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FIELD EVALUATION OF T-NASA: TAXI NAVIGATION AND SITUATION AWARENESS SYSTEM

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Abstract

This paper reports the results of a field evaluation of an advanced taxi navigation and situation awareness (T-NASA) system, aimed at improving the efficiency of aircraft ground taxi operations under low-visibility conditions. T-NASA consists of two main components: 1) a panel-mounted electronic taxi map display and 2) a heads-up scene-linked display (HUD). These components were installed in NASA's B-757 research aircraft and flight tested at Atlanta's Hartsfield International Airport. The results clearly demonstrated both the feasibility and effectiveness of the T-NASA system towards improving the efficiency of airport taxi operations. In addition, as a direct result of the evaluation, improvements were made to the design and procedures of the T-NASA system.

Introduction

Over the last five years, researchers at the NASA Ames Research Center have been involved in the development of an advanced taxi navigation and situation awareness system, called T-NASA. T-NASA was developed as part of the Low Visibility Landing and Surface Operations (LVLASO) element of NASA's Terminal Area Productivity (TAP) program, aimed at developing technology and procedures for improving the capacity, efficiency and safety of aircraft surface movements during the roll-out, turn-off and taxi in/out phases. More specifically, the goal of the program is to enable safe VMC surface movement capacities in IMC conditions down to 300' runway visual range (RVR). T-NASA attempts to accomplish this goal by providing the pilot (and ultimately the controller) with advanced navigation displays that provide information on ownship position and ground speed, traffic and other obstacles, and the path of the cleared taxi route.

Much has been previously published concerning the objectives of the LVLASO program, the development of T-NASA, and the results of various experiments and simulations aimed at determining the utility and usability of the T-NASA system.[1][2][3] However, while these studies provided valuable data towards the utility of T-NASA relative to the taxi displays

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[1] Andre, A.D. (1995). Information requirements for low-visibility taxi operations: What pilots say. *Proceedings of the 8th International Symposium on Aviation Psychology*, pp. 484-488, Columbus, OH.

[2] Foyle, D., Andre, A., McCann, R., Wenzel, E., Begault, D., and Battiste, V., "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, v105, pp. 1411-1418, 1996.

[3] McCann, R.S., Foyle, D.C., Andre, A.D. and Battiste, V. (1996). Advanced navigation aids in the flight deck: Effects on ground taxi performance under low-visibility conditions. SAE Transactions: Journal of Aerospace, 105, 1419-1430.

currently available to pilots (i.e., paper taxi charts), they were conducted under conditions and constraints that did not allow for an accurate assessment of the impact of T-NASA relative to the operational goals of the LVLASO program.

Accordingly, the objectives of this flight test were: 1) to demonstrate that the T-NASA system, and the required supporting technology infrastructure, can be implemented at a major airport facility, 2) to validate the utility of the T-NASA system in the context of normal handling conditions at a major airport facility, and 3) to determine necessary changes in the design or use of the T-NASA system.

T-NASA Description

As evaluated here, T-NASA consists of two main components: 1) a panel-mounted electronic moving map display and 2) a HUD.

Taxi Map

The taxi map is a secondary display intended to provide pilots with navigation and situation awareness information in a heads-down moving map format. It is not designed to support inner-loop control of the aircraft. The taxi map used in the Atlanta Flight Tests, seen in Figure 1, had the following features:

View of airport layout. The taxi map provided two viewing modes of the airport layout: 1) a track-up, perspective mode that rotated around the fixed aircraft symbol, and 2) an overview mode, which presented a north-up fixed view of the entire airport. Using the pilot input device (PID), pilots could select either view. Also, within the track-up view, pilot's could select from five zoom levels (5x, 4x, 3x, 2x, 1x) which each provided increasingly greater levels of visual detail.

Ownship position. The position of the NASA B-757 was updated on the taxi map at a rate of ~25 Hz. It was marked with a white triangle centered 1/3 up from the bottom of the

