INTEGRATING DATALINK AND COCKPIT DISPLAY TECHNOLOGIES INTO CURRENT AND FUTURE TAXI OPERATIONS

Becky L. Hooey, Monterey Technologies/NASA Ames Research Center, Moffett Field, CA
David C. Foyle, NASA Ames Research Center, Moffett Field, CA
Anthony D. Andre, and Bonny Parke, San Jose State University, San Jose, CA

Abstract

Two approaches for the implementation of a suite of cockpit navigation displays designed to increase the safety and efficiency of surface operations were developed and compared in NASA Ames' high-fidelity Advanced Concept Flight Simulator (ACFS). Eighteen airline crews completed fourteen low-visibility (RVR 1000') land-and-taxi scenarios at a simulated Chicago O'Hare airport. An *evolutionary* implementation approach integrated the new technologies into current operations. A *revolutionary* implementation approach proposed substantial changes to current operating procedures such as airborne, datalinked clearances. The impact of these implementation strategies on surface operations revealed that cockpit display technologies can provide substantial benefits for the efficiency and safety of surface operations, but further gains may be realized by revolutionary changes to current operations. This research highlights the importance of considering procedural and operational integration issues as part of a human-centered approach to cockpit technology design.

Introduction

Surface operations have been cited to be inefficient and prone to excessive radio frequency congestion that restricts pilots' ability to fully readback a clearance [1, 2] increasing opportunities for clearance misunderstandings and route conformance errors [2, 3]. Furthermore, in low-visibility and night operations, pilots can experience a loss of navigational awareness that leads to deviations from the cleared taxi route. In a high-fidelity simulation of low visibility and night taxi operations, pilots deviated from their cleared taxi route in 20% of taxi scenarios [4]. These communication and navigational concerns reduce both the safety and efficiency of surface operations. However, two cockpit technologies have been proposed that may improve both the efficiency and safety of surface operations: datalink and cockpit navigation displays.

Datalink

It has been suggested that datalink may be an effective means to reduce radio congestion and may reduce errors such as readback and hearback errors [2]. At the same time however, it is unclear what impact datalink will have on pilot procedures, and pilot-ATC communications during surface operations. For example, en-route studies have revealed that pilots are slower to respond to datalink than voice commands [5, 6]. This may have important implications for surface operations as dynamic route amendments, hold instructions, and expedited runway crossings are frequent. There exists resistance towards the use of datalink in the terminal area [5]. However, surprisingly, the impact of datalink on surface operations remains untested**.**

Taxiway-Navigation and Situation Awareness (T-NASA) Cockpit Displays

In order to increase pilots' navigational awareness, researchers at NASA Ames Research Center have developed a suite of cockpit displays called the Taxiway Navigation and Situation Awareness (T-NASA) system [7]. T-NASA makes use of a Differential Global Positioning Satellite (DGPS) system, surface radar, and datalink, to transmit the cleared taxi route to the cockpit graphically via a head-up display (HUD) and electronic moving map (EMM) (shown in Figure 1).

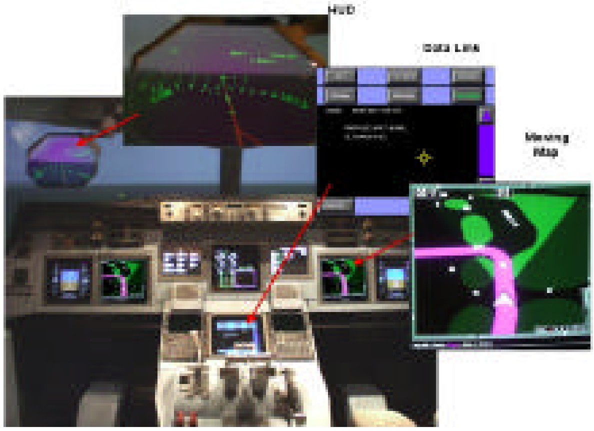

Figure 1. Cockpit Display Technologies

Past studies of T-NASA [4, 8] have provided evidence of increased taxi speed, reduced pilot deviations and improved hold short conformance. While increasing taxi speeds by 20%, pilot

Hooey, B. L., Foyle, D. C., Andre, A. D., and Parke, B. (2000). Integrating datalink and cockpit display technologies into current and future taxi operations. Proceedings of the AIAA/IEEE 19th Digital Avionics System Conference, 7.D.2-1 to 7.D.2-8.

deviations from the cleared taxi route were eliminated completely with the use of T-NASA [4]. Further, in current operations scenarios, 25% of the pilots stopped at an incorrect hold bar leaving their aircraft prone to a runway incursion. This was eliminated with the use of T-NASA.

