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The Effects of Advanced Navigation Aids and Different ATC Environments on Task-Management and Communication in Low Visibility Landing and Taxi

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ABSTRACT

The Taxiway Navigation and Situation Awareness (T-NASA) system of surface navigation aids have been shown to increase taxi speeds, almost eliminate taxi navigation errors, increase pilots' situational awareness, decrease pilot workload, and increase traffic awareness [1, 2, 3]. In this paper, we investigate how these aids affect task management and crew procedures in different Air Traffic Control (ATC) environments—datalink and datalink redundant with voice. We also examine the impact of these different ATC environments on task management and crew procedures without the T-NASA system. We find that although both types of datalink have benefits, there are also problems associated with them. In addition to the previously described advantages of the T-NASA system, we find that it alleviates many datalink problems.

INTRODUCTION

Two current problems at airports are (1) difficulty in getting the taxi clearance quickly and accurately due to radio frequency congestion, and (2) navigating the airport surface safely once the clearance has been received—especially in low visibility conditions. Findings from a recent simulation suggest that crew distraction with taxi clearance delivery immediately after runway turn-off may be a major cause of navigation errors [2]. The increasing rate of runway incursions gives special impetus to finding solutions to both problems. T-NASA navigation technologies have addressed these problems, but it is unclear how they interact with other solutions, namely, changes to the current ATC system to deliver clearances via datalink, both with and without voice. A simulation was designed to investigate these issues.

ATC Environments and T-NASA Navigation Aids. The effect of navigation aids on landing and taxiing was studied in three ATC environments: voice (current operations), datalink redundant with voice (mixed ATC), and datalink without voice (advanced ATC). Also, in the advanced ATC environment, the taxi clearance was given in the air instead of after turn-off. The navigation aids in the air were head up displays (HUDs) for the captains, with guidance for landing and for Roll Out and Turn Off (ROTO). In addition, both pilots had access to their own electronic moving maps (EMMs) of the airport surface. In the air, the pilots could access their EMMs by toggling their nav display, and could then view a track-up overview of the airport showing their highlighted runway, turn-off, and cleared taxi route. At weight-on-wheels the nav display was automatically replaced by the EMM and showed a track-up airport map with the cleared route in magenta (see refs. 3 & 4 for a complete description).

After turn-off, the landing and exit guidance in the captain's HUD made a seamless transition to taxi surface guidance, with cones marking both sides of a cleared route and X's marking the sides of an uncleared route. Corresponding symbology for the EMM was a magenta path for a cleared route and a white flashing path for an uncleared route. Both the EMM and HUD had hold short symbology—a flashing line for the EMM, and X's and a stop sign for the HUD. Traffic was shown on the EMM but not the HUD. Audio alerts were heard when the aircraft was off route and when traffic was too close.

Datalink. The arrival of a datalink message was annunciated by a chime and a visual alert on the upper Engine Instrument Crew Alerting System (EICAS). The message itself, when accessed, appeared on the lower EICAS between the two crew members, and the pilots could view a log of all messages. The pilots could either "Accept" or "Reject" the message by pressing buttons on the glare shield.[1]

[1] In the pre-simulation mixed trials, it worked best if the arrival of the datalink clearances preceded the voice clearance by several seconds. This allowed the FO to access the datalink clearance and then to follow along while the

Simulation. The simulation took place in a high fidelity simulator resembling a B757/B767 with a generic glass cockpit. Eighteen professional air carrier crews landed and taxied nine trials each in a simulated O'Hare airport in RVR 1000 feet. Nine of the crews were called "mixed" crews and had three trials in current ops, three trials in a mixed ATC environment (datalink and voice), and three trials in a mixed ATC environment with the T-NASA navigation aids (henceforth called nav aids). The other nine crews were called "advanced" crews and had three trials in current ops, three trials in advanced ATC (datalink no voice) and three trials in advanced ATC with the nav aids. In addition, the advanced crews had the taxi clearance delivered in the air.

Each trial began at 12 mile final where the crews were given a landing clearance and a preferred turn off of the landing runway so that once on the ground, the trials would be comparable. Captains (CAs) were the pilots flying (PFs); all landed with autoland.