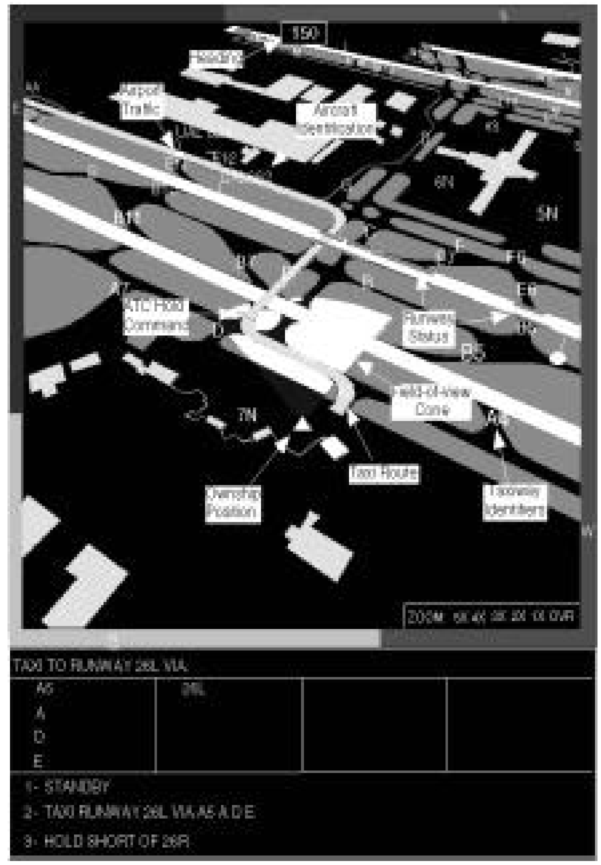

Figure 1. Taxi Map Display.

map. This icon was highlighted by a white arc or "wedge" in front of the triangle icon that highlighted the area of the map most important to the pilot; that is the area directly in front of the aircraft's path.

Airport traffic. Other aircraft were identified as white circular symbols and were labeled with their aircraft call numbers extending out from the aircraft symbol on a virtual flag pole. Pilots had the option to toggle aircraft labels on and off. Airport ground traffic was updated at ~1 Hz.

Hold bars. The taxi map displayed two types of hold bars. Hold instructions sent from ground control (GC) were designated using a red bar surrounded by a yellow border. The second type of hold bar was presented when another aircraft was taxiing on a runway. In this case, the map presented red hold bars across each taxiway that intersected the occupied runway.

Route guidance. The taxi map also presented route guidance information. The cleared path was painted magenta to be consistent with the existing cockpit symbology.

Clearances and messages. A text box underneath the map presented the GC instructions including the taxi route. Small pointers (<<, >>) on either side of the taxiway or runway name, indicated the aircraft's current position.

Heading bars. A moving frame rotated around the perimeter of the map representing the four compass directions. Each direction was represented as a uniquely colored bar.

Taxi HUD

The HUD displayed airport surface information and was intended to increase taxi speed and route navigation accuracy in low visibility conditions. The HUD was intended as a primary ground navigation display to be used in conjunction with the taxi map. The taxi guidance information was generated by the LVLASO software system. All information on the HUD was updated at ~25 Hz. The taxi HUD provided three dimensional scene-linked symbology to the left seat crew member during taxi. The HUD symbology is conformal in that it directly overlays elements that exist in the environment, but may be difficult to see under low-visibility conditions. The HUD symbology used in the Atlanta flight tests, presented in Figure 2, had the following features:

Taxi 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. Virtual road signs indicated the location and degree of turns.

Location information. The HUD also displayed information regarding the current

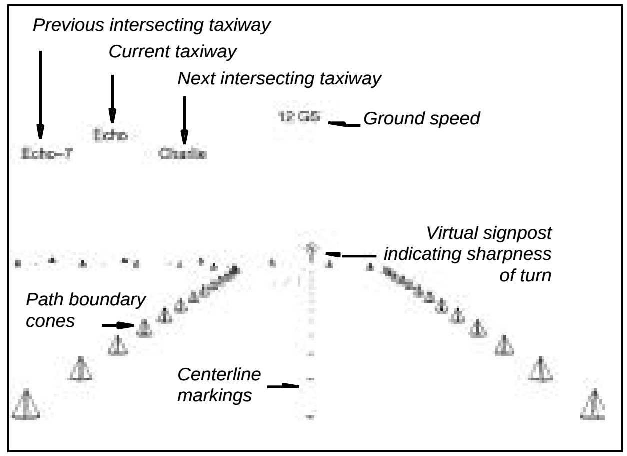

Figure 2. Taxi HUD Display.

taxiway/runway, the next taxi that intersects the current route, and the taxiway recently passed. This information was displayed in the upper left corner of the HUD (see Figure 2).

Ground speed. The HUD displayed ground speed in the form of a digital read out in the top-middle portion of the HUD.

