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Effectiveness of Ground-Based Direct Pilot Warnings in Mitigating Runway Safety- Critical Human Errors

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Three simulation studies were performed to determine opportunities and limitations of ground-based direct pilot warnings to increase runway safety. Sixty pilots participated in these studies and operated a flight simulator under active and passive warning. Passive warnings facilitated crew awareness about their current location on the airport. Active warnings provided time critical information about runway status and other traffic to facilitate safety mitigation behavior by pilots. Participants completed simulation scenarios with opportunities for safety incidents that could be avoided if pilots achieved complete situation awareness. Warning effectiveness was measured by comparing numbers of encountered safety incidents between baseline and warning conditions. Simulation findings indicate that passive warnings are frequently unable to correct erroneous pilot expectations, thereby replicating similar historic incidents such as the crash of a commuter jet in Lexington, Kentucky in August 2006, where the flight-crew took off from a too short runway. Visual ground-based active warnings on the other hand seemed effective in the runway entrance environment and for departure situations. For arrival situations, allocation of pilot attention seemed to play a crucial role in moderating warning effectiveness. We report opportunities and limitations of the described warning methodology and suggest next steps for runway safety research and system development.

Introduction

Runway safety is a high priority for the U.S. Federal Aviation Administration. Various research programs are currently investigating the possibilities of new system designs, procedures, and technologies to improve runway safety. The development of warning strategies has received special attention in the context of preventing runway incursions, and has been directly proposed by the Department of Transportations' National Transportation Safety Board (NTSB, 2000) to the Federal Aviation Administration (FAA). One such research program investigates the development of direct pilot warning systems to inform flight crews about potential runway safety hazards. Such warning systems are either located in the cockpit (cockpit-based warnings), or on the airport surface (ground-based warnings), and provide information about immediate safety hazards to the flight crew. The studies described here focus on ground-based warnings.

There is considerable agreement about the contribution of human error as a primary causal factor for runway incursions (e.g., Cardosi & Yost, 2000; FAA 1998). Latent factors that are not directly visible to observers contribute to the occurrence of unsafe acts which can in turn lead to runway incursions and accidents. Adam & Kelley (1996) surveyed 1437 pilots from two commercial airlines and interviewed some of them to accumulate a list of causal precursors to runway incursions[1]. Beyond these latent factors, models of organizational safety, such as Reason (1997), point to organizational and workplace conditions that influence the occurrence of unsafe acts. Therefore, human error is only one dimension of causal factors contributing to runway incursions.

Increasing operational safety can be accomplished in multiple ways, one of which consists of warning strategies, Lehto, (2006) lists several intervention strategies to increase safety, for example: by product design, task design, user selection, education, training, and supervision. Warnings are here considered to be supplemental ways to enhance safety and are seen as part of the whole set of runway safety risk mitigation.

The first step here is to define the term "warning". For our purposes a definition by Laughery & Wogalters (1997) is adapted: "Warning consists of information that facilitates operators' awareness of safety hazards and enables them to make informed decisions to initiate appropriate behavior to avoid the hazards." We

[1] The Federal Aviation Administration defines runway incursions as "any occurrence in the airport runway environment involving an aircraft, vehicle, person, or object on the ground that creates a collision hazard or results in a loss of required separation with an aircraft taking off, intending to takeoff, landing, or intending to land." FAA (2005).

distinguish between active and passive warnings. Active warnings warn about time-dependent hazards on the airport surface, such as other aircraft or vehicles. Passive warnings warn about static hazards that do not change over time, such as runways or areas where frequent runway incursions have occurred (“hot spots”). In addition, we distinguish between flight-deck based warnings and ground-based warnings. Flight-deck based warnings originate inside the cockpit, whereas ground-based warnings originate outside the cockpit. Flight-deck based and ground-based warnings can either be active or passive. Examples for passive flight-deck based warnings include airport moving maps, and runway awareness systems such as Honeywell’s Runway Awareness and Advisory System (RAAS). Examples for active warnings include applications of Automatic Dependence Surveillance Broadcast (ADS-B), such as Final Approach and Runway Occupancy Awareness (FAROA).

