McCann, R.S., Hooey, B.L., Parke, B., Foyle, D.C., Andre, A.D. and Kanki, B. (1998).
SAE Transactions: Journal of Aerospace, 107, 1612-1625.

985541

An Evaluation of the Taxiway Navigation and Situation Awareness (T-NASA) system in High-Fidelity Simulation

Robert S. McCann
San Jose State University

Becky L. Hooey
Monterey Technologies, Inc

Bonny Parke
San Jose State University

David C. Foyle
NASA-Ames Research Center

Anthony D. Andre
San Jose State University

Barbara Kanki
NASA-Ames Research Center

Copyright © 1998 Society of Automotive Engineers, Inc

ABSTRACT

The effects of an electronic moving map and a HUD on ground taxi performance in reduced visibility were examined in a high-fidelity simulation. Sixteen commercial flight crews completed 21 trials, each consisting of an autoland arrival to Chicago O'Hare and taxi to an apron area. Relative to a baseline (paper-chart only) condition, the EMM/HUD combination increased forward speed by 21%, and reduced navigation errors by nearly 100%. These results, together with workload ratings, situation awareness ratings, analyses of crew interactions, and pilot feedback, provide strong evidence that the combination of head-up symbology and an EMM can substantially improve both the efficiency and the safety of ground operations.

INTRODUCTION

Recent technological advances have generated unprecedented opportunities to increase the safety and efficiency of commercial airline operations, particularly in low visibility conditions. For example, the widespread availability of real-time, accurate positioning information (i.e., GPS), combined with increases in computer processing power, information storage capacity, and improved graphic rendering devices, have made it possible to incorporate innovative forms of flight-relevant information into the flight deck. However, generating and displaying this information requires an extensive infrastructure, including airport and terrain databases, advanced terminal area sensor systems, and datalink [1]. Furthermore, optimizing the form in which this information is displayed to the pilot may well require advanced display devices, such as Head-up Displays (HUDs) [2]. All of this adds up to a considerable investment on the part of aircraft manufacturers and the airlines. The only way to justify this investment is if displaying the information can be shown to have an economically significant impact on flight operations. Thus, if display developers want to succeed in getting their displays onto commercial aircraft, they must do two things. First, they must design their displays carefully in order to maximize the impact on pilot performance. Second, they must provide clear evidence of the performance benefits through rigorous evaluation.

Recently, human factors researchers at NASA-Ames Research Center have developed an advanced display suite, collectively known as the Taxiway Navigation and Situation Awareness (T-NASA) system, to help pilots navigate on the airport surface in low-visibility conditions. In the present article, we consider the system against the two criteria just defined. We begin by describing the human-centered approach to display design that was followed in order to optimize the effects of the T-NASA displays on pilot performance [3]. The approach began with a cognitive model of the navigation task that, together with an empirical "hands-on" assessment [4], provides a clear picture of the information requirements of ground taxi. We then describe how these requirements were incorporated into a display suite, following well-established human factors principles for optimizing display design in general, and navigation displays in particular. We then report the results of a recent high-fidelity simulation evaluating the effect of the T-NASA system on taxi performance. Consistent with our earlier work [5], we found that the T-NASA system produced substantial improvements in taxi efficiency, large enough to impact significantly on the costs of ground taxi operations. In addition, the simulation provided an opportunity to evaluate new display features designed to reduce the rate of noncompliance with hold short instructions. The results indicate that T-NASA could be a significant factor in improving the efficiency and the safety of ground operations in the near future.

NAVIGATION: A COGNITIVE MODEL – Navigation is one of the primary tasks facing the crew of a commercial aircraft. Successful navigation requires two forms of spatial knowledge [6]. The most important form is knowledge of the spatial relation between the aircraft's current location (where we are) and the cleared route (where we should be). This knowledge supports the task of local guidance, a closed-loop operation whereby the pilot monitors the real-time error (if any) between current position and the cleared route, and corrects the error via appropriate control inputs. The second form of knowledge, global awareness [7], combines knowledge of the aircraft's absolute position in a word-referenced (viewer-invariant) coordinate system with general knowledge about the immediate environment (i.e., the location and trajectory of nearby aircraft). Global awareness is necessary to recognize and react appropriately to hazardous situations.

Collectively, the two forms of spatial knowledge define a pilots' navigation (or geographical) awareness [6,7,8]. As long as navigation awareness is maintained, the pilot has a feeling of "foundness" that allows him or her to proceed rapidly and accurately along the prescribed route [9]. When navigation awareness is lost, the pilot becomes spatially disoriented. The results can range from merely increased workload, while the pilot recovers awareness, all the way to catastrophic accidents such as controlled flight into terrain.

In modern glass cockpit aircraft, the cognitive processing required to maintain navigation awareness varies considerably across different phases of flight. In the air, awareness is supported by the electronic navigation display, which provides a graphical depiction of the aircraft's current position relative to the programmed flight path. In addition, if the aircraft is equipped with a commercial HUD, the flight director symbology provides a high-resolution graphic depiction of the real-time error between the ownship location and the flight path. These displays simplify the information processing demands of airborne navigation by providing relevant information in an easy to understand graphical format. As currently engineered, however, neither navigation displays or head-up flight directors support the task of navigating on the airport surface. This leaves a paper chart as the only form of in-the-cockpit navigation aid available for taxi. Crews are forced to try and follow their ground clearance using the "pilotage" method [6], which relies on visual reference points rather than instruments.

Pilotage requires continuous integration of information from a variety of sources. If the pilot is unfamiliar with the airport, for example, the most common strategy is to select a set of landmarks, or distinguishing features, on the paper map, and then associate these features with the actual features in the out-the-window (OTW) view. This activity requires the pilot to cognitively "couple" or align navigation-relevant features in the OTW scene with the representation of these features on the paper map [7,8,9]. Once this coupling is achieved, the pilot can compute the spatial relation between his current location and the cleared route, and determine whether error-correcting actions are necessary. Of course, pilots who have experience at the airport are likely to have developed a personal mental model, or cognitive map, of the airport surface. This gives them more cognitive flexibility than the naïve pilots: they can mentally align elements in the forward field of view (FFOV) with the visual depiction of these features on the paper chart, with the abstract representation of these features in their cognitive map, or both [9,10]. However, the need to integrate information from several sources remains.

Pilotage can be a very inefficient way to maintain navigation awareness, particularly on the airport surface. The heavy reliance on information in the OTW scene means that awareness is easily disrupted by reductions in visibility (such as those that accompany night or poor weather conditions), and by misleading or inadequate signage and surface markings [4]. Furthermore, the reference frame of the paper map is world-centered, whereas the reference frame of the FFOV is viewer-centered. Bringing the two frames of reference into cognitive alignment typically requires various forms of processing, such as mental rotation, that are effortful, time-consuming, and error-prone [7,8]. In a high workload situation, where these operations are competing with other tasks for the pilot's attention, they may well be omitted entirely.

Once navigation awareness is lost, pilots are forced to engage in a variety of activities to recover it. These include communicating with other crewmembers, scrutinizing the FFOV in an effort to identify a landmark or surface sign, studying the paper map, and communicating with ground control. At best, these activities are likely to be accompanied by slower and more cautious taxi behavior, even if the pilot is on the cleared route [5]. At worst, loss of navigation awareness results in an outright navigation error, such as a missed or