Flight Test Design

The flight test involved two phases: The first phase served to validate the accurate operation of all systems involved and to refine the data collection and observation methods. The second phase represented the actual evaluation phase, in which both commercial airline pilots and NASA test pilots participated. We report here only the method and results of the evaluation phase (for a more detailed account, see Young and Jones, 1998).[4]

[4] Young, S., and Jones, D. (1998, January). Flight Demonstration of Integrated Airport Surface Movement Technologies, NASA TM-1998-206283.

Pilot Selection And Training

Four B757 captains from four different commercial airlines were recruited to participate in the evaluation phase of the Atlanta flight test. All captains reported being very experienced in taxiing an aircraft, but differed on their level of experience with taxiing in low-visibility conditions from not very experienced to very experienced. All pilots had previously flown into or out of the Atlanta Hartsfield Airport and were at least moderately familiar with the airport layout.

Prior to the Atlanta flight tests, the commercial pilots were provided with training materials for both the taxi map and taxi HUD components of T-NASA. Approximately one month prior to the Atlanta flight test, simulator training with the T-NASA system was conducted at NASA Langley Research Center.

Cockpit Configuration

The T-NASA cockpit configuration is shown in Figure 3. The LCD taxi map was mounted on the left side of the console between the primary flight displays and the EICAS displays. The map control device was situated such that it could only be reached by the captain or the co-pilot seated directly behind the center console. This control panel allowed the pilot to change the map field of view, show/hide traffic and show/hide traffic labels. The HUD was mounted in front of the captain (left seat).

The crew consisted of one commercial pilot and two NASA test pilots. The commercial pilot, the captain in the left seat, was responsible for the aircraft during landing and taxiing. One NASA pilot, sitting in the middle seat, acted as first officer and interacted with the captain, ATC, and GC to request clearances for taxi, take-off and landing. The second NASA pilot, in the right seat, remained isolated from experimental procedures. His task was to ensure the safety of the aircraft and crew.

Flight Test Trials

All 28 flight test trials were conducted during dusk and night hours (from 20:00 to 00:30 EDT). Each commercial pilot participated in seven trials which spread across two nights of testing. These trials were either taxi-only trials (including a high speed taxi) or taxi plus flight. The T-NASA display configurations that were tested were: 1) Jeppesen chart only, 2) taxi map only, and 3) taxi map + HUD. Table 1 depicts the number of trials that each pilot completed with each display configuration.

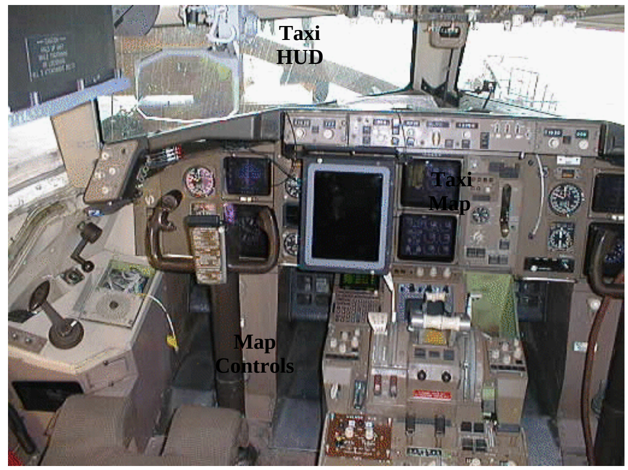

Figure 3. NASA B-757 Flight Deck

Table 1. Summary of Trials

Displays	**# Trials**
Jeppesen Chart (taxi only)	1
Map (taxi only)	1
Map + HUD (taxi only)	1
Map + HUD (taxi and flight)	4

Pilot Instructions

Before starting the taxi trials the pilots were briefed on the desired procedures, performance goals and design/implementation qualifications for the T-NASA system. Pilots were encouraged to use the taxi map on an occasional basis as a cross-check for resolving navigation or situation awareness issues. They were reminded that it was important that they not fixate too long on either the taxi map or the taxi HUD at the exclusion of the outside view.

Flight Test Procedure

Each flight test began in the ramp area just north of Runway 8L/26R, located at the Mercury Air Center FBO, which supported the test aircraft during testing. To begin each trial, the first officer called for taxi instructions from GC. On receipt of the instructions, the captain taxied the aircraft to the designated runway. The aircraft either completed a high speed taxi and exited the runway, or took off, circled, and landed. After roll-out and turn-off from the runway, the captain taxied the aircraft back to the ramp area.

The same route was used for the Jeppesen chart- and the taxi map-only trials to allow for a direct comparison between these conditions. This route involved a long taxi distance from the north side ramp to the south side of the airport and back to the north side ramp after a high speed taxi.

