A Post-Hoc Analysis of Navigation Errors During Surface Operations: Identification of Contributing Factors and Mitigating Solutions

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ABSTRACT

Two full-mission simulation studies of surface operations conducted at NASA Ames Research Center revealed that, in low-visibility and night conditions, pilots committed navigation errors on 17% of trials. A post-hoc analysis of these navigation errors uncovered three distinct classes of errors: Planning Errors, Decision Errors, and Execution Errors. Each class has a unique set of contributing factors, and therefore demands unique solutions to mitigate error. Results from the two full-mission simulations revealed that advanced navigation and communication technologies designed specifically to address each class of error can mitigate pilot deviations and increase surface operations safety.

INTRODUCTION

A runway incursion is defined as "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." Between 1988 and 2000 the U.S. Runway Safety Program Office (ATP-20) reported 3420 runway incursions, with 48% of these caused by pilots deviating from their ATC clearance. Recently, the Federal Aviation Association (FAA) held regional and national workshops to identify solutions to the increasing runway incursion problem. Numerous suggestions have been raised including procedural and operational changes, improvements to pavement markings and signage, and in-cockpit technologies (FAA, 2000). However, it is difficult to devise, prioritize, implement and predict the success of these potential solutions without first better understanding the nature of the runway incursion problem.

In contrast to en route and approach phases of flight, the aviation human factors community in general has devoted only minimal resources to understanding the factors that contribute to pilot error during surface operations. One exception was an examination of questionnaire data from 2,000 pilots that identified potential factors that contributed to errors during taxi operations (Kelley & Adam, 1997). Nine areas of importance were identified, five of which directly contribute to navigation errors: 1) Pilots' unfamiliarity with airports; 2) Inadequate airport navigation aids; 3) ATC-Pilot miscommunications; 4) Lack of standardized cockpit procedures; and 5) Pilot fatigue and poor eating habits. This paper extends Kelley and Adams' work (1997) via a post-hoc analysis of empirical data gathered from two full-mission surface operations simulations conducted at NASA Ames Research Center. These simulations revealed, as did Kelley and Adam's research, that navigation errors are not simply random errors and are not due to pilot inattention, but rather that a number of contributing factors support or allow these errors.

SURFACE OPERATIONS RESEARCH

The data reported in this paper were derived from two high-fidelity full-mission simulations (McCann, et al., 1998; Hooey, Foyle, Andre, & Parke, 2000) that were conducted in the NASA Ames Advanced Concept Flight Simulator (ACFS). The ACFS is a generic glass cockpit simulator with a full six degree-of-freedom motion system which allows for a realistic, yet controlled, environment to understand pilot performance during surface operations. The image generator provides a 180-degree field of view and a high-fidelity rendering of Chicago O'Hare airport replicating the airport layout, signage, painted markings, lights, concourses, and structures. The experimental Air Traffic Control (ATC) facility allows for a highly realistic representation of current-day surface operations by integrating confederate local and ground controllers and pseudo-pilots to provide ATC and background party-line communications that are synchronized to the movement of airport traffic.

The ACFS was equipped with a suite of advanced cockpit navigation displays, the Taxiway Navigation and Situation Awareness (T-NASA) system (Foyle, et. al., 1996) comprised of a head-up display (HUD), head-down electronic moving map (EMM), and directional audio alerts. T-NASA was designed to provide two classes of information: Global awareness and local guidance (Foyle, et al., 1996; Lasswell & Wickens, 1995). Global awareness, a pilot s general understanding and mental picture of the airport layout, location of runways, concourses, and ground vehicle travel areas, was provided by the EMM. The EMM presents a perspective and track-up view of the airport surface, dynamic real-time depiction of ownship location, and the cleared taxi route both textually and graphically. Local guidance refers to pilots' control task of maneuvering the aircraft along a route. Local guidance information was provided to captains via the

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HUD's scene-linked symbology (see Foyle, et al., 1996) which depicted the centerline and edges of the cleared taxiways. The ACFS was also equipped with advanced datalink technology that transmitted a written record of routine ATC communications including taxi clearances, hold short commands, and route amendments. New messages appeared on the lower Engine Instrument Crew Alerting System (EICAS). Either pilot could view the datalink message and access a log of previous messages.

