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Shared Information Between Pilots and Controllers in Tactical Air Traffic Control

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Air–ground datalink systems are being developed to enable pilots and air traffic controllers to share information more fully. The sharing of information is generally expected to enhance their shared situation awareness and foster more collaborative decision making. An exploratory, part-task simulator experiment is described that evaluates the extent to which shared information may lead pilots and controllers to cooperate or compete when negotiating route amendments. The results indicate an improvement in situation awareness for pilots and controllers and a willingness to work cooperatively. Independent of datalink considerations, the experiment also demonstrates the value of providing controllers with a good-quality weather representation on their plan view displays. Observed improvements in situation awareness and separation assurance are discussed.

Introduction

THE technology to deliver digital datalink communication between aircraft and the ground is well developed. Current datalink applications include predeparture clearance delivery via tower datalink services, VHF datalink communications (i.e., ACARS, the ARINC Communications Addressing and Reporting System), global voice and data communications via satellite (SATCOM), and weather uplinks via terminal weather information for pilots (TWIP).[1] The Federal Aviation Administration's proposed future national airspace system architecture[2] calls for expansion of existing datalink services to include applications such as the controller–pilot datalink communication system,[3] automatic dependent surveillance broadcasts (ADS-B), and aviation weather information systems.[4]

Such advances will allow information that is not uniformly accessible today to be shared between pilots, controllers, and other users (dispatchers, airport managers, etc.). This sharing of information, a digital party line, is expected to offer several benefits: 1) the ability to communicate graphical information between the air and ground, 2) improved shared situation awareness between agents, and 3) a common informational context on which to negotiate.

These benefits ultimately are expected to result in more cooperative interaction between agents, which will move airspace operations closer to the envisioned goal of collaborative decision making. For example, a shared representation of convective weather activity may enable controllers to recognize developing weather constraints better, to anticipate needed deviations, and to reorganize the traffic flow earlier and more effectively. Similarly, a shared representation of traffic information may improve a pilot's ability to anticipate sequencing instructions, correlate pilot reports, and identify available route alternatives.

However, the sharing of information may effect a less desirable outcome, one characterized by increased voice communications, increased workload, and increased contention between agents. Today, flight crews typically have superior weather information to that of air traffic controllers, whereas air traffic controllers typically have superior traffic information to that of the flight crews. These imbalances lend stability to a control system that is inherently ambiguous with regard to authority: Controllers are responsible for ensuring aircraft separation,[5] but pilots are responsible for the operation of their aircraft.[6] In practice, controllers typically defer to flight crews in matters involving hazardous weather. Conversely, flight crews typically defer to air traffic control in matters involving traffic conflicts. In effect, authority is assigned implicitly based on information superiority: The agent with the best information assumes authority. Midkiff and Hansman[7] found that pilots were more willing to comply with air traffic control (ATC) instructions when they knew their own information to be inferior to that of ATC. Conversely, they found that pilots were more assertive and willing to question ATC when they knew their own information to be equal or superior to that of ATC. The results of Midkiff and Hansman suggest that in some situations the availability of common information via datalink may result in increased negotiation and, with it, commensurate increases in frequency congestion and workload. In short, it suggests the potential for less collaborative, less efficient operations.

The goal of this study was to investigate the effects of shared traffic and weather information on pilot–controller shared situation awareness and negotiating behavior.

Approach

This study adopted an integrated human-centered systems approach to investigate the effects of shared traffic and weather information on pilot–controller interaction and performance in tactical rerouting situations. The approach considered the human elements of the system as functional components of a closed-loop control system.[8] The study began by identifying and comparing the goals and situation awareness information requirements of commercial pilots[9] and air traffic controllers[10] to determine their mutual and disparate interests and requirements. Based on the findings,[11] an exploratory experiment was conducted to investigate the extent to which shared traffic and weather information may lead pilots and en route air traffic controllers to cooperate or compete when negotiating route amendments. A part-task simulator experiment was designed to assess pilot and controller performance and behaviors in complex rerouting situations. To limit the number of interacting agents, test scenarios focused on tactical routing decisions that

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would preclude the involvement of airline operations centers (AOC). The availability of shared traffic and weather information (via digital datalink) was manipulated as the independent variable in the experiment. Objective and subjective measures of situation awareness, negotiating posture, and overall performance were used in combination with experimenters' observations and subjects' comments to assess the overall system effect.

Objectives

The objective of the experiment was to explore the effects of shared information on pilot–controller interaction and performance in rerouting situations. Of particular interest were the following:

1) Does the availability of shared information between pilot and controller improve their situation awareness?

2) Does the availability of shared information affect pilot and/or controller workload?

3) Does the availability of shared information affect the amount of pilot–controller communication?

4) How does the availability of shared information affect the posture of pilots and controllers with regard to reroute negotiation?

Experimental Design

To explore these issues, the study required a live, realistic, and challenging environment in which for pilots and controllers to interact. A part-task simulator experiment was developed in which two subjects, one pilot and one controller, would interact within a real-time simulated air traffic environment to handle complex en route tactical situations in real time. Scenarios were designed to provide enough structure to challenge the subjects, but also with enough latitude to allow the subjects to interact freely and develop their own options according to their goals and priorities. Scenarios were executed with and without a digital datalink of traffic and weather information between the pilot and controller. Comparisons were made both within and between subjects.

Test Matrix

The experiment involved six pilot–controller subject pairs. Each subject pair completed six test scenarios: three scenarios performed with the datalink disabled (no shared information), and three equivalent scenarios performed with the datalink active (shared traffic and weather information) (Table 1).

Independent Variable: Presence of Datalink

The independent variable for this experiment was the presence of a digital air–ground datalink that transmitted continuously updated traffic and weather information between ATC and the flight deck. Disabling and enabling the datalink provided the means to promote and negate information advantages between the subject pilot and controller.

The datalink was disabled in the baseline configuration, which was intended to emphasize the information advantages between pilots and controllers in the current national airspace system. With the datalink disabled, there was no sharing of information. Figures 1 and 2 show how the weather and traffic information was allocated between the pilot and controller in the nondatalinked configuration. Weather information was available only to the subject pilot via the cockpit map display; the subject air traffic controller received no direct weather information in the nondatalinked configuration. Conversely, traffic information was available only to the subject controller via the plan view display; the subject pilot received no traffic information in the nondatalinked configuration. [The traffic alert/collision avoidance system (TCAS) was disabled in the cockpit.] Information was partitioned in this way to establish, for each subject, an area of clear information superiority over the other. Thus,

Table 1 Test matrix

Configuration	Weather information	Traffic information
Datalink disabled	Pilot only	Controller only
Datalink enabled	Shared	Shared

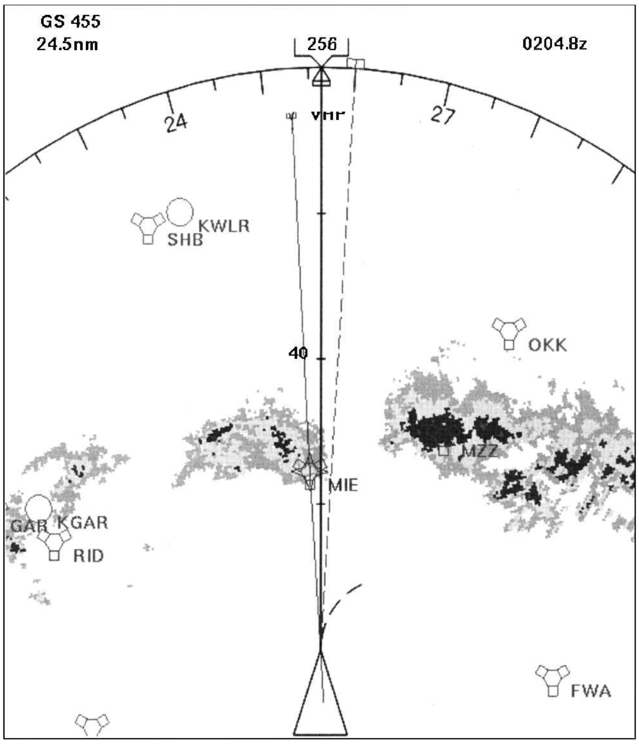

Fig. 1 Pilot's display in baseline configuration; no traffic information presented.

in the nondatalinked configuration, the pilot was in a superior position with respect to weather information, while the controller was in a superior position with respect to traffic information.

