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Analysis Methods for Determining the Safety Consequences of Mixed-Fleet Flying

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ANALYSIS METHODS FOR DETERMINING THE SAFETY CONSEQUENCES OF MIXED-FLEET FLYING

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This paper describes the development and implementation of analysis methods for identifying human factors safety vulnerabilities associated with the mixed-fleet flying of the Boeing 767-400 and 777. The results of the analysis were two sets of vulnerabilities: those with potentially critical pilot performance consequences that should be further tested, and those with minor consequences that should be considered when developing procedures and training for the mixed-fleet flying program. A longitudinal study was conducted that included data collection to address the potentially critical vulnerabilities. Examples of how vulnerabilities were addressed with video data from the study are presented and conclusions from the analysis are described.

Introduction

The current economic environment for airlines is causing them to consider all potential ways of reducing operating costs while maintaining high levels of safety. One of the ways that a few airlines have kept costs down is by flying only one type of airplane. This reduces training costs because pilots do not have to be trained as they transition within the airline to different airplanes. It also provides enhanced operational flexibility because any pilot can fly any airplane in the fleet. If there is a maintenance problem with one airplane, the pilots that were going to fly it will be able to fly any other airplane that the airline has available.

Airlines that have more than one type of airplane are looking into strategies for gaining some of the benefits of the single-type airlines. In hopes of realizing these benefits they are exploring is the possibility of mixed-fleet flying two or more airplane types. This means that the pilots would be simultaneously qualified in multiple airplane types and would be able to fly them indiscriminately as needed by the airline. Before such a program can be used by the airlines, however, the FAA must approve of their training and operations plan. Prior to FAA approval, the safety implications of the proposed mixed-fleet flying program are analyzed and a strategy is developed to mitigate any identified risks. Approval is given for a particular combination of airplanes and a specific training and operations program.

Airplane manufacturers are interested in mixed-fleet flying because it provides value to their customers if their airplanes can be flown by the same set of pilots. Traditionally, the manufacturer provides information to the FAA during certification of a new airplane model or type and the FAA gives approval for the type of training that must occur if that new airplane is flown with other models or types. At other times, the manufacturer may wish to explore the mixed-fleet flying option after an aircraft has been approved for operation. The current study follows this strategy. In this project, Boeing Airplane Company requested that the FAA assess the mixing of the Boeing 767-400 and 777 aircraft.

The Operator Differences Requirements Table includes details of differences between the designs of the airplanes and, for each difference, whether the difference results in flight characteristic changes or procedural changes, and what level of training and checking would be required at a minimum to address the difference.

The psychology of human behavior shows that it is not only the differences in airplane design that could cause difficulty, but problems may also result from similar designs that require different responses or procedures (Braune, 1989; Holding, 1987). The present study focuses primarily on this latter vulnerability as it relates to mixed-fleet flying. As part of this effort, we developed a systematic methodology for identifying and evaluating possible instances of negative transfer based on the mixed-fleet flying work by Lyall (1990). This approach has proven successful in its initial use and resulted in providing information about safety vulnerabilities, the potential for critical safety consequences, and possible mitigation strategies.

This paper describes the methodology; examples of specific safety vulnerabilities that were identified; and how the information can be used by airlines, airplane manufacturers, and the FAA.

Vulnerability Analysis Methodology

The objective of the vulnerability analysis was to identify pilot tasks for which there may be a potential for error as a result of mixing the airplanes. A full set of pilot tasks that was developed by the airline for their Advanced Qualification Program was used as the foundation of the analysis. The method was to document for each task the situations and actions required to accomplish the task on each airplane then analyze the similarities and differences between the airplanes, identifying potential vulnerabilities for pilot performance that could result from mixing the airplanes.

The documentation began by gathering information from the flight and training manuals for both airplanes. These manuals include normal and non-normal procedures and checklists. The information from the manuals was then expanded using interviews with pilots and instructors qualified on one or both of the airplanes and, if necessary, conducting directed sessions in simulators and training devices to understand how the pilots may need to operate differently in the two airplanes. This analysis resulted in a list of possible pilot performance vulnerabilities.

A “vulnerability” was identified if the required action or knowledge to accomplish a task was different in the two airplanes. Additionally, an item was categorized as a “major” vulnerability if it consisted of a critical behavior with safety consequences. All major vulnerabilities were further investigated as part of a separate analysis called the “longitudinal study.”

Analysis Results

Possible vulnerabilities that needed to be further verified in the longitudinal study were identified for 19 tasks. Minor vulnerabilities that should be considered when updating training and procedures were identified for 17 tasks.

