due to issues such as traffic congestion and collision avoidance. Controllers would not approve requests that would fly through heavy traffic or into the flight path of another aircraft. Although the distribution of numbers are not significant due to small sample size, the data suggest that Uplink/Downlink condition with CD&R on the flight deck had a higher number of accepted requests than the other three conditions, perhaps indicating that route requests that are probed for conflict-free paths have better chance of getting accepted by the controllers. In contrast, Uplink/Downlink condition without CD&R seemed to fare the worst, suggesting that requesting precise routes that have potential for conflicts may be worse than verbal requests that do not specify trajectories.

An interesting split occurred on the controller actions when the requests were initially rejected and approved at a later time. When the requests were made by voice (i.e. baseline and Uplink), the controller rejected the initial requests and then waited for a second request by the pilot before approving it. In contrast, when the requests were made through CPDLC, the controller viewed the requested route, found some problems with the surrounding traffic, and then immediately uplinked a route that was similar to the downlinked requests but one that also avoided potential conflicts.

This contrast in controller actions seems especially interesting for the Uplink condition, in which the controller had an option to uplink a route in response to a voice request but didn't. The data suggests that controllers were more likely to respond in the same modality – i.e. downlinked trajectory with uplinked trajectory and voice request with voice response. One possible explanation is that there is a closer match between the downlinked and uplinked routes, so that the controller can modify the downlinked routes to preserve the original pilot intent while also resolving potential conflicts of the proposed route, whereas the voice request is sufficiently underspecified (e.g. "requesting direct to Tucumcari") that crafting a trajectory based on the request would add inadvertent constraints that the pilot might not have intended. Alternatively, the controllers may prefer to respond within rather than cross-modality.

Despite expressed preference during debrief discussions for simple "unable" or "unable due to traffic" as a sufficient mode of communication when rejecting a request, an examination of the pilot-controller interaction reveals that controllers often suggested modifications to the pilots' requests. For example, one controller told the pilot that the request was "unabled due to traffic" but to make the request again in 10 minutes. In another example, the controller suggested to the pilot that his request can be approved if he changes his altitude from FL350 to FL310. These types of simple interactions seem feasible, either by voice or by simple text messages through CPDLC, without creating a significant workload for the controllers.

Feasibility / Acceptability of Trajectory Negotiation

Controller Perspective

Controller participants generally felt comfortable accepting pilot requests. They felt most comfortable accepting pilot requests during the Uplink condition (M = 4.8; 1=Not at all comfortable, 5=Very comfortable), followed by the Uplink /Downlink with CD&R (4.5), Baseline (4.4), and Uplink /Downlink (4.0). Indeed, during most trials the controllers reported no problems viewing and/or accepting pilot-initiated requests. One possible reason for the high acceptance rate of the requests is that they generally caused only a small increase in traffic complexity, both in their own sector and for the downstream sector, with average ratings of 1.8 (5=Very complex, 1=Not at all) or below for all conditions.

Controllers had mostly positive comments about the concept of trajectory negotiation, with one saying the concept "shows promise if all tools are working properly. Traffic volume would be key." Another said, "since pilot displays don't have sector boundaries it can be somewhat tedious with adjacent sector conditions, but since the requests are supposed to be conflict-free it should be easier to approve."

The two sector controllers who handled scripted pilot initiated requests had split views on receiving requests via CPDLC vs. voice. One controller was ambivalent about the idea that pilots can send route requests either by voice or CPDLC. The same controller also thought that requests through CPDLC should be accompanied by voice and given a choice, he preferred voice requests. He found voice feedback upon a rejection of a request to be acceptable method of communicating intent. In contrast, the other controller strongly favored pilot initiated requests via CPDLC than voice and found the concept to be quite acceptable.

In the questionnaire and subsequent debrief discussions, one controller elaborated on his ambivalence towards pilot initiated requests and the role of CPDLC that can potentially exacerbate the situation. He thought that the trajectory negotiation concept could significantly increase the controller workload in the field because given an easy mechanism to make requests pilots would bombard the controller with them in situations where a more efficient routing is possible. Interestingly, he thought that CPDLC made it *easier* to make requests, thereby potentially increasing the volume of requests which in turn would increase the controller workload. Another potential for increased volume of requests using CPDLC is that monitoring a voice frequency gives the pilots a sense as to how busy the controller is based on the voice channel congestion and it does not allow pilots to make requests during busy operations. However, CPDLC-based communication eliminates the voice chatter, creating an illusion of light controller workload.

