

Design and Evaluation of a Taxi Display with Integrated Data link

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Abstract:

To improve airport ground handling capacity and safety in all weather conditions, the introduction of moving map taxi displays in glass cockpit airliners is being considered. A digital data link to replace the current voice communication system can be used in combination with a taxi display to present dynamic information such as taxi clearances and moving obstacle locations. This paper describes a study in which the data link interface was graphically integrated with the taxi display itself to minimize the likelihood of communication errors and to maximize the crew situation awareness of the implications of new clearances. An experiment was conducted to compare the possible impact of the new graphical system with currently used procedure based operations and with an intermediate solution where Radio Telecommunications (RT) was not completely replaced by data link.

Keywords: Aircraft navigation, ground operations, cockpit displays, data link, SMGC, A-SMGC.

The Taxi Display

In the next two decades air traffic movements in the European airspace are expected to double (Eurocontrol 1998), stretching the present infrastructure to its limit. This infrastructure not only encompasses the airways and their associated surveillance and control components, but also airports with their runways and taxiways. This part of the infrastructure could very well be the bottleneck for continued growth of air traffic.

To allow the most efficient and safe use of existing runway resources, the supporting taxiing operations must be as efficient as possible in all weather conditions. With the technology used in present day airliner for taxiing, this goal cannot always be achieved. This is partly due to the discrepancy between the technology levels of the equipment

(already used as well as proposed) during landing (ILS, MLS, DGPS, Tunnel in the sky displays). Taxiing operations are still conducted with the technology level of decades ago: a paper map gives the pilot an overview of the airport and the ground controller uses a VHF radio to verbally provide clearances and, if needed, position updates derived from a ground radar system.

Present day tools are not sufficient to remain at peak efficiency when visibility levels drop, for instance at night or in adverse weather. In these lower visibility conditions pilots will have to taxi slower and the ground controller will have to increase separation for safety reasons, at the cost of airport throughput capacity. Also the danger of pilots losing situation awareness¹ is greatly increased in low visibility. It is therefore important to explore the use of technology already present in the aircraft to increase pilot situation awareness during those taxiing phases. These considerations set the stage for the introduction of the taxi display (Figure 1).

