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International Symposium on Aviation Psychology - 2011

International Symposium on Aviation Psychology

2009

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# DESIGN AND EVALUATION OF A CONTROLLER-PILOT DATA LINK COMMUNICATIONS (CPDLC) INTERFACE

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Data link communications will, for the most part, replace voice communications between aircraft and air traffic control (ATC) systems in Next Generation Air Transportation System (NextGen). One goal in implementing data link communications is to establish Controller Pilot Data Link Communications (CPDLC) procedures, logic and page designs with existing equipment that will maximize total system-pilot efficiency. A new message menu tree index was developed to provide quick and easy access to all CPDLC messages (uplinks and downlinks as defined by RTCA SC-214). Page formats were also developed to minimize errors and enhance the efficiency of pilots in data link communications. Four pilots evaluated the MCDU datalink prototype under realistic flight conditions. Subjective and objective measures from the evaluation suggests that using existing flight deck technology for data link operations is feasible but with some limitations. Workload when using the data link system was reasonable. However, the pilots focused on performing the data link tasks at the expense of monitoring aircraft flight path.

## Background

Controller Pilot Data Link Communications (CPDLC) is aimed at improving safety and efficiency by taking over many tasks now accomplished through voice communications. While voice communications has many benefits, it is also prone to certain disadvantages such as frequency congestion, missed calls, misunderstood clearances or communications, etc. Ultimately, data link communications will be the primary means of communication between the flight crew and the Air Navigation Service Provider (ANSP) for airspaces that require data communications capability for clearances and 4-dimensional trajectory amendments. For these aircraft, voice communications between the flight deck and ANSP will be used only for extraordinary purposes (JPDO, 2007). Implementing data link communications especially through the establishment of CPDLC infrastructure that takes advantage of existing equipage can introduce human factors issues such as excessive heads down time, entry error and recovery, excessive task time with finding, composing and sending messages and standard operating procedures.

Previous research shows that textual data link modality results in higher workload and increased interaction time compared to other candidate forms e.g. synthesized speech, digitized speech and text/synthesized speech (Lancaster, 2008). Data link communications in different flight phases will also have different workload and situation awareness demands and challenges. Additionally, data-link communication could lead to increased head-down time and attention issues. Pilots will also be required to monitor multiple data link transmissions at a time requiring pilot attention. Increased head down time implies decreased time looking outside the cockpit and the time available to properly monitor other flight deck displays. This is generally detrimental to flight safety (Wiener and Nagel, 1988).

CPDLC design should consider fundamental human limitations (e.g., memory, computation, attention, decision-making biases, and task timesharing) which should not be exceeded for effective use of the system. For example, in air traffic control (ATC) communication clearance negotiations, the current method of using voice to mediate ATC communications allows for flexible and elastic negotiation of the clearances. It also allows a closed loop verification of ATC or pilot intent. CPDLC may force crews to find message strings that are not inherently intuitive or represent the routine way or method of communicating. Searching, composing and sending datalink messages may place excessive memory demands on the pilot because of the inherent functional cognitive differences between ‘hearing and responding’ and ‘reading and responding’ to datalink message sets. Datalink interfaces that do not consider these limitations run a higher probability of increasing task time, workload, heads down time and errors. These human factors issues which have been identified in previous research and literature call for an efficient use of human factors design to develop CPDLC flight deck interfaces that meet the demands of NextGen requirements and accommodate pilots and industry’s needs for compatibility with existing flight deck displays, controls and procedures.

This paper outlines a pilot-in-the-loop part-task human factors evaluation that was part of an iterative design process to develop a CPDLC display based on human factors issues. The evaluation was directed at scrutinizing pilot performance under a broad range of operational conditions (to ascertain operational suitability).

## Human-Centered Design

The pilot-in-the-loop human factors evaluation was part of an iterative design process aimed at establishing the functionality and human factors issues relating to the new CPDLC design. The primary human factors considerations for the design were: crew acceptability, perception and information processing enhancement, and interface design features. Using human-centered design principles, a message menu tree index was developed to provide quick and easy access to over one hundred and fifty standard data link messages currently defined (RTCA, 2009). Page formats were also developed to minimize errors and enhance the efficiency of pilots in data link communications. The design philosophies were focused on the goal of allowing the pilot quick, simple and accurate data link communication with ATC. The menu system incorporates human factors design philosophies that have been researched and proven valid for effective pilot-controller communications.