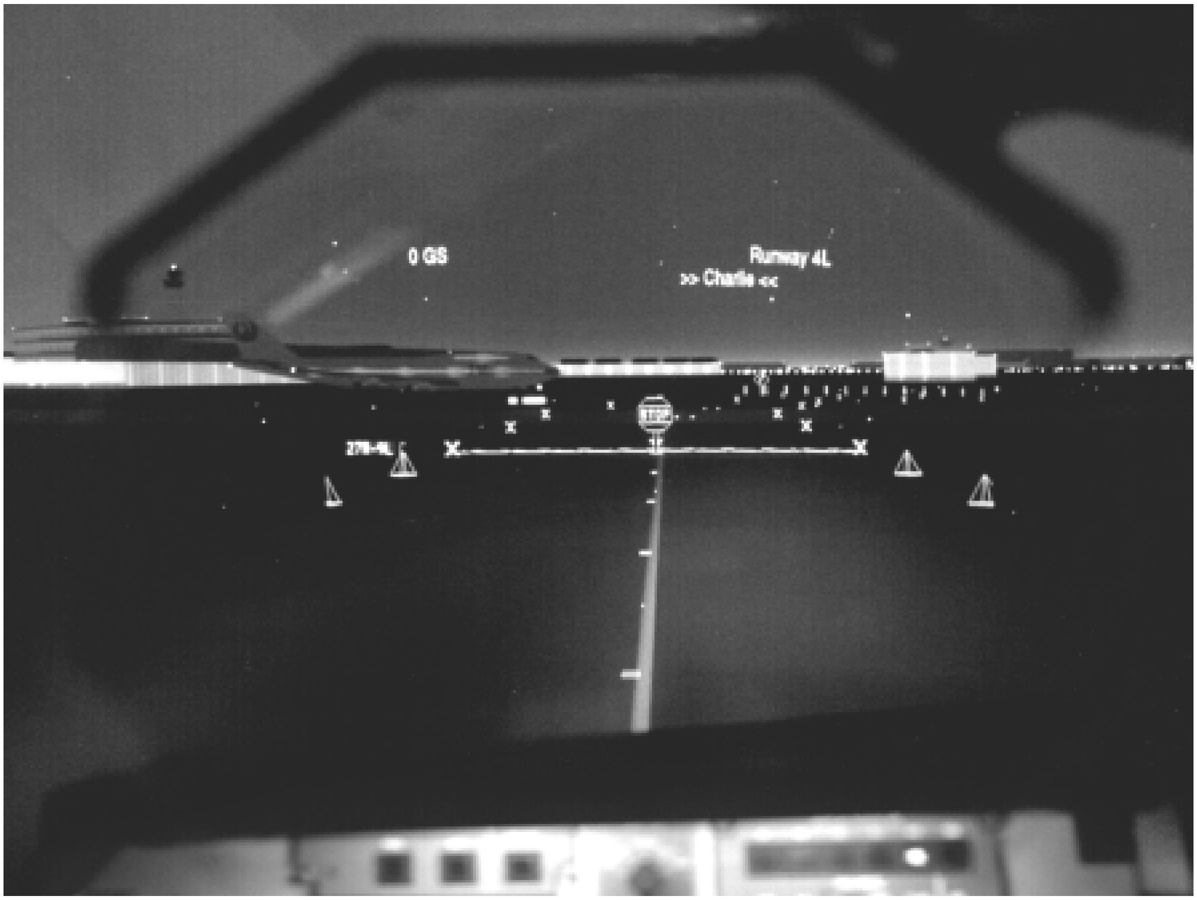

Figure 1. Photograph showing the T-NASA HUD symbology overlaid on the out-the-window night view approaching Runway 27R/9L on Taxiway Charlie at Chicago O'Hare. The cleared taxiway is demarcated by the series of rectangular centerline markers and the side cones. Hold short symbology includes the virtual stop sign, virtual stop bar, and the replacement of the side cones with "X"s at and past the stop bar. Note the A/C taking off on 27R/9L (upper left of figure).

incorrect turn. Once the plane has deviated from its cleared route, it may become a serious safety hazard, and considerable delays are likely while the pilot recovers enough awareness to navigate back to the cleared route [5]. Thus, loss of navigation awareness is directly associated with reductions in taxiing efficiency.

THE T-NASA SYSTEM. According to this analysis, loss of navigation awareness on the ground is primarily due to either inadequate or misleading information in the OTW view, or to a failure to carry out the difficult forms of information integration associated with pilotage. When designing the T-NASA system, therefore, our primary goal was to supply the information needed to maintain navigation awareness via cockpit displays, thus eliminating the pilots' reliance on the OTW view. In addition, we wanted to present the information in a form that greatly reduces the cognitive effort needed to maintain awareness.

Recall that navigation requires both global awareness and knowledge to support local guidance. This poses something of a design dilemma. Since local guidance is typically supported by processing information in the pilot's FFOV, the ideal support for local guidance is an "ecological" display [11], one that shares as many perceptual characteristics with the FFOV as possible [8,12]. The trade-off is that the more ecological the display, the less capable it is of supplying information that is relevant to geographic awareness [8].

Our solution to this problem was to design two displays, one primarily for local guidance, and the other primarily for global awareness. The local guidance display is a set of HUD symbology that we designed specifically to support ground taxi. Figure 1 shows the actual symbology that the pilot sees while approaching hold bars on taxiway "Charlie", the high-speed turnoff from Runway 27R at Chicago O'Hare. Note in particular the triangular shaped edge cones and the series of regularly spaced squares along the taxiway centerline. These HUD symbols delineate the edges and the centerline, respectively, of the cleared taxiway. Importantly, these symbols are "scene-linked" [13] such that, as the aircraft moves through the environment, the symbols undergo the same optical transformations they would if they were actual physical objects out in the world. Visually, the effect is similar to the appearance of raised reflective pavement markers that illuminate the edges and the centerline of a 2-lane highway during nighttime driving.

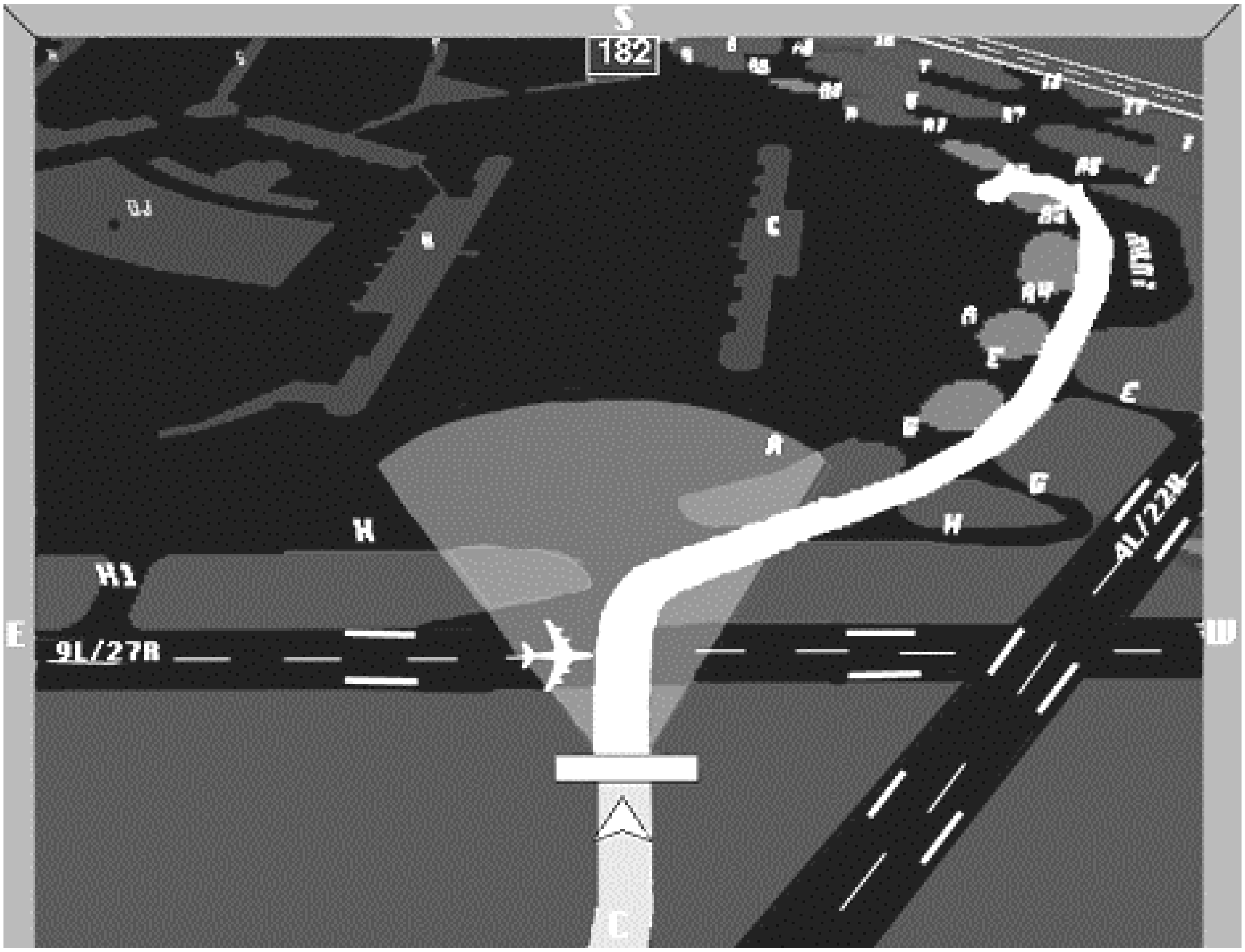

Figure 2. T-NASA EMM, showing the map view from the same location as in Figure 1 (i.e., holding short of Runway 27R/9L on Charlie) at a low zoom level. The ribbon shows the cleared route; the actual colors were magenta, leading up to the stop bar, and yellow (caution) thereafter. Light gray areas were generally green. The wedge-shaped region in front of the ownship symbol highlighted features of the environment than were in, or near, the pilots' forward field of view, such as the A/C taking off on 27R/9L (see Figure 1).

