PREPRINT, TENTH INTERNATIONAL SYMPOSIUM ON AVIATION PSYCHOLOGY, COLUMBUS, OHIO, USA, MAY 2-6, 1999

THE EFFECTS OF SHARED INFORMATION ON PILOT-CONTROLLER SITUATION AWARENESS AND RE-ROUTE NEGOTIATION

Todd C. Farley*, R. John Hansman*, Mica R. Endsley†, Keith Amonlirdviman*

*Massachusetts Institute of Technology
Cambridge, Massachusetts

†SA Technologies
Marietta, Georgia

ABSTRACT

The effect of shared information is assessed in terms of pilot–controller negotiating behavior and shared situation awareness. Pilot goals and situation awareness requirements are developed and compared against those of air traffic controllers to identify areas of common and competing interest. An exploratory, part-task simulator experiment is described which evaluates the extent to which shared information may lead pilots and controllers to cooperate or compete when negotiating route amendments. Results are presented which indicate that shared information enhances situation awareness and can engender more collaborative interaction between pilots and air traffic controllers. Furthermore, the value of providing controllers with a good-quality weather overlay on their plan view displays is demonstrated. Observed improvements in situation awareness and separation assurance are discussed.

INTRODUCTION

The FAA's proposed future National Airspace System Architecture [FAA, 1998] calls for expansion of existing datalink services to include applications such as the Controller–Pilot Data Link Communication (CPDLC) system, Automatic Dependent Surveillance broadcasts (ADS-B), and Aviation Weather Information (AWIN) systems. Such advances will allow information which is not uniformly accessible today to be shared between pilots, controllers and other users (e.g., dispatchers, airport managers, etc.). This sharing of information—a digital "party line"—is expected to offer several benefits, including the ability to communicate graphical information between agents, and improved shared situation awareness between agents. However, few studies have explicitly investigated how shared information may influence pilot–controller situation awareness and re-route negotiation.

PILOT AND CONTROLLER GOAL HIERARCHIES AND SITUATION AWARENESS INFORMATION REQUIREMENTS

In order to understand the effect of shared information in the system and how pilots and controllers may act on that information, it was necessary first to identify their roles, their motives and their informational needs. A comprehensive goal-directed task analysis was performed for commercial airline pilots [Endsley, *et al.*, 1998] to complement an existing analysis for en-route ATC specialists [Endsley & Rodgers, 1994]. Based on extensive focused interviews with subject matter experts, each task analysis constructed a comprehensive goal hierarchy from which the specific situation awareness information requirements were derived.

The individual pilot and controller task analyses were compared against one another in order to identify areas of common or competing interest between pilots and controllers. Figures 1 and 2 depict the high-level goals of pilots and controllers, respectively. At these higher levels, the goal structures are highly parallel, and there is considerable overlap between the two:

- Assure flight safety
- Avoid conflicts (e.g., aircraft, terrain, restricted airspace)
- Provide customer service
- Handle perturbations (e.g., weather, emergencies)
- Manage resources (e.g., people, systems)

The high-level goal comparison reveals the far-reaching effects of re-route decisions. All of the first- and second-level goals for both pilots and controllers are influenced by the current and future flight path. This suggests that re-route negotiations have broad and significant ramifications for both pilots and controllers and that each should have a vested interest in the outcome.