It is important to note that the term “warning” on the flight-deck is generally used in a more specific context than our proposed definition: that is (e.g., FAA 1987) in the cockpit, warnings are defined as necessarily associated with both auditory alerts and the color red, as well as requiring immediate compensatory action by the flight crew. In the cockpit, warnings are distinguished from “caution” (auditory alert and associated color yellow) and “advisories” (no auditory alert and any other color). In this current context, however, it is useful to utilize a wider definition of the term ‘warning’ that encompasses the rich operational information flows that pilots rely on during airport operations to mitigate runway safety hazards, and into which active warnings need to be integrated.

The objective of the current research is to understand the benefits and limitations of ground-based direct pilot warnings independent of the development of cockpit-based direct pilot warnings. In particular, for what situations may ground-based warnings be effectively used, and under which situations may other safety risk mitigation strategies be more appropriate?

Method

Sixty pilots participated in three human-in-the-loop simulations to evaluate the effectiveness of various ground-based direct pilot warnings. Warnings were either visual or auditory, and were either passive or active. Passive warnings were intended to enhance pilot awareness and consisted of modified lead-on lights, runway guard lights, and enhanced airport surface markings, see Figure 1. All three warnings were located at the entrance to the runway environment.

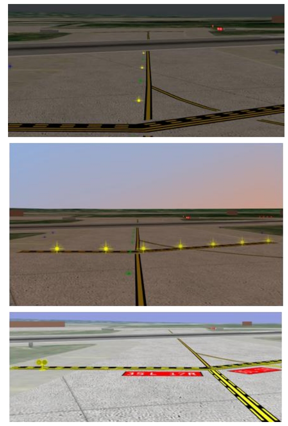

Figure 1. Passive Warnings Included Airport Surface Markings and Lightings

Active warnings consisted of three visual warning systems. Runway entrance lights (RELs) consisted of a row of red lights in the center of the taxiway that warned flight crews about entering an occupied runway. Take-off hold lights (THLs) consisted of red lights to warn pilots in take-off situations about other aircraft on the runway. Arrival warning lights (AWLs) consisted of lights warning pilots when approaching an unsafe runway, see Figure 2. In one warning configuration, arrival warnings were part of the precision approach path indicator lights (PAPI) that pilots use under visual landing conditions to determine their appropriate approach path angle. In this configuration, the PAPI lights were continuously lit for approaching aircraft and started pulsing to indicate an arrival warning. Active warnings also included auditory warnings in the cockpit that alerted a cockpit crew that a runway conflict was ahead. Warnings were played in the aircraft’s speaker system and included the aircraft callsign and the message “warning, runway unsafe”.

In all three simulations pilots operated a flight simulator under different safety levels, either with or without warnings. The flight crew was instructed to follow air traffic control clearances via radio. To measure safety performance, simulation scenarios contained the potential for runway safety conflicts. Safety conflicts included the air traffic controller providing a departure clearance that could lead to a conflict. Background radio communication provided clues to the flight crews that this clearance could lead to a safety critical situation. This manipulation was intended to test whether the warnings can help alleviate situations where pilots do not have sufficient situation awareness to avoid a safety critical situation, and compare this to a baseline where pilots might not be able to gain the necessary situation awareness in order to mitigate the safety hazard without warnings.

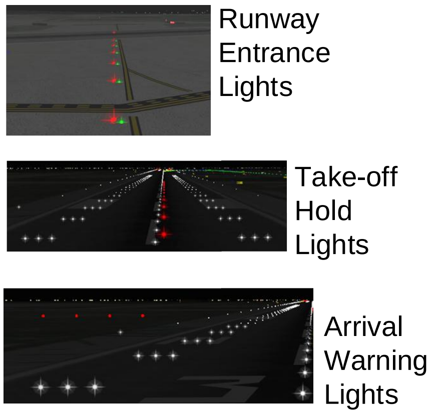

Figure 2. Active Warnings Included Airport Surface Lights Indicating Runway Occupancy

In all three simulations, participants consisted of pilots with mixed flight experience who operated the simulator in a crew setting (simulation 3) or single operations (simulation 1 and 2).

Study 1

In the first study, three levels of warnings were evaluated. In the baseline level (I), pilots operated the aircraft on an airport that approximated existing operational safety levels without additional warnings. At the visual warning level (II), pilots were exposed to visual active and passive warnings in the runway entrance environment, and on the runway. For arrivals, PAPI lights were placed on either one side of the runway. In the auditory warning level (III), pilots received auditory warnings in addition to visual warnings.