The datalinked configuration was intended to neutralize the weather and traffic information advantages held by the pilot and controller, respectively, in the baseline configuration. With the datalink enabled, weather and traffic information were shared between the pilot and controller. Figures 3 and 4 show how the weather and traffic information was allocated between the pilot and controller in the datalinked configuration. The baseline weather information available to the pilot via the cockpit map display was supplemented with a prototype cockpit display of traffic information (CDTI), as shown in Fig. 3. Similarly, the baseline traffic information available to the controller via the plan view display was supplemented with a prototype graphical weather overlay, as shown in Fig. 4.

The CDTI added to the baseline Boeing 747-400 displays was based on a prototype by Cashion et al.[12] Aircraft within 100 n mile and 2600 ft of the ownship were shown on an integrated map display. As shown in Fig. 5, the pilot was provided with traffic information elements on the CDTI that were equivalent to those available to the controller via the aircraft data blocks displayed on the plan view display (PVD): call sign, relative ground track, relative altitude, relative ground speed, and climb/descent indication. The CDTI also incorporated TCAS II alerting logic, including traffic advisories and resolution advisories.

The weather overlay added to the controller's baseline PVD provided precipitation reflectivity imagery identical to that presented on the pilot's weather display, based on NEXRAD ground-based weather radar data (refer to Figs. 3 and 4). The displays were capable of depicting seven distinct intensity levels of convective activity in shades of green (light intensity, from −8 to 0 dBZ), amber (moderate intensity, from 0 to +8 dBZ), and red (high intensity, greater than +8 dBZ).

Test Scenarios

Test scenarios were designed to probe pilot–controller situation awareness and behaviors in rerouting situations. Three basic scenarios were created, each representing common (albeit complex) en route air traffic situations involving convective weather and from moderate- to high-density traffic flows. The traffic and weather elements were scripted such that each scenario presented the test

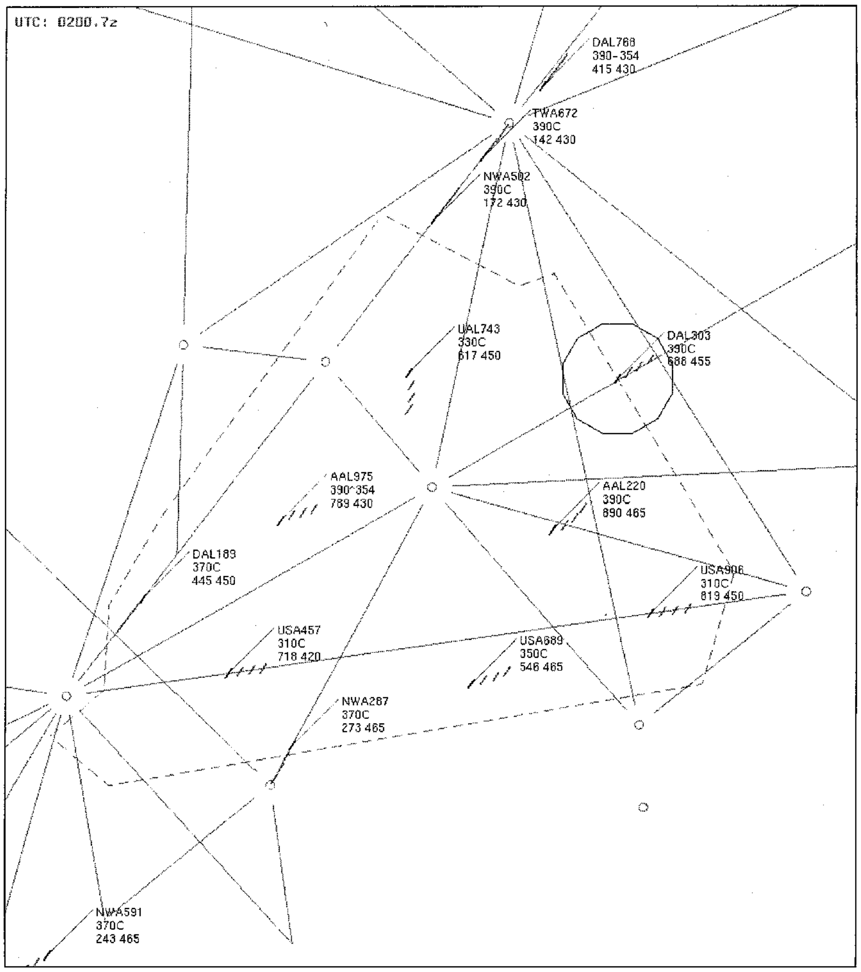

Fig. 2 Controller's display in baseline configuration; no weather information presented. The cockpit display in Fig. 1 belongs to DAL303, shown here inside the 6-mile segmented circle, or J-ring.

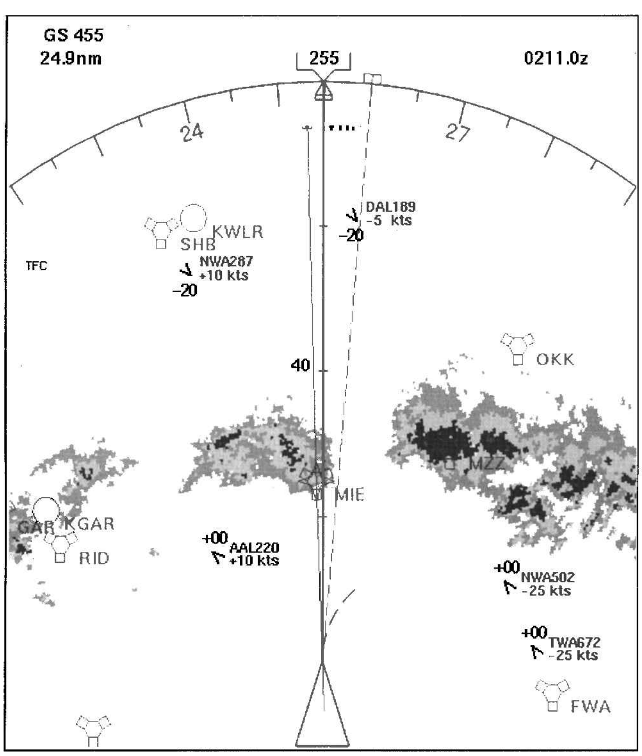

Fig. 3 Pilot's display in datalink enabled configuration; note the addition of CDTI symbology.

subjects with two fundamental tasks: a recognition task and a resolution task.

The recognition task consisted of two situation awareness probes applied in parallel: one weather related and one traffic related. Both employed the situation awareness testable-response probe method.[13] Under this performance-based methodology, potentially hazardous traffic and weather conditions (one of each) were scripted into each scenario. The hazards were significant enough that a test subject who was aware of the hazard(s) would be compelled to respond. Thus, a subject's action or inaction in response to each hazard provided a binary indication of his or her situation awareness with regard to the specific hazard.

