

## **Evaluations of Data Communications in Tower, TRACON, and En Route Air Traffic Control**

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The Federal Aviation Administration (FAA) has embarked on a large effort to create the Next Generation Air Transportation System (NextGen). NextGen will prepare the National Airspace System to accept increasing air traffic levels and complexity in a safe and efficient manner. Data Communications (Data Comm) is one of the core technologies of NextGen. The use of Data Comm will improve information exchange between pilots and air traffic controllers. In 2009, the FAA conducted three human-in-the-loop experiments to address the use of Data Comm in the Airport Traffic Control Tower, the Terminal Radar Approach Control, and the En Route airspace. The experiments focused on human factors aspects of air traffic control tasks under a variety of conditions including varying percentages of aircraft equipped for Data Comm, different interface designs, and changes in roles of responsibilities of air traffic controllers.

### **INTRODUCTION**

The Federal Aviation Administration (FAA) projects that the number of flights in the National Airspace System (NAS) will increase by 40% by 2025 (FAA, 2009a). The Joint Planning and Development Office (JPDO) has developed the Next Generation Air Transportation System (NextGen) plan to address increasing air traffic levels and complexity (JPDO, 2007a). NextGen consists of three research and development phases (JPDO, 2007b). Phase 1 began in 2007 and continues through 2011. It focuses on the development and implementation of the core technologies deemed necessary for enabling new concepts and procedures. These technologies include Data Communications (Data Comm) to improve information exchange between the controller and pilot. During Phase 2, extending from 2012 to 2018, the available technologies will enable the implementation of new procedures and concepts. Phase 3, from 2019 to 2025, will expand the new capabilities throughout the NAS and will phase out older technologies.

NextGen will greatly alter the roles of both pilots and controllers. The flight crew will become responsible for some procedures, and the controller will become more responsible for airspace management. Augmenting voice communications with digital communications affects visual, auditory, and cognitive workload and attentional demands for both aircrew and controllers. Data Comm implementations must take into account human capabilities and limitations; must integrate well into human tasks; and facilitate rapid and accurate human performance. Appropriately, the JPDO (2007b) has identified human factors as a crosscutting research and development area in assessing NextGen initiatives.

Data Comm will support the efficient exchange of trajectory information between air and ground, enabling Trajectory-Based Operations, including Continuous Descent Arrivals and Tailored Arrival Procedures (TAPs). Once a controller issues a clearance, a pilot can respond to the message with a WILCO (will comply), and the Flight Management System (FMS) can execute that message without

re-entering the information, thus eliminating potential sources of errors. The messages persist until the recipient has acknowledged them, eliminating errors due to misidentifying the intended recipient or forgetting. Data link requires less bandwidth and have inherently greater noise immunity than analog voice transmissions.

FAA research into data link for air traffic control (ATC) dates back to the 1970s (e.g., Hilborn, 1975). By the time of Kerns' (1991) review, simulation studies had addressed a wide range of issues, including redundant versus complementary use of voice and data link, application areas (non-control or tactical or strategic control), procedures, and human-machine interface (HMI) design. Kerns suggested to use voice and data as complementary modes of communication, that data link is useful for all but urgent tactical messages, that controller interfaces should offer a variety of ways to construct messages, and that the system should show message status in close proximity to the aircraft symbol on the controller's display. Areas identified for further research included detailed HMI design and more precise specification of clearances, such as maneuver start and end-points and climb or descent rates.

The FAA will introduce the Data Comm concepts into ATC in several segments. Segment 1 spans 2012–2017 and Segment 2 spans 2018–2023 (approximately). The message set for Data Comm includes the following services: vertical clearances, crossing constraints, lateral offsets, route modifications, speed changes, frequency changes, and surveillance updates. Pilots may downlink requests for services and reports and the controller can uplink clearances and requests for reports. Both pilot and controller may send negotiation requests, system management messages, and response or acknowledgement messages such as WILCO and UNABLE.

### **Data Comm in the Tower Environment**

Today, pilots of departing aircraft must call the ground controller in the tower and request a taxi clearance. The ground controller responds by ensuring the pilot has the current airport and weather information and by providing a

taxi clearance. The taxi clearance may be lengthy and include a complex taxi route including hold short instructions. The pilot must read the taxi clearance back to the ground controller and the ground controller must ensure that the readback was correct (i.e., hearback). The controller must correct any errors in the pilot's readback, and this exchange continues until the controller is sure that the pilot understands the taxi clearance. This exchange can take a considerable amount of time, congest the voice radio frequency, and present the opportunity for readback and hearback errors that may result in pilot deviations, runway incursions, or worse.