Scene-linked HUD symbology may represent the ultimate ecological display, since the symbols appear to integrate perceptually with the actual OTW scene [14], and they provides a host of intuitive cues to support local guidance. For example, consider an aircraft currently located on a straight section of a cleared taxiway, as in Figure 1. As long as the ownship stays aligned directly with the taxiway centerline, the scene-linked centerline markers will appear to extend outward directly along the pilot's line of sight, just as the actual taxiway centerline does. As soon as the pilot initiates an incorrect turn, however, an angle is created between the pilot's line of sight and the line formed by the centerline markers. At the same time, the side cones quickly drop out of sight, due to the HUD's limited display area. Essentially, the scene-linked symbols turn local guidance from a demanding cognitive operation, in which the pilot constantly has to integrate perceptual features in the OTW scene with either his personal cognitive map or a paper chart, into a purely perceptual exercise of "follow the highway on the ground". In addition, since the scene-linked symbols only outline the cleared route, they provide emergent features relevant to the control of forward speed. For example, if the current straight section is long enough, the cones along the side of the taxiway gradually foreshorten and converge with increasing distance from the A/C. This informs the captain that the current straight section is reasonably long. Eventually, as the A/C proceeds along the taxiway, the symbols veer off to the left or to the right, signaling the distance to, and the severity of, the next turn. These "look-ahead" cues can be useful for maximizing forward speed along the straight sections, and timing the deceleration into the turn [15].

Unfortunately, although scene-linked symbology provides high quality information for local guidance, it provides very little information for global awareness. In principle, a pilot could follow the symbology, and stay on route, while remaining completely ignorant of his actual position on the airport surface, or of any hazards in the vicinity. The other obvious limitation of the HUD display is that it is not available to the First Officer (FO). Thus, the second visual component of the T-NASA system is a panel-mounted electronic moving map (EMM). Shown in

Figure 2, the T-NASA EMM provides a perspective view of the airport surface from a vantage point above and behind the ownship position. This shows the crew the position of the ownship as well as nearby traffic on the airport surface. The "height" of this viewpoint is adjustable, allowing crewmembers to "zoom" in and out of the vicinity of the ownship. Graphical route guidance is provided in the form of a magenta-colored ribbon extending along the cleared taxiway(s).

Whenever a designer decides to support a task with two physically separate displays, the user has to integrate information across the displays. We encountered a similar problem earlier when discussing the processing needed to cognitively align features on a paper chart with the FFOV. To minimize this problem in the T-NASA system, the EMM incorporates a number of features designed to create "visual momentum" between it and both the FFOV and HUD symbology. Most obviously, the selection of the "tethered" perspective keeps the EMM in a "track-up" orientation, the same as the FFOV, thus eliminating the need for mental rotation and other effortful processes. In addition, the prominent "wedge" in front of the ownship symbol highlights elements on the map that are close to, or actually in, the FFOV. This feature has also been shown to improve pilots' ability to associate features on the EMM with the same features in the OTW scene [7].

The tethered viewpoint of the EMM represents a compromise between two opposing considerations. Previous research suggests that global awareness is best supported by a 2-D planned view map in a "North-Up" orientation [7,16]. However, such a display imposes essentially the same cognitive integration demands with the FFOV (and the scene-linked HUD symbology) as a paper chart. On the other hand, a fully ecological display minimizes the integration problem, but does not support global awareness. The "tethered" perspective provides the pilot with considerable information for global awareness, while still maintaining a high degree of visual momentum with the FFOV [8,17,18].

PREVIOUS WORK - A preliminary evaluation of the T-NASA system was recently carried out in a medium-fidelity, part-task simulator [15; see also 5]. Nine commercial airline pilots taxied a simulated B-737 through a series of gate-to-runway departure sequences at Chicago-O'Hare. Taxi speed and navigation accuracy was assessed under three different levels of "in-the-cockpit" navigation support. In the baseline condition, emulating today's taxiing environment, the only navigation aid available was a Jeppesen-Sanderson paper chart of Chicago-O'Hare. In the EMM condition, the paper chart was supplemented by an EMM, similar to the version just described. In the EMM + HUD condition, the pilot had access to the paper chart, the EMM, and the taxi HUD symbology.

The results of the study were straightforward. Compared to the baseline (paper-chart only] condition, pilots taxied .76 kts faster and made 56% fewer errors with the EMM. These results added to a number of earlier studies showing performance benefits with electronic moving map displays [5,19,20,21]. The addition of the taxiway HUD symbology yielded a substantially larger speed increase, 3.2 kts, and virtually eliminated navigation errors.

Unfortunately, two aspects of the part-task simulation facility may have biased the results in favor of the T-NASA displays. As a single-pilot facility, the pilot had no opportunity to support or recover navigation awareness by communicating with his FO, something that is quite common in a two-crew flight deck. It seems plausible that the lack of another crewmember impacted most strongly on the baseline condition, where the effort needed to maintain awareness is greatest. Second, the part-task facility had no side-windows, preventing any left-window or cross-cockpit viewing of the OTW scene. Again, it seems plausible that this restriction would be particularly deleterious to the baseline condition, where reliance on the OTW scene is greatest. If baseline performance was indeed depressed by these factors, T-NASA performance benefits were overestimated.

A HIGH-FIDELITY SIMULATION - To more accurately evaluate the performance benefits associated with the T-NASA system, we recently evaluated the system in NASA-Ames' Advanced Concepts Flight Simulator (ACFS), a two-crew high fidelity simulation environment. The ACFS vehicle model emulates a wide-body, low-wing B757, and the flight deck contains a standard suite of glass cockpit displays as well as a Flight Dynamics HUD. Experienced commercial flight crews participated in a daylong series of simulated autolandings and taxi-sequences at Chicago-O'Hare. As in our earlier study [15], these sequences were carried out under three conditions of navigation support. In the Baseline condition, the crews navigated using only a paper chart of Chicago-O'Hare. In the EMM condition, the paper map was supplemented by the T-NASA EMM, which replaced both the Captain and FOs' Navigation Displays at weight-on-wheels. In the EMM + HUD condition, the Captain had access to both the EMM and the HUD taxi symbology. In all conditions, the pilots were informed of their expected turn-off during final approach, and then were issued a clearance after completing the rollout and turnoff phase.

Prior to this simulation, the T-NASA displays had been evaluated only in low-visibility daytime conditions. Although low visibility can be extremely detrimental to ground operations, weather-related reductions in visibility at ground level are rare, particular at Midwestern airports such as Chicago O'Hare. On the other hand, airports operate under nighttime conditions every day. Darkness brings a unique form of visual degradation to an airport; the OTW view at night may be even more confusing than low-visibility daytime views, due to the “sea of blue” phenomenon caused by taxiway lighting. The full-mission simulation gave us an opportunity to evaluate the effects of T-NASA in night VMC as well as daytime IMC.

T-NASA AND SAFETY - Finally, the ACFS simulation allowed us to take advantage of feedback regarding T-NASA from a recent flight test conducted at Atlanta-Hartsfield airport [1]. The primary theme of the feedback was to encourage us to consider ways in which we might enhance the T-NASA displays so as to improve pilots’ compliance with hold short instructions. In today’s environment, failures to obey such directives are relatively common, and the resulting runway incursions pose a significant challenge to the safety of ground operations. The danger posed by active runway incursions will only grow as the amount of traffic in the terminal area increases. In response, we developed specific hold-short symbology for both the HUD and the EMM, and evaluated its effectiveness in the present simulation by including trials in which the clearance included an instruction to hold short at an active runway.

METHOD

PARTICIPANTS - Thirty-two highly experienced pilots (16 captains and 16 first officers) currently flying a glass equipped Boeing 757, 767, 747-400, or 777 were recruited from commercial airlines. Crews were formed by pairing a Captain and FO of the same aircraft type and airline. The final crew composition consisted of 15 crews from one major airline, and one crew from another. Eight (50%) were 747-400 crews, seven (44%) were 757/67 crews, and one was a 777 crew. Two crews were replaced due to simulator sickness, and one crew was replaced due to equipment failure.

The mean age of the 16 male captains was 53 years (range 44 - 60) and that of the 16 male first officers was 42 years (range 26 – 60. The mean number of hours logged in glass cockpits was 4599 for the captains and 2625 for the first officers. Seven captains and seven first officers reported that they currently fly into Chicago O’Hare on at least a monthly basis.