The second fundamental task in each scenario was a resolution task. If the subject controller and/or subject pilot recognized one or both of the testable-response conflicts, their next task was to resolve the situation by determining an acceptable route amendment to avoid the hazard(s). The rerouting decisions were tactical in nature and, therefore, did not involve an AOC. The intent was not to create situations that were necessarily difficult for the pilot or controller to resolve. Rather, the intent was to design situations that would use the competing goals of the pilot and controller to offer each subject a fairly obvious, yet different, solution, thereby raising the need for reroute negotiation.

Airspace Sector

Test scenarios were set in Indianapolis Center airspace in a high-altitude en route sector centered at Muncie, Indiana (MIE) (see Fig. 6). Sector airspace spanned approximately 70 n miles east–west and 85 n miles north–south at its widest points, and it included altitudes 14,000 ft and above. Neighboring sectors were not depicted for

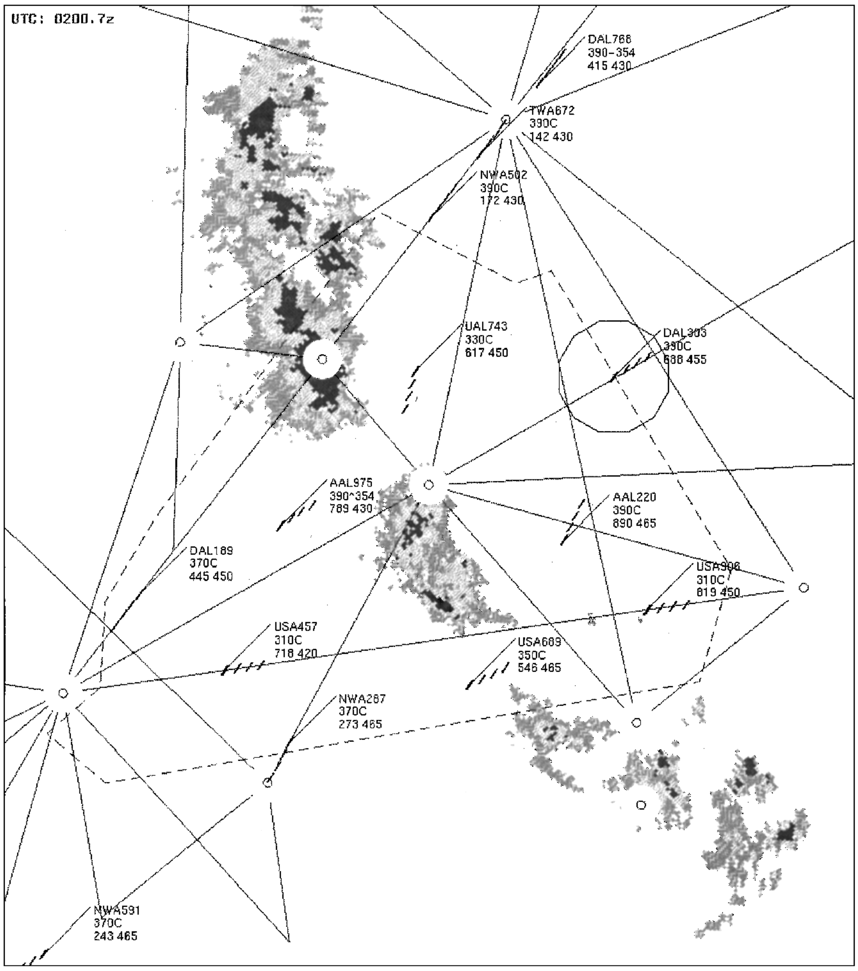

Fig. 4 Controller's display in datalink enabled configuration; weather overlay to the PVD display added. The cockpit display in Fig. 3 belongs to DAL303, shown here inside the 6-mile J-ring.

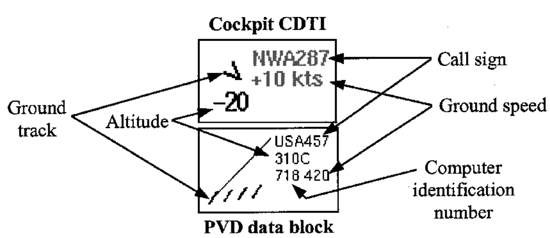

Fig. 5 Cockpit and PVD traffic symbology.

the controllers. In situations requiring coordination with a neighboring sector, the subject controller was instructed to coordinate with the experiment monitor (a confederate) at their side who would accept or reject requests as they were made.

Traffic Flow

Traffic flow through the assigned sector was fairly uniform. The traffic mix was approximately 15% widebody aircraft, 80% narrowbody aircraft, and 5% regional/commuter aircraft. All aircraft transitioned the sector in the cruise phase of flight; the subject controller was not faced with any departures or arrivals. Aircraft generally adhered to the published airways, except where deviations or direct clearances were approved by ATC. Subject controllers were provided with a flight strip for each aircraft filed to transition their sector.

Traffic densities were high by design to make the scenarios challenging, given the homogeneity of the aircraft and their routes (for example, no departures or arrivals). The number of aircraft in this relatively small sector averaged about eight aircraft at any given time. Scenarios were designed to maintain a regular flow of traffic of between 5 and 11 aircraft. Controllers were given the liberty not to accept an arriving aircraft if the sector workload became too high.

Every scenario was designed to have at least one potential traffic conflict. Scripted traffic conflicts involved merging traffic only; there were no scripted blunders or busted clearances, although some inadvertent cases did occur. Merging aircraft maintained constant airspeed and heading.

Weather Elements

Every scenario featured one or more weather elements. These elements were restricted to convective weather patterns (cells and fronts), which were observable in the NEXRAD weather data. The weather elements were static; there was no dynamic buildup, dissipation, or drift. This simplification was mitigated by the short duration of the scenarios (approximately 10 min each). Weather patterns were retrieved from a commercial archive of NEXRAD weather data recorded from various sites across the continental United States. The elements used in these scenarios ranged from local, low-level precipitation (Fig. 7) to broad, high-intensity frontal systems (Fig. 8).

Scenario Design

Three basic scenario templates were created for this experiment. The first template featured relatively light traffic flow and localized weather. The second template featured high traffic flow and a front of moderate-level convective activity. The third template featured moderate traffic flow and high-intensity weather.

Experimental Protocol

Test Facility

The part-task simulator study was conducted in the Distributed Air Traffic Simulation Facility[14] located at the Massachusetts

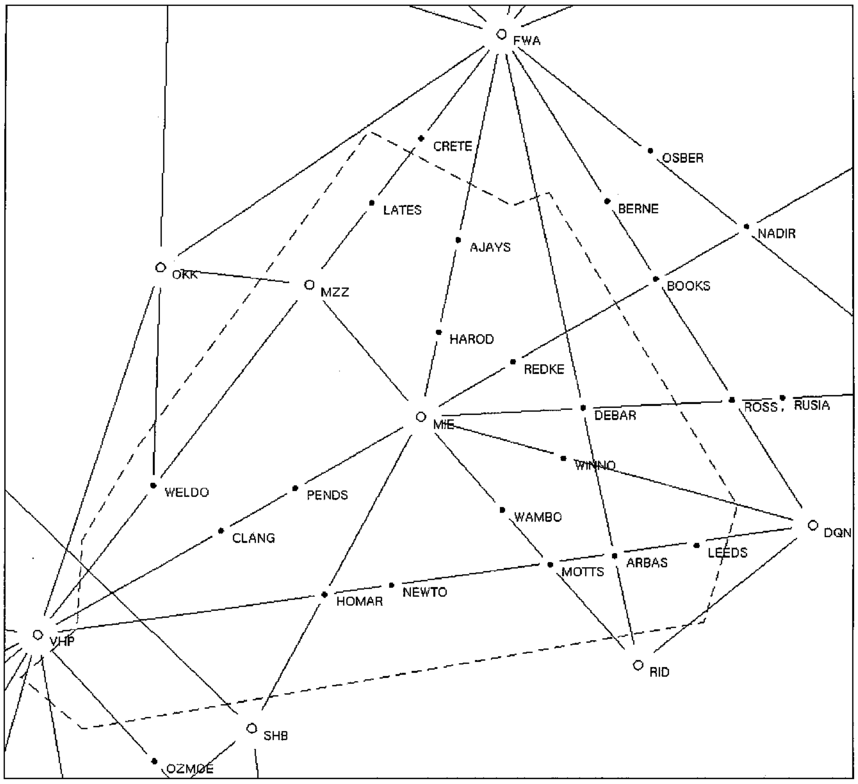

Fig. 6 Indianapolis Center high-altitude sector airspace features.