Simulation Experiments - Table 1 provides a summary of the taxi conditions examined in the two simulation studies. In the first study (McCann, et al., 1998), 16 two-pilot commercial crews completed 18 land and taxi-to-the gate scenarios at the simulated Chicago O'Hare airport. Each crew completed six trials in current-day operations with only a Jeppesen chart for navigation, six trials with the EMM, and six trials with both the EMM and the taxi HUD. Half of the crews (8) completed the trials in low visibility (Runway Visual Range, RVR, 700') and half completed the trials in night VMC (Visual Meteorological Conditions). In the second simulation (Hooey, et al., 2000), 18 two-pilot commercial crews completed nine nominal land and taxi-to-the gate scenarios at O'Hare airport in RVR 1000' conditions. Each crew completed three nominal trials in current-day operations, three with datalinked text clearances, and three with the EMM and HUD coupled with datalinked ATC communications. Additional off-nominal trials were completed but not included in the current analyses.

In the current-operation trials in both studies, pilots were equipped with standard Jeppesen paper charts and received a verbal taxi clearance after exiting the runway. As the current-day operations trials for the two studies differed only in visibility (RVR 700, night VMC, or RVR 1000), the data were combined for a total of 150 current-operation trials that provided a rich understanding of navigation errors in current-day operations. Navigation errors were also examined with each technology package (EMM, EMM+HUD, Datalink, Datalink+EMM+HUD).

Table 1. Summary of Simulation Studies.

	Visibility (Number of crews)	Taxi Conditions (# of trials /crew)
Study 1	Night VMC (8 crews) RVR 700' (8 crews)	Current-Day (6) EMM (6) EMM + HUD (6)
Study 2	RVR 1000' (18 crews)	Current-Day (3) Datalink (3) Datalink+EMM+HUD (3)

Navigation Error Data - Each trial was analyzed for the occurrence of a navigation error defined as taxiing on a portion of the airport surface on which the aircraft had not been cleared, and deviating from their cleared taxiway centerline by at least 50 feet. Additionally, videotape analyses were used to verify the occurrence and nature of errors. Of the 150 current-operation trials, 26 or 17.3%, contained navigation errors. The number of errors observed in each of the three visibility conditions (RVR 700', Night VMC, and RVR 1000') is presented in Figure 1. That navigation errors occurred as often or more often in night VMC than low visibility suggests that this is a pervasive problem that is not isolated to inclement weather days or to airports with frequent low-visibility problems (McCann, et al., 1998).

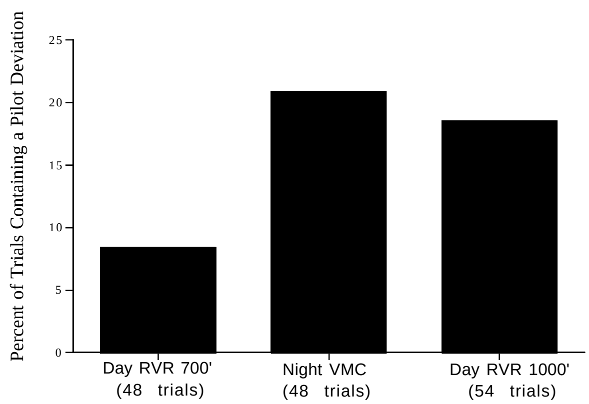

Figure 1. Navigation Errors as a Function of Visibility

UNDERSTANDING PILOT DEVIATIONS

In order to better understand the nature of navigation errors, it is helpful to turn to existing models of human error. Reason (1990) developed the Generic Error Modeling System (GEMS) which uses a cognitive model to develop a context-free taxonomy of human errors. Two general classes of errors within the model are mistakes and slips. Mistakes are errors in the formulation of intention or actions whereas slips are unintentional errors of execution. Applying Reason's classification of mistakes and slips retroactively to the surface operations simulation data provides insights c into the factors that contribute to pilot deviations, and therefore runway incursions. A post-hoc analysis revealed two classes of mistakes (Planning Errors and Decision Errors) and slips (Errors of Execution) that led to pilot deviations from the cleared route. Following is a descriptive analysis intended to provide insights into the causal factors of navigation errors. Statistical analysis of error rates may be found in the original papers (McCann, et al., 1998; Hooey, et al., 2000; Parke, Kanki, McCann, & Hooey, 1999).

Planning Errors - Planning Errors are errors in which the pilot formulated an erroneous plan or intention, but carried out the plan correctly. A retrospective analysis of the full-mission simulation data revealed that planning errors accounted for 23% (6 of 26) of all errors made in the 150 current-day baseline conditions. In these instances, pilots formulated and verbalized an erroneous taxi plan, or inadvertently modified a taxi plan, and then made navigation decisions based on the incorrect plan. Two contributing factors have been identified: Miscommunication, and expectations and confirmation bias. Each are discussed below.