APPARATUS - NASA’s Advanced Concept Flight Simulator (ACFS), which emulates a wide-body, T-tail, low wing aircraft with twin turbofan engines. The ACFS is configured as a generic commercial transport aircraft equipped with a full six degree-of-freedom motion system. The handling characteristics most closely resemble a B757 with full load. The flight deck, a generic glass cockpit, contains many advanced flight systems, including touch sensitive electronic checklists, programmable flight displays, and graphical aircraft systems schematic (i.e., a surface position indicator). A Flight Safety International VITAL VIIIi image generator, providing a 180-degree field of view with full cross-cockpit viewing capability, generated the out-the-window view.

EMM – The EMM provided the pilots with navigation and situation awareness information such as ownship position on the airport surface, taxi route and hold locations, and the real-time position of other aircraft. The Captain and FO each had their own EMM, which shared display space with the left-and right-side Navigation Displays. On those trials where the EMM was available, the Captain and FO could each independently preview their cleared taxi route in the air by toggling between their Navigation Display and the EMM. In addition, a 2-D planned view representation of the entire airport surface, showing the entire cleared route, was available as an insert in the lower right hand corner of the EMM display. At touchdown, both the left and right side Navigation Displays were replaced by the EMM at an intermediate zoom level. Thereafter, the two pilots had independent control over the zoom level of their own display. The Pilot Input Device normally used to toggle between different modes of the Navigation Display was used to toggle between the overview and perspective modes, to change the zoom level, and to toggle the overview inset on and off.

The EMM supported hold short commands with the following modifications. First, the location of the stop bar was approximately represented on the EMM by a flashing yellow bar. Second, to alert the crew that they weren’t officially cleared to proceed past the hold short point, the ribbon representing the rest of their route was yellow (as in “caution”), rather than magenta. As soon as the hold short was lifted, the flashing bar disappeared, and the cleared route returned to its normal magenta.

Taxi HUD - A Flight Dynamics HUD, consisting of a semi-transparent silvered glass sheet (combiner) measuring 24 cm in height and 20.4 cm in width, was mounted over the left seat. The HUD remained blank until after touchdown, at which point the scene-linked symbology designating the cleared route became visible at the designated turn-off. As shown in Figure 1, The Taxi HUD displayed an array of information designed to increase taxi speed and adherence to the cleared route. The cleared route was displayed in the form of a series of virtual “cones” located along both edges of the cleared taxiway, and a series of small squares arranged along the taxiway centerline. Ground speed was displayed in the upper left-hand corner, and a textual display, designed to promote geographical awareness, appeared in the upper right-hand corner. This information took the form of the triangular arrangement showing the current taxiway/runway name in the lower middle location, and the upcoming taxiway (if any) on the left, up and to the left, and the upcoming taxiway (if any) on the right, up and to the right. Turns were denoted by count down markers 200 feet before the turn, as well as virtual turn signs which indicated the angle of the curve.

The HUD supported hold short commands with the following modifications. First, conformal stop bars were depicted graphically on the HUD; rising directly out

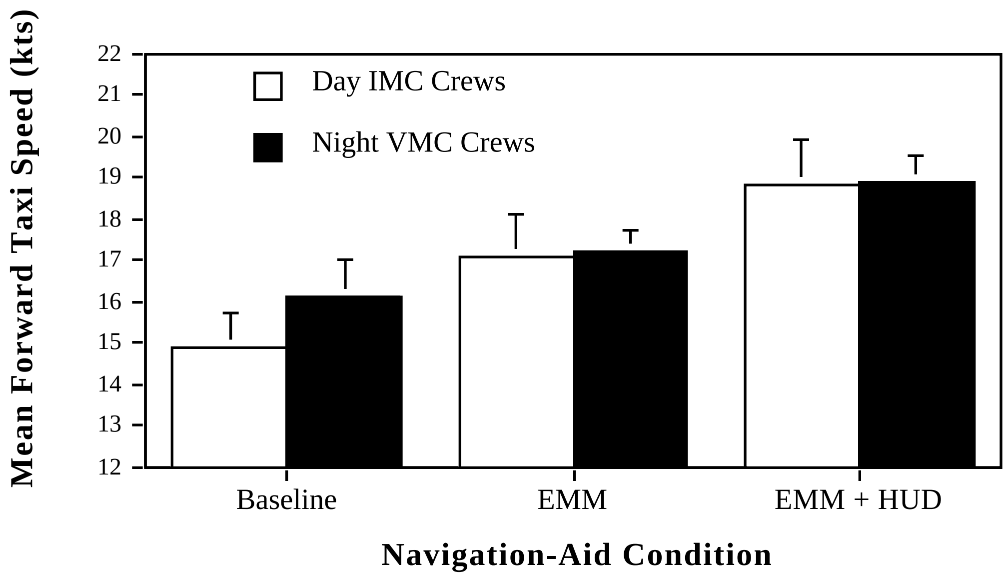

Figure 3. Mean forward taxi speed (kts) as a function of visibility (Day IMC crews vs. Night VMC crews) and navigation-aid condition.

of the stop bar was a virtual stop sign (Figure 1). Second, to alert the pilots that they weren't cleared to proceed past the hold short point, the cones outlining the edges of the cleared route were changed to virtual X's. Pilots were instructed to taxi up to the location of the stop sign/hold bar and then stop. As soon as the hold short was lifted, the stop sign and conformal stop bar disappeared, and the normal cones replaced the X's.

Taxi routes - Twenty-one taxi routes currently used at Chicago O'Hare were recreated in the simulation. To avoid duplication, all major terminals and runways were utilized. The routes averaged .88 NMI in length and required approximately 3 minutes to complete. Four of the 21 routes involved landing on Runway 22R, and then crossing the active runway 27R either via the high speed Charlie exit or at the intersection of 22R and 27R.

Confederate Ground Controllers and Pilots - The realism of the full-mission simulation was enhanced by radio communication provided by a confederate Ground Controller and a Pseudopilot, who played the role of the pilot of other traffic. The Ground Controller provided verbal clearances to the pilots including, after clearing the runway, verbal taxi clearance to the ramp area. Communication between the Ground Controller (GC) and the Pseudopilot over the active radio frequency provided background "chatter" on the active radio frequency, consistent with the movement of the other traffic on the airport surface.

All trials included four to six other aircraft, in close enough proximity to the ownship that they appeared at lower zoom levels on the EMM. These other aircraft were under the control of the confederate ground controller. In the event that a conflict appeared to be developing, the ground controller altered either the speed and/or the course of the other aircraft to avoid the conflict.

EXPERIMENTAL DESIGN - The experiment was a 2 (Visibility condition) X 3 (type of navigation aid available) mixed factorial design. Half of the crews flew all of their trials in Day IMC conditions (RVR = 700 ft); the remainder flew all of their trials in night VMC conditions. Each crew completed 21 trials, seven Baseline, seven EMM, and seven EMM+HUD. Each successive set of three trials included one of each kind of navigation-aid condition. Within each successive triplet, the assignment of navigation-aid condition to trial was randomized separately for each crew. All crews received the same randomly ordered sequence of routes.

PROCEDURE

TRAINING - Prior to their arrival at the center, an information package was sent to each pilot explaining the simulator, the EMM, the Taxi HUD, and procedures for the day of the experiment. On the day of the study, the Captain and FO met with researchers for an initial briefing. The procedures for the day were reviewed, as were details of the EMM and Taxi HUD. It was emphasized that the Captain should taxi as rapidly and accurately as he could, keeping in mind the normal constraints associated with a plane full of passengers, wear and tear on brakes and tires, and fuel conservation. The pilots were told that no set crew roles and procedures were developed for using the T-NASA displays, so they should work it out between them as best as possible.

The crew was then lead through a 90-minute introduction and training session on the simulator. Similarities and differences between the ACFS and other aircraft were discussed. Both pilots completed a manual landing and taxi with the EMM and the HUD. This gave the FO an opportunity to see the information that was available to the Captain on the HUD.

EXPERIMENTAL TRIALS - Before each trial, the experimenter informed the pilots of the landing runway and concourse assignment. Each trial began on final approach, approximately 12 miles from Chicago O'Hare, at 3000 AGL, with wings level. While airborne, the aircraft was under the control of an autoflight system (AFS) which consists of the Autopilot Flight Director System (AFDS) and the Auto Throttle System (ATS). The flight management computer automatically controlled the pitch, roll and thrust through simultaneous control of the AFDS and the ATS. The aircraft was on autopilot up to and including weight-on-wheels to ensure that all crews touched down at the same point on the runway. Shortly after weight-on-wheels, control of the aircraft was given over to the Captain, who commenced braking for rollout and turn off.