METHOD

The following methods were used to ascertain crew roles, procedures, and communications. 1) An expert jumpseat observer noted use of procedures and errors, and also rated crews on situational awareness (SA), work load, and crew resource management (CRM) variables after every trial. 2) Crew communication was coded online with a field coding method which has shown to be reliable in previous work [2]. 3) Video tapes were reviewed and procedures were coded in more detail. Inter-rater reliability on procedures coded from the video tape was 86% using a point-by-point agreement method. 4) Crew feedback was obtained through extensive debriefings.

RESULTS AND DISCUSSION

Writing, Understanding, and Accepting Clearances

Datalink Reduced Writing Down Clearances. Datalink for both mixed and advanced crews reduced the number of trials in which the FOs wrote down the preferred exit, taxi clearance after turn-off, and amended route clearances. When the taxi clearance was delivered after turn-off for the mixed crews, the FOs wrote the clearance in 100% (27/27) of the current ops trials, in 22% (6/27) of the datalink trials, and in only 11% (3/27) of the datalink trials with the nav aids, Pearson Chi Square (df 2)= 51.3, p<.001. All of the crews received an amended route clearance in one third of their trials, enabling us to compare all conditions. The FOs in the mixed crews wrote this clearance down in 100% (9/9) of the current ops trials, 44% (4/9) of the datalink trials, and 11% (1/9) of the datalink trials with the nav aids. The FOs in the advanced crews wrote down the amended route in 100% (9/9) of the current ops trials, in none (0/9) of the datalink trials, and in none (0/9) of the datalink trials with the nav aids (Pearson Chi Square, df 5, = 41.3, p <.001). Hence datalink eliminated the FOs writing the clearances when there was no voice component.

Datalink Helped the Crews to Understand the Taxi Clearance the First Time. When the taxi clearance was delivered after turn-off for mixed crews, datalink reduced additional contact with ATC at this juncture from 33% (9/27) in current ops to 13% (7/54) with datalink, Pearson Chi Square (df 1) = 4.7, p <.05. (Adding the nav aids provided no additional reduction.) What did this further contact consist of? In current ops, the FO asked ATC questions in 19% (5/27) of the trials and ATC corrected the FOs readback in 15% (4/27) of the trials. When datalink was added, the FO asked further questions in only 4% (2/54) of the trials, and ATC corrected the FOs readback in only 9% (5/54) of the trials.

Datalink Vulnerabilities

Datalink Procedures. Five vulnerability points have been described in receiving datalink transmissions [5]. Crew behavior at three of these vulnerability points is presented here.

(1) There was a low rate of verbalizing the arrival of the datalink messages. In the simulation, there were 396 datalink messages. The arrival of these messages in the cockpit was verbalized by at least one of the crew members, either partially or fully, only 30% (116/393) of the time. This rate is similar to the rate found in other studies [5].

(2) The datalink taxi clearance in the air was not always read fully. In the conditions with voice and datalink, all clearances were repeated twice, once by the controller and once by the FO. In the advanced datalink trials without the nav aids, where reading the clearance aloud is important, the shorter critical clearances in the air (landing and exit) were always verbalized by the FO. However, the contents of the taxi clearance were not fully verbalized in the air in this condition almost half of the time (45%). This was due to the timing of the datalink taxi clearance, which

controller was reading it and to compare the voice with the datalink. The FO then gave the readback from the datalink clearance. Datalink taxi clearances in the mixed trials were delivered at turn-off, and the FO could call ATC when ready for the voice clearance, as is customary.

was about 10 seconds after glide slope capture and about 50 seconds before final approach fix, when many crews were busy configuring the aircraft for landing.[2] This timing of the datalink taxi clearance in the air allowed for a study of possible negative consequences and of the procedures and techniques which reduced them. One negative consequence was that the crews did not catch the taxi clearance errors (mismatched concourses purposely put into additional trials) when the taxi clearance was delivered in the air instead of on the ground [see 3].