Miscommunication - Miscommunications between pilots and ATC or between crew members during the initial communication of the clearance contributed to two of the six planning errors. In one case, the first officer made an error while reading the clearance back to ATC and the captain followed the erroneous route. In the second, the first officer read back the clearance correctly to ATC, but communicated it incorrectly to the captain. The captain followed the first officers' erroneous guidance. In an actual operational environment, there are multiple opportunities for miscommunications or misunderstandings to occur during the clearance issuance process, perhaps even more so than in a controlled simulated environment. ATC may make an error, the radio transmission may not be clear, the first officer may write it down incorrectly, might read it back incorrectly, or might communicate it to the captain incorrectly. Because ground control frequencies currently operate as a party-line, pilots may hear clearances from other aircraft and mistake them, or parts of them, for their own clearance. Further, the opportunities for this type of error increase as workload and airport congestion increase.

Expectations and Confirmation Bias - In four of the six errors, ATC issued the clearance correctly, and the first officer read it back correctly, however, mid-way in the taxi route, the plan was inadvertently altered during a crew communication. In one trial, the captain substituted a similar non-cleared taxiway (A10) for one in the clearance (A11). Even though the captain verbalized his erroneous intent, the first officer did not notice or correct the error and actually repeated the erroneous taxiway back. In three trials, in which the clearance required a turn away from the concourse in order to avoid a conflict with another aircraft, the pilots omitted one taxiway element from the clearance resulting in a deviation from the cleared route. It is likely that these pilots had formulated expectations based on their knowledge of the destination concourse and doubted their understanding of the clearance when it conflicted with their expectations. Their solution was to omit the conflicting taxiway from the clearance. Pilots' expectations may be based on their knowledge of the airport layout and their past experiences at the airport. This suggests that a route that deviates from pilots' expectations may leave very experienced pilots prone to planning errors - even more so than pilots who are unfamiliar with the airport layout.

Mitigating Planning Errors - Planning errors occurred because pilots formulated an incorrect understanding of the taxi clearance. Therefore, it is reasonable to hypothesize that presenting the clearance in a clear and unambiguous manner that is readily available in the cockpit might mitigate these errors. The full-mission simulations examined navigation and datalink technologies that provide an in-cockpit presentation of the taxi clearance and found that these technologies did eliminate planning errors (Figure 2).

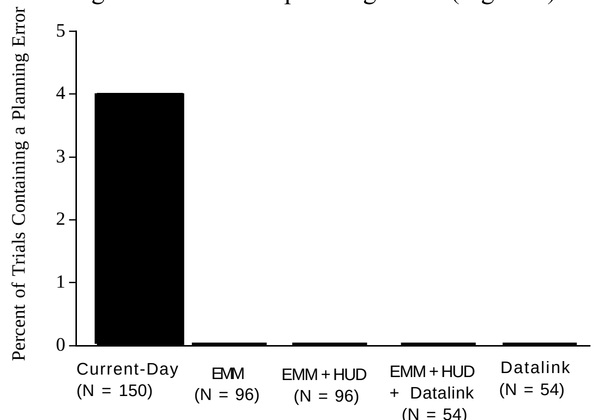

Figure 2. Planning Errors: Formulating an Erroneous Flight Plan.

As can be seen in Figure 2, there were no planning errors when the EMM or the EMM + HUD were available to the pilots. The T-NASA EMM depicted the cleared route both graphically (via a magenta path overlaid on the perspective view of the airport surface) and textually (as a text display on the bottom of the map) and helped mitigate misunderstandings and confusions regarding the cleared route. Pilots rated the ease of communication (both pilot-pilot and pilot-ATC) higher with T-NASA than without (Hooey, et al., 2000).

Datalink text messages that either replaced or supplemented ATC voice commands were provided in the second simulation. Figure 2 also shows that with datalink, planning errors did not occur. Parke, et al. (2001) noted that pilots utilized datalinked clearances differently than voice clearances. Pilots tended to communicate and formulate a plan for the entire clearance when received by voice, however with datalink, pilots formulated shorter sequential plans that allowed them to navigate turn by turn. Datalink might encourage pilots to make more frequent checks of the datalinked clearance and could further minimize the possibility of mid-route substitution and omission errors.