During final approach, the GC communicated the expected exit from the runway. Immediately after turning off on this exit, the crew contacted ground control, and was provided with a verbal clearance to the destination concourse. The route guidance information was also provided on the EMM and the HUD, when those navigation aids were available. Pilots were asked to follow the cleared route to the designated concourse as safely, quickly, and accurately as possible. The trial ended on the apron area in front of the concourse.

After each trial, both pilots were asked to complete a short questionnaire to assess their workload and situational awareness. At the completion of the experiment, both crewmembers completed a post-experiment questionnaire, giving them an opportunity to express their opinions of the T-NASA system. The day finished with a structured debriefing, during which pilots were asked to comment on how these technologies could be used in the actual environment, how T-NASA technologies could be trained and standardized most effectively, and what modifications to existing standard operating procedures may be required.

RESULTS

The simulation provided a wide variety of measures that fall roughly into three categories. The first category, taxi efficiency, encompasses measures such as taxi speed, route-following accuracy, route completion time, and subjective assessments of the impact of the T-NASA components on taxi efficiency. The second category includes objective and subjective measures assessing the impact of T-NASA on navigation awareness and workload. The third set of measures pertains to safety-related issues, most particularly the effects of the T-NASA symbology on hold short directives. We start with measures of taxi efficiency. In these and all subsequent analyses, the first three trials were considered practice, and were omitted.

Taxi speed - Taxi speed was recorded at a rate of 30 Hz. These values were then averaged to arrive at a mean forward taxi speed for each trial. Average taxi speed for Day IMC and Night VMC crews is shown in Figure 3 as a function of navigation-aid condition. It is clear in the figure that taxi speeds were quite similar across the two visibility conditions, $F(1, 14) < 1$, but were affected quite strongly by navigation-aid condition, $F(2,28) = 42.9$, $p < .001$. Compared to the baseline condition, Day IMC captains taxied an average of 2.2 kts faster when the EMM was available and 3.9 kts faster when the EMM and HUD symbology were available. The corresponding values for the Night VMC captains were 1.1 and 2.7, respectively. The interaction between navigation-aid condition and visibility was not significant, $F(2,28) < 2$. Planned comparisons revealed that the difference between the EMM and baseline condition was significant, $F(1,14) = 20.5$, $p < .001$, as was the difference between EMM and EMM+HUD conditions, $F(1,14) = 25$, $p < 001$.

Route-following accuracy - To evaluate navigation accuracy, three "occupancy zones" were designated (5). Zone 1 included an area 2 m on either side of the centerline of the cleared taxiway; Zone 2 included an area within 11 m of either side of the Zone 1 boundary; Zone 3 included all remaining locations on the airport surface. Navigation errors were recorded whenever the center of gravity of the airplane intruded into Zone 3. Using a simulator replay function and video playback, these errors were then inspected and classified into two categories. The first category, major error, indicated a loss of navigation awareness that lead to either a wrong turn, or a failure to turn. The second category, minor error, encompassed local failures to remain on route that the Captain corrected quickly. Examples of minor errors are overshooting a turn, and starting to make a wrong turn but then correcting it immediately.

Figure 4 shows the percentage of trials on which a navigation error was recorded, broken out by type of error (major vs. minor), visibility condition (night VMC crews vs. day IMC crews) and navigation-aid condition (EMM + HUD condition excluded; see below). One obvious pattern is the higher number of errors in clear night conditions than in low-visibility day conditions. This result is interesting but, since separate crews were assigned to these conditions, it is not clear whether the effect is truly due to visibility, or to crew differences (in fact, one of the eight night crews was responsible for 31% of the major errors). At any rate, the main effect of visibility condition was not significant, $F(1,14) = 1.56$. More germane to present concerns is the dramatic reduction in errors between the Baseline and the EMM condition, particularly in the major error category. The main effect of navigation-aid condition was significant, $F(1,14) = 11$, $p < .01$, as was the main effect of error

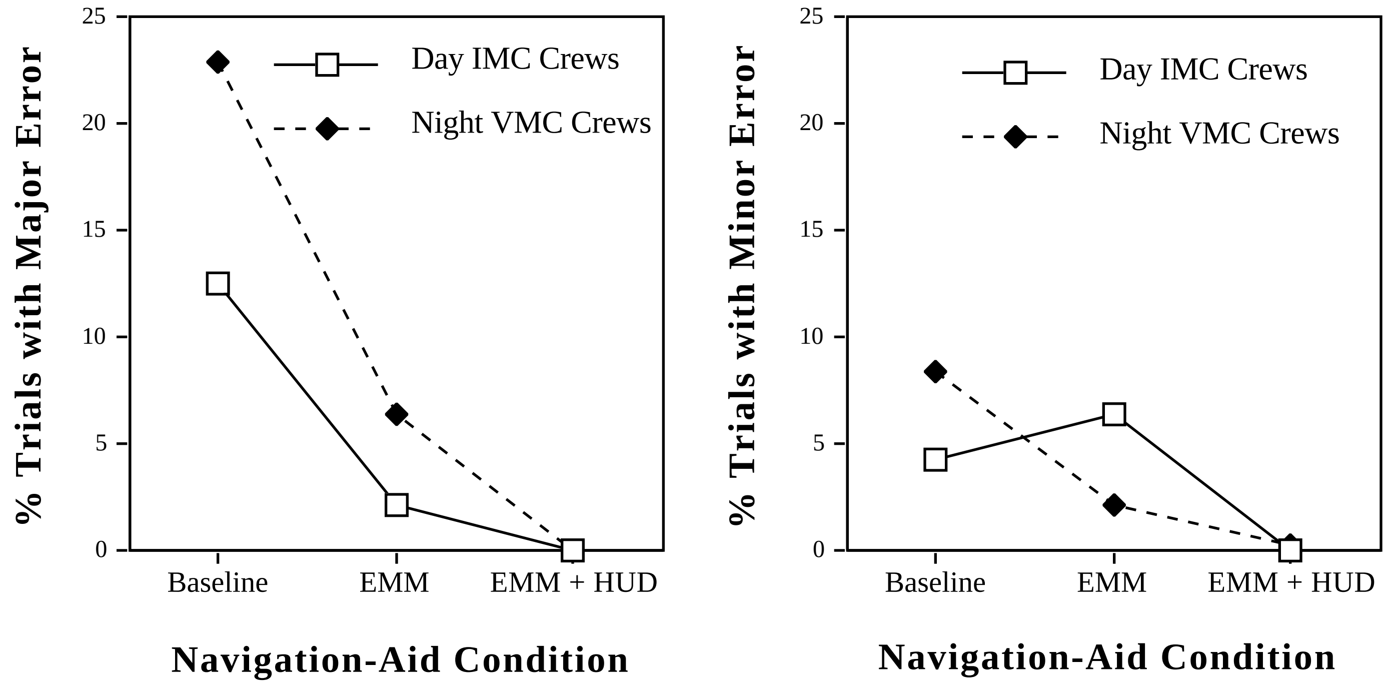

Figure 4. Navigation errors as a function of error type (Major vs. Minor) and navigation-aid condition.

classification, $F(1,14) = 6.52$, $p < .05$. The interaction between these variables was also significant, $F(1,14) = 5.5$, $p < .05$, reflecting the fact that the EMM reduced major errors to a greater extent than minor errors. Importantly, there was a further error reduction in the EMM + HUD condition: indeed, we omitted this condition from the ANOVA because, over the course of almost 100 EMM + HUD trials, only a single minor error was recorded.

Upon completing the simulation, pilots rated on a scale from 1 (not at all) to 5 (very much) how beneficial each T-NASA configuration was towards their ability to accurately navigate on the airport surface. These data were then averaged and submitted to an ANOVA with crew category (Captain vs. FO) and visibility condition (Day IMC vs. Night VMC) as between-subjects factors, and navigation-aid condition as a within-subjects factor. Consistent with the objective data, there was a large main effect of navigation-aid condition, $F(2, 56) = 72.84$, $p < .001$, with pilots rating the EMM (M = 4.6) and the EMM + HUD (M = 4.7) much higher than the paper map alone (M = 3.0). No other main effects or interactions were significant. Planned comparisons revealed a significant difference between the Baseline and EMM conditions, $F(1,28) = 100.6$, $p < .001$. and between the Baseline and EMM+HUD conditions, $F(1,28) = 85.8$, $p < .001$.