If not in the air, when did these crews verbalize the taxi clearance fully? In only one trial (out of 27) did the FO do so after turn-off in the advanced datalink trials. In the other 26 trials, the FO instead used the datalink to give progressive taxi instructions. This meant that there could be hold short errors if, in fact, the hold shorts were written at the end of the taxi clearance, as they were in this simulation.[3]

(3) The FOs verbalized pushing the accept button only 29% (113/393) of the time. This may have contributed to the high rate of forgetting to push it (accept it) especially on the ground. In the air, two FOs forgot to accept the preferred exit clearances for several minutes in mixed datalink only trials. One FO forgot to accept the taxi clearance in the air in a datalink only trial, and discovered this at turn-off.[4]

On the ground, the FOs forgot to push the accept button in 26% (7/27) of the taxi clearances in the mixed datalink only trials. (None, 0/27, did so in the mixed trials with the nav aids, Pearson Chi Square, df 1 = 8.4, $p < .01$.) Further, the FOs forgot to accept 28% (5/18) of the hold short releases in the mixed and advanced datalink only trials, and 22% (4/18) of the amended routes in these conditions. Although in the mixed trials, these clearances were accepted verbally, the rate of forgetting in the advanced trials was about the same (22%, 4/18). This rate is high, and would impact ATC operations. The graphics depicting a pending route on the HUD and EMM were salient but unobtrusive reminders which prevented the crew from forgetting to accept the clearances.

Datalink Transactions

Who Accepted the Clearances and Related Consequences. Having datalink in the cockpit changes who makes the decision to accept the clearances. For example, the PF (CA, in this case) made the decision regarding the preferred exit clearance in 19% (10/54) of the current ops trials, in 52% (28/54) of the mixed datalink trials), and in 93% (50/54) of the advanced datalink trials (Pearson Chi Square, df 2, 59.9, $p<.001$). Typically, it is the pilot-not-flying (PNF) who handles the radio communication, and who therefore accepts the clearances verbally in current ops, and, in this study, frequently did so without input from the PF. When a datalink message arrives *without* voice, however, the PNF generally reads it, and then waits for the PF to decide to accept or reject it. The conversation is no longer one between the PNF and the controller; it is now one between the crew members. In this conversation, it is frequently the case that the clearance will be discussed more in the datalink only conditions than in the verbal conditions, especially without the promise of the guidance technologies on the ground. Having to push an accept or reject button instead of quickly answering ATC verbally also adds a formality and an element of decision into the process that engenders discussion. This adds to the verbal workload as well as to the time it takes to accept the clearance. An example is the preferred exit, where 56% (15/27) of the crews discuss the exit in the advanced datalink only trials and 26% (7/27) in the mixed datalink only trials, Pearson Chi Square (df 1) = 4.9, $p<.05$. One therefore can't necessarily expect a shorter clearance transaction time for a datalink clearance in the advanced ATC trials simply because there is only one clearance to accept instead of the two (voice and datalink) in the mixed ATC trials.

Clearance Transactions Took Longer In Both Datalink Environments than in Current Ops; The Navigation Aids Reduced This Increased Time. Efficient operations in the terminal area depends on the length of ATC transactions. Considering *both* the mixed and advanced crews, and excluding those trials in which the crews forgot to push the accept button, the mean lengths of ATC transactions[5] for the hold short release were: 10.4, 16.8, and 12.8 seconds respectively for current ops, datalink only, and datalink + nav aids trials; MS(Cond) =33.6, $F(2,27)$, = 5.0, $p = .03$ (datalink different from current ops at $p < .01$ and datalink + nav

[2] The goal in IFR is to have the plane completely configured for landing at the final approach fix or outer marker in this case (1500 ft). Many pilots are still configuring for landing just before then (gear, final flaps, & final descent check list).

[3] The one hold short error in this simulation was, in fact, due to the taxi clearance being only partially read in the air and read progressively on the ground as the crew taxied. The crew didn't notice the hold short which was at the end of the clearance and busted the hold short. Hold shorts should definitely be placed in sequence in a datalink clearance.

[4] He became preoccupied with accepting it at turn-off, and while thus distracted, the CA made a major navigation error.