Integrating the Technologies

Independently, both technologies show promise to increase the safety and efficiency of surface operations. However, the integration of any technology into the cockpit has the potential to introduce unanticipated human performance costs [9] that can compromise safety and even negate expected benefits. The success of these technologies depends greatly on the manner in which these technologies are implemented in the cockpit. Based on a series of formal focus groups that involved commercial pilots and air traffic controllers [10], two operational implementation approaches were developed for the deployment of datalink and T-NASA technologies. The two implementations differed in philosophy, with one taking an evolutionary approach, and the other a revolutionary approach.

Evolutionary Approach. In the evolutionary implementation, the technologies are added to current day operations and serve as a redundant source of information inside the cockpit. This approach allows the technologies to be integrated easily into near-term operations, and requires minimal procedural and equipment modifications. The focus group pilots and controllers [10] felt that an evolutionary approach would be necessary to phase in the technologies and overcome problems associated with mixed-equipped fleets, where some aircraft are communicating via datalink, and others via voice.

Revolutionary Approach. The revolutionary implementation promises greater efficiency benefits, but requires substantial modifications to current operations such as the sole use of datalink for all routine ATC-Pilot communications and the introduction of airborne taxi clearances. In a taxi simulation study it was found that 76% of navigation errors occurred during the initial phase of taxi when clearances were issued [3]. Providing airborne clearances would reduce workload at this bottleneck phase of flight and free the first officer to assist the captain in navigation and traffic awareness. We acknowledge this is futuristic and can only be successful if taxi clearances can be determined and issued in advance so as to not disrupt critical approach and landing procedures. This approach assumes that advanced technologies such as those being developed in NASA's Advanced Air Transportation Technologies (AATT) program will allow reliable predictions of aircraft touchdown times and automatically generate taxi routes to optimize efficiency and throughput.

Current Study

The current study set out to evaluate the use of datalink for surface operations as well as examine the use of T-NASA in a datalink environment. Further, this research will examine two approaches for implementing these technologies: Evolutionary and revolutionary. This research was intended to identify and address operational issues such as the modality and timing of the taxi clearance delivery in order to increase the likelihood that the safety and capacity benefits of datalink and taxiway navigation systems such as T-NASA might be achieved.

Method

Participants

Eighteen crews, consisting of one captain and one first officer from the same aircraft type and airline, participated in this high-fidelity simulation. Pilots represented six commercial airlines. All pilots were current on glass-equipped aircraft with a mean of 2645 hours logged. Five of the captains reported experience flying with HUDs, ranging from 5 to 2000 hrs.

Apparatus

The simulation was conducted in NASA Ames' high-fidelity Advanced Concept Flight Simulator (ACFS) which emulates a wide-body, T-Tail, low wing aircraft with twin turbofan engines. A Flight Safety International VITAL VIIIi image generator providing an 180-deg field of view with full cross-cockpit viewing capability generated the out-the-window view. Radio communication was provided by a confederate controller who served as both the local and ground controller. Also, a confederate pseudo-pilot represented the pilots of all other aircraft in the airspace and on the airport surface.

The flight deck, a configurable generic glass cockpit, contains advanced flight systems including touch sensitive electronic checklists and programmable flight displays. In addition, it was configured to accommodate the head-up display (HUD), the electronic moving map (EMM), and the datalink text display.

Head-Up Display (HUD). A Flight Dynamics HUD, consisting of a semi-transparent silvered glass combiner measuring 24 cm in height and 20.4 cm in width was installed over the left seat, as is standard in all U.S. HUD-equipped airlines. The HUD provided typical airborne and landing symbology [11]. Upon runway turnoff, the HUD displayed the T-NASA taxi symbology which utilized scene-linked symbology [7] overlaid upon the airport surface to display the cleared taxi route. The route was marked by a series of virtual cones located along both edges of the cleared taxiway and a series of squares that overlaid the centerline. Ground speed and a textual display intended to promote awareness of location on the airport surface were also displayed. The HUD supported ATC-issued hold short commands by depicting a virtual stop sign and hold bar that overlaid the hold short position on the taxiway. See [4, 7] for a more detailed description.