Route Completion Time – Navigation errors, particular major errors, typically add a considerable amount of time to reach the intended destination [5]. This is not surprising, given that the crew must first realize they are off course, recover enough navigation awareness to plot a return to the clear route, and then make their way back. Obviously, route completion time is also sensitive to the forward speed at which the pilot taxis the aircraft. Thus, route completion time can be viewed as a composite measure of the impact of the T-NASA displays on taxi efficiency. Figure 5 shows the average route completion time, measured from approximately the start of turnoff to arrival at the correct apron area. It is clear from the figure that route completion times were quite similar across the two visibility conditions, $F(1, 14) < 1$, but were affected quite strongly by navigation-aid condition, $F(2,28) = 13.2$, $p < .001$. Compared to the baseline condition, Day IMC crews completed their routes 21 sec faster when the EMM was available, and 45 sec faster when the EMM and HUD symbology were available. The corresponding values for the Night VMC crews were 22 and 45 sec, respectively. The interaction between navigation-aid condition and visibility was not significant, $F(2,28) < 1$. Planned comparisons revealed that the EMM condition was significantly different from the Baseline condition, $F(1,14) = 7.89$, $p < .02$, and the EMM+HUD condition was significantly different from the EMM condition, $F(1,14) = 13.2$, $p < .005$. Thus, as with forward speed and accuracy, the EMM and HUD made separate contributions to reducing taxi time.

After completing the simulation, pilots were asked to rate the contribution of the paper chart, the EMM, and the EMM + HUD combination to overall taxi efficiency on a five point scale from 1 (not at all) to 5 (very much). Consistent with the empirical data, the EMM (M = 4.6) and the EMM + HUD (M = 4.8) were rated higher than the paper map (M = 2.7), $F(2,56) = 118.83$, $p < .001$. The pilots were presented with a list of possible reasons that taxiing might be more efficient with T-NASA configurations. They responded that the EMM was particularly advantageous because it gave them a greater

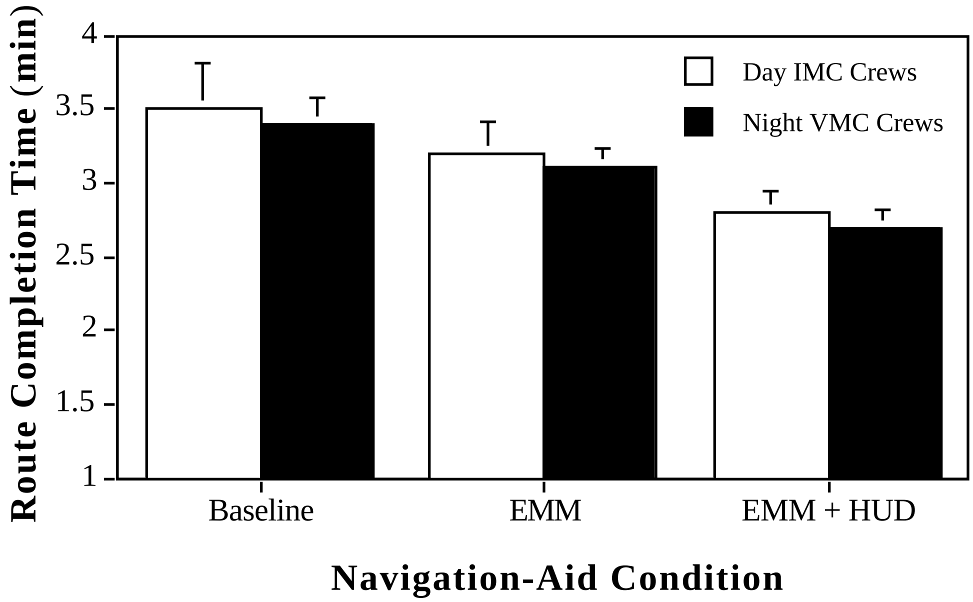

Figure 5. Route completion time (min) as a function of visibility (Day IMC crews vs. Night VMC crews) and navigation condition.

awareness of route, greater confidence in their position on the airport surface, produced more efficient communication between crewmembers, and reduced the time required to plan the route. The HUD was judged to be advantageous in reducing the number of times pilots needed to stop along the route for directions, and reducing time spent at confusing intersections.

NAVIGATION AWARENESS AND WORKLOAD - The simulation yielded two measures of navigation awareness. One measure, which indicated navigation awareness of the captains, was the number of questions (e.g., “Where’s the turn?”) and statements of uncertainty (e.g., “I’m not sure if this is Charlie”) that the captains directed to the first officers. This was ascertained by the online field coding method SYMLOG [22]. The number of these acts coded by an online observer correlated .88, $p < .001$, with a later count of these acts by another observer who watched and heard videotapes of the trials. Figure 6 shows the average number of communications acts as a function of navigation-aid condition and visibility. As shown in the figure, these acts were relatively frequent in the Baseline condition, considerably less frequent in the EMM condition, and even more infrequent in the EMM + HUD condition. An ANOVA with visibility condition and navigation-aid condition as factors revealed a large main effect of navigation-aid condition, F (2,28) = 50.3, p < 001. Planned comparisons revealed that the EMM condition differed significantly from the Baseline condition, $F(1,14) = 43.9$, $p < .001$, and from the EMM+HUD condition, $F(1,28) = 17.6$, $p < .001$.

The pilots also rated their navigation awareness after every trial. On a scale from 1 (very low) to 5 (very high), they rated the following five dimensions: Overall Awareness, Taxi Route Awareness on Final Approach, Taxi Route Awareness while Taxiing, Awareness of Other Aircraft, and Awareness of Direction of Travel. The mean of the five dimensions was calculated to form a composite Navigation Awareness score for each trial. These scores were submitted to an analysis of variance (ANOVA) with crew position (Captain vs. FO), visibility (Day IMC vs. Night VMC) and navigation-aid condition as factors. Pilots rated their navigation awareness much lower in the Baseline condition (M = 3.14) than in the EMM (M = 4.16) and the EMM + HUD (M = 4.28) conditions. An ANOVA revealed a large main effect of condition, $F(2, 56) = 66.74$, $p < .001$. Planned comparisons revealed that the difference between the Baseline and EMM conditions was significant, $F(1,28) = 71.59$, p<.001, as was the difference between the EMM and the EMM+HUD conditions, $F(1,28) = 17.98$, $p < .001$.

Finally, at the end of each trial pilots also rated their perceived workload on seven dimensions. These dimensions, slightly modified versions of the NASA TLX scales [23], consisted of Overall Workload, Mental Demand, Time Demand, Visual Demand, Communication Demand, Stress, and Effort. As with navigation awareness, the scale ranged from 1 (very low) to 5 (very high). The mean of these seven dimensions was calculated to form a Composite Workload Score for each trial.

Averaging across trials, workload was rated slightly higher by the day IMC crews (M=2.6) than by the night VMC crews (M=2.2), $F(1, 28) = 3.99$, $p < .06$. Once again, there was a highly significant effect of navigation-aid condition, $F(2,56) = 77.5$, $p < .001$, with workload being rated considerably higher in the Baseline

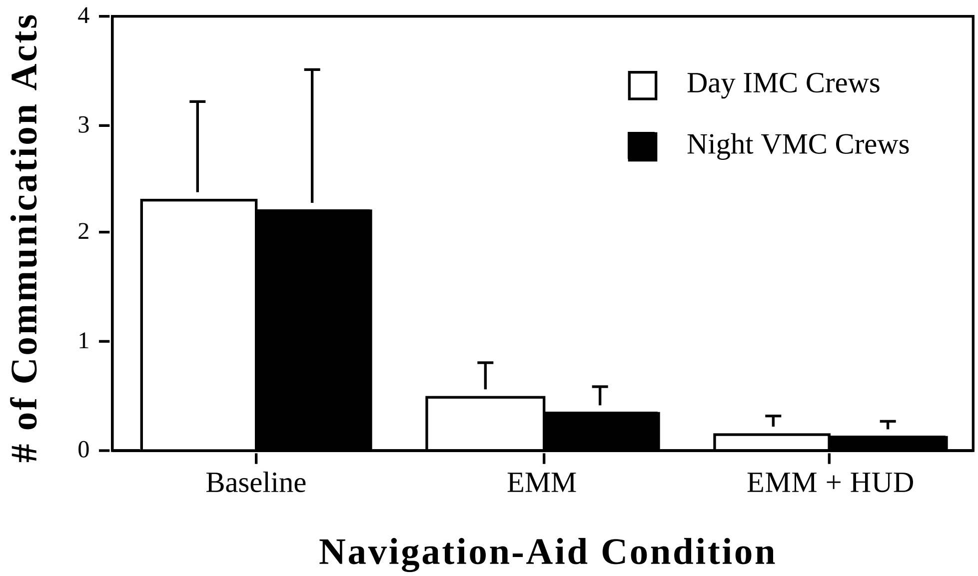

Figure 6. Mean number of communication acts (questions and statements of uncertainty) directed to the FO from the Captain, as a function of visibility (Day IMC crews vs. Night VMC crews) and navigation-aid condition.

condition (M = 3.2) than in the EMM (M = 2.11) or the EMM+HUD condition (M = 1.99). No interactions approached significance. Planned comparisons revealed that the EMM condition differed significantly from the Baseline condition, $F(1,28) = 82.63$, $p < .001$. The difference between the EMM and the EMM+HUD conditions, while quite small, was also significant, $F(1,28) = 12.27$, $p < .005$.