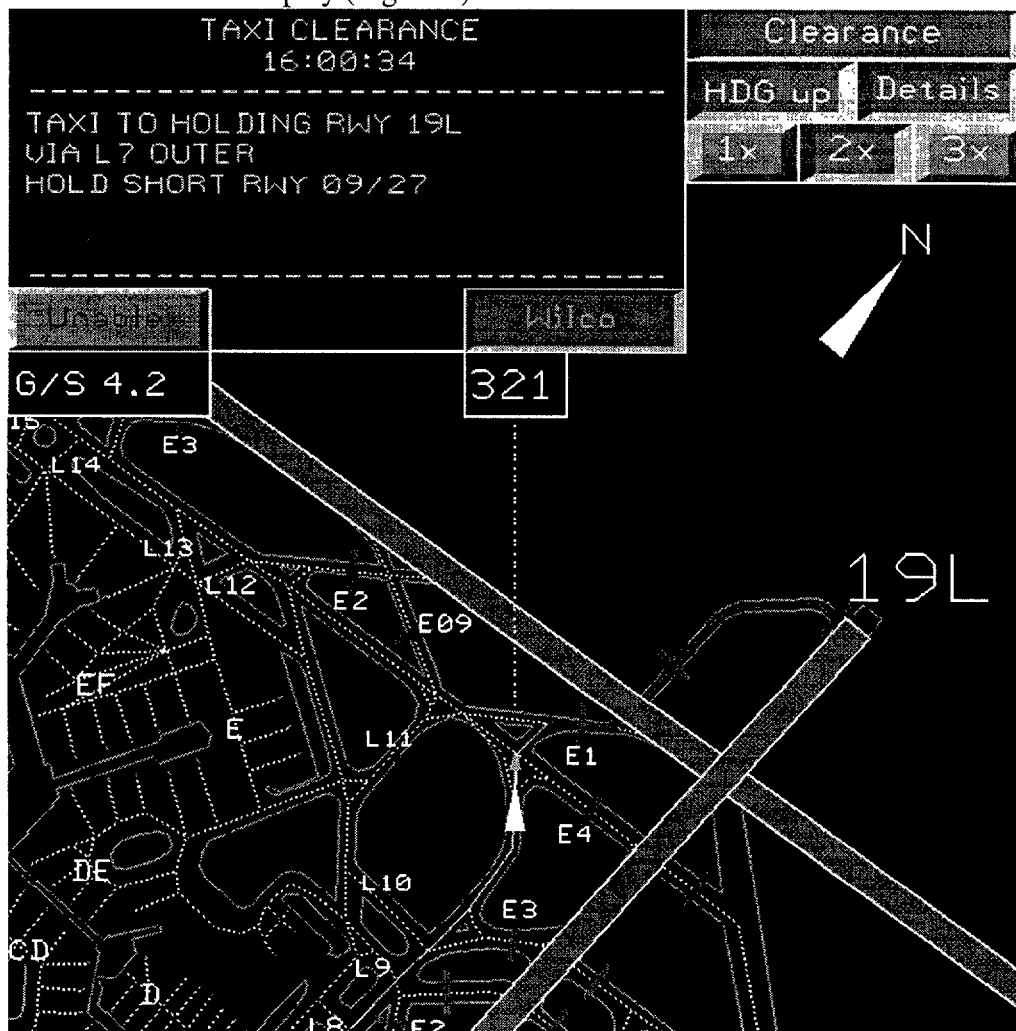


Figure 1 Taxi Display

¹ Situation awareness: The perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future. (Endsley, 1995)

A taxi display uses one of the Multi Function Displays present in modern glass cockpits, to present an up-to-date electronic map of the airport. With the help of high-precision navigation systems, such as DGPS, the current position of the aircraft can be superimposed on the map. This virtually eliminates any uncertainties in the cockpit regarding the aircraft's position and has been proven to have a positive effect on taxi performance in several studies (Batson et al. 1994, Battiste et al. 1996, McCann et al. 1996)

An enhancement of the basic moving map taxi display is the representation of the cleared taxi route. This would significantly increase the pilot's situation awareness regarding controller's intentions and would help to further alleviate the problem of unintended runway incursions.

A problem arises from the way this route has to be stored in the airborne system. When the clearance is conveyed through RT, the pilot has to manually input the clearance, which leads to unacceptably long periods of the pilot's attention being 'inside' the cockpit. Also this extra step also introduces an additional source for errors (a.o. typos) and is not practical.

When a direct datalink between ATC and the taxi display is used for clearance conveyance, these problems are solved immediately. Besides the possibility of direct incorporation of clearances in aircraft systems (generally known as gating), a digital datalink has several other advantages:

- a datalink can handle a larger amount of traffic if the ground controller's side of the connection is properly supported
- misunderstandings due to poor signal quality or language problems are eliminated
- a standardized message set can be strictly enforced
- automated functions, such as route negotiation between the FMS and ATC planning systems, are made possible

The technology for several kinds of datalinks is already available and could easily be integrated in the aircraft. One of the promising candidates originates from Sweden and uses the VHF band in combination with time multiplexing (e.g. STDMA). However it should be noted that other promising alternatives are also under investigation (e.g. VDL 2 and SSR Mode S) and are supported by the aeronautical community for other reasons and purposes.

With the communication process of requesting and receiving taxi clearances being transformed through the use of datalink, the tasks of the pilot during taxiing are also changed, introducing the danger of the pilot losing situation awareness with regard to the communication process.

Another problem with a datalink is the shift in the use of pilot resources when compared to conventional RT. Normal speech communication demands very little from the pilot's manual, visual and attentional resources. A datalink implementation will almost certainly require the pilot to manually generate some input using an input device such as a keyboard or a touchpad, at least until the arrival of reliable speech recognition and synthesis systems. The output from the system must be visually read from a display by the pilot, who must also commit a reasonable amount of attention to the system. All these issues necessitate a careful design of the datalink system, minimizing the amount of workload the pilot has to invest into the system.