**System Description.** The menu system accommodates message element standards envisioned for NextGen operations (RTCA, 2009). The design covers over one hundred and fifty uplink and downlink RTCA SC-214 pre-defined standard message elements which are structured so that finding and sending the intended messages can be accomplished in a timely and accurate manner (RTCA, 2009). Previous designs (EUROCONTROL, 2009), industry standards (RTCA, 2000) airline standard operating procedures (UAL, 2009), as well as practical pilot experience were all considered in developing the design concept. The menu system design consists of the menu pages and the menu logic. The menu pages are designed using current 24x14 character Multi-Function Cockpit Display Unit (MCDU) page formats. The pilot is made aware of his location in the page tree index by displayed navigation options to go to any page. The prime initiative for the menu page organization is to reduce the number of menu navigation levels to locate a required page. Design of the menu organization and control logic was based on two considerations: (1) frequency of use and (2) match the way a pilot would typically prioritize/organize messages in categories. The SC-214 Message sets were divided into two logical groups: Message Type and Message Category. The message type and menu category logic are shown in Figure 1. This grouping approach minimized page clutter by organizing screen contents and eliminating unnecessary text to create a clean and refined design.

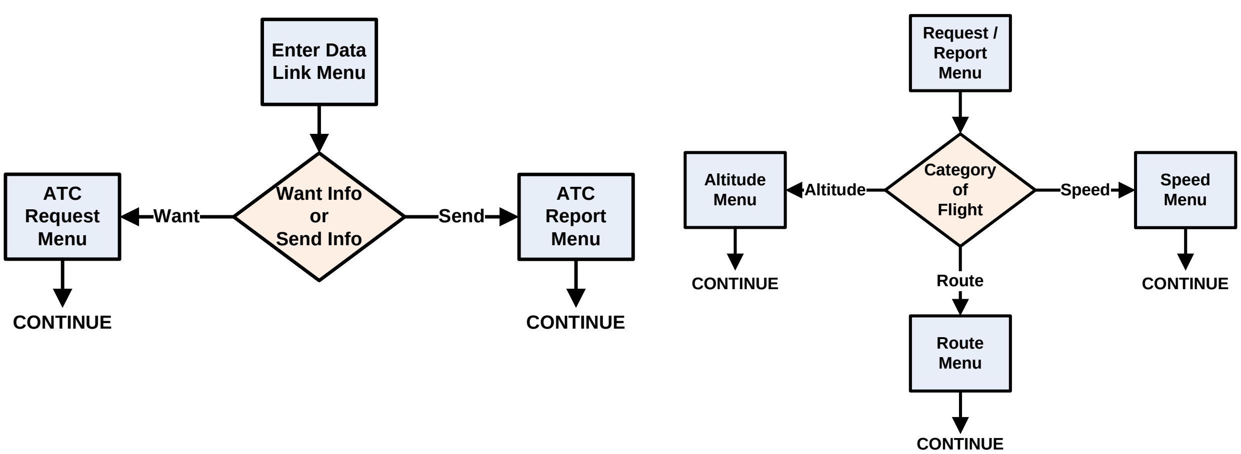


*Figure 1.* Data link message type and menu category logic.

An embedded help feature was implemented as a quick way for the pilot to “jog” his memory for the appropriate syntax to be used for data input. The embedded help feature that allows the display of proper input syntax (for a particular SC-214 message) while remaining on the same menu page. Based on analysis, it was found that the majority of datalink clearances were heading, speed, altitude or DIRECT TO clearances. Because a pilot would spend the majority of time responding such messages, an MCDU page was designed to handle this communication traffic. Thus a pilot could handle the majority of ATC communications using to a single page, thus mitigating a lot of the antecedent issues contributing to total task or heads down time. This single menu page enables the pilot make quick, easy and accurate routine requests. In addition, the menu system visually and aurally alerts the pilot of new uplink data link messages and displays the number of active messages in the queue on each menu page. This method of alerting the pilot to a new message de-conflicts the use of the scratchpad as an ATC alerting area.