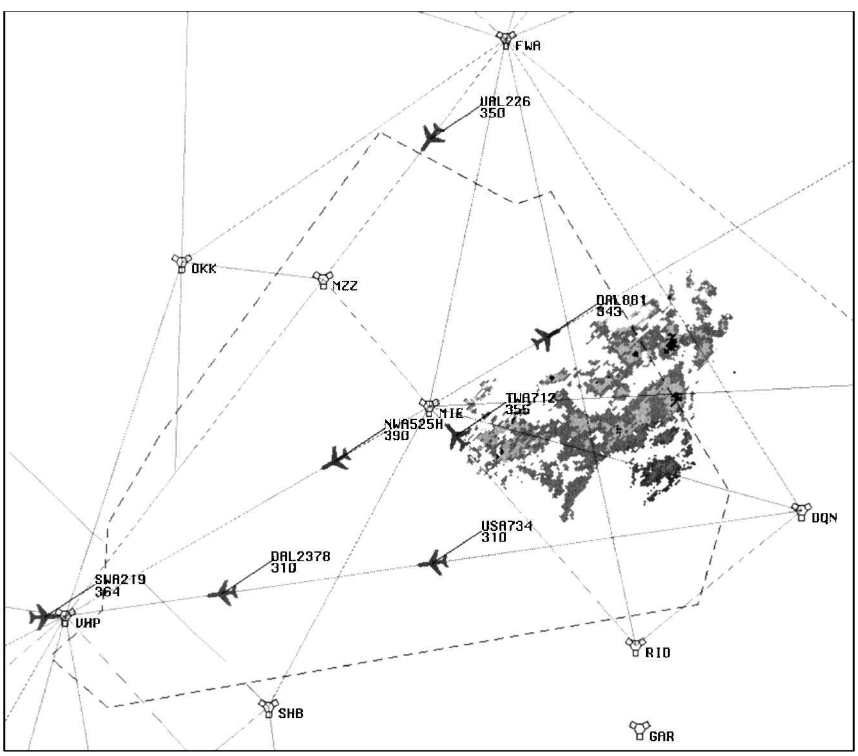

Fig. 7 Example of local, low-level precipitation (viewed from pseudopilot display).

Institute of Technology International Center for Air Transportation. This facility provides a virtual airspace environment capable of hosting multiple flight simulators, ATC simulators, and pseudoaircraft simulators in a single, interactive, real-time simulation. For this experiment, the facility was configured with one advanced cockpit simulator, one ATC simulator, and one pseudopilot station. The pseudopilot station's specially designed graphical user interface enabled the pseudopilot to manage the route planning, course changes, and radio communications of all 18 pseudoaircraft involved in a given scenario. Live digital voice and data communication were provided between each simulator and the simulation host. To minimize nonradio interaction between the two subjects, the cockpit simulator and the ATC simulator were located in separate rooms.

Subjects

Six air traffic control specialists and six commercial pilots were recruited to participate in this study. All participants were volunteers.

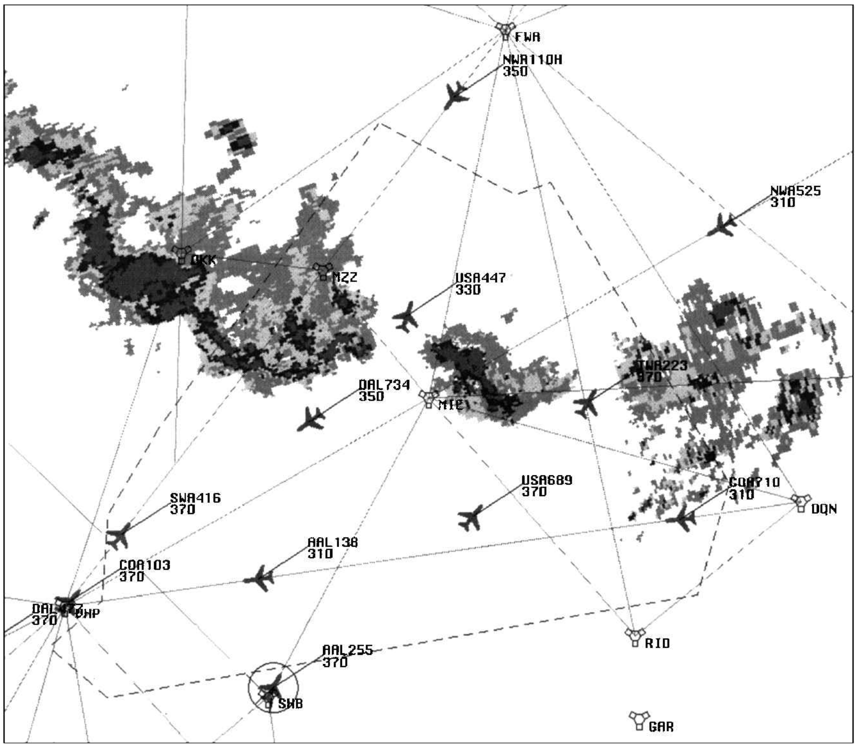

Fig. 8 Example of broad, high-intensity frontal system (viewed from pseudopilot display).

All six ATC specialists were full performance level controllers currently on staff at an air route traffic control center in the United States. Radar experience ranged from 7 to 20 years, with a mean of 13.3 years. The controllers were between 31 and 48 years of age, with a mean of 38.0.

All six pilots were active jet aircraft pilots with an air transport pilot rating. Flight experience ranged from 6000 to 16,000 h, with a mean of 10,117 h. All had flown glass cockpit aircraft with flight management systems. Pilots were between 40 and 53 years of age, with a mean of 45.2. Two of the pilots were corporate pilots, and four were pilots with major airlines.

Formal Testing

Following an initial training and familiarization period (60–90 min), formal testing commenced. Controllers worked their sector alone, without the benefit of a D-side controller. (Note that in en route center operations, a busy sector is typically managed by two ATC specialists: the R-side controller, who works at the radar display and interacts with the pilots by radio and the D-side controller, who handles the flight strips and other data management and coordination issues.) Similarly, pilots operated their flights solo, without the benefit of a copilot. Each formal test scenario began with the simulation frozen. The subject pilot's aircraft was initialized in cruise trim and on course with the autoflight system engaged and tracking its preprogrammed route. Both subjects were given time to survey their static situation as shown on their respective simulator displays. Controllers were allowed to organize and annotate their flight strips to develop a picture of the traffic in and about their sector. Pilots were allowed to review their flight plan and the local weather as portrayed on their map display. The subjects were told in advance whether the air–ground datalink would or would not be active. This was intended to establish a priori an understanding of their relative information superiority (or inferiority) as a basis for any subsequent negotiation. No suggestions were given as to how they should make use of the available information or how to exploit any information advantage they might have. For cases in which the datalink was disabled (cases in which controllers were not provided a weather overlay and pilots were not provided a traffic display), controllers were briefed on convective weather activity in the area, but the specific location and intensity of the weather was not specified. Similarly, pilots were briefed on traffic in the area, but the specific location and altitude of the traffic was not specified. Except for the datalink status (enabled or disabled), the simulator setup was identical for each experimental run.