Decision Errors - Decision errors occurred when the route had been properly received and communicated, however, a pilot made an erroneous choice at a decision point along the route. Most often this was observed as a turn in the wrong direction, such as turning left when they should have turned right. Pilots formulated, and verbalized, the correct intention, but failed to execute the correct action to accomplish their goal. There were 11 occurrences of this type of error across the 150 current-day operation trials accounting for 42% of all errors observed. Excessive operational demands and inadequate navigational awareness have been identified as two of the major contributing factors to these errors.

Excessive Operational Demands - Of the decision errors in current-operation trials, 55% occurred at the first decision point encountered after exiting the runway. At this decision point the first officer was occupied with his/her tasks (changing radio frequencies, contacting ground control, receiving the taxi clearance, writing it down, reading it back to ATC, checking the Jeppesen chart, and communicating the route to the captain), while the captain is pressured to clear the runway and may begin taxiing before the first officer is ready to assist with navigation. In at least half of the decision errors, the captain was taxiing solo at the time of the error, while the first officer was communicating with ATC or head-down consulting the Jeppesen chart (see also Parke, et al., 1999).

Inadequate Navigational Awareness - In taxi operations, pilots must have two pieces of information. First, they must possess knowledge of the spatial relationship between the aircraft's current location and the cleared route. Second, they must possess general knowledge of the airport surface environment such as the direction and locations of runways, and concourses. Together, both of these forms of knowledge are necessary for successful navigation. If lacking one or both of these forms of awareness, the pilot may become spatially disoriented which, in the worst case scenario, can lead a pilot to inadvertently taxi onto an active runway. This problem is compounded in low visibility or night conditions, or when pilots have little experience or familiarity with the airport layout.

Four of the 11 decision errors were associated with uncertainty of the aircraft position on the airport surface. Pilots' made navigation decisions assuming they were somewhere on the airport surface that they were not. On at least two of these occasions, the first officer had been head-down checking the Jeppesen chart immediately prior to the error. At the time the first officer provided navigation guidance to the captain, he was uncertain of the location or heading of the aircraft. After one error a first officer stated "Oops, I didn't see you had gone that far, I had my head down in the Jepp chart."

In 7 of the 11 errors, pilots were aware of their location on the airport surface but made a turn in the wrong direction demonstrating a poor understanding of their location relative to their destination concourse. After realizing the error, pilots made comments such as "I didn't realize the concourse was [to the right]." The crew member responsible for the error was equally distributed between captains and first officers: Captains made the decision without involving the first officer (2 of 7), first officers provided incorrect guidance that the captain followed (2 of 7), both crew members shared in the decision process (2 of 7), and the first officer and captain disagreed, with the captain ignoring the first officer (1 of 7).

Mitigating Decision Errors - Given the nature of these decision errors, it would be expected that technologies that decrease workload at runway turnoff, and that contribute to a pilots' navigational awareness may successfully mitigate these types of errors. The error rates associated with the advanced navigation displays and datalink are presented in Figure 3. As can be seen, there were no decision errors when pilots were taxiing with the EMM+HUD combination. The T—NASA system was shown to reduce pilot-rated workload in both studies (McCann, et al., 1998; Hooey, et al., 2000). Also, together, the EMM and HUD provided a clear indication of the location of ownship relative to the cleared route (local guidance provided by the HUD) and the direction of the cleared turn or destination concourse (global awareness provided by the EMM) (Foyle, et al., 1996; Lasswell & Wickens, 1995). Only one decision error was observed in the 96 trials conducted with the EMM alone. In this trial, the pilot was cognizant of the route, that a turn was required, and the direction of the turn, but remarked that he didn't realize the turn was as close as it was. Presumably, this error occurred because the EMM required pilots to make a translation from their position on the map to their position on the airport surface. The EMM provided global awareness but not local guidance. Also, the captain was taxiing without support from the first officer who, at the time of the error, was busy communicating with ATC.

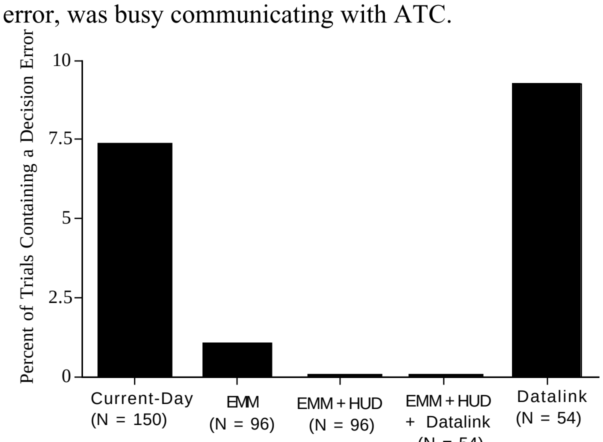

Figure 3. Decision Errors: Choosing an Incorrect Action (Turn Direction).