To minimize the extra workload of a digital datalink coupled with a taxi display, the interaction with the datalink system required from the pilot can be graphically integrated with the taxi display itself. This provides the pilot with a single source where all the information regarding the taxi task can be found.

Such a taxi display with integrated datalink is the subject of this paper. It subscribes a study in which a taxi display system with the integrated datalink functionality was compared to an intermediate 'low-tech' solution in which conventional RT was retained for requesting clearance and the taxi route was displayed textually instead of graphically. Issues being investigated encompass acceptability, navigation performance and safety.

The Taxiing Task

General

To navigate to his destination safely and in accordance with the instructions from ATC, a pilot has to be successful in two areas: global awareness and local guidance (Lasswell & Wickens, 1995). Global awareness comprises of knowledge about the own position relative to the desired destination and detection of hazards. Local guidance means the manoeuvring of the aircraft along a specified route, while optimising speed and accuracy.

Although both of these aspects are primarily supported by the visual outside scene, their information requirements can be quite different. For global awareness, a pilot relies heavily on the position of taxiway signs and landmarks such as terminal buildings and runways. Local guidance is mostly supported by elements such as the position of the centre line and flow cues in the peripheral view to assess ground speed. These differences will express themselves in the way these aspects can be supported by new tools.

The taxiing task can be broken up into several subtasks, which can be identified as (Lasswell & Wickens, 1995):

- lateral loop closure in order to follow the taxi way centre line
- directional loop closure when making turns
- longitudinal loop closure to maintain optimal speed and brake for obstacles
- information gathering inside and outside the cockpit, for instance cockpit instruments, taxi way markings, communication with ground control, etc.

- hazard detection in the outside scene

Together, these tasks serve to provide both local guidance and global awareness. The loop closure tasks can be seen to support mostly local guidance, while global awareness is gained by information gathering and hazard detection. In the development of ways to assist the crew while taxiing, this breakdown can operate as a framework for defining the different functions to be incorporated into for instance a taxi display.

It is important to realise that of these tasks, maintaining control of the aircraft must be considered paramount. The decreased tolerance for lateral deviations during taxiing require the pilot to allocate a major part of his resources to the control task. Any other tasks that require pilot resources, be it either visual, attentional, or otherwise, should be regarded as secondary and only be performed when it is safe to do so. Examples of these secondary tasks include communicating with the ground controller or the studying of an airport map. It comes as no surprise then, that these secondary tasks are mostly performed by the pilot non-flying (PNF), while the pilot flying (PF) controls the aircraft.

The distinction between global awareness and local guidance are summarised in table 1.

Global Awareness	Local Guidance
Outer control loops	Inner control loops
Mainly performed by PNF	Mainly performed by PF
Requires occasional attention	Requires constant attention
Lower position accuracy allowed	High position accuracy required

Table 1 Global awareness and local guidance

Problem areas

The problems pilots encounter while taxiing can also be divided into the aspects of global awareness and local guidance. Communication, as an element necessary for maintaining global awareness, poses some unique problems which also will be addressed.

Global awareness can be degraded or even lost by the reduction of visual cues in the outside scene, which are so vital in determining one's own position in the world. Knowledge on the whereabouts of other traffic, another important part of global awareness, also degrades when no visual cues are present. The times at which such a

situation can occur, are mostly at night or in low visibility conditions. The loss of visual cues can be moderated somewhat by position updates from the ground controller via radio, if the airport is equipped with a ground radar system.

Another cause for reduced global awareness is the ever growing complexity of modern airports. The construction of new runways and terminals has led to an elaborate system of taxiways, which can result in confusion and mistakes by pilots, even in clear weather conditions. This problem of course only worsens when visibility deteriorates.

Visibility levels can also affect local guidance, although the critical visibility levels are much lower. It is only when the visibility is so bad that even taxiway edge lights cannot be seen anymore, that local guidance becomes a serious problem. However, pilots will normally slow down far sooner, to maintain a sufficient safety margin, thus also affecting the local guidance component.