Data Collection Methods

Surveys

After each trial, the captain completed a brief 'post-trial survey' specific to the display configuration that was just tested. They were asked to reflect only on the trial that was just completed. Upon completion of the last flight test, both the captain and first officer were given a 'final survey' regarding the entire T-NASA system.

Debriefings

Each night, after the last trial was completed, an interview and debriefing session was conducted to allow the captain and first officer to express any observations, concerns, or suggestions about the T-NASA system.

Observations

T-NASA researchers observed and recorded crew behavior and communications related to the use of the T-NASA system. Researchers observed monitors located either in the hotel control operations room or from monitors and audio tracks in the aircraft cabin. Further, whenever possible, a researcher sat in the jump seat to record communications between pilots and observations of the out-the-window scene.

Video and Audio

For each trial, six cameras were used to record the following views: tail perspective, nose perspective, flight deck activity, scan-converted HUD, scan-converted taxi map, and a view from as close to the pilot's eye point as possible. Also captured on audio tape were communications within the cockpit, among the pilots, ATC, and GC.

Performance Data

A number of objective performance parameters were recorded for each flight test. Of particular interest to the T-NASA team were navigation errors, ground speed and the zoom level selections.

Results

Post-Trial Survey Results

Survey data illustrate how the commercial pilots felt that terminal area productivity may be improved by T-NASA technology. Specifically, pilots reported that, compared to the Jeppesen chart alone, the taxi map and taxi HUD reduced total taxi time, increased the safety of taxiing, were less distracting and reduced mental navigational workload while taxiing.

Reduced taxi time. Commercial pilots in both the taxi map and the taxi map + HUD conditions subjectively reported decreased taxi times over having no navigation aid at all.

Those pilots that reported a taxi time advantage were asked to select from a list of options that may have contributed to this positive result. Pilots responded that T-NASA technology reduced taxi times because less time was required to plan routes, taxi speeds were increased, less time was spent at confusing intersections, and, to a lesser extent, fewer stops were required while taxiing. Other reasons cited were that the taxi map + HUD combination allowed for greater situation awareness when changing tasks (i.e. clearing the runway and converting to taxi), and afforded the pilot greater confidence in his position on the airport surface.

Increased safety. Not surprisingly, all pilots commented that both the taxi map and the taxi map + HUD improved safety over having no navigation aid at all. However, only 75% of the pilots reported that the Jeppesen chart increased safety over having no map at all.

Increased situation awareness. All pilots reported that the Jeppesen chart, taxi map, and taxi map + HUD increased SA over having no navigation aid at all. In addition, pilots were asked to rate how easy it was to identify and locate their cleared taxi route on a scale from 1 (very easy) to 5 (very difficult). Pilots rated having more difficulty locating the cleared taxi route with the Jeppesen chart (M = 4.0) than with the taxi map (M = 1.25).

Reduced navigational workload. All pilots agreed that both the taxi map and the taxi map + HUD reduced mental navigational workload. Only 50% of the pilots reported reduced workload in the Jeppesen chart condition over having no navigation aid at all.

Final Survey Results

All four commercial pilots agreed unanimously on the following statements regarding the T-NASA system:

· T-NASA is beneficial relative to taxi information currently available.

· T-NASA aids the pilot in safely and accurately navigating the aircraft.

· T-NASA is very beneficial towards overall taxi efficiency (taxi speed, planning time, navigation awareness, communication needs).

· T-NASA will increase airport terminal area capacity in low visibility/IMC conditions.

· T-NASA increased situation awareness during taxi operations.

· T-NASA decreased cognitive navigation workload during taxi.

· T-NASA improved communications with Ground Control.

· T-NASA improved communications with flight crew.

· T-NASA allowed more time to look out the window, and required less time consulting the Jeppesen chart.

Taxi Performance

Taxi errors. An error was committed in one of the four trials using only the Jeppesen chart. The pilot taxied past the instructed taxiway turn and instead turned on the following taxiway. No errors were committed using the T-NASA system.

Taxi speed. Average taxi speeds were compared for each pilot's two south-side, taxi-only trials which were conducted with the Jeppesen chart alone and the taxi map. These two trials are directly comparable as they were closely matched for route length and number of turns. Unfortunately, it was not possible to include a matched route to allow a direct comparison with the taxi map + HUD trials. A moving velocity was calculated using velocity values greater than or equal to 6 Kts (values below 6 Kts were not recorded reliably). Three of the four pilots increased their taxi speeds with the taxi map over the Jeppesen chart. The mean taxi speed across all pilots was higher when taxiing with the taxi map (16.3 Kts) than when taxiing with the Jeppesen chart (14.6 Kts).