Electronic Moving Map (EMM). The EMM, on both pilots' navigation displays, presented navigation and traffic information in a head-down moving map format. If selected while airborne, the EMM presented a 'runway-up' view of the airport surface and depicted runway traffic and runway occupancy bars to highlight all occupied runways. Upon touchdown, the navigation display automatically switched to the EMM in a track-up, perspective view. The cleared taxi route was presented on the EMM as a highlighted magenta strip. The map also supported hold short directives by depicting a yellow, flashing hold bar for both ownship and traffic at the appropriate location as per ATC clearances. Real-time traffic icons depicted traffic located on the airport surface. See [7, 8] for a complete description of the EMM.

Datalink. A datalink interface, modeled after the B777 specifications [12], was added to the ACFS display suite. The arrival of a message was annunciated by an aural alert (datalink chime) and visual alert on the upper Engine Instrument Crew Alert System (EICAS). The text message appeared on the centrally-mounted lower EICAS. Both pilots were able to respond to the datalink message using response buttons mounted on the glareshield. The two response options were: 'Accept' to acknowledge the message and 'Reject' when unable to comply. Pilots were also able to view a log of all datalink messages.

Experimental Design

As shown in Table 1, each crew completed three blocks of trials: Current operations, future operations with datalink, and future operations with datalink and T-NASA. The future operations blocks included either the evolutionary implementation (Group 1) in which taxi clearances were issued by both voice and datalink after runway turnoff, or the revolutionary implementation (Group 2) in which ATC issued taxi instructions by datalink only while airborne. Within each experimental block, each crew completed three nominal trials that represented common taxi scenarios with hold shorts and route amendments. In addition, each block contained one trial that included an intentional clearance error designed to assess the impact of the technologies on ATC-Pilot communications. The presentation order of blocks was assigned using a Latin Square design, and the order of trials within each block was randomized with constraints.

Procedure

Each crew received an instructional package in advance, and viewed a training presentation that provided information about the simulator, and introduced the new operations and technologies being tested. Each crew also completed a 90-min cockpit training session that included an overview of the simulator controls and displays and three land and taxi attempts without the new display technologies. The technologies were introduced incrementally, and crews were provided with training and practice time with each technology.

Each trial began approximately 12 nautical miles (nmi) out on a level approach into Chicago O'Hare airport. Pilots performed an autoland, and taxied to the gate in RVR 1000' conditions. Prior to each scenario, the runway and gate destination were provided. While airborne, pilots received a clearance to land and a preferred runway exit from ATC. Pilots were encouraged to take the preferred exit when safe, but it was emphasized that pilots could refuse the exit and select another if they felt the preferred exit was unsafe.

All crews received current operations trials, and either the evolutionary implementation or the revolutionary implementation (see Figure 2). In the current operations scenarios, which were the same

Table 1. Experimental Design

Group 1	**CURRENT OPERATIONS**	**FUTURE: EVOLUTIONARY IMPLEMENTATION**	
	Voice, Jeppesen Chart	Datalink complements voice. Clearances issued on ground	
	Taxi Clearance on ground	DATALINK	DATALINK + T-NASA
	3 nominal + 1 clearance error trial	3 nominal + 1 clearance error trial	3 nominal + 1 clearance error trial
Group 2	**CURRENT OPERATIONS**	**FUTURE: REVOLUTIONARY IMPLEMENTATION**	
	Voice, Jeppesen Chart	Datalink replaces voice. Clearances issued while airborne	
	Taxi Clearance on ground	DATALINK	DATALINK + T-NASA
	3 nominal + 1 clearance error trial	3 nominal + 1 clearance error trial	3 nominal + 1 clearance error trial

for both groups of subjects, pilots received all ATC communications via radio. While airborne, they received a clearance to land followed by a preferred runway exit. After exiting the runway, pilots were expected to switch to ground frequency and contact ground control for their verbal taxi clearance. Pilots were provided with standard Jeppesen charts for navigation.

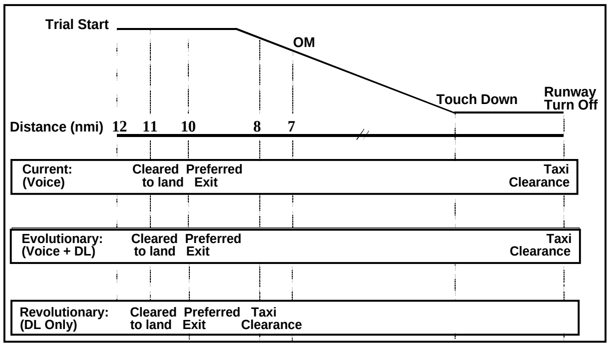

Figure 2. Operational Implementations

In the evolutionary implementation trials, pilots received all ATC communications by both radio and datalink, including the clearance to land, preferred exit, and taxi clearance. For airborne communications (cleared to land and preferred exit), the datalink was transmitted to the crew immediately preceding the ATC voice message. For taxi clearances, the datalink message was transmitted as the aircraft exited the runway, but they did not receive the clearance by voice until they requested it from ATC. When T-NASA was available, the taxi route was shown graphically in pending form on the EMM and HUD simultaneous with the datalink transmission. On the EMM, the pending route was shown as white and flashing. On the HUD, the sides of the cleared taxiway were represented by a series of X's. Once pilots accepted the route via datalink, the EMM updated to show a solid magenta route and the HUD X's converted to cones.