Also noteworthy in Figure 3, is that five decision errors occurred in the 54 trials in which pilots had datalink but not the T-NASA displays, representing an error rate of 9.26%. Datalink served to clarify the issued taxi clearance but because it did not provide local or global awareness, it did little to guide pilots' at each decision point. In the NASA simulations, the datalink replicated an actual ATC voice communication and as a result did not dictate the direction of the turn. Providing this type of global guidance (i.e., Left on Bravo) to pilots by datalink could have helped mitigate some of the errors.

Execution Errors - Errors of execution are those in which the clearance was correctly communicated, pilots identified the correct intersection and direction of the turn, however erred in carrying out the maneuver. There were 9 execution errors that accounted for 35% of all errors. Several factors contributed to these errors including complex taxiway geometry, confusing signage, and the "sea of blue lights." In all cases, the environmental cues were inadequate or misleading.

Complex taxiway geometry - Navigating complex taxiway geometry such as intersections with multiple intersecting taxiways, taxiways that changed names but not direction, and intersections that possessed two or more turns in the same direction but at different angles, accounted for 78% (7 of 9) of the execution errors. The most frequent factor associated with these errors of execution was a failure to disambiguate the multiple centerlines painted on the airport surface. Not only was it difficult for pilots to discern which was the correct centerline to follow, it was also difficult for the first officer to decipher the Jeppesen chart, and communicate the information to the captain.

Confusing signage - Pilots reported confusion regarding the taxiway signage, even though the signage in the simulator replicated the actual O'Hare signage in content, size, and location on the airport surface. Because signs can only be placed on grass or concrete islands, it is sometime difficult to discern which taxiway corresponds with the angle on a sign. Some errors occurred because pilots misunderstood which taxiway corresponded to the signage.

Sea of blue lights - In Study 1 which compared taxiing in Day RVR 700' and Night VRF, all but one of the execution errors occurred in night conditions. The blue lights that mark the taxiways at night can be disorienting, particularly when viewed off-axis. Although anecdotally known, McCann, et al. (1998) was the first, and only, study to our knowledge to objectively document the problems associated with taxiing at night, or the 'sea of blue' effect.

Mitigating Execution Errors - As discussed above, environmental factors play the largest contributing role in execution errors. Therefore it is reasonable to expect that providing pilots with a visual display that augments the outside world would mitigate these errors. Figure 4 shows that this is the case, as the EMM+HUD eliminated these errors, but the EMM alone, and datalink alone did not. The HUD symbology, which presents the centerline and sides of the cleared taxi route, naturally disambiguates the correct and incorrect centerlines, thus serving to mitigate the errors of execution. Of the 96 trials that were completed with the EMM alone, 3 (3.1%) contained errors of execution. It is likely that the EMM assists pilots in navigating complex intersections and interpreting signage. However in the three error trials, the captains were taxiing without support from the first officer, and exhibited difficulty utilizing the head-down EMM while taxiing. There were three execution errors with datalink alone (5.5% of the 54 datalink trials). That datalink did not eliminate errors is not surprising as it served to communicate the taxi clearance but did not disambiguate the external environment

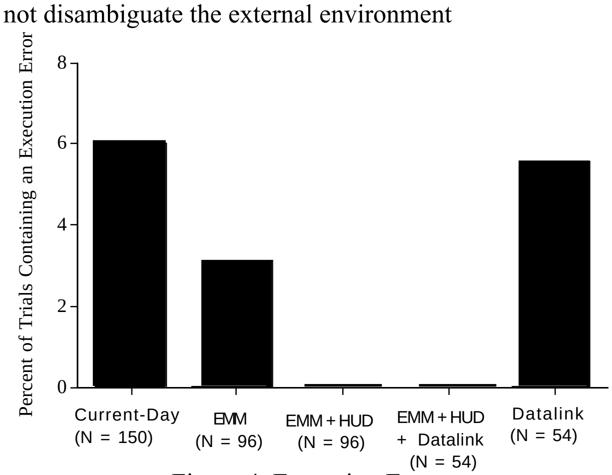

Figure 4. Execution Errors: Incorrectly Executing a Turn

DISCUSSION

Three classes of errors (Planning, Decision, and Execution) have been identified through a post-hoc analysis of two full-mission simulation studies of surface operations. Each class of error is associated with a unique set of contributing factors and therefore requires unique mitigating strategies. Table 2 summarizes the contributing factors and possible mitigating technologies for each class of error.