SAFETY MEASURES - Four of the 18 experimental trials involved landing on Runway 22R/4L and holding short of runway 27R/9L, either at the intersection of the two runways, or on turnoff taxiway Charlie (Figure 7). The pilots' level of compliance with hold short commands was the primary measure of the impact of the T-NASA displays on ground safety. Real time observations, and video and simulator replay capabilities, were used to examine each crew's performance at the appropriate hold bar. In the baseline condition, one of the 16 crews failed to obey the instruction to hold short at the intersection of 22R/4L and 27R/9L, representing a 6% noncompliance rate. In addition, the hold short of 27R/9L on Charlie produced particularly interesting performance. As illustrated in Figure 7, Charlie has two stop bars, one to hold departing planes short of 22R/4L, the other to hold arriving planes short of 27R/9L. In the present study, the crews were told to exit 22R/4L on Charlie and hold short of 27R/9L, so the correct set of hold bars was the second set. Nevertheless, in the Baseline condition four crews (25%) stopped at the initial (incorrect) stop bar, leaving part of their aircraft hanging out over 22R/4L until they realized the error. None of the crews made this error in the EMM or the EMM + HUD conditions.

Following the study, pilots were asked to rate on a scale from 1 (not at all) to 5 (very much) how beneficial each navigation aid (or combination of aids) was to their ability to safely taxi the aircraft. Analyses of these ratings revealed a large main effect, $F(2, 54) = 49.16$, $p < .001$, with pilots rating the EMM (M = 4.4) and the EMM + HUD (M = 4.7) considerably higher than the Baseline (M = 3). Planned comparisons revealed that the difference between the Baseline and the EMM conditions was significant, $F(1,27) = 60.77$, $p < .001$, and the difference between the EMM and the EMM+HUD conditions was marginally significant, $F(1,27) = 3.7$, $p < .07$.

DISCUSSION

As the commercial aviation industry approaches the end of the 20th century, it faces a variety of pressures. Delays in airlines' schedules are commonplace, and are often caused by a shortfall between the amount of traffic and the airport's traffic-handling capacity. These shortfalls, and the accompanying delays, are expected to increase in the next decade, as traffic volume grows by an expected 30%. At the same time, there is growing concern over the fact that if the current rate of airline accidents is maintained, the absolutely frequency of airline accidents will increase along with the volume.

One way to relieve these pressures is to exploit new and emerging technologies to bring new forms of flight-relevant information onto the flight deck. The idea is that pilots would use this information to fly more efficiently and safely under a wide range of weather conditions, increasing the capacity of existing airports and at the same time reducing the accident rate.

However, as we noted in the introduction, developing the infrastructure to provide this information is not a trivial enterprise. It will not happen unless industry can be convinced that displaying new information produces enough improvement in pilot performance to significantly impact the efficiency of airspace operations.

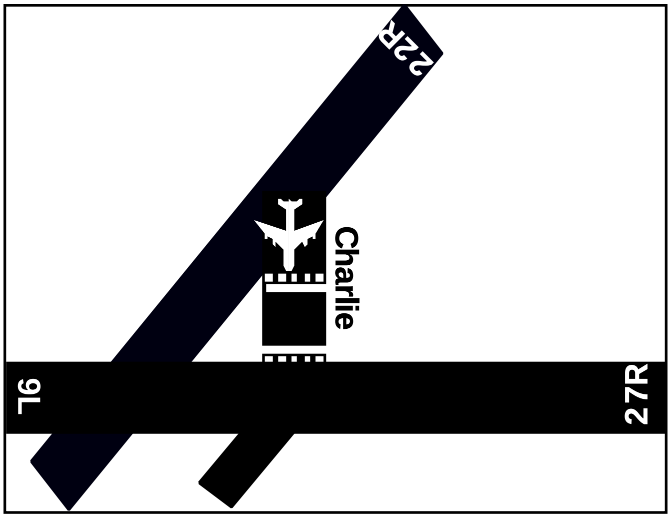

Figure 7. Idealized depiction of the Chicago-O'Hare layout in the vicinity of Taxiway Charlie (not to scale). The ownship is shown holding short of the incorrect stop bar.

According to the pilots who took part in our simulation, navigating around the surface of a complex airport is the most difficult part of their job, particularly in reduced visibility conditions. According to our analysis, the difficulty stems largely from the fact that wayfinding, even in modern glass cockpit aircraft, is accomplished in the same way it was 50 years ago – without any sort of in-the-cockpit aid other than an old-fashioned paper chart. Navigation awareness is often difficult to maintain under these circumstances, and loss of navigation awareness can have a serious impact on taxi efficiency and the safety of ground operations.

Surface operations provide an ideal area of operations within which to explore the effects of displaying new forms of information on the flight deck. In an attempt to optimize the impact of the information, we applied a human-centered design philosophy, beginning with a model of the information processing components of ground taxi. Key to the model is the notion of navigation awareness, the feeling of spatial well being that occurs when the flight crew knows where their aircraft is in relation to the cleared route (supporting local guidance), where the aircraft is in absolute space, and some knowledge of the surrounding environment.

The T-NASA system was designed to supply the flight-crew with the information they need to maintain navigation awareness through an integrated system of cockpit displays. The system frees the crew from relying on the OTW view, protecting navigation awareness from disruptions due to low visibility or missing or confusing surface markings. Furthermore, the system was designed to support navigation awareness with a great deal less cognitive effort than the effort needed in today's environment. Using "scene-linked" HUD symbology and graphical route guidance on the EMM, we changed local guidance from a task that requires effortful cognitive processing to a task that can be carried out with little more than low-level perceptual analyses. In addition, we attempted to minimize the effort needed to cognitively integrate the OTW view and the HUD symbology with the EMM display, by adopting a "tethered" perspective view for the EMM, and including EMM features such as a wedge that highlights map features that are also in the FFOV.

By tying the design of the T-NASA system so closely to the information processing associated with ground taxi, a straightforward conceptual framework is created within which to consider the results of the present experiment. T-NASA was designed to support a high level of navigation awareness with a minimum of effortful processing. Thus, we should have found that the T-NASA displays yielded higher navigation awareness coupled with lower workload. If the displays were successful in eliminating losses of navigation awareness, we should have reduced performance impairments associated with the loss of navigation awareness, such as route-following errors and reductions in taxi speed. These effects should have combined to produce substantial reductions in total taxi time.

The results of the simulation were right in line with this framework. Both objective and subjective measures indicated that pilots had a much higher level of navigation awareness with the T-NASA system than without it. Workload was also judged to be significantly reduced. These effects were accompanied by large improvements in taxi efficiency. When the captains had access to both the EMM and the HUD, they taxied 20% faster than in the baseline (paper-chart only) condition. Virtually no navigation errors were committed, despite the fact that exactly the same routes, and the same visibility conditions, yielded mean error rates as high as 22% without the T-NASA displays. And last but not least, the combination of faster speed and improved accuracy reduced the average total taxi time by approximately 20%, or almost three quarters of a minute.

ECONOMIC BENEFITS – Based on this simulation's estimates of performance improvement with the T-NASA system, the system would be expected to yield significant savings in fuel costs. This is partly due to the absolute reduction in taxi time, but also to the fact that T-NASA virtually eliminates fuel-wasting slowdowns and/or stoppages due to loss of navigation awareness. With civil transport fuel costs of approximately $50/min, and with direct taxi reduction time (arrival and departure total) of 1.5 min per flight, the savings per airport/airline would be large (it is likely that this taxi reduction time is a low estimate, since the routes chosen in this simulation, although actual routes, were shorter than average for simulator reasons). In their debriefing, a number of pilots commented on the fuel-saving implications of the fact that T-NASA allowed them to better manage the deceleration dynamics on the runway, reducing the incidence of premature deceleration. Another economically noteworthy aspect of the simulation results is that T-NASA delivered virtually identical improvements in taxi efficiency in day IMC and night VMC conditions. A large fraction of the airport operations of an airport such as Chicago O'Hare takes place at night, particularly in the winter months. These results strongly suggest that T-NASA can have a positive impact on a much larger portion of ground operations than just driving during low-visibility daytime conditions.