In the revolutionary implementation, pilots received all ATC communications via datalink only. Voice communication was used only for non-routine circumstances that couldn't be resolved via datalink. Crews received a clearance to land, preferred exit, and taxi clearance while airborne, all before the outer marker. The datalink transmission was timed to allow pilots to respond and return their attention to landing the aircraft. After landing and exiting the runway, pilots continued taxiing to the gate and required no further contact with ATC. On trials where T-NASA was available, the EMM showed the pending route (white and flashing), that changed to solid magenta once the pilot accepted the datalinked clearance. While airborne, only flight-relevant information was presented in the HUD, but the symbology automatically transitioned to show the cleared taxi route at runway turnoff.

Upon completion of the experimental trials, both crew members completed a questionnaire and participated in a final semi-structured debrief session that solicited further information regarding their experiences in the simulator and the operational implementations.

Results

A wealth of data was collected throughout this high-fidelity simulation, however, this report will focus only on a subset of the data. First, the impact of the cockpit displays on taxi performance (speed and navigation errors) will be presented followed by data that illustrate the differences between the two implementation styles. The implementation approach had substantial impact on operational efficiency, communication efficiency, and the quality of communications. Except where stated, the analyses that follow summarize the data from the three nominal trials per experimental block. Where appropriate, means are plotted with plus and minus one standard error. All dependent variables were subject to a 2 (implementation style group) X 3 (technology) mixed-design analysis of variance (ANOVA). Planned comparisons were conducted using t-tests. Recall that the two implementation style groups differ only in the implementation of future operations. Current operations conditions serve as a baseline measure, and were identical for both groups.

Effect of Cockpit Technologies

Taxi Speed

The T-NASA displays increased taxi speed by approximately 16% from 13.9 kts in current operations to 16.1 kts, $F(2,24)=12.77$, $p<.0001$. This increase replicates findings from previous T-NASA simulation and field research [4, 8]. Not surprisingly, datalink had little effect on taxi speed, increasing speed only slightly to 14.5 kts, $p>.05$.

Navigation Errors

A navigation error was defined as deviating from the cleared route by failing to turn or turning incorrectly. In current operation trials, pilots committed an off-route error in 22% of the trials. With the presence of T-NASA, off-route navigation errors were eliminated completely, replicating previous findings [4]. The effect of datalink on navigation performance has not been previously tested. With datalink, navigation errors occurred on 13% of trials, which was not significantly less than current operation scenarios, $p>.05$.

Comparison of Implementation Approaches

Operational Efficiency

Operational efficiency was affected by the implementation approach in two ways. First, the two approaches differed in their effect on taxi efficiency at the typical bottleneck phase of taxi, immediately after runway turnoff. Second, the approaches differed in the efficiency of executing dynamic mid-route amendment instructions.

Initial Taxi Efficiency. Two measures were examined: Initial taxi speed, averaged over a 60-sec window starting at runway exit, and time stopped after runway exit. The effect of the technologies on initial taxi speed differed as a function of the implementation style, F(2,24)=6.14, *p*=.000 (see Figure 3). Adding datalink and datalink + T-NASA to current operations in an evolutionary manner had no effect on taxi speeds after runway exit, *p*>.05, however datalink + T-NASA provided a significant speed increase over datalink alone, t(8)=2.29, *p*<.05. Taxi speed at runway exit was significantly higher in the revolutionary implementation than current operations with both datalink, t(8)=9.88, *p*=.000, and the datalink + T-NASA combination, t(8)=5.95, *p*=.000.