The results of the simulation indicated that warnings increased the safety of runway operations, as counted by the number of safety incidents in each condition, see Figure 3. The number of safety incidents was statistically significantly reduced in the warning conditions compared to the baseline condition ($p < 0.05$ using a McNemar-test). Warnings given by RELs helped pilots avoid all runway safety incidents in runway crossing situations. In the baseline condition, 14 pilots entered an occupied runway, but no pilots entered the runway when visual warnings were provided.

Warnings that were given by THLs reduced the number of safety incidents from 28 to 5. The five pilots who continued their departures after the THLs illuminated reported not noticing the lights. Auditory warnings again decreased the number of incidents from 5 to 1. The one pilot who initiated a take-off despite hearing the warning was hesitant about aborting the take-off because he was unable to see an aircraft on the runway, and delayed the abort until it was too late. Arrival warnings reduced the number of safety incidents from 16 to 6. The six pilots who continued their arrivals reported not noticing the warning lights. The auditory warning further reduced the number of runway safety incidents to one. The one pilot who continued the arrival with the auditory warning heard the warning, and initiated a hazardous compensatory action that resulted in an unsafe runway safety situation.

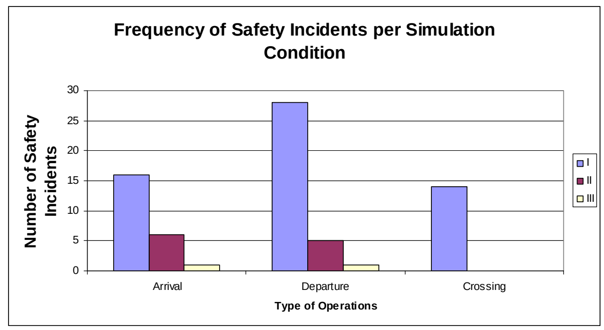

Figure 3. Occurrence of Simulation Incidents as Function of Warning Levels

The simulation findings also brought insight into the limitation of passive runway warnings, showing similarities to a recent runway safety incident that happened subsequent to the study. At Lexington, Kentucky, in August 2006, a commuter jet mistakenly departed from a runway too short for the aircraft. It crashed, killing 49 people. The flight-crew took off from runway 26 instead of main runway 22. In our simulation, precursors for this incident were investigated in one scenario where pilots were positioned at an unexpected location on the simulated airfield. This location was different from where the pilots expected to be. The pilot was then given a take-off clearance on the presumed closest runway. However, the closest runway (35R) was different from the runway participants expected to take off from (17L). Pilots had passive warning information at their disposal to detect the hazard of departing on an incorrect runway. There was taxiway and runway signage, as well as hold-short markings and runway markings indicating the runway they were actually on. By processing that information, pilots should have been able to determine that they were about to take-off on a runway from which they were not cleared. Also, pilots could use the heading indicator on their cockpit display to determine their direction on the airport.

Of the 36 pilots in this scenario, 22 pilots initiated a take-off maneuver on the wrong runway, effectively disregarding the passive warning information. The other 14 pilots used the available information to correct their initially faulty expectation and did not initiate the take-off. Specifically, five pilots used the heading information on their flight display, three pilots relied on runway and taxiway signage, and one pilot used the runway markings to determine the mismatching runway[2], see Figure 4

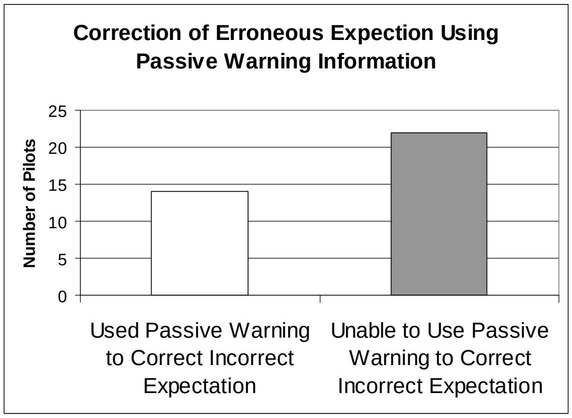

Figure 4. Number of Pilots Correcting an Incorrect Runway Expectation

The simulation findings indicate that active visual and auditory warnings in general increased runway safety, by reducing the likelihood that pilots with incomplete situation awareness encounter safety incidents. Visual warnings however, were sometimes not detected by pilots. Auditory warnings were generally effective, and always detected by pilots, but pilots sometimes initiated hazardous compensatory behavior as a result of the warning. It may be possible that cross-modal processing of auditory information during a mostly visual task may lead to this finding, though this hypothesis awaits further confirmation. The simulation findings also indicate that passive warnings have limited capability to correct erroneous expectations of pilots.