Following the situation assessment period, the simulation was started. No special operational concepts were introduced; pilot and controller roles and responsibilities were per the Federal Aviation Regulations and the ATC handbook, respectively. Each scenario began with a number of scripted radio calls from one or more of the confederate pseudoaircraft. The subject pilots were instructed to check in with Indianapolis Center at their first convenience as though they had just been handed off by the previous ATC sector. The subject pilot and subject controller were then free to take whatever action or contact whichever person they deemed necessary to accomplish their goals within the bounds of their assigned roles and responsibilities. Each scenario was allowed to run for approximately 10 min, enough time for the subject aircraft to transition the airspace sector.

At the conclusion of each nondatalinked scenario, the controllers were asked to perform a simple weather recall task to assess their inferred awareness of weather. At the conclusion of the experiment, both the pilot and controller were individually and collectively debriefed. Subjective evaluations were taken during the debriefing sessions.

Results

Situation Awareness

Two approaches were taken to the situation awareness (SA) analysis. The first approach used the performance-based testable-response methodology to assess the situation awareness of the subject pilot and subject controller with respect to weather and traffic in real time. The second approach used a visual recall task at the conclusion of each scenario to focus on the situation awareness of the subject controllers with respect to weather only.

Testable Response Data

Each test scenario included one weather-related testable-response condition and one traffic-related testable-response condition. Both the pilot and the controller were monitored for their awareness of each testable-response condition.

Figure 9 summarizes the results of the traffic-related testable response probes. Pilots, without the benefit of a traffic display in the

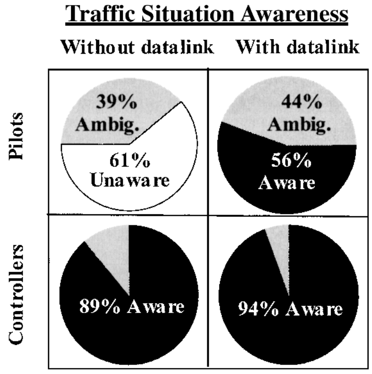

Fig. 9 Pilot and controller awareness of traffic-related testable-response conditions.

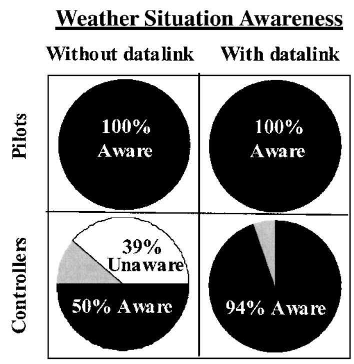

Fig. 10 Pilot and controller awareness of weather-related testable-response conditions.

nondatalinked configuration, did not demonstrate awareness of any of the traffic-related testable-response conditions. When provided a shared traffic display, pilots demonstrated awareness of 56% of the traffic-related testable-response conditions. In many cases, the controller recognized the traffic conflict before it became a significant threat to the pilot and either advised the pilot of the traffic or vectored the pilot accordingly. In such cases, the pilot's opportunity to recognize and respond to the hazard independently was precluded, and the testable-response result for the pilot, therefore, was labeled ambiguous.

Controllers, having the benefit of their plan view traffic display for all test scenarios, demonstrated a high level of awareness of the traffic-related testable-response conditions. In some cases, a deviation requested by the subject pilot resolved the traffic-related testable-response condition before it arose; such cases were labeled ambiguous with respect to controller situation awareness.

Figure 10 summarizes the results of the weather-related testable-response probes. Pilots, having the benefit of the weather display for all test scenarios, demonstrated awareness of all of the weather-related testable-response conditions. Controllers, without the benefit of a weather display in the nondatalinked configuration, demonstrated awareness of only 50% of the weather-related testable-response conditions. When provided a shared weather display, controllers demonstrated awareness of 94% of the weather-related testable-response conditions. In one case, a controller gave conflicting indications of awareness of the weather conditions. For that case, the controller's testable-response result was labeled ambiguous.

These results indicate that pilot situation awareness with respect to traffic improved with the addition of a CDTI. Similarly, the results suggest that controller situation awareness with respect to weather improved with the addition of a weather overlay to their PVD. These results confirm that shared information via air–ground datalink can improve situation awareness for both pilots and controllers.

Controllers' Weather Awareness Data

To illustrate the degree of improvement in controllers' weather situation awareness, the controllers were asked to perform a simple recall task at the conclusion of each nondatalinked scenario (each scenario in which no weather overlay was provided). Each controller was asked to indicate the size and location of the weather cell(s) as inferred from the aircraft trajectories and voice communications from the pilots. Figures 11 and 12 are a sample of the results. Figures 11 and 12 are each comprised of three panels arranged vertically. Each panel contains a map of the sector with a controller's estimate of the weather cell locations hand drawn in black. The actual location of the weather cells is overlaid for reference. Gray lines represent a time exposure of the trajectories flown by all aircraft during the scenario. The three panels of Fig. 11 show the variation between controllers in their ability to build an accurate mental model of the weather situation for scenario 3. The three panels of Fig. 12 show how a particular controller's performance varied for three nondatalinked scenarios.

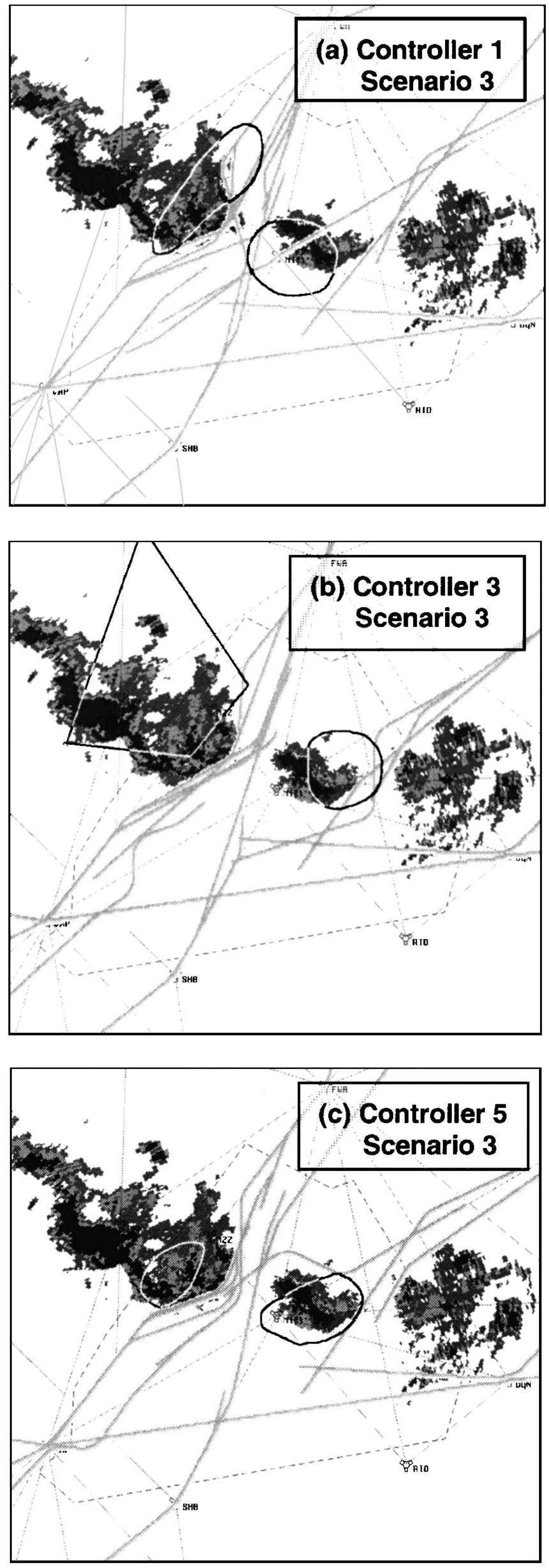

Fig. 11 Between-controllers comparison of weather recall results for scenario 3 (time exposure of aircraft tracks overlaid).