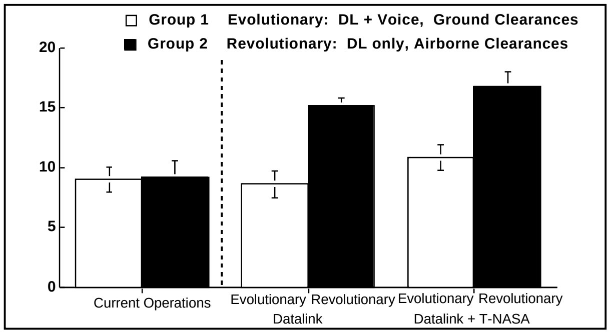

Figure 3. Average Taxi Speed (60 sec Window After Runway Turnoff)

The time spent stopped after runway turnoff (not graphed) represents the time required to receive and comprehend the clearance and determine the direction and location of the first turn. The effect of technology on time stopped differed as a function of implementation style, F(2,24)=4.63, *p*=.020. In the evolutionary implementation, time stopped did not differ significantly among the current operations (M=11.18), datalink (M=13.42), and datalink + T-NASA (M=8.50) conditions, *p*>.05. However, compared to current operations, the time stopped was significantly reduced in the revolutionary implementation that transmitted taxi clearances while airborne via datalink (M=1.73), t(8)=3.0, *p*=.017, and datalink + T–NASA (M=.02), t(8)=3.51, *p*=.008. The latter virtually eliminated the time stopped after clearing the runway observed in current operations (M=8.5). Airborne taxi clearances eliminated the traditional bottleneck associated with communicating taxi clearances after the runway exit, increasing both efficiency and safety by clearing traffic away from active runways.

Mid-Route Efficiency. The ability to use datalink for dynamic mid-route modifications was also assessed. In each experimental block, crews received one hold short clearance, followed by a proceed instruction once the traffic passed. As can be seen in Figure 4, the time required to initiate forward movement after the proceed instruction differed as a function of both technology and implementation style, F(2,32)=3.42, *p*=.045.

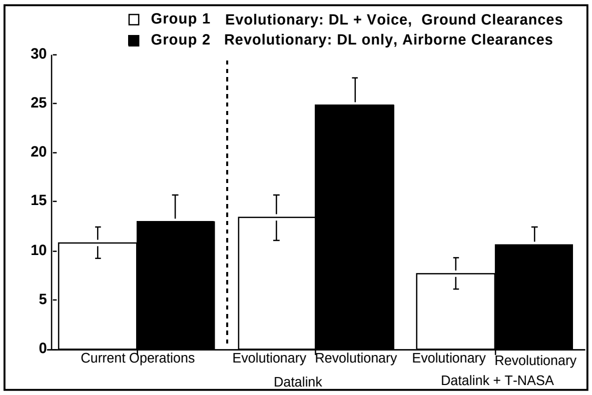

Figure 4. Time to Initiate Forward Movement After ATC Clearance is Issued

In the evolutionary implementation, where the datalink accompanied the voice message, there was little effect of datalink or T-NASA on the time to initiate forward movement over the current operations, *p*>.05, though the time was significantly longer with datalink than the datalink + T-NASA combination, t(8)=2.93, *p*=.019. In the revolutionary implementation, however, the time to initiate forward movement was significantly longer when the instruction was presented via datalink alone versus current voice communications, t(8)=3.02, *p*=.017. This is consistent with datalink research in other phases of flight [5, 6]. This excess delay was mitigated however, by coupling datalink instructions with the T-NASA displays. The time to initiate forward movement in the datalink + T-NASA condition was significantly lower than datalink alone, t(8)=4.89, *p*=.001, but not significantly different than current day operations, t(8)=.64, *p*=.542. This suggests that issuing route amendments via text datalink only may be problematic, especially for safety-critical ‘expedite’ clearances.

Communication Efficiency

One concern with current operations is that radio frequencies are congested preventing full readbacks and hindering effective communications between pilots and ATC [1, 2, 3]. Both the number of radio calls made by the flight deck to ATC, as well as the duration of radio frequency usage throughout a trial were investigated. The number of crew radio transmissions is graphed in Figure 5.