[5] The time from when the verbal clearance was first begun, or the datalink clearance received, until accepted.

aids at p =.07). For the amended route, the transaction times for the same conditions were 23.8, 33.9, and 23.2 seconds, MS (Cond) = 356.3, F(2,30)=3.9, p =.03 (datalink only condition different from current ops at p= .06 and datalink+nav aids at p =.02). If one included the times where the crews forgot to push the accept button, of course, the times to accept the datalink clearances would be even longer.

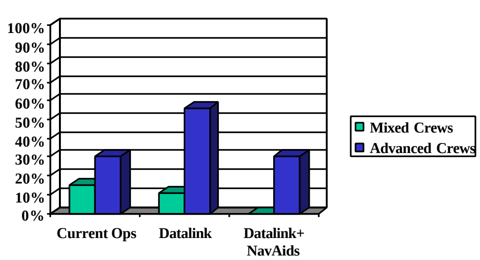
The navigation aids may reduce the transaction times because they reduce the crews' discussion of these clearances. In the hold short trials, one or more of the crew discusses the hold short clearance in 61% (11/18) of the datalink trials without the nav aids and in only 11% (2/18) of the trials with the nav aids (Pearson Chi Square, df 1, =9.75, p <.01). In the amended route trials, one or more of the crew discusses the amended route clearance in 94% (17/18) of the datalink trials without the nav aids vs. 33% with the nav aids (Pearson Chi Square, df 1, =14.6, p<.001).

Increased transaction times with datalink have been noted in many studies [5,6]. To our knowledge, this is the first time that technologies such as navigation aids have resulted in the reduction of these transaction times, possibly by reducing crew discussion. The increased transaction time is associated with delayed forward aircraft movement in the advanced datalink hold short trials but not in the mixed datalink only trials [3]. This may be because in the mixed trials, the pilots have already communicated their acceptance of the clearance verbally to ATC, and therefore feel they can start moving, whereas the pilots in the advanced datalink trials have not.

<u>Datalink Taxi Clearance in the Air</u>. Although frequently the advanced crews did not fully read the taxi clearance in the air when it first arrived due to its timing, the crews in the datalink only trials did discuss it later, and, as will be seen, at lower, less safe altitudes than in other trials. Figure 1 shows that crews in the datalink only condition discussed the taxi route in the air the most. This higher rate of discussion was not due to the conversation and formality issues mentioned earlier, but to the fact that these crews were going to be landing at Chicago O'Hare in a few moments, they had their taxi route, there was no need to stop after turning off the runway where crews sometimes study the route, and there were no graphic displays to help them navigate.

Figure 1

Proportion of Crews
That Discussed the Taxi Route in Air

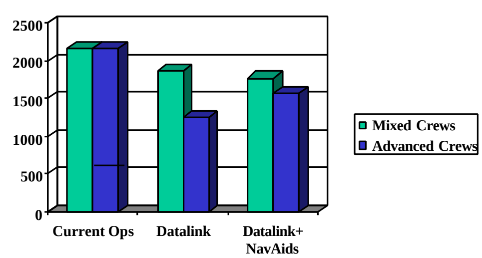


Pearson Chi Square (df 5) =28.3, p =.001

Figure 2 shows that this focusing on surface ops occurred at lower altitudes in the advanced datalink only trials than in other trials. The jumpseat observer rated the last altitude that the crews focused on surface (as opposed to landing) operations. On average, the advanced crews in the datalink only trials focused on surface operations at a lower altitude and after the final approach fix. In the debriefings, many pilots said that the earlier they are able to focus solely on landing, the safer. Hence focusing on surface operations at this stage of landing would be considered less safe, even if the plane were configured for landing.