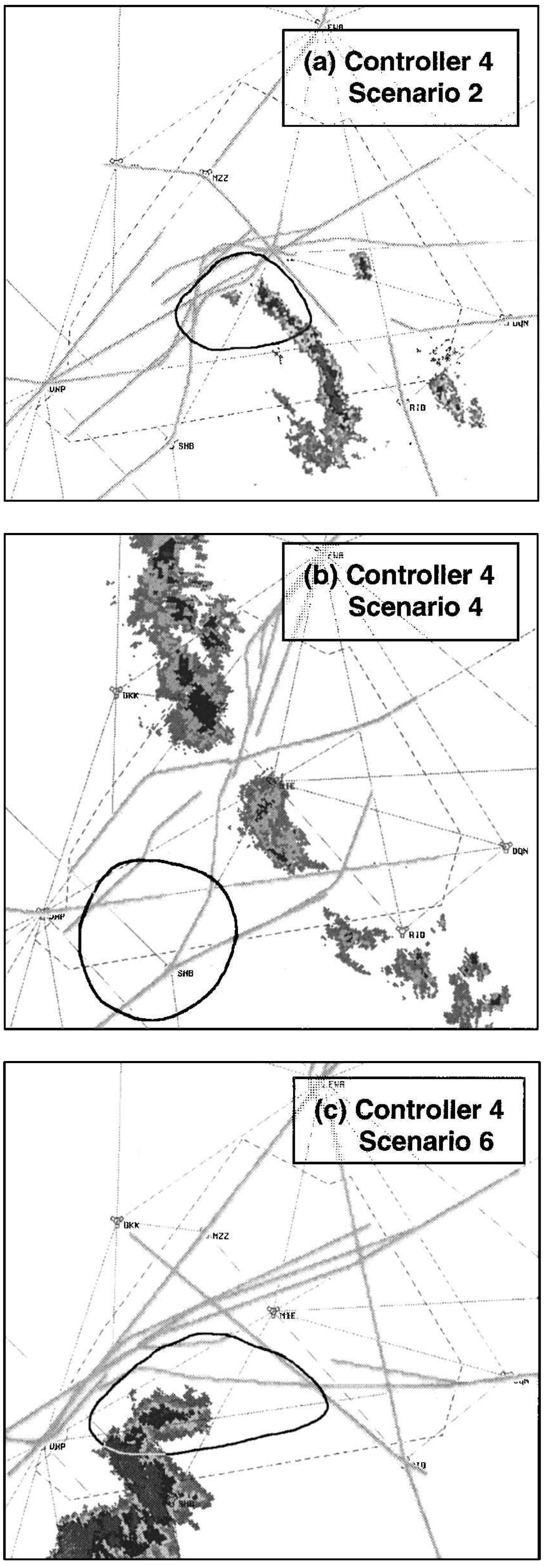

Fig. 12 Weather recall results for controller 4 (with time exposure of aircraft tracks overlaid).

For an indication of how situation awareness is affected, consider Fig. 11. To first order, the aircraft trajectories tend to wind around the regions drawn by the controllers. This is consistent with the strategy controllers report using to develop situation awareness with respect to weather disturbances. In the absence of displayed weather, controllers attempt to identify and bound the weather-impacted areas within their sector, and they mentally set those boundaries based on the trajectories of the aircraft they control as best they can recall them.

When examining the trajectory data, note that the regions drawn by the controllers closely reflect the curved trajectories of aircraft who negotiated course deviations with ATC. Note, too, that there are several cases in which a controller drew a weather region over an area that had clearly been traversed by one or more aircraft. The most flagrant cases involve aircraft that made no course deviations and, in general, did not have radio contact with the controller other than on their arrival to and departure from the sector. This suggests that during periods of high workload the trajectories of nonroutine, deviating aircraft may figure more prominently as controllers attempt to build and maintain a mental picture of the weather situation.

Loss of Separation Events

In the 36 test cases (6 scenarios performed by each of 6 different pilot–controller pairs), 5 loss of separation events were observed, all of which occurred with the datalink disabled. A loss of separation was defined in accordance with en route ATC standards: lateral separation of less than 5 n miles and vertical separation of less than 1000 ft. Figure 13 indicates the closest points of approach for the five separation violations. The upper right corner corresponds to the 5-n mile, 1000-ft separation standard, which defines a loss of separation for en route operations. The lower left corner corresponds to zero separation, a collision.

Note that several factors made the controllers' tasks in these test scenarios unusually demanding. First, the test scenarios were challenging by design. The sector's small size coupled with higher-than-typical traffic densities increased the tempo of activity in the sector and shortened the planning time frame from strategic to tactical. Furthermore, controllers were operating an air traffic sector other than their usual home sector and did not have the benefit of a conflict alert function or a D-side controller to assist them.

The five separation violations fall into two general categories. Events 1 and 2 were serious near-miss incidents that appear to be attributable to poor situation awareness, in this case the by-product of severe weather and traffic constraints. Events 3–5 were borderline cases attributable to high workload and distraction on the part of the controller, pilot, or pseudopilot.

Events 1 and 2 occurred as several aircraft were attempting to deviate through a hole in a weather front. In each case, with no weather information available, the controllers had difficulty anticipating deviation requests and developing a coherent flow strategy. As a result, they had to react to several urgent requests in a short time period.

Event 1 is shown in Fig. 14. UAL323 (the aircraft indicated by the northbound track line) was descended from flight level (FL) 370 to FL 350 near Richmond (RID) to separate it from conflicting traffic. As the scenario developed, four aircraft requested clearance through the same hole in the weather. In attempting to accommodate all of their requests, the controller apparently lost awareness that two aircraft were coaltitude and in opposite directions through the hole (as a result of an earlier instruction from the controller). UAL323 and UAL751 eventually closed to within 100 ft. The controller recognized the situation after the two aircraft had passed.

Event 3 is an example of an event which appears to be due to high workload on the part of the controller. As shown in Fig. 15, event 3 occurred outside the sector boundary between an inbound aircraft and an outbound aircraft. The outbound aircraft, NWA847, was under the control of the subject controller, but the inbound aircraft, COA636, was not. The inbound and outbound aircraft were both level at FL 350 on headings of 190 and 340 deg, respectively (just within the 180–359 deg heading-for-altitude standard). At the time of the encounter, the controller was busy responding to ride requests and deviations around weather in the southern part of the sector. Eventually, the subject controller recognized the impending conflict at the northern fix, Fort Wayne (FWA), and issued avoidance instructions to both COA636 and NWA847.