MAP VS HUD – The T-NASA system was designed as an integrated display system. The functionality of the HUD symbology complements and extends the functionality of the EMM, and vice versa. However, it is clearly much less costly to equip a glass cockpit aircraft with an EMM than it is to install the full T-NASA system, unless the aircraft is already outfitted with a HUD. Thus, at least initially, EMM's are likely to reach commercial aircraft in far greater numbers than the full T-NASA system. We have the following observations about this. First, it is clear from the results of this study that the T-NASA EMM would be of great benefit to ground operations even without the HUD. Many crews summarized their views of the relative merits of the two displays as the EMM being the cake and the HUD being the frosting. At the same time, however, the HUD did yield a considerable improvement in efficiency relative to the EMM alone. This improvement stems from two sources. First, the HUD provides route guidance in a form that enables the pilot to maximize forward taxi speed, particularly on straight sections of the route. Second, navigation errors continued to be committed in the EMM condition; it took the EMM plus the HUD to eliminate them (virtually) completely. Inspection of the video tapes revealed that most of the errors in the EMM condition occurred at the highest-workload phase of taxi, right after the aircraft had exited the runway and while the FO was receiving the ground clearance. In this situation, the FO was typically paying attention to ground control rather than to the EMM, and the pilot was eyes out, steering the aircraft. When the OTW scene encompassed a taxiway intersection, there was often a confusing plethora of taxiway centerlines, and the pilot would make an incorrect choice as to which centerline to follow. Since neither crewmember was attending to the EMM at this time, the error was not caught right away. In contrast, when the captains had access to the taxi HUD symbology, the centerline/sideline symbols naturally disambiguated the correct and incorrect centerlines, preventing an error.

SAFETY IMPLICATIONS – The safety implications of the T-NASA system, while less easy to evaluate for their economic impact than the efficiency measures, are nevertheless important to the bottom line. The decrease in workload, together with the increase in reported navigation awareness, are likely to improve the ability of the pilot and copilot to recognize and avoid hazardous situations. Indeed, one of the most common themes of the pilots during debriefing was the great value they saw in seeing other airport traffic on the EMM. One pilot pointed out how useful this would be at LAX even in daytime VMC, since the angle of the taxiways prevents the crew from having a clear view of the traffic on the departure runway. Furthermore, the T-NASA displays yielded perfect compliance with hold short commands, something that was not observed in the baseline condition, and is certainly not observed in the real world. Indeed, after a period in the early 1990's, when the number of reported runway incursions remained fairly steady at around 200 per year, they appear to be on the increase again, reaching 287 in 1996. The results of our simulation suggest that, if installed on commercial aircraft, T-NASA would virtually eliminate the incursion problem.

CONCLUSION

The airline industry is facing important decisions regarding whether or not to invest in advanced technologies to bring new forms of flight-relevant information into the flight deck. The development and evaluation of the T-NASA system provides an illustrative example of how innovative displays, carefully designed from a human-centered approach, can indeed yield dramatic improvements in pilot performance. There is clearly considerable potential for new forms of information display to impact the safety and efficiency of commercial airline operations.

ACKNOWLEDGMENTS

We gratefully acknowledge the staff of the ACFS facility, particularly Don Bryant, Matthew Blake, Anna Dabrowski, Dave Brown, Elliott Smith, and Ian MacLure, for their support of this research. We also thank Steve Elkins and Dominic Wong, Sterling Software, for programming assistance.

REFERENCES

1. Young, S. D., & Jones, D. Flight testing of an airport surface guidance, navigation, and control system. *Proceedings of the Institute of Navigation's National Technical Meeting*, January 21-23, 1998.

2. Fadden, S., & Wickens, C. D. (1997). Improving traffic awareness with a head-up flight path highway display. In R. S. Jensen and L. Rakavan (Eds.), *Proceedings of the Ninth International Symposium on Aviation Psychology.* (pp. 329-333). Columbus, OH: Ohio State University.

3. 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.

4. Andre, A. D. (1995). Information requirements for low-visibility taxi operations: What pilots say. In R. S. Jensen and L. A. Rakovan (Eds.), *Proceedings of the Eighth International Symposium on Aviation Psychology* (pp. 484-488). Columbus, OH: The Ohio State University.

5. McCann, R. S., Foyle, D. C., Andre, A. D., & Battiste, V. (1996). Advanced navigation displays in the flight deck: Effects on ground taxi performance under low-visibility conditions. *SAE transactions: Journal of Aerospace*, *105*, 1419-1430.

6. Jeppesen-Sanderson (1990). *Private Pilot manual* (Fifth Ed.). CO: Jeppesen-Sanderson.

7. Aretz, A. J. (1991). The design of electronic map displays. *Human Factors*, 33, 85-101.

8. Wickens, C. D., & Prevett, T. (1995). Exploring the dimensions of egocentricity in aircraft navigation displays. *Journal of Experimental Psychology*: *Applied*, *1*, 110-135.

9. Battiste, V. (1993). Geographic orientation. In B. Huey and C. Wickens (Eds.), *Workload transition: Implications for individual and team performance* (pp. 171-190). Washington, DC: National Academy Press.

10. Mainwaring, S. D. (1991). *Information integration in cognitive maps: Conceptual analysis of Dissertation Area*. Stanford University: Unpublished manuscript.

11. Warren, R., & Wertheim, A. H. (Eds.). *Perception and the control of self-motion*. Hillsdale, NJ: Erlbaum.

12. Olmos, O., Liang, C., & Wickens, C. D. (1997). Electronic map evaluation in simulated visual meteorological conditions. *International Journal of Aviation Psychology*, *7*, 37-66.

13. Foyle, D. C., Ahumada, A. J., Larimer, J., & Sweet, B. T. (1992). Enhanced/synthetic vision systems: Human factors research and implications for future systems. *SAE Transactions: Journal of Aerospace*, *101*, 1734-1741.

14. Foyle, D. C., McCann, R. S., & Shelden, S. G. (1995). Attentional issues with superimposed symbology: Formats for scene-linked displays. In R. S. Jensen and L. A. Rakovan (Eds.), *Proceedings of the Eighth international symposium on Aviation Psychology*, 98-103. Columbus, OH: Ohio State University.

15. McCann, R. S., Andre, A. D., Begault, D., Foyle, D. C., & Wenzel, E. (1997). Enhancing taxi performance under low-visibility: Are moving maps enough? *Proceedings of the 41st annual meeting of the Human Factors and Ergonomics Society*, *37-41*. Santa Monica, CA: Human Factors and Ergonomics Society.

16. Harwood, K., & Wickens, C. D. (1991). Frames of reference for helicopter electronic maps: The relevance of spatial cognition and componential analysis. *International Journal of Aviation Psychology*, *1*, 5-23.

17. Andre, A. D., Wickens, C. D., Moorman, L., & Boschelli, M. M. (1991). Display formatting techniques for improving situation awareness in the aircraft cockpit. *International Journal of Aviation Psychology*, *1*, 205-218.

18. Mejdal, S., & Andre, A. D. (1996). An evaluation of electronic map display features for aircraft ground navigation. *Proceedings of the Silicon Valley Ergonomics Conference and Exposition* (pp. 43-52). San Jose, CA: Silicon Valley Ergonomics Institute.

19. Batson, V. M., Harris, R. L., & Hunt, P. J. (1994). Navigating the airport surface: Electronic vs. paper maps. *Proceedings of the 13th Digital Avionics Systems Conference (pp. 515-520)*. IEEE/AIAA: Cambridge, MA.

20. Battiste, V. Downs, M., & McCann, R. S. (1996). Advanced taxi map display design for low-visibility operations. *Proceedings of the Human Factors and Ergonomics Society 40th annual meeting (pp. 997-1001)*. Santa Monica, CA: Human Factors and Ergonomics Society.

21. Zimmerman, S. L. (1994). Development and test of a pilot display for surface operations. *Proceedings of the SAE Aerotech 94 Conference*. Warrendale, PA: SAE.

22. Bales, R. F., & Cohen, S. P. (1979). *SYMLOG: A system for the multiple level observation of groups*. NY: The Free Press.

23. Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In P. A. Hancock and N. Meshkati (Eds.), *Human Mental Workload* (pp. 139-183). North Holland: Elsevier Science Publishers B. V.