## Evaluation

### Method

**Simulation Facility.** A part task crew station was used to evaluate the CPDLC system. Each pilot had a ‘glass’ large screen Primary Flight Display (PFD) and shared Multi-Functional Display (MFD) and a center console with throttles, flaps, speed brake, gear handle, radios, and other controls to control the simulation. The simulation had an outside moving visual scene. The simulation was controlled with various parameters such as initial position, weather, pause and simulation acceleration factors.

The MCDU was simulated using a stand-alone Tablet PC computer which was networked with a desktop computer that simulated the ATC controller. The MCDU was mounted just adjacent to the throttle quadrant on the center console. As closely as possible, the reach envelope was approximately the reach required in a 737 series aircraft. The ATC station was a PC station located behind the cockpit station and oriented so that the ATC controller could view subject pilot actions with the MCDU. The ATC station was capable of sending and receiving datalink communications with the MCDU. Although data link communications shared the same MCDU as the Flight Management System (FMS), pilots were not required to modify the FMS route during the experiment.

**Scenario.** To evaluate the HMI, a simulated real time flight was planned from Albuquerque, NM to Phoenix, AZ. Subject pilots evaluated a prototype of the Honeywell CPDLC menu design under realistic flight conditions in a flight simulator. The test set-up as previously described included a part-task crew station and an ATC station for sending and receiving ATC messages. The scenario tested data link communications from approximately 10,000 ft. out of Albuquerque to approximately 10,000 ft. inside the Phoenix TRACON area as shown in Figure 2. This figure shows the different points in the experiment were complex data link communication exchanges are simulated.

**Experimental Design.** A within-subjects design was used for the study. All subjects completed the same scenario conditions. The experiment assessed (i) the CPDLC interface design; (ii) pilot errors and error recovery; (iii) pilot task completion data; (iv) pilot workload measures; and (v) unprompted pilot comments. Prior to designing the test scenario research questions were formulated based on the human factors issues identified so that scenario elements could be designed to elicit data around each research issue. The scenario played a fundamental role in ‘steering’ the pilot into situations or events that could be measured. However, the experiment design also needed to balance the need for data against introducing artificial workload factors (e.g. unrealistic communications or too many communications for that phase of flight). Subjects were provided with a training scenario to familiarize them with the simulator and CPDLC system operation. Pilots were furnished with Standard Operating Procedures and Checklist for the scenario.

**Subjects.** Four professional pilots were recruited for the study. The pilots had between 800 and 10000 total hours of flying experience (median = 2850 hours). The median age of the pilots was 44 years (range= 28-67 years). Participation in the study was voluntary and pilots were not paid. The experiment time ranged between 60 and 80 minutes.

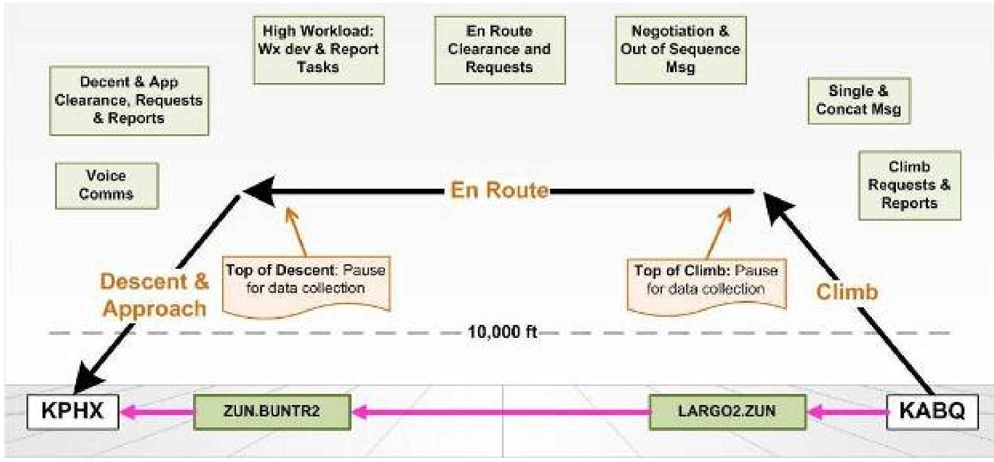


*Figure 2.* Simulation evaluation scenario flight profile.