During the discussion, we talked about various workarounds to this potential problem, such as putting a priority filter on the requests that allow appropriate number of requests to reach the controller based on the importance of the request and the controller workload. The filter may be set by the controller to block out some or all requests, or it may be set by the automation based on quantitative metrics such as sector capacity or dynamic density.

Controllers felt the interface for trajectory negotiation was somewhat adequate (M = 3.75; 1=Completely inadequate, 5=Completely adequate). They believed it was somewhat difficult to detect downlink clearance requests sent from the aircraft (M = 3.33; 1=Very difficult, 5=Very easy), with one participant saying “what few requests I did have it didn’t seem real obvious that something was being requested at first. As familiarity increased it became much more obvious.” Observations during the simulation runs seem to suggest that providing highly salient cues on the CPDLC status list was not always enough to properly alert the controller that a request came in because when busy, the controller looked at the status list intermittently. A stronger cue should in the datablock itself seem to be the correct solution to this problem but a highly salient cue in the datablock must not be so strong that it becomes a distraction.

For the trajectory negotiation procedures, the controllers preferred requests through CPDLC slightly over voice (M = 3.75; 1=Prefer verbal channels, 5=Prefer CPDLC), although they rated the level of workload associated with reviewing and responding to downlinked pilot requests through CPDLC very low (M = 4.67; 1=Very high workload, 5=Very little workload). In general, the en route controllers felt that the workload levels during CE 6 trials were acceptable. Overall, controller workload and performance-related metrics were comparable across conditions. They also responded that the ability to data link clearances was much more useful compared to voice clearances (M = 4.75; 1=Data link much less useful, 5=Data link much more useful), and the ability to data link clearances reduced their overall workload (M = 4.25; 1=Greatly increased, 5=Greatly reduced).

During pilot/controller debrief discussions, we asked the pilots and controllers if it was sufficient to have a procedure that simplified the trajectory negotiation interaction to a) a pilot initiated request via CPDLC, b) a controller response via CPDLC, and c) an accompanying voice response with a rejected request. We also asked them if they could suggest better tools and/or procedures to convey pilot and controller intent during trajectory negotiation. Interestingly, both the pilots and the controllers expressed that a simple interaction was sufficient. Controllers commented that they didn’t really need to know why a pilot made a particular request and that often they could guess the intent based on the context. Controllers thought that a simple “unable” or “unable due to traffic” was sufficient communication to convey why a request was rejected. In contrast, pilots wanted to better understand the reason behind the controller action but found the simple controller response acceptable.

Pilot Perspective

Post-simulation questionnaire results indicate that the pilot participants found CE 6 to be a practical and acceptable approach (M = 3.9; 1=Not practical/unacceptable, 5=Practical/acceptable). All pilots rated the acceptability of the concept element with a score of 3 or higher.

In the tool evaluation, pilots rated the CDTI a 3.6 average (1=Never supported the task, 5=Always supported the task) in terms of its ability to support construction and execution of new routes. They were also asked to rate the degree to which data link reduced workload in the en route environment. The ten pilots’ average response was 4.0 (1=Never helpful in reducing workload, 5=Always helpful in reducing workload), with all ten pilots selecting a value of three or higher. Only two pilots described the CPDLC as neither increasing nor decreasing workload. In this environment the pilots perceived, on average, the tools to be superior to the current operational environment. They believed that the CDTI supported the construction of new routes and that the data link had a noticeable effect on reducing workload.

Pilot and controller criticisms mainly focused on aspects of the interface, not on the concepts as a whole, which was well received. This was reflected by the post-simulation questionnaires, in which one pilot noted, “This study shows some promising improvements to the pilot and controller environments, which includes increased levels of safety and better efficiencies in our airspace, cockpits, and control rooms.” Another pilot commented, “Overall I like the CDTI tools. [They] made looking at the big picture much easier.”

This desire for pilots to understand the “big picture” came up again during the pilot/controller discussions. For example, pilots expressed an interest in being notified if the controller was busy and could not fulfill their requests. Potential solutions were discussed, such as considering the ability to make requests as a center-wide or sector-specific service which could be turned on or off based on the traffic complexity and controller workload. Pilots would be alerted on the status of this service upon entering a new sector so that the requests can be made only when the controllers can accommodate them. We also discussed ideas to present pilots with cues similar to voice congestion to convey controller workload in CPDLC-based communication, which can be used by pilots to not make requests when controllers are busy.