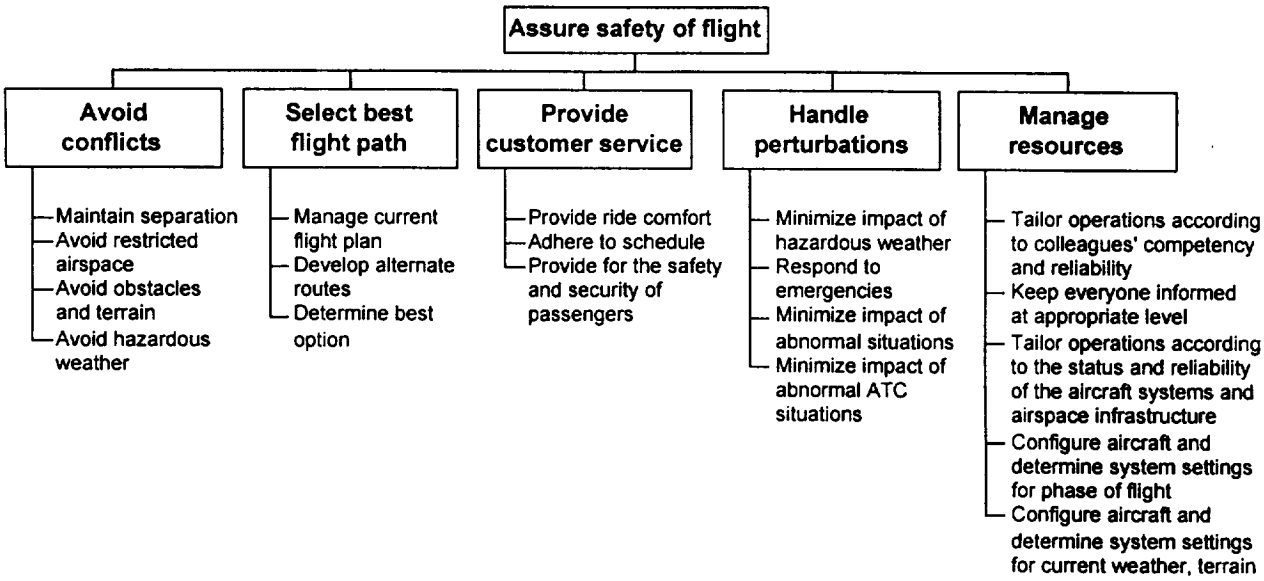

Figure 1. Commercial airline pilot top-level goal hierarchy

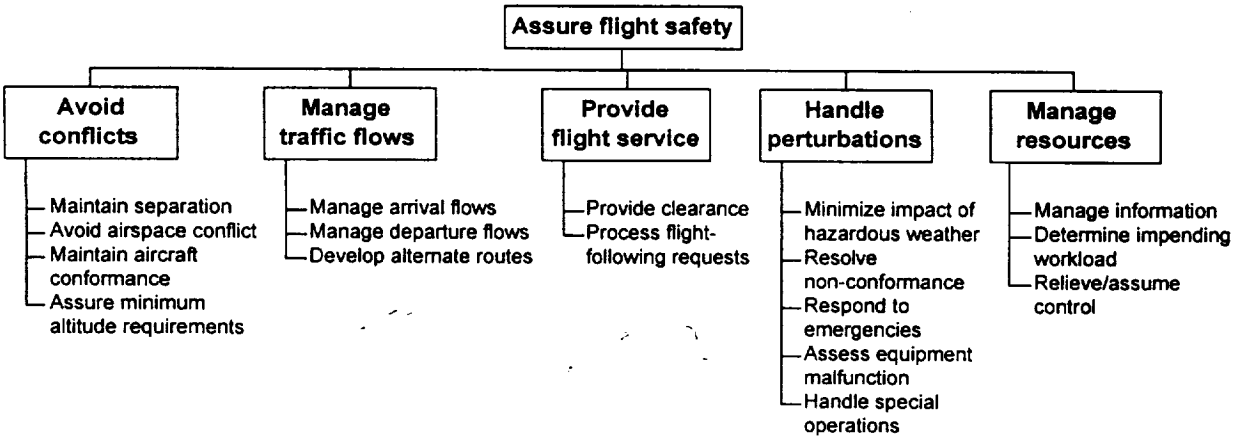

Figure 2. En-route air traffic controller top-level goal hierarchy

Comparison of the lower-level goals revealed that pilots and controllers often have competing interests with respect to re-route decisions. For example, pilots assess route amendments in terms of time or fuel efficiency, whereas controllers assess them in terms of their effect on separation and traffic flows. More generally, pilots' aircraft-centered goals often conflict with controllers' system-centered goals, creating the potential for less collaborative negotiations.