## Results and Discussion

**Acceptability.** Subjective ratings by subject pilots confirm the overall acceptability and usability of the page format and page navigation scheme and logic. Three of four pilots rated the CPDLC system as GOOD (4 on a 5-point scale). The remaining pilot rated the CPDLC system as FAIR. Pilot comments also indicated that the CPDLC system will be highly acceptable to pilots. Pilots rated eleven interface usability attributes (for example comprehension, readability, clutter, page labels, message formats and navigation) of the menu design on a dichotomous scale (ACCEPTABLE/UNACCEPTABLE). There was a unanimous ACCEPTABLE rating for eight of eleven evaluation design attributes. Two UNACCEPTABLE ratings were due to specific issues identified by the pilots. These issues were: (i) data format for the "fuel remaining" parameter, and (2) meaning of "NEXT DATA AUTHORITY" downlink message. There was no consistently repeated design comment that was critical to the functionality or operational design of the CPDLC Menu system. Supporting pilot comments suggest that the system is usable and is acceptable to the representative group of users. Pilots also reported that the CPDLC menu structure and page formatting facilitated error detection and enabled pilots to recover from a majority of their errors.

**Errors.** Error rate percentages were calculated as the ratio of the number of errors of a particular category to the number of "opportunities for error" for the scenario. The overall error rate (mean error rate for all categories of error) was 8.7%. The highest category of error was missed altitude callouts (14%). This is because there was direct visual competition between the datalink and other visual monitoring tasks. The relatively high observed altitude missed call out error rate suggests that datalink communications may impact current crew procedures such as monitoring aircraft flight path, navigation or systems. This is most likely due to the amount of head's down visual attention commanded by the MCDU position which is exacerbated by increased task time caused by excessive search time and message complexity (number of required keystrokes).All non-callout errors were detected and corrected. Pilot recovery from all non-callout errors means that the CPDLC design adopted for the experiment was effective in helping pilots recover from errors.

**Workload.** Subject pilots were asked at specific points in the scenario to provide a workload rating number (instantaneous self-assessment) that best describes their workload on a five-point scale ranging from 1-VERY LOW to 5-VERY HIGH. Half scale units were acceptable (e.g. 2.5). Figure 3, is a plot of reported workload for each phase of flight: Climb, Enroute and Descent. Although the majority of workload ratings were LOW-MEDIUM (2-3 rating), all pilots during debriefing mentioned some loss of situation awareness during the flight. Pilots did not focus attention on navigation, flight path or out of the window view due to the visual attention required for the CPDLC tasks. Both the median and inter-quartile ranges for each phase of flight show that the workload ratings incremented during the flight. There is no statistically significant difference in workload ratings between the three phases of flight ($p$ = 0.24). The results of the self assessment workload ratings suggest that the there is no significant high workload effect on pilot workload as a result of using datalink.

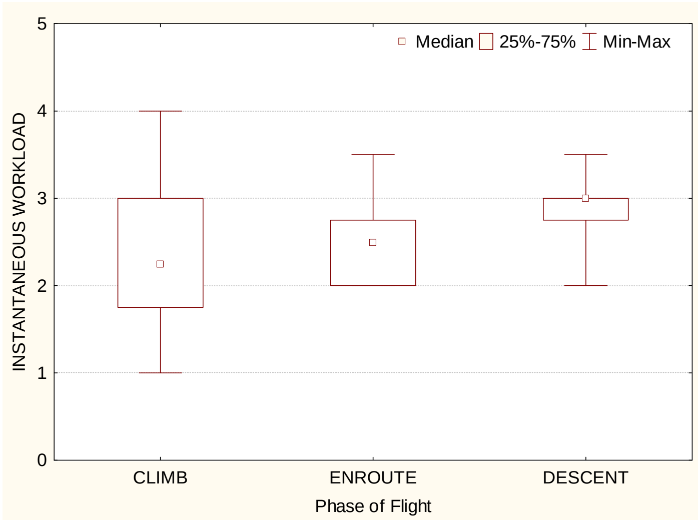


*Figure 3*. Box-Plot of subject pilot's impression of workload during Climb, Enroute and Descent.