That every loss of separation occurred in the nondatalinked environment suggests that shared information may help controllers build and maintain situation awareness with regard to separation issues. In events 1 and 2, it appears that controllers did not have sufficient situation awareness to anticipate and plan for adequately the disturbances in the traffic flow brought about by the severe weather

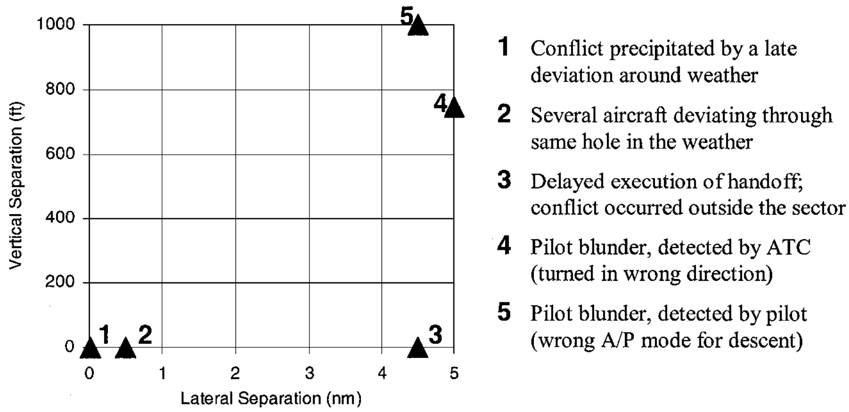

Fig. 13 Closest points of approach for the five loss of separation events.

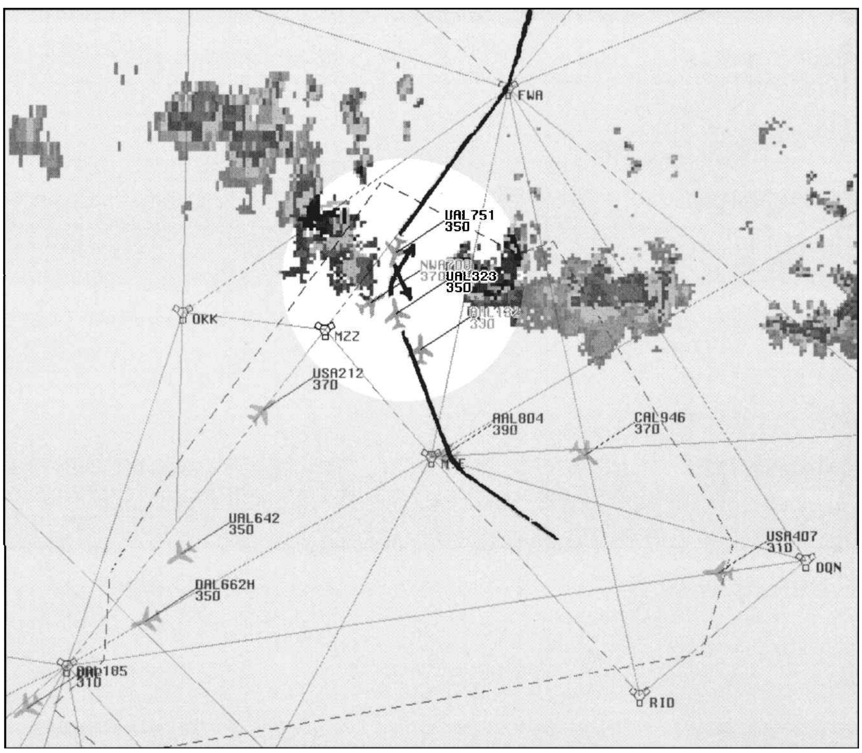

Fig. 14 Loss of separation 1 (closest point of approach: less than 100 ft) viewed from pseudopilot display.

constraints. In events 3–5, high workload in one part of the sector appears to have caused the controller to be less vigilant with regard to handoff status and aircraft conformance in another part of the sector.

Communication and Negotiation

All radio communication between the controller, subject pilot, and pseudopilot was recorded and coded by category and topic. Figure 16 shows how the transactions conducted over the voice channel changed with the introduction of the datalink. As shown at the left, the number of transactions between the pilot and controller decreased slightly when the datalink was introduced. Despite this decrease, the number of transactions for negotiating reroute clearances remained effectively constant, and the number of other transactions (including traffic advisories, ride reports, etc.) decreased. These results, however, are not statistically significant ($p > 0.05$).

Figures 17 and 18 show how the character of pilot–controller interaction changed when the datalink was introduced. Figure 17 shows that commands by the subject controller (to any aircraft) and requests by the subject pilot both dropped slightly, albeit not significantly ($p > 0.05$). With the datalink enabled, the subject pilot and subject controller made more voluntary suggestions to one another for specific route amendments. An example is the following exchange:

AAL303 (subject pilot): INDY CENTER AMERICAN THREE OH THREE, FLIGHT LEVEL THREE NINE ZERO, LIKE TO DEVIATE HEADING ABOUT TWO FIFTEEN FOR ABOUT FORTY MILES FOR WEATHER.

INDY CENTER (subject controller): AMERICAN THREE ZERO THREE, ROGER. I SHOW A BREAK IN THE WEATHER THAT'S ABOUT YOUR ONE O'CLOCK. HAVE YOU CONSIDERED A DEVIATE (sic) ABOUT TEN TO THE RIGHT AND THEN DIRECT INDY?

The deviation suggested by the controller was a more direct path than the pilot's requested deviation, saving the pilot approximately 4 min flying time. There was no apparent benefit to the controller other than the satisfaction of having provided improved service. Furthermore, the controller appeared to incur additional workload, as the suggested deviation required careful sequencing with merging traffic from the north. This kind of verbal exchange of rerouting ideas, options, and preferences was rarely evident when the datalink was disabled. This result is marginally significant at the 91% confidence level ($p < 0.09$). In addition, Fig. 18 shows that controllers were more proactive in providing weather advisories to pilots when they had the weather information overlay. This result is statistically significant at the 99% confidence level ($p < 0.01$). Together these

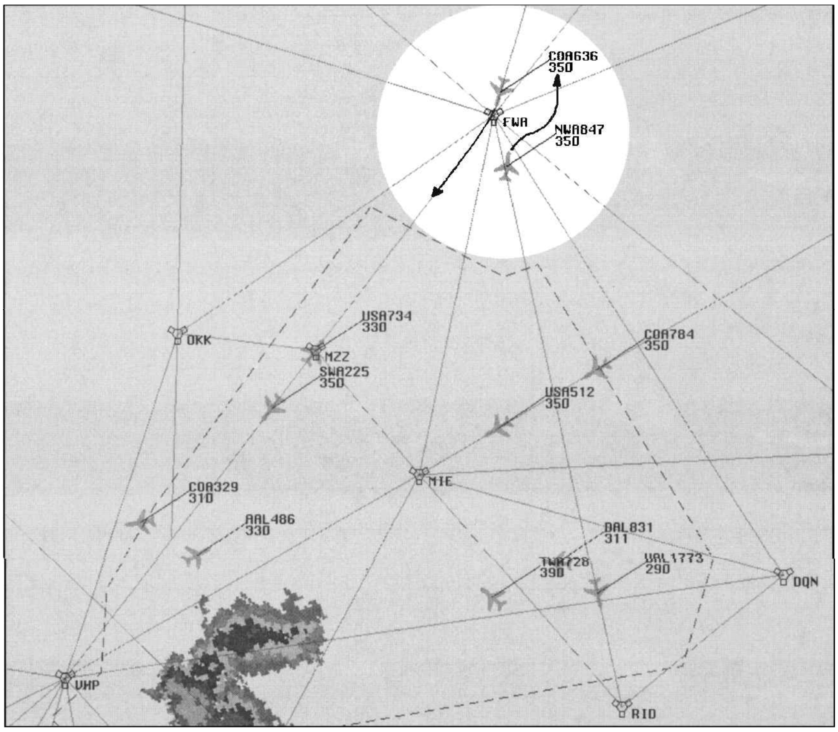

Fig. 15 Loss of separation 3 (closest point of approach: 4.5 n mile and 0 ft) viewed from pseudopilot display.