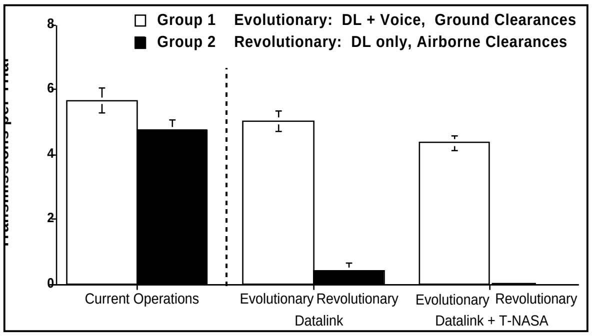

Figure 5. Number of Crew Radio Transmissions

The effect of technologies differed by implementation style for both the frequency of use, F(2,32)=19.63, *p*=.000, (Figure 5) and the duration of use, F(2,32)=46.31, *p*=.000 (not graphed). In the evolutionary implementation, where datalink was added to voice communications, datalink did not reduce the number of radio transmissions (M=5.04) from that required in current operations (M=5.67), t(8)=1.22, *p*=.257, however the datalink + T-NASA combination did (M=4.37), t(8)=2.72, *p*=.026. Presumably, T-NASA's graphical depiction of the taxi route and traffic reduced the number of navigation and traffic-related inquires that pilots made to ATC. Even though the number of transmissions was reduced, neither set of technologies, datalink nor datalink + T-NASA, significantly reduced the duration of radio frequency usage, *p*>.05, when implemented in the evolutionary manner. In the revolutionary implementation, datalink and the datalink + T-NASA combination were equally effective at reducing both radio frequency use (Figure 5) and duration of use, virtually eliminating radio use all together. In the revolutionary implementation, the frequency of radio use was significantly lower than current operations with both datalink, t(8)=13.02, *p*=.000 and datalink + T-NASA, t(8)=15.7, *p*=.000. The datalink and datalink + T-NASA conditions did not differ in the revolutionary implementation for either variable.

Pilots rated the efficiency of communications with ATC in a post-experiment questionnaire on a scale from 1 (low) to 5 (high). Ratings did not differ as a function of implementation, but efficiency was rated higher with datalink + T-NASA (M=4.55), than datalink (M=4.00), and current operations (M=3.12), F(2,58)=21.03, *p*=.000. Pilots perceived communications with ATC to be more efficient with the use of the technologies. Also, pilots were asked to rate the efficiency of communications between pilots. T-NASA was rated higher (M=4.52) than datalink alone (M=3.88), and current operations (M=3.76), F(2,62)=9.36, *p*=.000. Datalink alone did not improve rated communication efficiency between crew members over current operations, t(32)=.68, *p*=.50.

Communication Quality

A reduction in radio usage may represent an improvement in ATC-Pilot communications, however this is not necessarily the case. An examination of the quality of communications is also warranted.

Clearance Error. The quality of communication was observed in one trial per experimental block in which the clearance contained an intentional error. The clearance was internally inconsistent, leading pilots to an incorrect destination. An example of the clearance that was either datalinked or presented by voice is shown below. The EMM depiction also led pilots to the incorrect concourse.

NASA 227:
Taxi to Concourse G via Alpha, Bravo, Concourse E

A liberal criterion was applied, such that any crew that formally rejected the clearance, queried ATC, or discussed it within the cockpit, was considered to have caught the error. Regardless of error detection, the clearance was amended by ATC 45 sec after the issuance and the discrepancy rectified. Figure 6 shows the percentage of crews that erroneously accepted the clearance. Two patterns of results are of interest. First, errors were almost universally undetected when issued airborne via datalink and second, the technologies, datalink and T-NASA, did not improve error detection.

Two explanations are plausible for the low error detection rate of the airborne datalink clearances. First, although pilots accepted the clearance, it is likely that they deferred serious scrutiny and cross-checking until on the ground due to the high workload demands of final approach. Still, 63% of the pilots reported that if issued before the outer-marker they would prefer airborne clearances over ground clearances. They cited the ability to plan landing and roll-out procedures, smoother braking, and taxi route preview and planning as large advantages of airborne clearances. An alternative explanation for the low error detection rate is that the airborne clearances were issued by datalink only. It is possible that the absence of a spoken clearance may have reduced pilots' ability to detect errors. Without the requirement to write the clearance and repeat it back to ATC, the information may not have been fully processed. Not writing and reading back the clearance is a frequently cited cause of clearance confusion and errors under current operations [1, 2], but may be even more prevalent with datalink.