The information upon which such negotiations are conducted varies, but pilots and controllers reported that traffic and weather information often provide the impetus to change path and typically impose constraints on the available alternatives.

SIMULATOR-BASED EXPERIMENT

Based on the results of the comparative analysis, an exploratory experiment was conducted. The experiment paired an air transport pilot with an en-route air traffic controller in a real-time simulated air traffic environment under present-day air traffic control procedures. The experiment was directed at re-routing situations. In order to limit the number of interacting agents, test scenarios focused on tactical routing decisions which would preclude the involvement of Airline Operations Centers (AOCs). The identified importance of traffic and weather information in re-routing situations was reflected in the experiment's use of traffic and weather elements in the test scenarios and the availability of a traffic and weather datalink as the independent variable.

Experimental Design

Test scenarios were designed to represent complex en-route air traffic situations involving convective weather and moderate- to high-density traffic flows. Weather and traffic hazards were scripted to pose routing conflicts to the pilot–controller subject pair. The intent was to design conflicts which would play on the competing goals of the pilot and controller to offer each subject a fairly obvious—yet different—solution, thereby raising the need for re-route negotiation. The traffic and weather elements were designed to create testable responses, a performance-based situation awareness probe [Pritchett, Hansman, & Johnson, 1996]. Testable response scenarios incorporated a hazard element (e.g., an intruder aircraft, a weather cell) that required the subject to take action, provided s/he was aware of the situation. An appropriate action taken by the subject indicated situation awareness; inaction indicated a lack of situation awareness. Subjects interacted within the simulation environment to resolve the traffic and weather conflicts. The availability of shared traffic and weather displays (via datalink) was manipulated as the independent variable as shown in Table 1. Typical cockpit and ATC displays are shown in Figures 3 and 4.

Table 1. Test Matrix

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

With the datalink disabled, there was no sharing of information. Weather information, in the form of six-color NEXRAD reflectivity imagery, was available only to the subject pilot on the cockpit map display; the subject air traffic controller received no weather information. Conversely, traffic information—including aircraft position, call sign, track, altitude, and ground speed—was available only to the subject controller via the plan view display; the subject pilot received no traffic information. Information was partitioned in this way to establish clear information superiority for one party relative to the other.

In the "datalink enabled" configuration, weather and traffic information were shared between the pilot and controller. The weather information, previously available only to the pilot via the cockpit map display, was displayed as an overlay on the controller's Plan View Display (PVD). Similarly, the traffic information was displayed on a prototype Cockpit Display of Traffic Information (CDTI).

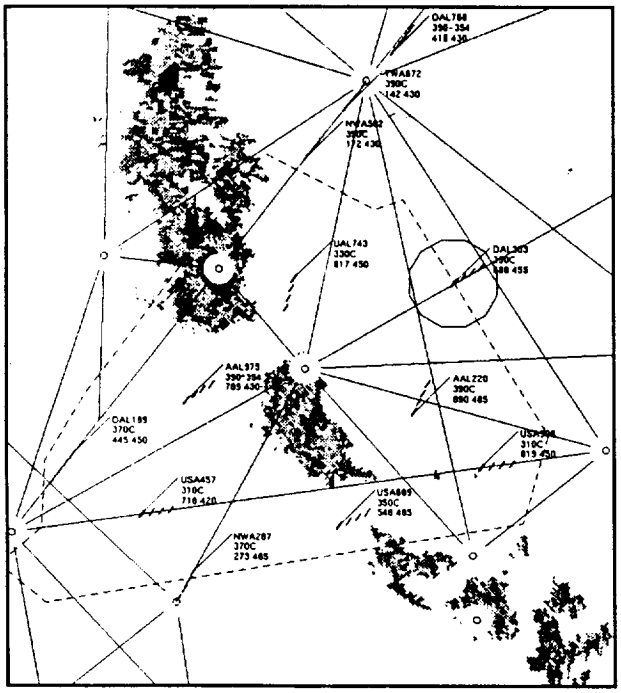

Figure 3. ATC plan view display with datalink enabled. DAL303, positioned inside the six-mile radius "J-ring", is the subject pilot's aircraft. The weather overlay is six-color NEXRAD imagery.