The most safety critical design difference that was discovered to have a vulnerability was the use of the Takeoff/Go Around (TOGA) switch for automatically advancing the thrust levers to takeoff power. The TOGA switch is used in three tasks: takeoff, missed approach, and rejected landing. The difference in design of the TOGA switch in the two airplanes may lead to a classic negative transfer situation because the tasks for which the switches are used are the same in the two airplanes, but the response the pilots must make in using the switches is different. In the 777 the TOGA switch is located only on the forward side of the thrust levers and would, therefore, be activated with the pilots fingers reaching forward and downward as the hand in on the thrust lever. The 777 TOGA switch is highlighted in the picture in Figure 1.

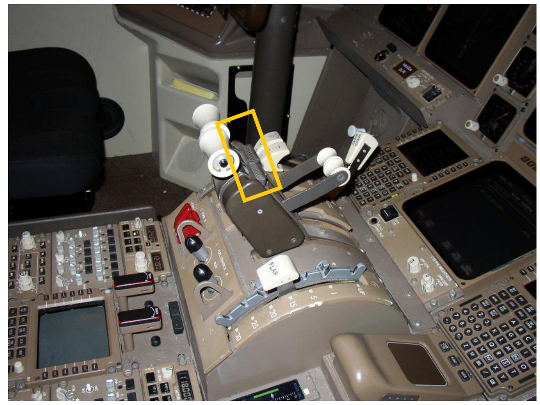

Figure 1. *Boeing 777 throttle quadrant with TOGA switch highlighted.*

On the 767-400, the TOGA switch can be activated from both the forward and aft positions related to the thrust levers. During our analysis we interviewed and observed several 767-400 pilots and instructors in the simulator and found that 100% of them used the aft TOGA switch exclusively. This gave us evidence that the difference in switch design could lead to safety consequences when the pilots who had habits formed in the 767-400 were flying the 777: They could take longer in activating the TOGA switch if they tried first to activate it at the aft of the thrust levers and had to realize that the switch was not there before activating the forward switch. We knew that the consequences of this response vulnerability had to be further investigated to determine its criticality and we recommended that it be included in determining the data to be collected in the longitudinal study.

Another example of a vulnerability that was further investigated in the longitudinal study is related to the engine start procedures. The 777 is designed so that both engines can be started simultaneously. It also has automated engine monitoring functions that alert the pilots if the engines are not starting properly. On the 767-400 the engines must be started separately, and the engine parameters must be monitored by the pilots to ensure a safe start. In our analysis process we found that the 777 pilots still closely monitored the engine status during start even though they had the assistance of the automation; however, they always quickly started both engines, which would not be appropriate in the 767-400. Therefore, we recommended monitoring the behavior of the 777 pilots when they started the 767-400 engines during the longitudinal study. In this case, the vulnerability was due to the differences in system logic and the resulting procedures used by the pilots and not to a difference in physical design characteristics. In fact, the controls used to start the engines were very similar, and this was noted as making it more likely that the pilots might perform the wrong behavior.

The minor vulnerabilities that were identified in the analysis were communicated to the airline to consider when developing training and procedures for their mixed-fleet flying program involving these two airplanes. Several of these vulnerabilities were due to the differences in the size of the two airplanes: The 777 is much larger in overall size and wing span than the 767-400. Because of this, there are several tasks during which the pilots must consider the size differences, and these differences are not necessarily evident while sitting in the flight deck. One example is during taxi procedures: The pilots in the 777 must ensure that they do not stop the airplane during a turn when the wheels of the main gear are still cocked in a turn. The main gear wheels of the 767-400 do not turn, so this is not a consideration on that airplane. Therefore, the vulnerability is for the pilots used to flying the 767-400 not monitoring the angle of the main gear wheels while taxiing the 777. This can be information given to the pilots during training. The consequences are wear and tear on the main gear assembly, but not safety related outcomes.

Verification of Vulnerabilities in Longitudinal Study

The scenarios and maneuvers used in the longitudinal study included elements to test all the safety critical vulnerabilities identified in the analysis. The study included pilot participants who were currently flying one of the airplane types and had never flown the other type. Participants were 10 captains and 10 first officers from each airplane, for a total of 40 pilots.

Longitudinal Study Design

The elements that make up this study are

- Simulator evaluation in current airplane
- Training in new airplane
- End-of-training simulator evaluation in new airplane
- 90-day simulator evaluation in new airplane
- 180-day simulator evaluation in new airplane

There were 10 crews per fleet (i.e., 10 crews were current in the Boeing 777 and received training in the Boeing 767-400 and 10 were current in the Boeing 767-400 and received training in the Boeing 777). Each crew consisted of a captain and a first officer. Half of the crews for each fleet were given a simulator evaluation in their current aircraft before any training began. Immediately after training, all of the crews were given a simulator evaluation in the newly trained aircraft. All the crews then returned to the line to fly their normal aircraft. At the 90-day interval, half of the crews from each fleet were given a simulator evaluation in the newly trained aircraft. At the 180-day interval, all the crews were given a simulator evaluation in the newly trained aircraft.