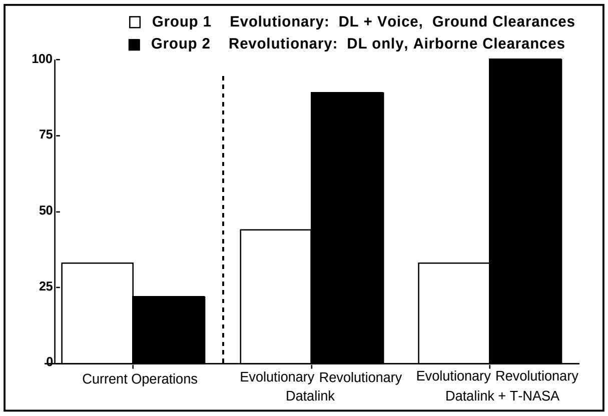

Figure 6. Clearance Error Detection

It might be expected that the technologies would improve error detection. However, this was not the case in either implementation. It may be that the important elements of error checking are hearing, writing, and repeating back the clearance, and that the additional visual information does not help, or may even induce complacency or unwarranted trust. Evidence for this over trust in technology can be seen in the questionnaire data. On a scale from 1(low) to 5(high), pilots rated their perceived trust in the accuracy of the taxi clearance for each transmission method. Despite that the clearance was incorrect once in each condition, the trust rating for T-NASA (M=4.59), was significantly higher than for datalink (M=4.18) which was higher than voice (M=3.65), F(2,62)=12.81, *p*=.000. Pilots also rated which transmission method was most effective for issuing route clearances. Datalink + T-NASA was chosen by 82.5% of the pilots and the remaining 17.5% chose datalink. When asked which was most effective for detecting errors in the clearance, 62% chose datalink + T-NASA, 32% chose datalink, and only 6% chose voice. These data suggest a discrepancy between pilot preference and performance. Pilots prefer the technology aids for taxi clearances, however performance was not enhanced by them.

Hold Short Conformance. There was one instance of a busted hold that occurred in the revolutionary - datalink only condition. When the crew crossed the hold bar, the hold short text clearance was displayed in the datalink display. While only one data point cannot indicate the nature of the problem, two possibilities merit investigation. Datalink may be processed superficially by pilots because they do not hear it, write it, and repeat it back to ATC. This may be an indication of potential dangers associated with issuing hold commands via datalink only. Alternatively, because the clearance was received while airborne, the pilots may have forgotten about the hold instruction by the time they reached the hold. The likelihood of forgetting increases as a pilot’s attention is distracted by ATC and other duties [6]. These data suggest that the quality of communications, and the way that pilots process and use information, may be degraded when ATC information is transmitted airborne via datalink.

Summary of Results

Table 2 summarizes the effect of the technologies in each implementation approach as compared to current operations. When implemented in the evolutionary approach, the technologies provided little benefit over current operations. In fact, the only benefit observed was a slight reduction in the number of radio transmissions when both datalink and T-NASA were deployed. However, implementing the same technologies in the revolutionary approach produced many clear advantages over current operations including increased taxi efficiency, reduced radio transmissions, and reduced duration of radio use. At the same time, the revolutionary approach also indicated possible problem areas where careful attention is required to ensure safety is not endangered. Specifically, the quality of ATC-Pilot communications may be negatively impacted by transmitting ATC instructions via datalink only. In the present study this manifested as reduced operational efficiency during mid-route amendments, reduced error detection, and a busted hold clearance. Further investigations are required to better understand other possible manifestations of this reduced quality of ATC-Pilot communications.

Table 2. Comparison of Implementation Approaches: Summary of Performance Data

Dependent Variable	**Evolutionary**		**Revolutionary**	
	Datalink	Datalink + T-NASA	Datalink	Datalink + T-NASA
Initial Taxi Efficiency	O	O	+	+
Mid-route Taxi Efficiency	O	O	-	O
Number of Radio Transmissions	O	+	+	+
Duration of Radio Transmissions	O	O	+	+
Clearance Error Detection	O	O	-	-
Hold Short Conformance	O	O	?	O

(+)Better than current ops; (-)Worse than current ops; (O)Not different than current ops; (?) Requires further investigation

Conclusions

The use of datalink coupled with T-NASA shows great promise to increase both the efficiency and safety of surface operations. It has been shown here, and in past studies [4, 8], that these display technologies can increase taxi speeds while simultaneously eliminating navigation errors. If carefully implemented, these benefits may be extended to include increased operational efficiency at runway exit and during taxi operations, increased communication efficiency, and reduced radio frequency congestion.

These results also highlight the importance of researching not only technology solutions, but the manner in which they are implemented. If datalink and T-NASA are implemented in what may seem to be a logical sequential order, or in the manner that is most feasible (i.e., adding datalink to current operations and later T-NASA as airlines acquire the necessary equipment) some important benefits may be lost. For example, this evolutionary implementation approach would do little to increase the efficiency of communicating taxi clearances at runway turnoff, and would have little impact on radio frequency congestion.