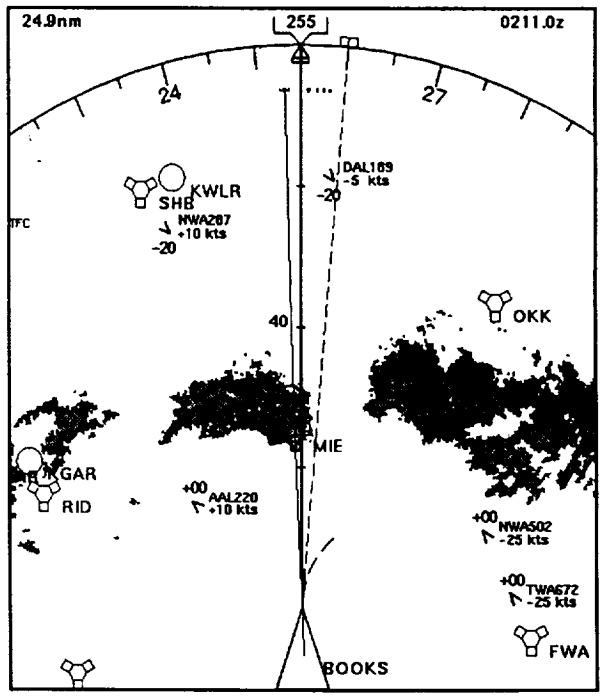

Figure 4. Cockpit map display with datalink enabled, as seen by the subject pilot of DAL303. The integrated CDTI shows proximate traffic co-altitude at the 11–, 2– and 3–o'clock positions.

Each pilot–controller subject pair performed three test scenarios, once with shared traffic and weather information (i.e., datalink enabled) and once without (i.e., datalink disabled). All scenarios took place in a high-altitude sector in Indianapolis Center airspace. Each scenario ran for approximately ten minutes and featured between 12 and 18 aircraft transitioning the sector in the presence of convective weather activity.

Those aircraft not piloted by the subject pilot were controlled by a confederate pseudo-pilot, who also interacted with the subject controller and subject pilot via radio communication. Certain elements of each repeated scenario were changed (e.g., aircraft call signs, trajectories of non-factor traffic, etc.) in order to disguise the second iteration.

In order to observe pilot–controller interaction in a real-time, complex workload environment, MIT's distributed, interactive, multi-agent simulation facility was used [Amonlirdviman, *et al.*, 1998]. The facility was configured to network one part-task advanced cockpit simulator, one part-task en-route ATC workstation, one multi-aircraft pseudo-pilot station, and live voice communications between them, creating a real-time interactive air traffic environment.

Pilot and controller situation awareness was measured using the testable response method. Aircraft state and trajectory data were digitally recorded at 20 Hz. Radio communications were digitally recorded and coded using a methodology adapted from Foushee, Lauber, Baetge, & Acomb [1986]. Workload measurements were taken using the NASA Task Load Index (NASA–TLX) [Hart & Staveland, 1988]. Subjective ratings regarding the value of the shared information were also collected.

Results

Six pilot–controller teams performed the experiment. All controller subjects were Full Performance Level (FPL) ATC Specialists with an average of 13.3 years of experience, currently working the radar position at an Air Route Traffic Control Center (ARTCC) in the U.S. All pilot subjects were jet transport rated pilots with an average of 10,117 hours.

Situation Awareness. Figure 5 summarizes the results of the traffic-related testable response probes. Pilots, without the benefit of a traffic display in the non-datalinked 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 some 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 independently recognize and respond to the hazard was precluded, and the testable response result for the pilot therefore was labeled "ambiguous".