A more important problem for local guidance are the large sizes of today's airliners. Besides the reduction of lateral margins (wheels need to remain on the taxiway), also the control distance for the pilots is increased. For instance the pilot tries to control a 747 from a height of approx. 9 meters from the ground. Both factors make it increasingly difficult to keep the wheels on the pavement, while still maintaining a reasonably fast taxi speed, especially in turns. Preventing such errors requires a great amount of skill and concentration from the pilots.

Specific incidents which can occur when global awareness is lost, include navigation errors, such as wrong turns or exits, and, more seriously, runway incursions². Local guidance deterioration can lead to wheels off the pavement, collisions due to judgement errors regarding for instance wingtip clearance, or slower taxi speeds, which is less serious but leads to decreased capacity and costly delays.

Today, part of the information necessary to maintain global awareness, such as position updates and clearances, is transmitted over voice radio links. There are however difficulties associated with this medium. Misunderstandings can easily occur, especially if sound quality is poor or the controller speaks with an accent or very fast. Also, growing traffic amounts give rise to an overcrowding of communication channels. This frequency congestion can lead to long waiting times and cancellation of time consuming safety measures such as read-back.

From a human factors standpoint, voice delivered taxi clearances force the pilot to make a mental translation from spoken words to a route he has to follow over the aerodrome, increasing his mental workload. This process can also result in errors and uncertainties on the part of the pilot. Also the relatively large amount of time involved in planning the

² Runway incursion: Any occurrence at an airport involving an aircraft, vehicle, person, or object on the ground that creates a collision hazard or results in loss of separation with an aircraft taking off, intending to take off, landing, or intending to land. (Harrison, 1991)

route based on a verbal instruction alone, has an impact on the efficiency of ground operations.

The main result of these communication problems is a loss of efficiency, for instance when aircraft have to wait for the frequency to clear before they can receive their clearance. More serious consequences regarding safety can be runway incursions caused by misunderstood clearances.

Taxi Display Design

Taxi display functions

In general, the functions a taxi display can provide are:

1. an up to date layout of the airport as a digital map
2. same as 1 but include the aircraft's position
3. same as 2 with the cleared route
4. same as 3 with other traffic and obstacles
5. same as 4 but with increased precision and other indicators to support local guidance

The first four functions are mostly concerned with supporting global awareness by providing information the pilot would normally extract from paper maps and the outside scene. This information can be degraded by low visibility and inefficient voice radio links.

For supporting local guidance in the form of e.g. steering cues and wingtip position predictors, a high precision is needed for both the positioning system and the airport database. Furthermore, providing the PF with steering cues on a head down display unfortunately draws his or her attention into the cockpit at a time when the pilot's attention should lie outside, looking for hazards not present on the display, such as one of the numerous baggage carts roaming the airport. This drawback could be mitigated by giving local guidance support on a head up display, as is done in the T-NASA system (Foyle et al. 1996).

Experimental taxi display

The taxi display described in this paper concentrates on supporting global awareness by providing some of the cues necessary for successful navigation, i.e. an electronic map of the airport, the aircraft's position and the cleared route. It focuses especially on the implementation of the digital data link and the impact of technological limitations on the taxi display system as a whole.

A mature 'high tech' taxi display system is envisaged in which the data link communication process is graphically integrated in the taxi display. All communication between pilot and ground control is conducted through the taxi display and the data link. An input device such as a touchpad is used by the crew to input requests and reports into

the system. The cleared route is integrated in the map as a graphical line, colour-coded to indicate the clearance status.

The 'high tech' system was compared to an intermediate 'low tech' system which places less demands on airborne and ground based equipment and is therefore more likely to be implemented in the transition period between the use of RT and exclusive use of data link in the future. In this 'low tech' variant RT is retained for requesting clearances and giving reports by the crew. The cleared route is transmitted and presented in a textual format.

In both versions the textual clearance was presented in a removable 'window' on the taxi display, together with two buttons labelled 'unable' and 'wilco' which the pilot used to respond to new clearances. Further interactions in the 'high tech' system included requesting runway crossing clearance by selecting a red stopbar along the runway to be crossed. A data link message was then dispatched, followed by a new clearances to cross the runway. Common map controls such as zoom and declutter were provided in both variants.