Study 2

In study one, five pilots did not notice the illumination of THLs. Study two then focused on identifying benefits and limitations of alternative THL configurations. In study two, twelve pilots were presented with departure scenarios with three different THL configurations. First, lights were arranged in one row of lights that were offset from the centerline lighting (see I in Figure 5). Second, lights were arranged in two rows of lights, one on each side of the center line halfway between the centerline lighting and runway edge (II). And third, three rows of lights were arranged on each side of the centerline (III). After presentation of the scenario in an approximated realistic airport environment but without background traffic, participants completed a survey and responded to interview questions to determine the limitations and benefits of the different configurations.

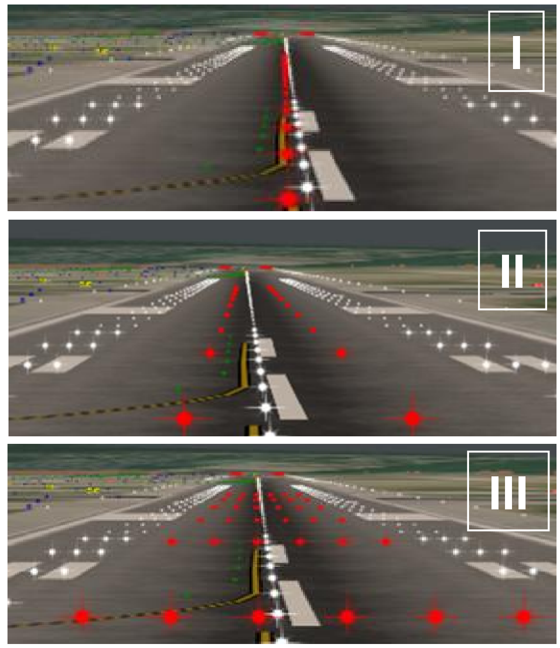

Figure 5. Alternative THL Lighting Configurations for Study 2

Pilots commented that THLs in configuration I were ambiguous, and similar to runway-remaining lights. Runway-remaining lights consist of a row of red lights placed in the last 1000 feet of a runway, and are used by pilots as an indication that the end of the runway is close (see Figure 6). Runway-remaining lights replace the otherwise white runway centerline lights and have different implications for the flight crew than THLs. Pilot comments were compatible with observations during the simulation, where observers identified several cases in which pilots misidentified THLs in configuration I with runway-remaining lights.

Figure 6. Simulation Representation of Runway Remaining Lights

[2] The other five pilots did not indicate how they corrected their location expectation.

Overall, pilots indicated on surveys that configuration III was the easiest to detect, and best facilitated the intended action of stopping an unsafe take-off roll because of the lateral arrangement. Pilots did not identify limitations of configurations II and III.

Study 3

Results from study 1 showed that during arrival operations, six pilots continued to land despite the illumination of AWLs. This was, according to pilot reports, the consequence of increased focus inside the cockpit, as well as attention allocation on the runway itself. The AWL consisted of flashing PAPIs that were mounted at the side of the runway. To address this limitation, a second arrival warning configuration was designed and tested. This new lighting design contained two lighting configurations: PAPIs at the side of the runway, and THLs located on the runway itself.

Twelve pilots participated in study 3 and operated the flight simulator with a pilot-not-flying (PNF) on the right seat. The PNF completed regular crew work that included checklists and communication with air traffic control (ATC) but did not help the pilot flying (PF) in decision making concerning runway safety. Similar to study one, other aircraft were simulated on the airport that correlated to the radio communications participants heard. Participants performed departure, arrival, and taxi operations on two simulated airports: Louisville International Standiford field (SDF) and Los Angeles International airport (LAX).

Results indicated that the addition of a second lighting configuration to the arrival warning was effective; all pilots saw the warning and initiated a go-around. In addition, the distance of the go-around initiation significantly increased from 3744 feet in the baseline condition, to 6557 feet in the arrival warning condition, facilitating earlier conflict avoidance, see Figure 7.

Though the placement of arrival warning lights on the runway showed safety benefits for arrival operations, operational issues were encountered when using the same lighting system (THLs) for departure operations. In some cases, departing aircraft misinterpreted THLs as applicable to arrival aircraft and continued their take-off. This indicates an apparent problem of pilots establishing an accurate mental model about the functioning of THLs in order to distinguish between warnings that are intended for arrivals and those intended for departures. This further indicates that an integration of take-off hold lights as departure and arrival warnings is not a desirable design solution.