Pilot Training The training on the new airplane consisted of two systems training modules, a written systems evaluation, and five simulator training modules.

Evaluation Development The protocol and content for all evaluations were developed with input by the Boeing members of the MFF study team and FAA AEG inspectors. It was determined that the maneuvers to include in the evaluations should be those in the standard Appendix F required maneuvers list, with a few exceptions.

Evaluation Protocol The evaluation profile consisted of a line-oriented segment that included both crew members followed by a maneuvers evaluation segment that each of the participants flew separately. An instructor pilot served as the pilot-not-flying during the maneuvers segment to control for the possible confounding effects of having a non-qualified MFF participant serving that role. Because the instructors routinely serve this role during regular training and evaluation, they are familiar with the policy to neither help, nor hinder the pilot-flying during the evaluation.

Evaluation Data Collected The evaluation data listed in Table 1 was collected for each of the simulator evaluation segments. The data collected were the same for all evaluations.

The evaluation data were collected in the following ways:

- Instructor/evaluators provide yes/no assessments during the simulator evaluations. (Note: These assessments were also verified later during the video analysis.)
- Instructor/evaluators assign grades and identify errors during the simulator

evaluations (see Attachment 1 for details).

- Pilots complete modified NASA TLX worksheet assessment instruments following each module to measure perceived level of workload and provide workload ratings.
- Research Integrations conducts video analysis to collect data about the length of time required to complete the after landing checklist and the altitude at autopilot disengagement.

Video Analysis

All simulator sessions were video taped. The tapes were received and organized by evaluation modules, participant numbers, and participant positions (captain or first officer). The tapes were given unique numerical identities (1 – 113). The video analysis focused on the tasks for which there were safety critical vulnerabilities. We will describe here the analysis related to the use of the TOGA switch on the 777. Two tasks were analyzed: the missed approach at minimums and the rejected landing.

Hardware and software set up The video lab consisted of the following hardware:

- Apple Macintosh Powerbook with OS X
- 2 – Lacie 500 Gigabyte external hard drives
- 1 – Lacie 250 Gigabyte external hard drives
- 1 – Sony 20 inch color television
- 1 – LXI Video Cassette Recorder

The video lab used the following software to digitize and produce viewable files and DVDs

- Apple iMovie
- Apple iDVD
- Apple Quicktime

The LXI video cassette recorder's audio/video output was connected to the Powerbook audio/video input by a RCA cable consisting of left and right audio lines and a video line. All three Lacie External hard drives were daisy chained together using FireWire 800 cables and connected to the Powerbook through an iLink 6-to-4 pin cable.

Only the 777 tapes were digitized (45 in total), and an excel file was created capturing all of the data for each 777 tape. The tapes were imported and monitored to confirm:

- The proper functioning between VCR and iMovies as well as importation of video
- The tape's content corresponded accurately with the information on the tape spine and in the excel file:
  - Aircraft Type
  - Participant Position
- The video captured the entire simulation session without interruption or failure
- Any discrepancies were investigated and resolved

The file size for each digitized video tape was approximately 15 Gigabytes

Two segments of the simulation video were isolated for analysis: missed approach at minimums and rejected landing at approximately 100 feet

In capturing clips of the missed approach:

- All clips were edited to begin just before the airplane automated callout at "minimums."
- All clips were edited to end after the "gear up" callout by the pilot flying.

In capturing clips for the rejected landing

- Clips began just before the instructor command to "go around."
- Clips ended after the "gear up" call by the pilot flying.

In measuring the reaction times for the missed approach

- Reaction time began at the beginning "m" of the airplane automated "minimums" callout.
- Reaction time ended at the point of first observable hand or finger move going forward to activate the TOGA switch.

In measuring reaction times for the rejected landing

- Reaction time began with the instructor pronunciation of the "g" in "go around."
- Reaction time ended at the point of first observable hand or finger move going forward to activate the TOGA switch.

The file size for each of the clips was approximately 35 Megabytes.

The following information was recorded for each of the missed approach clips:

- Event time (duration of the clip)
- Reaction time for selecting TOGA
- Observations about how the pilot responded when selecting the TOGA switch: no hesitation, hesitation, went for aft button first, anticipated, etc.