Pre-experimental hypotheses

The introduction of taxi displays and especially data link systems will follow an evolutionary path, where the intermediate systems must already provide clear benefits for the user, if the system as a whole is to be successful. It is expected that an intermediate system such as the 'low tech' taxi display described in this paper scores lower on performance and safety benefits than the more mature 'high tech' system. It should however still offer an improvement over the present day baseline condition.

The presence of time delays in the data link system, either caused by technical limitations or by high ground controller workload, can have a more severe impact than they would have in an equivalent system based on RT. This is caused by the 'sterile' environment a datalink creates in the cockpit. The crew can no longer listen in on the communication with other aircraft (the 'party line') to assess traffic densities, expected procedures, etc. Non-verbal clues indicating for instance the controller's workload or message urgency, are also lost. These drawbacks could possibly limit the number of applications data link can be used for in terms of safety criticality. If sufficient performance regarding time delays can not be guaranteed, RT would have to be retained for time critical message such as runway crossing clearances and emergency messages.

Experiment

Goal of the experiment

The objective of this study was to design and evaluate a taxi display with an integrated data link module. The display is to be used specifically for global navigation and is not designed for supporting local guidance in extremely low visibility. Of the functions established earlier, this taxi display provides:

- up to date information on the airport layout
- position of own aircraft for (global) navigation purposes
- the cleared route

The evaluation considered the acceptability of different technology levels and possible time delays. Furthermore the benefits on navigation performance were explored. Also any changes in pilot behaviour that can influence safety, were to be identified. These elements include head down time, misunderstood clearances, etc.

Method

Apparatus and setup: The subjects were seated in a simplified mockup of a modern commercial airliner. A 21 inch monitor in front of them provided an outside view. A 14 inch LCD screen was mounted head down to present the taxi display. Control was exerted through a throttle mounted on a pedestal and a set of rudder pedals for steering through differential braking (see 2).



2 Figure Experimental apparatus

A simplified taxiing model of a Boeing 747 was used for taxiing over a flat representation of Schiphol Airport. The same database was used for the outside view and the taxi display. The outside view was rendered with simulated fog limiting the RVR to approximately 400 m.

Subjects and instructions to subjects: Eight pilots participated in the experiment. They all had considerable experience in taxiing and were moderately or highly familiar with

the used airport. They were instructed to concentrate on global navigation and not so much on local guidance, although gross local guidance errors were to be avoided.

Independent measures: The experiment explored the impact several hardware limitations can have on taxi performance. It compared three different technology levels: present day, low tech and high tech, as described below. Furthermore, two levels of time delays for the used digital data link were considered.

Present day operations were conducted using a paper map of the airport and clearances given over the radio by the ground controller. The pilot also had knowledge of the aircraft's speed and heading through the instruments. This was the baseline condition. Low tech operations assumed the use of digital data link for receiving clearances and responding to them in a wilco/unable fashion. RT was still used to request clearances and for non-standard communication. The representation in the cockpit was on a textual basis, together with the taxi display. In the high tech case communication was exclusively conducted through data link, and the presentation to the crew was integrated with the taxi display to show clearances and other messages in a graphical format in addition to the textual output.

Time delays were incorporated in both the low and high tech scenarios. Information exchange was either immediate, much like today's radio traffic, or there was a significant, non-deterministic pause between sending a message and receiving an answer or acknowledgement of around 60 seconds.

Design: The experiment contained 10 trials per subject, 2 in the baseline condition, and 4 in each of the datalink conditions. Half of the datalink trials incorporated transmission time delays with an average length of 60 seconds and a standard deviation of 15 seconds. Each trial used a different route, divided randomly across the conditions and subjects within two blocks. Each block consisted of a baseline run without a taxi display, followed by a training run with the display and 4 data runs with the display. The routes contained 3 arrival and 7 departure scenarios, some of which incorporated a mid-course change in clearance. Each pilot encountered one scenario in which the graphical route line deviated from the official textual clearance to investigate the way pilots process the cleared route.