Controllers 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 6 summarizes the results of the weather-related testable response probes. Pilots, having the benefit of the weather display for all test scenarios,

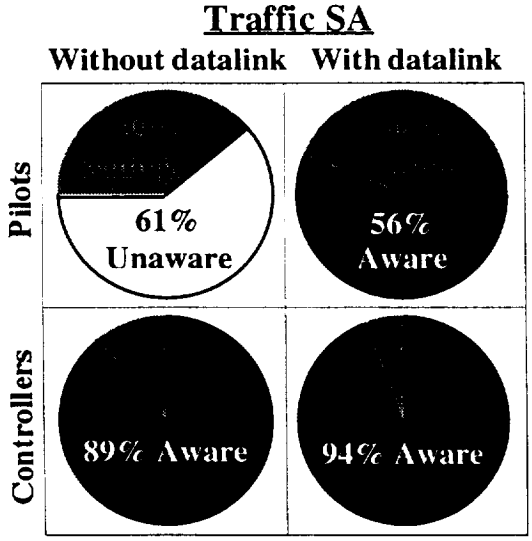

Figure 5. Pilot and controller awareness of traffic-related testable response conditions

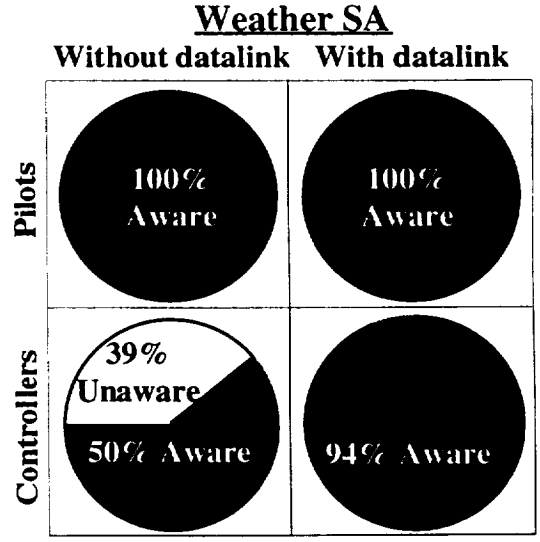

Figure 6. Pilot and controller awareness of weather-related testable response condition

demonstrated awareness of all of the weather-related testable response conditions. Controllers, without the benefit of a weather display in the non-datalinked 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.

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 the plan view display. These results confirm that shared information via air–ground datalink can improve situation awareness for both pilots and controllers.

Controllers' Weather Awareness. En-route controllers report that the the weather information currently provided on their plan view displays is of limited value. To compensate, they use pilot reports (PIREPs), aircraft trajectories, and pilot requests to construct a mental picture of the areas affected by weather and to project how the traffic flow will be affected. To gain some insight into the accuracy of this heuristic, controllers were asked to perform a simple recall task at the conclusion of each non-datalinked scenario. Each controller was asked to indicate, on a blank sector map, the size and location of the weather cell(s) as inferred from the aircraft trajectories and voice communications from pilots. Figure 7 is a sample of the results. 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 infer the location of weather in their sector. Controllers' skill at inferring the location of weather using this heuristic was found to vary widely, both within and between subjects.

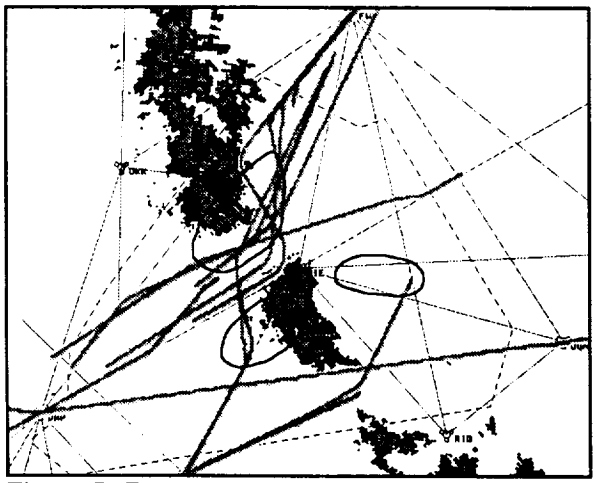

Figure 7. Example of controller's inferred weather location (black). Aircraft tracks (gray) and weather image have been overlaid for reference.