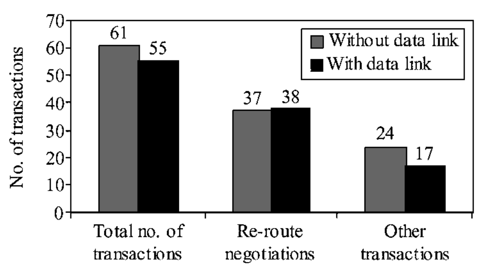

Fig. 16 Voice communication transactions by topic.

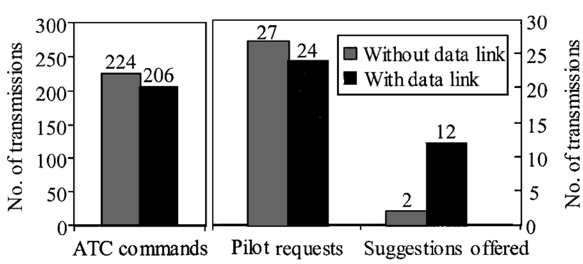

Fig. 17 Voice transmissions by category.

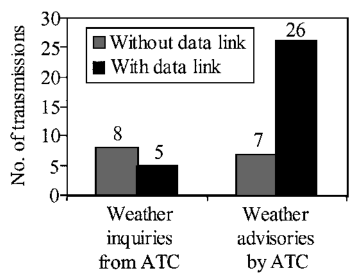

Fig. 18 ATC voice transmissions regarding weather.

results are indicative of more cooperative interaction between pilots and controllers when shared information is available.

Workload

Pilot and controller workload was measured using NASA–Task Load Index. The results exhibited high variance, both between subjects and within subjects. In general, the availability of shared information did not appear to affect pilot or controller workload in any systemic way.

Subjective Responses

At the conclusion of each test session, subjects were asked to provide a subjective rating of the value of the shared information on a scale ranging from "very detrimental" to "neutral" to "very valuable." Pilot feedback regarding the shared traffic information was unanimously favorable (valuable or very valuable), and all six of the controllers rated the shared weather information as very valuable.

Whereas controllers were enthusiastic in their support for the shared weather display, their opinions on sharing their traffic information with the cockpit were mixed. Some controllers suggested that it could be useful to controllers and pilots when sequencing aircraft in the terminal area, providing a common visual reference system. Others expressed concern that arming pilots with such information in some cases might make pilots "less complacent" with their approved clearances or assigned vectors.

Discussion

It was anticipated that the sharing of information would change the balance of information and, given an environment of competing goals between pilots and controllers, introduce instability into the ATC system in the form of increased negotiation and contention. The evidence does not appear to support this hypothesis. Although there were instances of contention and extended negotiation, such instances were rare when compared to the overall spirit of cooperation and teamwork between controller and pilot, even when cooperation meant acting contrary to their supposed competing goals.

There is the possibility that the test subjects may have been predisposed to cooperative behavior. The test subjects for this experiment were unpaid volunteers and, for the most part, self-selected. As such, they may represent the more charitable, cooperative elements of their populations. In addition, knowing that their words and actions would be recorded and studied, subjects may have made an effort, conscious or subconscious, to be less egocentric and more synergistic in their problem solving approaches. Furthermore, due to the close proximity of the cockpit and ATC simulators and the occasional banter on the frequency between the subjects during the scenarios, the two subjects had the opportunity to become somewhat acquainted over the course of the day. As a result, the subjects tended to establish a friendly rapport that would not typify pilot–controller relations on the line. This rapport may have biased the subjects toward more cooperative, compliant behavior than is typical in actual operations.

The availability of a NEXRAD weather overlay clearly benefited the controllers and the control system in general. Without the weather overlay, controllers had a difficult time anticipating the effects of weather on the traffic flow. As a result, controllers were faced with a high number of tactical deviations requiring time-critical conflict management. Attention to these immediate-term situations generally came at the expense of longer-term strategic planning. Furthermore, without good situation awareness regarding the location of weather-impacted areas, the controllers' primary conflict resolution strategy was simply to meet the pilots' reroute requests wherever possible. However, as suggested by the situation awareness analysis that preceded this study,[11] the pilots' requests typically reflected a desire to select the most efficient route that would avoid the weather; the impact of said route on the broader traffic flow was not an apparent goal of pilots. Thus, in attempting to honor pilots' reroute requests, controllers were in effect subordinating their own goal of maintaining an orderly traffic flow to the pilots' goal of selecting an efficient route. Ultimately, several separation violations occurred.

When the weather overlay was provided, controllers were better able to anticipate aircraft needs and constraints, enabling them to shift their attentions from tactical management and resolution to strategic planning and prevention. To varying degrees, the controllers adopted a more proactive role in routing aircraft around weather. Whereas in the nondatalinked configuration controllers typically waited for pilots to request deviations for weather and deferred to them for routings, in the datalinked configuration controllers often assigned vectors around weather in advance of any pilot requests. In such cases, pilots did not attempt to inject their goal of selecting the most efficient route into the rerouting decision. The controllers were free to select route amendments that optimized the overall traffic flow. In effect, this subordinated the pilots' goal of selecting an efficient route to the controllers' goal of maintaining an orderly traffic flow. No separation violations occurred in this datalinked configuration. These results illustrate how the allocation of information can influence the authority structure.

One controller expressed that it was a goal to assign the vectors before the pilot asked for them, because the earlier the vectors were assigned, the more likely the pilot would be to accept them. Indeed, pilots accepted all of the controller-initiated weather vectors without contention, even when the vectors followed a different route than the pilots had requested in the same scenario performed without the datalink. Thus, the controller's use of the weather information as a competitive advantage went unchecked by pilots, and the stability of the control system was not adversely affected.

The markedly improved performance (in terms of separation assurance) and strong subjective preference of controllers for the weather display suggests that weather information of a quality equivalent to NEXRAD should be made available on the PVD.

Conclusions

The results of this study tend to corroborate the hypothesis that the sharing of information between pilots and controllers can lead to improved operations. By sharing traffic and weather information, pilots' and controllers' situation awareness with respect to traffic and weather was improved. Sharing of this information led to more collaborative interaction, as evidenced by more frequent advisories from ATC and the unsolicited exchange of suggestions for alternative, more favorable routings. With improved situation awareness and increased air–ground cooperation, safety was improved, as evidenced by the lack of loss of separation events in the datalinked case.

Outside the laboratory, the effect of shared information on pilot–controller interaction will depend on the degree to which pilots and controllers approach their work with the same spirit of cooperation as was evidenced in this study. When the pressures and realities of line operations begin to weigh on the pilot–controller relationship, it is possible that the spirit of cooperation may succumb to the more competitive, distributive interests identified in the situation awareness analysis associated with this study.[11] In such cases, it is possible that by sharing information between the pilot and controller, reroute negotiations could become more protracted and more contentious. In addition, the effects of interaircraft gaming behavior were not studied in this experiment, as the pseudopilots did not actively compete with the subject pilots.

Independent of the effects of shared information on pilot–controller interaction, there appears to be a clear benefit to the provision of NEXRAD-type weather information to center controllers as an overlay on the PVD. Such displays appear to significantly improve controller situation awareness with respect to weather. More important, there appears to be a corollary benefit by which controllers are able to acquire better situation awareness with respect to traffic, particularly at the higher levels: comprehension and projection. In so doing, controllers appear to shift from reactive control strategies to more proactive ones, resulting in safer, more routine traffic operations.

Acknowledgments

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