Table 2. Summary of Error Classes, Contributing Factors, and Mitigating Solution

Error Class	Error Description	Contributing Factors	Mitigating Solutions	Technology Solutions
Planning	- Formulate incorrect taxi plan - Inadvertently alter taxi plan	- Miscommunication - Expectations/confirmation bias	- Provide unambiguous clearance readily available in cockpit	Datalink EMM
Decision	- Turn wrong direction - Fail to turn - Unnecessary turn	- Excessive operational demands - Poor global awareness - Lack of local guidance	- Reduce operational demands - Enhance global awareness - Enhance local guidance	EMM HUD
Execution	- Follow wrong taxi centerline - Choose wrong taxiway - Misinterpret Signage	- Complex taxi geometry - Confusing signage - Visibility conditions (night)	- Disambiguate environment - Enhance local guidance	HUD

Planning errors, formulating an erroneous taxi plan, occurred because of miscommunication or misunderstanding of the required taxi route. Technologies such as datalink and T-NASA, that provide clear, unambiguous and readily available representations of the clearance within the cockpit may mitigate these errors. Decision errors, making an incorrect choice at a decision point, occur because of high operational demands at runway exits as well as inadequate navigational awareness. Technologies that provide both global awareness and local guidance, such as the T-NASA HUD and EMM together, may mitigate these errors. Finally, execution errors, incorrectly navigating an intersection, occur due to inadequate or confusing environmental cues. Solutions, such as the T-NASA HUD, that disambiguate the external environment will help mitigate these errors. These results suggest that advanced cockpit technologies can be used to augment pilots' cognition, decision making, and perceptual abilities, resulting in fewer navigation errors, and increased runway safety. While T-NASA and datalink were examined as potential mitigating strategies, any number of procedural, operational, and technology solutions that address the key contributing factors could also be successful.

These full-mission simulations have greatly enhanced our understanding of procedural, operational, and environmental factors that contribute to pilot error. However, it is important to validate these findings and determine the extent that the data generalizes both to the actual environment (Chicago O'Hare during low visibility and night conditions, and non-peak traffic loads) as well as to other airports and operational environments. To do this it will be necessary to follow through with the FAA's plan (FAA, 2000) to develop and institute a standard method of investigating and analyzing the human factors aspects of pilot deviations to further our understanding of the root causes of these navigation errors. The FAA's intention to establish a standardized, non-punitive data collection program (FAA, 2000) will be critical to this process.

REFERENCES

Federal Aviation Association, (2000). National Blueprint for Runway Safety. http://www.faarsp.com/blueprint/.

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.

Hooey, B. L., Foyle, D. C., Andre, A. D., & Parke, B (2000). Integrating datalink and cockpit display technologies into current and future taxi operations. *Proceedings of IEEE/AIAA Digital Avionics Systems Conference.* Philadelphia.

Kelley, D. R., & Adam, G. L. (1997). The human factors of runway incursions caused by "pilot error": A survey of U.S. Airline pilots. . In R. S. Jensen & L. Rakovan (Eds.) *Proceedings of the 9th International Symposium on Aviation Psychology*, 911-917, Columbus, OH: Ohio State University.

Lasswell, J. W. & Wickens, C. D. (1995). *The effects of display location and dimensionality on taxi-way navigation* (Tech. Report ARL-95-5/NASA-95-2). Savoy, IL: University of Illinois Aviation Research Laboratory.

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

Parke, B., Kanki, B., McCann, R. S., & Hooey, B. L. (1999). The Effects of Advanced Navigation Aids on Crew Roles and Communication in Ground Taxi. *Proceedings of the 10th International Symposium on Aviation Psychology*. (pp. 804-809). Columbus, OH: Ohio State University.

Parke, B., Kanki, B. G., Munro, P. A., Patankar, K., Renfroe, D. F., Hooey, B.L., & Foyle, D. C. (2001). The effects of advanced navigation aids and different ATC environments on task-management and communication in low visibility landing and taxi. In *Proceedings of the 11th International Symposium on Aviation Psychology*, Columbus, OH: Ohio State University.

Reason, J. (1990). *Human Error*. New York: Cambridge University Press.