Data Comm addresses many of the problems associated with voice communications by enabling the entire taxi clearance exchange between the pilot and ground controller to be accomplished digitally. A Digital Taxi (D-Taxi) clearance can provide both the pilot and controller with a textual and graphic display of the taxi clearance and reduce voice frequency congestion.

### **Data Comm in the Terminal Radar Control Environment**

Terminal Radar Control (TRACON) controllers may use data link differently or less often than their en route counterparts. TRACON separation minima are smaller and more complex than en route, there are fewer available routes and trajectories, the aircraft are slower but closer together, and the precise timing of instructions is critical. Data link response times that are acceptable in en route might not be acceptable in TRACON. Data link HMIs developed for en route might require more time or attention than TRACON controllers have available. In the simulation, we adapted data link procedures and HMIs developed for en route to make them better suited to TRACON and examined how and when controllers used data link.

In addition, unlike en route controllers, TRACON controllers do not routinely make data entries when issuing control instructions. For example, when en route controllers issue altitude changes, they make Assigned Altitude or Interim Altitude data entries. In contrast, TRACON controllers enter altitude changes only in unusual circumstances. Furthermore, the current TRACON automation systems do not provide functions for controllers to enter heading, speed, or route changes into the system. Historically, when TRACON controllers issued such instructions, they would make corresponding marks on flight progress strips. In en route, paper strips have been almost entirely replaced by electronic flight data systems. Paper strips are also no longer used at many large TRACONs, but currently there is no equivalent in TRACON to the electronic flight data capabilities in en route. For these reasons, TRACON controllers do not associate issuing control instructions and interacting with automation. Data Comm requires that this change for at least some types of instructions in some circumstances. In the simulation, we provided a variety of flight data capabilities that do not currently exist and examined how controllers used them.

Finally, unlike many en route sectors, TRACON sectors are normally staffed by only one controller. When needed, some sectors also may be staffed by a handoff controller who

is responsible for accepting and initiating handoffs, and coordinating with adjacent sectors and facilities. However, one possible operational concept for data link in TRACON involves the handoff controller becoming more like the en route data controller, where the handoff controller would be responsible for data link communications while the radar controller would be responsible for the voice communications. This would represent a fundamental change in controller responsibilities and would affect functional and HMI requirements for data link. In the simulation, we asked if a handoff controller is necessary for the effective use of data link in the TRACON, and what capabilities and responsibilities that controller should have.

### **Data Comm in the En Route Environment**

An early study (Data Link Benefits Study Team, 1995) showed that with the addition of the RTCA DO-219 message set and 90% equipage, data link reduced aircraft transit times and distance flown within the sector by approximately 20%. Recent simulation studies at the Research, Development, and Human Factors Laboratory (RDHFL) have used the Future En route Work Station (FEWS). The FEWS simulations emulated the En Route Automation Modernization (ERAM) system with a number of enhanced capabilities, including digital communications. The FEWS studies have shown that the availability of data link reduces the number and duration of voice communications and controller workload, resulting in an increase of 20% in sector capacity at equipage levels of 70% (Willems & Hah, 2008).

The message set available in en route includes numerous complex clearances, that is, clearances that either describe complex routes or that instruct aircraft to execute maneuvers at a specified time, at a specified location, or after a completion of a preceding clearance. In the en route experiment we approached implementation of complex messages in several ways. We examined the application of data link to support TBO and the implementation of advanced aircraft procedures. We expect that our results will help identify the extent to which data link will increase airspace capacity.

## **METHOD**

### **Simulation Environment**

The RDHFL provides an ATC simulation environment that was developed by the FAA. Incorporated into that environment are several measurement techniques that researchers can use to collect dependent variables.

*DESIREE*. The Distributed Environment for Simulation, Rapid Engineering, and Experimentation (DESIREE) is a high fidelity simulation platform that emulates National Airspace System logic and creates HMIs that emulate several ATC systems. DESIREE can emulate current systems such as the Airport Surface Detection Equipment, Model X (ASDE-X), the Standard Terminal Automated Radar System (STARS), the Display System Replacement System (DSR), and the ERAM system. RDHFL programmers and researchers have also emulated modifications to current systems to accommodate

Data Comm and Separation Management and have created future concept systems such as the Tower Operations Digital Data System (TODDS), the Future Terminal Workstation, and the FEWS. The emulated systems used in the experiments described here were adapted to accommodate data link capabilities that currently do not exist in the fielded systems.