Dependent measures: Besides data from questionnaires, several other measures were deduced from the logged data. Most important was the planning time, i.e. the time between receiving a clearance and the acknowledgement of it through the wilco-button.

The aircraft position was logged for later comparison with the cleared route. Since the display was not meant for local guidance and pilots were not instructed to follow the centre line precisely, the lateral deviation from the centre line was not incorporated into the analysis. Positional data was only used to identify navigation errors such as wrong turns, and to provide a reference frame for the other recorded data.

Experimental hypotheses: The hypotheses tested in this experiment on the areas of acceptability, navigation performance and safety are:

Acceptability:

- (1) More integration leads to higher acceptability
- (2) Time delays reduce acceptability

Navigation performance:

- (3) Showing the clearance graphically reduces the effort of processing the clearance, resulting in a shorter planning time when compared to a textual representation

Safety:

- (4) Graphical clearance representation leads to less navigation errors

Results and discussion

In the questionnaires submitted after each run, the subjects reported a significantly lower effort rating in navigating using the 'high tech' graphical route display compared to the 'low tech' textual route display: $F(1,7) = 11.41$, $p = 0.012$ (see Figure 3). Also the 'effort to determine the exact route' from the display required significantly less effort ($F(1,7) = 6.72$, $p = 0.036$).

With regard to the intermediate communication system of the 'low tech' variant, the subjects were less satisfied. They rated their 'satisfaction with the communication system' significantly lower than the all-datalink system ($F(1,7) = 10.80$, $p = 0.013$). Often the 'low tech' system scored lower on this aspect than the baseline condition of only RT. The presence of delays did not produce a significant drop in score.

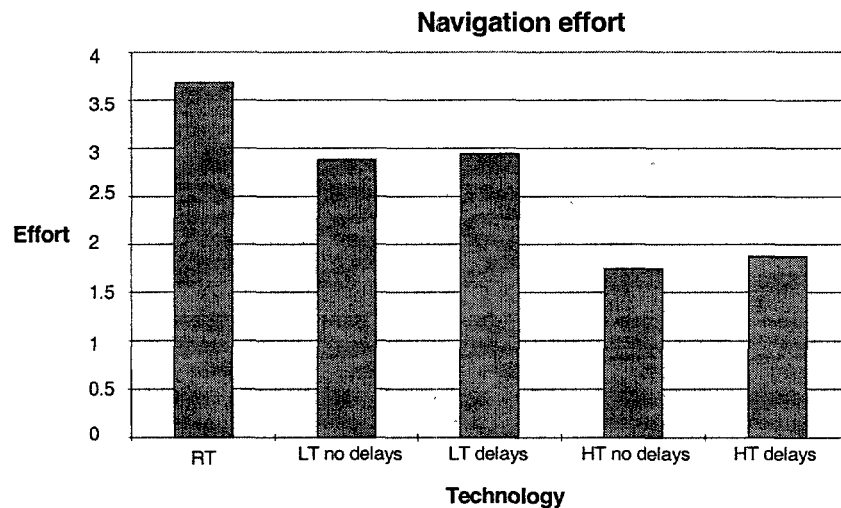


Figure 3 Navigation effort per technology level (RT = baseline condition, LT = 'low tech' taxi display, HT = 'high tech' taxi display; 1= "very little effort", 6 = "very much effort")

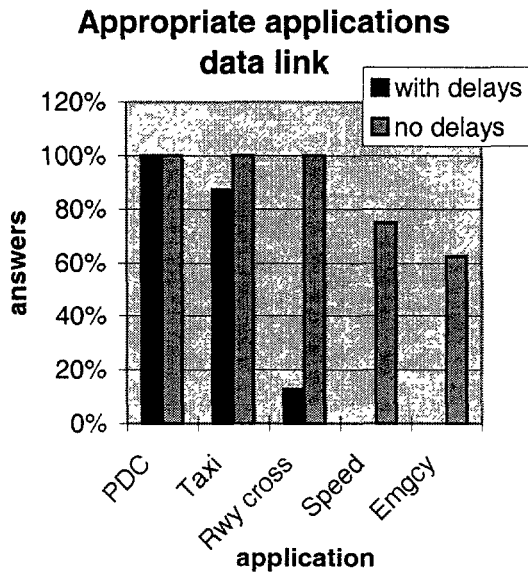


Figure 4 Reported usefulness of a data link during ground operations. Applications are the Pre Departure Clearances (PDC), taxi clearances (Taxi), runway crossing clearances (Rwy cross), taxi speed directives (Speed) and emergency messages (e.g. “Stop now”, Emgcy)