**Pilot Transaction Times (Head Down Time).** The head down time for each phase of flight is an approximate percentage of visual attention the subject pilot focuses on the CPDLC menu system for both uplink and downlink messages. The percentage of time spent head-down for each phase of flight is calculated as the ratio of the cumulative sum of downlink and uplink message times for a phase of light to the total flight time for the phase of flight. The rationale for this calculation is that downlink and uplink message time give an approximation of the head down time on the MCDU. The percentage of head-down time for each phase of flight is shown in Figure 4. There is no statistically significant difference in head down time between the different phases of flight. The mean head down percentage time for all phases is 45% (range 30-76%). This represents the percentage of total flight time during which subject pilots allocated visual attention to the MCDU for CPDLC related tasks. For the scenario, pilots spent approximately 45% of the flight time visually focused on the MCDU. This leaves the remaining 55% of the time available for other required flight desk tasks.

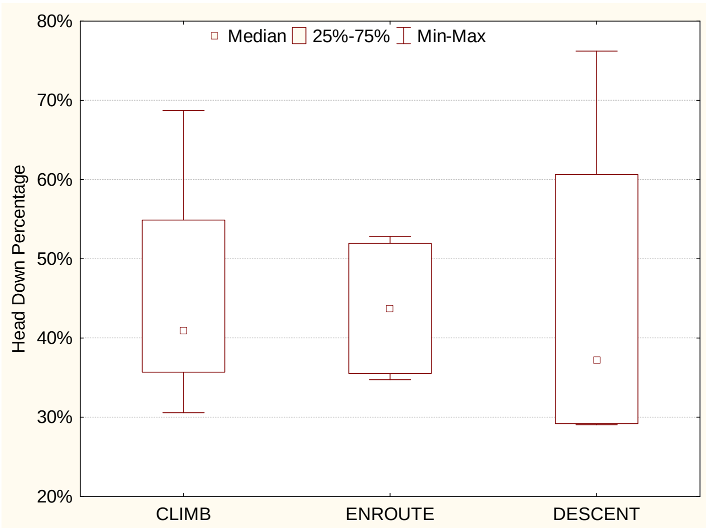


*Figure 4.* Box-Plot of calculated percentage of pilot head- own time for Climb, Enroute and Descent Flight phases.

## Conclusions

Subjective and objective measures from the evaluation suggest that using existing flight deck displays for data link operations is feasible.

- All four subject pilots thought that the operation of the CPDLC system was easy to learn and easy to operate. In general, the subject pilots rated the CPDLC interface and menu design features to be intuitive and of an acceptable good design. With the given design, all pilots thought that minimal training would be required.

- Low workload ratings suggest that pilots had spare cognitive capacity for other flight deck tasks when using the CPDLC display.

- Visual attention, measured by head down time, suggests that pilot situational awareness could be reduced by heads down data link tasks. This does not necessarily suggest a page format, or page navigation design issue. Rather, the head down time is more of a reflection of an MCDU based implementation that is located out of the pilot's primary field of view.

- Because of the competition for the visual channel, the pilots believed that CPDLC would take visual attention away from other tasks during critical phases of flight (i.e. altitudes below flight level (FL) 180 where pilots must practice SEE and AVOID). In the future, it is recommended that shortcut devices, better placement of CPDLC components, better alerting for incoming or open messages be investigated so that the operational use of CPDLC can be expanded into other flight phases.

- Because of visual focus required (head down time) the pace and frequency of transmitting ATC messages during different phases of flight should also be a consideration when developing CPDLC procedures and SOPs. Lengthy or complex communications or messages may require too much head down time during periods requiring visual attention elsewhere.

- Overall, a clear picture emerged that confirms that pilot performance with a single MCDU CPDLC system was acceptable and improved over time even under high workload conditions. The results support the Honeywell implementation of an MCDU based datalink communications system for the proposed use. Additional research on the mitigating effects associated with primary-field-of-view annunciation should be considered before determining appropriate critical phase-of-flight limitations.

**Acknowledgement**

The presented work was sponsored by the FAA under contract DTFAWA-10-A-80003. Findings contained herein are not necessarily those of the FAA.

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