*TGF.* The Target Generation Facility (TGF) software provides a high fidelity simulation of aircraft behavior including the ability to use human simulation pilots to maneuver the simulated aircraft. Each of the aircraft consists of an airframe, power plants, and control logic that provides realistic aircraft responses to control instructions and atmospheric conditions. The TGF software was adapted to accommodate the use of data link messages used in the experiments described here.

### En Route Experiment

*Participants.* Twenty-eight Certified Professional Controller (CPCs) from en route facilities participated. The CPCs had an average age of 44 years (range 24-55). They had an average control experience of 20 years (range 3-30). Controllers worked in teams consisting of a Radar (R-side) and Radar Associate (D-side) controller.

*Simulation environment.* The En Route Data Comm used a modified ERAM emulation. The R- and D-side controllers each had a radar display with integrated automation functions. Data link message support included heading, direct-to-fix, several vertical and speed clearances, and complex routes.

*Airspace.* We used a generic high altitude sector (ZGN08). ZGN08 had a roughly rectangular shape and extended for approximately 120 nm from North to South, approximately 100 nm from East to West, and from FL240 and up. It contained several intersections that contributed to sector complexity. ZGN08 was above and north of a low altitude en route sector, ZGN18. ZGN18 contained two metering fixes for aircraft that transition into the terminal sector to GEN.

*Conditions.* The experiment used six independent variables: HMI (keyboard- graphical-, or template-oriented functions or a combination of functions), Service Priorities (First Come, First Served or Best Equipped, Best Served), Data Comm Equipage Levels (0, 10, 50, or 100% of the aircraft were data link equipped), FMS Integration (50 or 100% of the aircraft had an integrated flight deck), End-to-End Message Delays (pilot response times were either based on Segment 1 or shorter as may be expected for Segment 2), and Failure Modes (failures included individual aircraft losing their data link session, a transceiver outage causing part of the airspace to lose data link capabilities, or a system wide outage)

*Dependent Variables.* The data collected during the experiment included questionnaires and surveys (post scenario questionnaire, over-the-shoulder rating form, , exit questionnaire, and exit debrief), subjective workload (workload assessment keypad recordings), system variables (aircraft data and controller interactions), audio and video recordings (voice communications between aircraft and pilots as well as ambient conversations between controllers), eye

movement recordings, and functional Near Infrared Recordings (fNIR).

### TRACON Experiment

*Participants.* Twelve controllers drawn from the 50 busiest TRACONS served as participants. The participants served in teams of two and alternated between the roles of radar and handoff controller.

*Simulation environment/Airspace.* Controllers staffed a busy arrival sector in our Genera TRACON airspace, which contains one large central airport with several nearby regional airports, similar to Philadelphia, Charlotte, and Detroit TRACONS. The traffic scenarios lasted 30 minutes and represented busy but routine operations with no weather or other special events.

*Controller responsibilities.* We simulated three conditions with different sets of controller responsibilities. In the R-Only condition, one controller staffed the sector and was responsible for all voice and data communications. In the R&D/C&S condition, two controllers staffed the sector. The radar controller (R-side) was responsible for all voice communications and was in charge of the sector. The handoff controller (D-side), assisted the R-side with whatever tasks the two controllers agreed upon. The D-side could not communicate directly with aircraft by voice, but could compose and uplink data link messages of all kinds. This condition provided D-sides with capabilities that handoff controllers currently do not have. Handoff controllers today cannot take action on aircraft without going through radar controllers. In the simulation, the D-sides could uplink messages directly to aircraft, but with the expectation that they would only do so after coordinating with and receiving authority from the R-sides.

In the R&D/CNS condition, the D-sides could compose data link messages but were prevented by the automation from uplinking the messages. Instead, the messages composed by the D-sides were automatically placed into a queue. The R-sides could then select and send the queued messages as they wished. The R-sides also could delete queued messages. This condition is more analogous to the current division of responsibility for voice-only aircraft. However, this condition also limits the potential workload benefits that a D-side might provide because even when a D-side composes a data link message, the R-side must still interact with the automation to review and uplink the message.