Figure 2

Average Altitudes (AGL) Crews Finished
Focusing on Surface Ops



RMS = 1,173 F(2,32) = 3.5, p <.05
Within mixed, current ops dif from others at p<.05
Within advanced, all conditions dif from others at p<.01

Crew Strategies and Workload Management

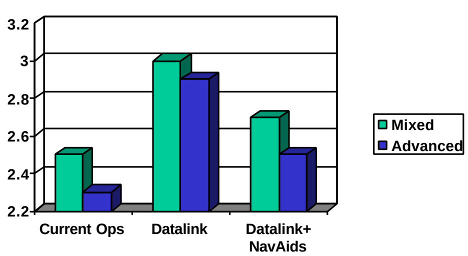
<u>Procedures and Technologies that Help: Configuring the Aircraft Before Accessing the Taxi Clearance and the Navigation Aids</u>. In 76% of the trials (41/54), the advanced crews with datalink configured the aircraft for landing (gear down, flaps 25 or 30) before the taxi clearance was accessed. This appeared to be an important consideration for crews in the datalink only condition (n=27). If they did not configure the aircraft before accessing the taxi clearance, they focused on surface operations at a significantly lower altitude: mean 589 feet vs. 1396 feet, t=4.0 (df=25), p <.001. With the navigation aids, it did not appear to matter

that the crews configure the aircraft before accessing the taxi clearance (mean 1575 feet vs. 1656 feet if configured earlier). Rather than suggest that the crews configure the aircraft earlier, it would be better to deliver the taxi clearance well before the need to configure the aircraft. Even so, it is not clear whether the crews would study and discuss the taxi route at unsafe altitudes. Pilots like to keep ahead of the aircraft, and usually this insures their safety. That the pilots were not as tempted to discuss the taxi route at lower altitudes when they had the navigation aids suggests that if taxi clearances are to be delivered in the air, the guidance technologies should be considered an important safety feature.

<u>CA's and FO's Workload on Approach and Landing</u>**.** The CA's workload was rated by the jumpseat observer as low, close to a 2 (on a scale of 1 to 5) in all trials. The FO's workload was rated as being highest in the datalink trials without the navigation aids, as shown in Figure 3. Hence, even though datalink provides some reductions in workload such as reducing writing of clearances, over-all, the accessing and accepting of datalink clearances is seen as increasing the FO's workload over current ops. The navigation aids are seen as reducing the workload from the datalink only conditions.[6]

Figure 3

FO's Workload
on Approach and Landing



MS(Cond) =3.7, F(2,32)=7.4, p <.01, Datalink dif. from others, p<.01

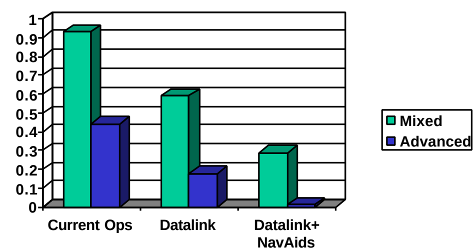
[6] In mixed crews with datalink, the FO must accept both verbal and datalink cleared to land and preferred exit clearances. In advanced crews with datalink, the FO must access the landing, preferred exit, *and taxi clearance*, communicate it to the CA, and accept it via datalink. Although the FO would seem to have even more to do when the nav aids are added to datalink, since in addition the exit on the ROTO must be selected for input into the HUD, there is no need for the FO to focus on surface operations in the air, since there will be guidance on the ground. Also, landing ends at turn-off, and the FO's workload on the runway is reduced when the CA has ROTO guidance.

ATC Contacts

A primary goal at airports is to reduce ATC frequency congestion by reducing ATC contacts. Datalink without voice ATC does this admirably on standard, nominal, clearances—almost eliminating these ATC contacts altogether [3]. Other studies have found that datalink reduces additional, off-nominal, calls to ATC as well. These calls can be due to crew questions about clearances or hold shorts, etc. Figure 4 shows the number of additional ATC contacts in each of the conditions. As can be seen, datalink in both