Loss of Separation Events. In the 36 test scenarios, five loss of separation events[1] were observed, *all of which occurred with the datalink disabled.* It is important to note that the test scenarios were challenging by design. 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. However, the fact that every loss of separation occurred in the non-datalinked environment does suggest that shared information may help controllers build and maintain situation awareness with regard to separation issues.

Communication and Negotiation. All radio communication was recorded and coded by category and topic. With the datalink enabled, the pilot and controller made more voluntary suggestions to one another for specific route amendments. This verbal exchange of re-routing 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, 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 ($p < 0.01$).

Workload. Pilot and controller workload was measured using the NASA–TLX. In general, the availability of shared information did not affect the workload in any systemic way, either individually or in a team sense.

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 was unanimously favorable, and all six of the controllers rated the shared weather information as "very valuable". While 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. Others expressed concern that arming pilots with such information might make pilots "less complacent" with regard to their approved clearances or assigned vectors.

[1] A loss of separation is defined as lateral separation of less than five miles and vertical separation of less than 1000 feet.

CONCLUSIONS

It is generally expected that by sharing information between pilots and controllers, situation awareness will be improved on either side. With improved situation awareness, more collaboration between the two parties is anticipated. Such collaboration is expected to lead to improved performance on an individual and system-wide basis.

The results of this study tend to corroborate these expectations. 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 separation violations in the datalinked configuration.

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' re-route requests wherever possible. However, as suggested by the situation awareness analysis, 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' re-route 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 routing constraints, enabling them to shift their attentions from tactical control to strategic planning. No separation viloations occurred in this configuration. The markedly improved performance (in terms of separation assurance and situation awareness) and strong subjective preference for the weather display suggests that NEXRAD-type weather information should be made available on the PVD.

ACKNOWLEDGMENTS

This work was supported by the NASA Ames Research Center under grant NAG 2-716 and by TASC as part of the FAA Center of Excellence in Operations Research.

REFERENCES

Amonlirdviman, K., Farley, T.C., Hansman, R.J., Ladik, J.F., & Sherer, D.Z. (1998). A distributed simulation facility to support human factors research in advanced air transportation technology. In Proceedings of the SISO Simulation Interoperability Workshop. Orlando, FL.

Endsley, M.R., Farley, T.C., Jones, W.M., Midkiff, A.H., & Hansman, R.J. (1998). Situation awareness information requirements for commercial airline pilots. MIT International Center for Air Transportation: ICAT-98-1, Cambridge, MA.

Endsley, M.R. & Rodgers, M.D. (1994). Situation awareness information requirements for en route air traffic control (DOT/FAA/AM-94/27). Federal Aviation Administration Office of Aviation Medicine, Washington, DC.

FAA. (1998). National airspace system architecture (draft). FAA Office of System Architecture and Investment Analysis (ASD-1), Federal Aviation Administration, Washington, DC.

Foushee, H.C., Lauber, J.K., Baetge, M.M., & Acomb, D.B. (1986). Crew factors in flight operations: III. The operational significance of exposure to short-haul air transport operations. NASA Technical Memorandum 88322.

Hart, S.G., & Staveland, L.E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In: Human Mental Workload (P. Hancock and N. Meshkati (Eds.)), pp. 139-183. North-Holland: Elsevier Science.

Pritchett, A.R., Hansman, R.J., & Johnson, E.N. (1996). Use of testable responses for performance-based measurement of situation awareness. In (D. Garland and M. Endsley, eds.) Proceedings of the International Conference on Experimental Analy-sis and Measurement of Situation Awareness. Daytona Beach, FL: Embry-Riddle Univ. Press.