*Human-machine interface design.* The number of available controller workstations is limited at many TRACONS. Handoff controllers and radar controllers typically share a single radar display, and two or even three keyboards and trackballs may be located at one workstation. When two or three controllers are working, two or three cursors and message composition areas appear on the radar display. Outside of ATC, HMIs employing multiple cursors on one display are rare, and they do not conform with most HMI conventions and practices. For example, if there are two cursors and each cursor is located in a different window, which window has focus? In the simulation, participants used two

workstation designs. In the one-display condition, the R- and D-sides shared one radar display with multiple keyboards and cursors. In the two-display condition, the R- and D-sides each had their own radar display.

*Data Comm equipage.* In the main simulation, the traffic scenarios contained one of three levels of Data Comm equipage: 0%, 40%, and 75%. In an exploratory research activity, we examined two levels of Flight Management System (FMS) integration: 20% and 60%.

### Tower Experiment

Researchers at the RDHFL tested the Data Comm Segment 2 concept of D-Taxi clearances for departure aircraft to assess the potential human factors impact on controller behavior and performance.

*Participants.* Sixteen current tower controllers from some of the busiest facilities participated in the experiment.

*Simulation environment/Airspace.* The experiment used a DESIREE/TGF-based tower simulation platform to present a 270-degree out-the-window view. The airport environment was similar to Boston Logan International Airport. The traffic scenarios simulated landing and arrival aircraft to runways 27, 33L, and 33R. Runways 27 and 33L intersected one another while runway 33R provided parallel runway operations. The participants managed a relatively high level of traffic volume that comprised approximately 35 arrivals and 45 departures during each 40-minute scenario. Six simulation pilots provided pilot communications and made computer entries to affect aircraft behavior.

*Procedure/Conditions.* The participants worked in groups of two at both the ground and local control positions. They used the Integrated Tower Operations Digital Data System (I-TODDS; see Truitt, 2006, and Truitt & Muldoon, 2009) and one tower STARS display to control the airport traffic. The participants worked in three counterbalanced experimental conditions. In the baseline condition, there were no data link capabilities and the participants issued all taxi clearances by voice (i.e., radio transmission), just as they do today. The participants also worked in two Data Comm conditions where either 40% or 75% of the departure aircraft were data link equipped. The D-Taxi functions were embedded in I-TODDS and provided the participants with the ability to construct, modify, and issue D-Taxi clearances to the data link equipped aircraft. Each D-Taxi clearance included the current ATIS information and a detailed taxi route including hold short instructions. The D-Taxi clearances also enabled taxiway conformance monitoring that alerted the participant if an aircraft deviated from the assigned taxi route.

In addition to the three experimental conditions, the participants worked in two 30-minute exploratory scenarios that focused on taxiway conformance violations and a complete data link failure and recovery.

*Dependent Variables.* Dependent measures included usability measures of the D-Taxi functions, number and duration of radio transmissions, airport system measures (e.g., duration on ramp, duration of taxi out, duration of taxi in,

number of arrivals and departures, number and duration of delays), and subjective ratings of workload and awareness.

## RESULTS AND DISCUSSION

We have completed data collection for all three experiments. Data reduction and analysis for each experiment are at different stages of completion, and we will briefly discuss some of our initial results.

### En Route

We will discuss two selected results from Push-to-talk (PTT) and Post Scenario Questionnaire data.

*PTT as a Function of Equipage Level.* We calculated the number and mean duration of PTT events for each simulation scenario. The repeated measures analysis showed a significant effect of the effect of Equipage Level on the number of controller PTT events ( $t(3,9)=.004$ ,  $F(3,4)=700.821$ ,  $p<.05$ ). A post-hoc Tukey HSD test revealed that the number of controller PTT events did not significantly differ between voice only and 10% equipage, but did differ significantly between 50% and 100% equipage levels (see Figure 2). Our analysis of PTT event duration data did not reveal differences as a function of equipage level.

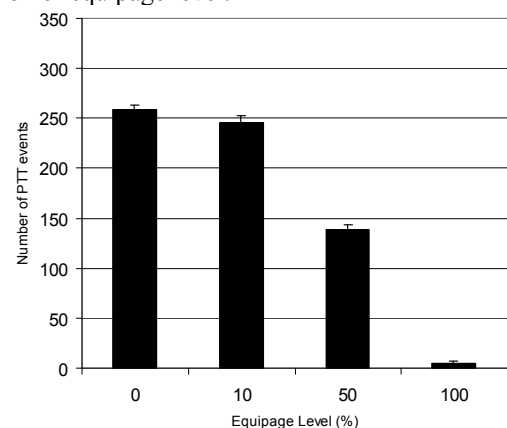


Figure 1. Number of Controller PTT events as a function of equipage level.