Another potential problem for CE 6 is that CDTIs do not display sector boundaries and pilots may make requests that will rarely be honored because the controller is about to transfer control to the next sector. There were examples of pilots being concerned that the time elapsing between downlinking requests to controllers and receiving a response was be too long, which could exacerbate this problem. This is particularly true if the pilot is not aware if the controller is working to resolve a potential loss of separation cued by the CD&R. Pilots also voiced an interest in understanding why controllers make decisions instead of simply receiving their requests without any additional information.

Feasibility / Acceptability of CPDLC Transfer-of-Communication

The controller participants had highly favorable responses to the CPDLC-based transfer of communication (TOC) in comparison to voice communication. All of the participants said that their workload was greatly reduced by using CPDLC for TOC transmissions (mean (M) = 4.75; 1=Greatly increased workload, 5=Greatly reduced workload). The controller participant comments stated that CPDLC communication should "reduce pilot readback and controller hearback errors, reduce frequency congestion," "reduce controller's workload greatly", and is a "great enhancement", but a disadvantage was that one had to "ensure conflict-free path prior to handoff" in the TOC-auto mode since the frequency transfer happened automatically once the handoff was accepted. In the debrief sessions, one participant commented that ensuring a conflict-free path prior to handoff actually increased situation awareness near the sector boundary.

All of the participants thought that the concept and procedures for TOC through CPDLC, fashioned after the implementation in the Miami Center, worked very well in our simulation (M = 5.0; 1=Not well at all, 5=Very well). They also thought that the CPDLC interface for TOC was highly useful (M = 5.0; 1=Not useful, 5=Very useful) and usable (M = 5.0; 1=Very difficult to use, 5=Very easy to use). Given a choice between TOC-manual vs. TOC-auto, all of the participants overwhelmingly favored TOC-auto mode (M = 5.0; 1=Favor TOC-manual, 5=Favor TOC-auto). All of them endorsed the CPDLC-based TOC and stated that they would use it if it was available in the field today.

CONCLUSION

Controllers responded favorably to the CPDLC-based transfer of communication. They thought that both the concept and the implementation were quite acceptable and that it had a potential for significant workload reduction. Interestingly, when we gave them a choice between TOC-manual (TOC message is autoloaded but manually released by the controller) and TOC-auto (automatic TOC when the handoff is completed), the controllers overwhelmingly chose TOC-auto – unlike Miami center where controllers mainly use TOC-manual mode.

Controllers generally felt very comfortable accepting pilot requests during all conditions. The majority of scripted pilot-initiated requests were approved during the pilots' initial request for all of the simulation conditions. Most requests that were not approved immediately were approved on a later request, leaving only a few pilot requests that were never approved. While the number of requests was too small to lead to any conclusion, it is interesting to note that the Uplink/Downlink with CD&R condition had a slightly higher percentage of requests honored initially. This may be explained by the fact that pilot requests submitted in the Uplink/Downlink with CD&R were supposedly conflict-free.

Both pilots and controllers had positive comments on the concept of trajectory negotiation, however, they felt that the interfaces for trajectory negotiation, both air and ground-side tools could use improvements. Pilots had a difficult time using the tools to gain a "big picture" of the traffic scenario so that they could understand which criteria the controllers were using to accept or reject the requests. Controllers sometimes had difficulty detecting downlinked clearance requests but they agreed that the ability to uplink clearances was much more useful than by voice, and that the ability to uplink clearances reduced their workload.

Finally, when the controllers rejected route requests, it didn't always seem to be due to a predicted conflict based on the separation requirement. Rather, the controllers seemed to be aware of situations in which potential conflicts could occur and actively avoided those situations when other solutions were available. For example, when a pilot requested a route at FL310 that flew across an arrival stream in descent from FL350 to 11000 ft, the controllers were likely to wait until the paths would not cross, even if the crossing paths were not likely to be in conflict. It seemed that the controllers were using heuristics that lead to safer operations than those under the minimum separation requirements that the conflict probes were using. It would be interesting in future studies to compare these differences which could significantly impact future systems that rely heavily on human-automation synergy.

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