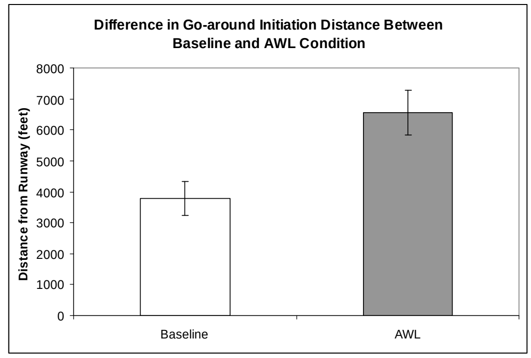

Figure 7. Difference in Go-around Initiation as Response to Arrival Warning Lights (AWL) Versus Baseline Condition

In study 3, an eye-tracker was used to determine the amount of attention pilots allocated inside the cockpit versus out-the-window as a function of departure, arrival, and taxi operations. The details of these results are described by McGarry & Moertl (2006), who find that pilots spent about a third less time looking out-the-window during arrival scenarios as compared to departure and taxi operations. This poses significant concern for the effectiveness of ground-based visual arrival warnings because pilots' increased head-down time in the cockpit may reduce the likelihood of timely detection of the arrival warnings. Results from study 1, where not all pilots detected the arrival warnings, support these findings.

In addition to arrival warnings, study 3 explored the use of RELs at closely spaced parallel runways, such as at LAX, where an aircraft exiting one runway can immediately enter the second, parallel runway. Runway incursions have occurred where flight crews have continued across the parallel runway that, at the time was occupied by another departing or arriving aircraft. RELs in this scenario may provide a warning about the closely spaced parallel runway. However, due to higher taxi speed and the small space between the runways, the flight crew may not be able to recognize and respond to the warning as effectively as at other locations. Indeed, in the simulation it was found that in one case a pilot, after exiting the runway after a landing, continued to taxi through the illuminated RELs, across the parallel runway where a departure had been cleared for take-off. Compared to the baseline condition, RELs reduced the number of safety incidents slightly, from 2 incidents in the baseline condition to one incident in the warning condition. Taken together with the findings in study 1, RELs show a somewhat reduced effectiveness for closely spaced parallel runway situations.

Summary and Conclusions

Three simulations were performed to identify safety benefits and limitations of active and passive ground-based direct cockpit warnings. Sixty pilots participated and assessed direct warnings under various conditions. Results indicate that active warnings provide a significant reduction of safety incidents, even when pilots did not achieve optimal situation awareness. This was found specifically for runway entrance events and departure operations. Passive warnings were found to have limitations for correcting erroneous pilot expectations concerning departure runway decisions. Pilot's attention allocation during arrival operations indicated that warning modalities need to account for increased pilots' head-down time. Alternative warning modalities to ground-based visual warnings include cockpit-based auditory or visual warnings.

Overall, direct pilot warnings provide only one layer of protection against runway incursions and collisions. We found in our studies that the auditory stimulation inside the cockpit is a rich one that makes it hard for pilots to orient themselves through radio communication about the intent and location of other aircraft on the airport. We observed that flight crews frequently filter out information that is only applicable to them and disregard communication and clearances to other aircraft. This can lead to incomplete situation awareness about airport surface movements, and thereby reduce the likelihood of runway safety problem detection when other pilots or air traffic controllers may commit errors.

Runway safety is a complex issue that involves many contributing factors (see e.g. Adam & Kelley, 1996).
Other strategies may include procedural changes in surface operations, and changes in the task distribution of flight crews and air traffic controllers for the management and implementation of airport surface movement. Such alternatives may include systems that assist pilots and controllers in the development, surveillance, monitoring, and communication of surface movement. Such operational changes in airport surface operations will require time but steps have been set by U.S. governmental agencies in the development of surface management systems (SMS), the deployment of improved position reporting in the National Airspace through ADS-B, as well as through the deployment of the Airport Surface Detection Equipment Model X (ASDE-X) in airport control towers. Future development efforts will need to integrate the separate development activities to facilitate the change in the tasks and responsibilities of air traffic controllers and pilots that will ultimately facilitate a safe airport surface environment.

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