During the training of the controllers for the use of data link, we emphasized that in time critical situations voice is the communication modality of choice. Consequently, we expected that even under the 100% equipped condition, controllers would still have a considerable amount of tactical voice communications with pilots. The results indicated that there was hardly any communication using voice when 100% of the aircraft support data link. This suggests that controllers either adopted a different control strategy that did not require time critical clearances or that they used data link for time critical clearances as well.

*Exit Questionnaire HMI Rating.* We asked controllers about their preference for using the template, keyboard, graphical, or combined interface as the sole input mode. Responses could range from -5 (absolutely not) to 5 (absolutely). We used non parametric statistics to test the effect of experimental manipulations because we had a small

sample size, had missing data, and had data that were not normally distributed. We used the non parametric Friedman test as a substitute of the repeated measure ANOVA. As a post hoc test to follow up the significant Friedman test results, we used two-tailed non-parametric Wilcoxon Matched-pair Tests. We found a significant effect of HMI condition on controller preference ( $Chi-square = 26.045, p < .05$ ). The post Wilcoxon Matched-Pair Tests showed that the R-side controllers did not want to use the template as the sole HMI for data link input mode (see Figure 3).

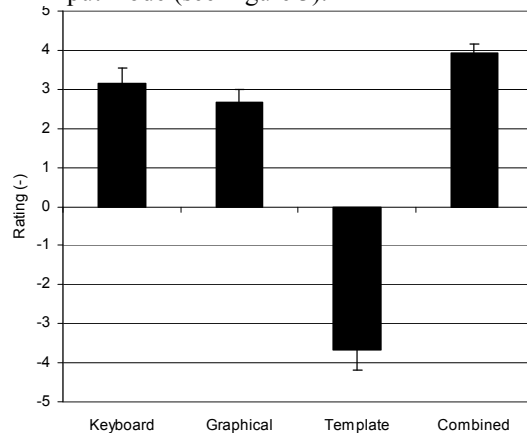


Figure 2. R-side Controller preference to use an HMI input mode as the sole data entry method.

We created four HMI environments to assess how to best integrate data link capabilities in the controller workstation. Although a clearance template is available in the current oceanic ATC system, the participants strongly suggested that a template is not well suited for en route operations. This result may be due to the high traffic levels used in this experiment. At these traffic levels, controllers were under more time pressure and may not have had enough time to interact with a template to issue data link clearances.

## TRACON

Observation data suggest that data link substantially reduced voice communications in the TRACON with a corresponding increase in data entries. TRACON controllers opted to use data link for routine control instructions when the instructions used the same parameter values (e.g., altitude, voice frequency) from aircraft to aircraft and did not involve negotiation with pilots. Controllers also made frequent use of command macros that allowed them to send the same message to multiple aircraft. It did not appear that a D-side was necessary for effective use of data link, especially when workload was reduced by other technology and capabilities, such as heavy utilization of Area Navigation (RNAV) routes. In addition, observations suggest that the R&D/CNS condition was not beneficial because it required substantial coordination between the R- and D-sides without an accompanying reduction in workload for the R-side. Finally, the one-display condition contained a number of HMI issues related to the use of two cursors on one display, but the one-display condition allowed better coordination and awareness between the controllers than the two-display condition.

## Tower

D-Taxi clearances for departure aircraft reduced the usage of the ground control voice radio frequency by 12.5% when 75% of the aircraft were data link equipped without increasing workload or heads-down time. The participants preferred issuing taxi clearances via D-Taxi compared to voice because it reduced their communication responsibilities and removed the potential for readback and hearback errors. D-Taxi did not adversely affect overall surface operations, the arrival/departure rate, or the number and duration of delays even though aircraft waited on the ramp longer when they received a D-Taxi clearance due the technical and pilot response delays associated with data link communications. The participants provided a number of suggestions for improving D-Taxi and the overall design of the I-TODDS.

## Conclusions

Data link by design reduces voice communications and we find a positive effect in the en route, TRACON, and tower environments. Surprisingly, in the en route environment with 100% data link controllers hardly used voice communications at all. The use of data link will require more data entry but has a potential to greatly reduce readback and hearback errors.

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