Also, from this implementation comparison, we have identified procedural issues that must be addressed in order to ensure the successful integration of these technologies. Concerns about cognitive processing of datalink messages, and slowed response time to datalink messages were identified. These may be addressed through modifications to technology (i.e., timely reminders could be datalinked when the pilot nears the hold location and datalink messages could express the degree of urgency), or through training and procedural changes (i.e., pilots could implement procedures to ensure adequate processing and crew communication of datalinked messages).

It is important that the design of cockpit technologies follows a human-centered approach [9]. It is not sufficient to merely ensure that the display elements adhere to good human factors design principles without considering the impact of the technology on the pilots, ATC, and the entire aviation system. As was seen in these results, the procedural integration of these cockpit display technologies is equally as important as the design of the displays themselves. Without consideration of the procedural integration, the designers' intended benefits may be lost, and may be replaced with unintentional costs to human performance.

ACKNOWLEDGEMENTS

We gratefully acknowledge George Lawton, Raytheon Systems, Co., for developing the scenario generating environment and data processing software that created unprecedented capabilities in NASA Ames' ACFS facility. We also acknowledge Kevin Purcell and Susan Dowell, San Jose State University, for assistance in scenario programming and data collection, and the staff of NASA's ACFS facility for their support of this research. Finally, we are grateful to the commercial airline pilots who devoted their time and expertise.

REFERENCES

[1] Kelley, D. R., & Adam, G. L. (1997). The human factors of runway incursions caused by "pilot error": A survey of U.S. airline pilots. In R. S. Jensen and L. A. Rakovan (Eds.), *Proceedings of the Ninth International Symposium on Aviation Psychology*, 911-917. Columbus, OH: Ohio State University.

[2] Burki-Cohen, J. (1995). *An analysis of tower (ground) controller-pilot voice communications.* DOT/FAA/AR-96/19.

[3] Parke, B., Kanki, B., McCann, R. S., & Hooey, B. L. (1999). The effects of advanced navigation aids on crew roles and communication in ground taxi. In R. S. Jensen, B. Cox, J. D. Callister, & R. Lavis (Eds.), *Proceedings of the Tenth Symposium on Aviation Psychology,* 804-809. Columbus, Ohio: Ohio State University.

[4] McCann, R. S., Hooey, B. L., Parke, B., Foyle, D. C., Andre, A. D. & Kanki, B. (1998). An evaluation of the Taxiway Navigation and Situation Awareness (T-NASA) system in high-fidelity simulation. *SAE Transactions: Journal of Aerospace, 107*, 1612-1625.

[5] Kerns, K. (1990). *Data link communication between controllers and pilots: A review and synthesis of the simulation literature*. (MP-90W00027). The MITRE Corporation.

[6] Mackintosh, M., Lozito, S., McGann, A., & Logsdon, E. (1999). Designing procedures for controller-pilot datalink communication: Effects of textual datalink on information transfer. *Proceedings of the SAE World Aviation Congress*. (Paper Number 1999-01-5507), San Francisco, CA.

[7] Foyle, D. C., Andre, A. D., McCann, R. S., Wenzel, E., Begault, D. & Battiste, V. (1996). Taxiway Navigation and Situation Awareness (T-NASA) System: Problem, design philosophy and description of an integrated display suite for low-visibility airport surface operations. *SAE Transactions: Journal of Aerospace, 105*, 1411-1418.

[8] Andre, A. D., Hooey, B. L., Foyle, D. C. & McCann, R. S. (1998). Field evaluation of T-NASA: Taxiway navigation and situation awareness system. *Proceedings of the AIAA/IEEE/ SAE 17th Digital Avionics System Conference,* 47:1 - 47:8.

[9] Wickens, C. D., Mavor, A. S., & McGee, J. P. (Eds.). (1997). *Flight to the future: Human factors in air traffic control.* Washington D.C.: National Academy Press.

[10] Hooey, B. L., Schwirzke, M. F. J., McCauley, M. E., Renfroe, D., Purcell, K., & Andre, A. D. (1999). Issues in the procedural implementation of low-visibility landing and surface operation displays. In R. S. Jensen, B. Cox, J. D. Callister, & R. Lavis (Eds.), *Proceedings of the Tenth Symposium on Aviation Psychology*, 797-803. Columbus, Ohio: Ohio State University.

[11] Weintraub, D. J., & Ensing, M. (1992). *Human factors issues in head-up display design: The book of HUD* (SOAR 92-2). Dayton, OH: CSERIAC.

[12] Boeing Commercial Airplane Company (August, 1997). *Boeing 777 operations manual* (Chapter 5, Section 40). Seattle, Washington.