Figure 4

Average Number of Additional ATC
Contacts Per Trial



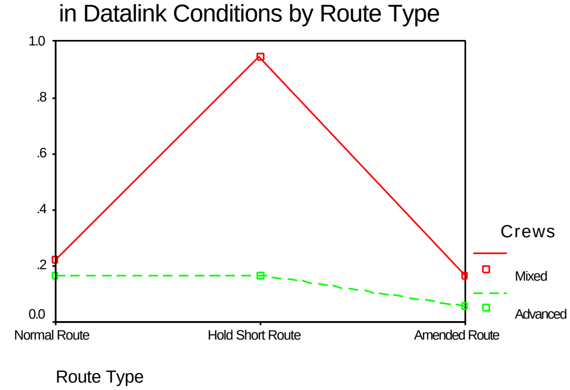
MS (Cond) =3.4, F(2,32)=9.4, p <.001. All conditions dif. from each other at p<.05. MS(ATC) = 5.5 (1,16)=9.9, p <.01

mixed and advanced crews causes the number of additional ATC calls to drop. To some extent, this is due to the increased clarity of datalink taxi clearance messages, as well as fewer error-related ATC calls in the datalink conditions due to fewer errors being made [3]. However, it can be seen in Figure 5 that within all datalink conditions, the calls to ATC rise during hold

Figure 5

Average Number of Additional ATC Calls

in Datalink Conditions by Route Type



MS (Rts X ATC) =1.45, F(2,32)= 5.8, p<.01

short routes for mixed crews, when they have a radio conversation in place, and do not for the advanced crews who do not have a radio conversation in place. In current ops, these same advanced crews did increase their additional calls in the hold short condition from an average of .3 per trial in the normal route to .7 in the hold short route, down to .3 again in the amended route. Hence there is an inhibitory effect of advanced datalink on additional calls to ATC, which might be detrimental in certain situations and result in crew loss of SA. In the hold short routes, the crews call ATC partially to increase their own awareness of the status of the hold short, and partially to let ATC know where they are. The navigation aids counteract the inhibitory effect that lack of radio contact has on off-nominal calls in the advanced datalink condition by providing enhanced SA for the crews,[7] [8] but don't address letting ATC know their status.

SUMMARY

Datalink by itself provides some benefits in the terminal area. Datalink without voice dramatically reduces nominal ATC contacts [3], which would alleviate frequency congestion. Both datalink/voice and datalink only environments also reduce off-nominal ATC contacts (especially after turn-off, for those crews who received their taxi clearance there). Data not presented here suggests that datalink may reduce errors in the taxiway once past turn-off. Finally, giving the taxi clearance in the air has been shown to reduce delays after turn-off [3].

However, there are some major problems that affect the feasibility of datalink in the terminal area, problems that the navigation aids alleviate. First, previous research indicates that the loss of traffic awareness from not monitoring the radio frequency in the datalink only environment may largely be replaced through the depiction of traffic on the EMM [2]. Second, for clearances given on the ground in either datalink environment, the navigation aids reduced the increased transaction times that datalink clearances take. In the datalink only environment, the aids eliminated the delay in forward movement of the aircraft found after receiving a datalink clearance [3]. Third, if the taxi clearance is given in the air, the navigation aids reduce the time that the crews need to focus on their taxi route in the air and reduce the likelihood that they will do so at unsafe altitudes. Fourth, the navigation aids counteract the inhibitory effect that lack of radio contact has on off-nominal calls in the datalink only environment by providing enhanced situational awareness for the crews. Fifth, there is evidence that the navigation aids reduce the increased workload that datalink entails for the FO. Sixth, the navigation aids alleviate the problem of not fully verbalizing the contents of the clearances in the datalink only environment by providing graphic guides. Seventh, the navigation aids reduce the high rate of forgetting to accept the clearances in both types of datalink environments by providing unobtrusive reminders that a clearance has not been accepted.

[7] When the nav aids are added to the mixed datalink trials, they also reduce calls to ATC in the hold short routes (from an average of 1.2 to .6, t, df 16,=1.7, p =.10). They do this by increasing the crews' SA of the status of the hold short, other traffic, and ATC directives to other traffic (the EMM depicts hold shorts for other traffic as well).

[8] In 67% (36/54) of datalink trials, the advanced crews did not change their radio frequency from tower to ground, since there was no reminder to do so from tower at turn-off. This is a safety hazard since it not only adds seconds of delay if the crew wants to reach ground, but also makes it impossible for ground control to reach the crew quickly with voice rather than with datalink.

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