Map zoom usage. Prior to each trial, the pilots were asked to select the zoom level that they wanted to start taxiing with. This provided an estimate of the preferred taxi level, at least for the initial taxi out of the ramp phase. The 4x view was chosen most often (on 40% of the trials), followed by the 3x view (30%).

During the trials, all four pilots adopted a consistent strategy of zooming the taxi map in close when approaching turns and hold bars (5x, 4x, 3x), while zooming the map further out (1x, OVR) when planning the route, and while holding short. It was also determined that all five zoom levels were not necessary and that four zoom levels may be more desirable.

Usability of T-NASA Features

Taxi Map. Pilots were asked how easy it was to identify and quickly understand the symbols and information presented in the taxi map. They rated each feature on a scale from 1 (very difficult) to 5 (very easy). All map features were rated 3.0 (neutral) or higher. Compass Headings, Clearance Text, and Text Messages received the lowest ratings.

Taxi HUD. Pilots were asked how easy it was to identify and quickly understand the taxi HUD features. They rated each feature on a scale from 1 (very difficult) to 5 (very easy). All taxi HUD features were rated a 3.0 (neutral) or higher. While the edge cones, center line, and ground speed were easily understood, three problem areas were noted: The triad which depicts the previous, current, and next taxiway received ratings just slightly above neutral. Also the symbology that presents information about upcoming turns (distance to turn and degree of turn) received only neutral ratings. Finally, pilots noted problems with the HUD symbology during turns. In effect, the HUD showed no symbology during 90 degree turns since the forward view of the pilots is not aligned with the taxiway/runway.

Pilots' Comments

T-NASA system:

· "I can't wait until this system is installed in real-world aircraft."

· "I want to see this in the industry as soon as possible."

· "I'd like to go back to my company and say we ought to proactively endorse the development of this technology."

· "Once you get used to T-NASA it would be hard to live without it."

· "In Cat II and III it would really help. I can think of a couple of accidents it would have prevented."

· "This research represents a quantum step in air operations safety and technology, on the same level as the development of GPWS and TCAS."

Jeppesen chart:

· "I felt lost without the use of the LCD taxi map."

· "Mike-Juliet - Dixie - was a difficult corner to navigate. The Jeppesen chart was confusing."

Taxi map:

· "I'm really getting spoiled by this [taxi map] display."

· "I'm really developing an affinity for this display; it's value increases as the out-the-window visibility decreases."

· "Of everything I see here, what I like the most is the map with the magenta line showing my route."

· "I'm going to have a hard time taxiing an airplane without the map."

· "The map allows you to accelerate with confidence and taxi at higher speeds".

Taxi HUD:

· "I was constantly processing the information on the HUD."

· "It [the HUD] improves situation awareness when changing tasks."

Design Implications

Beyond providing data to validate the utility of T-NASA, several important design issues were raised from the pilot's comments and researchers observations. The design suggestions listed below have already been studied and incorporated into a revised version of the T-NASA system.

Taxi Map

· Add ground speed indicator.

· Add aircraft type to traffic data tags.

· When hold bars are present on the taxi map, the portion of the route beyond the hold bar should be colored yellow.

· A taxi ATIS view should be added to the taxi map, providing static and dynamic information from the Jeppesen chart and ATIS (winds, closed runways, RVR, radio frequencies, etc.).

Taxi HUD

· Hold-short information should be provided on the taxi HUD.

· Eliminate the previous intersection ID on the taxi HUD. Place the current taxiway ID below the next intersection ID.

· Provide better turn guidance symbology in the taxi HUD.

Conclusions

The Atlanta field evaluation clearly demonstrated both the feasibility and effectiveness of the T-NASA system towards improving the efficiency of airport surface operations. The performance data, pilot surveys and observational data showed that the T-NASA system results in the following:

· reduced total taxi time

· reduced mental navigation workload

· increased situation awareness

· improved communications

- increased taxi efficiency
- increased safety

In addition, as a direct result of the field evaluation, improvements were made to the design and procedures for both the taxi map and the taxi HUD. These design and procedural changes have had a positive impact on the utility and usability of T-NASA.

We acknowledge that the ultimate goal of T-NASA—to increase taxi throughput under low-visibility conditions, was not demonstrated (due to safety precautions). Notwithstanding, based on the positive results obtained here in clear-weather night conditions, we are even more confident that T-NASA will safely enable VMC capacities in IMC conditions.

Acknowledgments

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