An area where the presence of delays has a considerable impact is in the usable applications of data link, as reported by the subjects in a questionnaire completed at the end of the session (see Figure 4). When time criticality increases the presence of delays severely limits the application possibilities of data link.

To evaluate the impact a graphic presentation has on navigation performance, the planning time was measured. The planning time is the time between receipt of the datalink message and the acknowledgement by the crew. This is not entirely accurate, since ‘push first, think later’ behavior was observed in some subjects, who acknowledged the clearance before having checked it.

Typical local guidance performance measures such as taxi speed and centre line tracking error were not analyzed since the display is primarily intended to support global awareness.

An analysis of the planning time results showed a significant decrease in planning time when the ‘high tech’ system was used. This is consistent with the difference in required mental processing by the pilot between a textual route representation and a graphical one superimposed on the map.

In a way the graphical route line transforms the pilot’s task from a navigation to a less effortful tracking task. With this transformation comes the danger of complacency and decreased situation awareness when the pilot solely relies on tracking the route line, instead of monitoring the clearance and checking the map. This effect was observed on

two occasions in the experiment when the subjects erroneously continued to follow the route line, even though it deviated from the official textual clearance. Other types of navigation errors were few and far between, inhibiting a statistical analysis.

From comments provided by the subjects it became clear that they frequently used the display for local guidance, even though it was not designed for this. One of the reasons was the lack of realism of the simulation, especially the absence of side windows for turn anticipation. Also a fascination with the technology and a desire to use it, even for inappropriate tasks, played a role. This undesirable behavior could lead to more head down time of the PF, which is a concern to researchers and future users alike. It is expected that this effect will diminish in more elaborate simulations, where visual cues are more realistic and some tasks, steering the aircraft and communication in particular, are shared between the two members of the crew.

Conclusions

The objective of this study was to assess the acceptability, effect on navigation performance and safety consequences of a taxi display and digital data link. The evaluation conducted with the developed taxi display system provided some insight in all these factors.

Acceptability ratings from the evaluation showed that the graphically integrated data link is highly acceptable for most communication during taxi operations. A mix of RT and textual data link presentation was considered less favourable and could even be regarded as inferior to today's system of RT.

The usefulness of the systems was considered lower by the subjects when time delays were present. The possible applications of data link are dramatically reduced when time delays of this magnitude are present. Time delays should consequently be kept to a minimum, especially for communication during taxiing itself, such as for runway crossing clearances.

Navigation performance, especially planning time was significantly improved when the clearance is presented graphically, instead of textually. The subjects also reported that the planning process and navigating itself required less effort.

Due to the limited number of navigation errors committed, no firm conclusions can be drawn regarding *safety*. Nevertheless, safety issues which were observed included trends towards a reduction in serious navigation errors when a taxi display is present and a possible decrease in situational awareness regarding the cleared route when it is shown graphically and acknowledged too swiftly.

Generally, it was found that it can be very tempting to use a taxi display for local guidance, even when it is not appropriate to do so for various reasons, such as positional inaccuracy or increased head down time.

Also, a wrongly implemented data link communication system with regard to procedural or technical issues, can overshadow the other benefits of the entire taxi display system. The present system of RT can, with its limitations, still be considered superior to a deficient data link system.

Finally, using a graphical representation of the cleared route on the map eases the pilot's effort in understanding the clearance and leads to shorter planning times, when compared to a textual clearance. The conversion of a navigation task to a simpler tracking task requires the pilot to absorb and process less information regarding his position on the airport, but this can lead to a decrease of situational awareness when something unforeseen happens.

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