The following information was recorded for each of the missed approach clips:

- Event time (duration of the clip)
- Reaction time for selecting TOGA

- Observations about how the pilot responded when selecting the TOGA switch
- Minimum altitude reached before climb out

The results of the video analysis show that there were several pilots who tried to select the aft TOGA switch when it was not there. The reaction times for these pilots were longer than for those who did not hesitate when choosing the forward TOGA switch. Figure 2 presents the numbers of pilots who reached for the aft TOGA switch before the forward switch while doing the missed approach. Figure 3 presents the same numbers for the rejected landing.

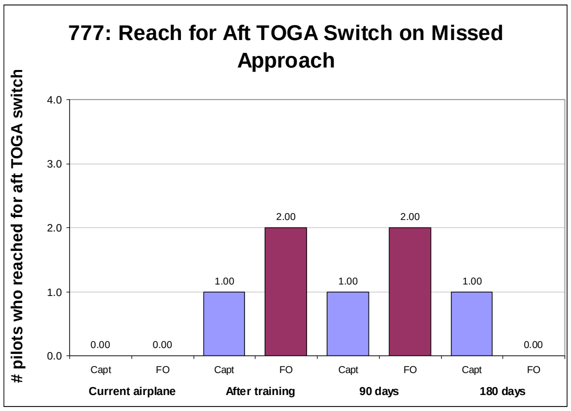

Figure 2. *Number of pilots who reached for the aft TOGA switch during the missed approach for each evaluation module.*

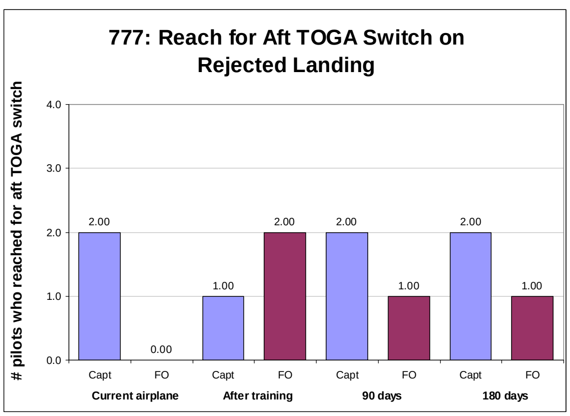

Figure 3. *Number of pilots who reached for the aft TOGA switch during the rejected landing for each evaluation module.*

Figure 4 shows the reaction times on the missed approach for those pilots who went for the aft switch first and those who went for the forward switch only. Figure 5 shows the same data for the rejected landing. The reaction times for the pilots who went for the aft switch first are significantly longer than those who directly activated the forward switch (both $p < .01$).

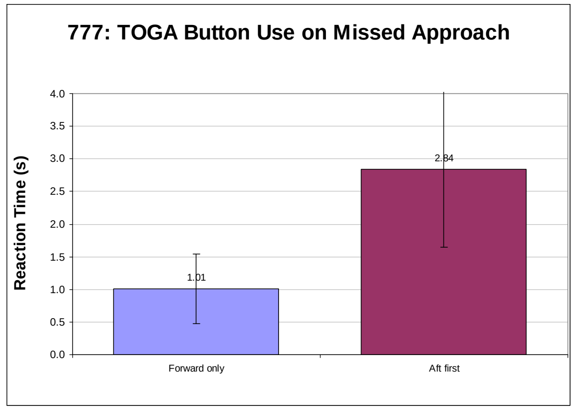

Figure 4. *Reaction times for activating the TOGA switch on the missed approach for pilots who reached for the forward switch only and the aft switch first.*

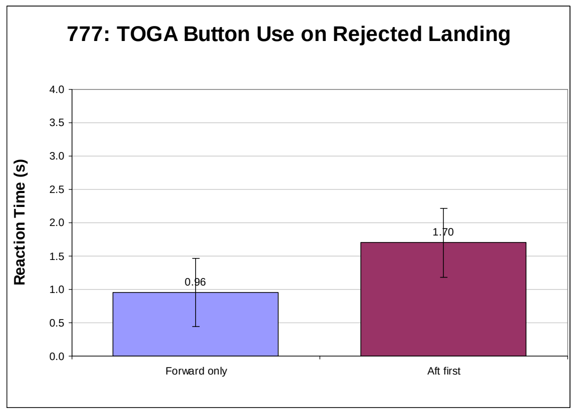

Figure 5. *Reaction times for activating the TOGA switch on the rejected landing for pilots who reached for the forward switch only and the aft switch first.*

These are the type of data that can be used to assess the criticality of vulnerabilities. It would be expected that negative transfer would occur more likely occur in situations that are unexpected and urgent or under time pressure. For the TOGA switch design vulnerability, the data show that more pilots, even those with current experience in the 777, reach for the aft TOGA switch in an unexpected situation like the rejected landing (Figure 3) than in a situation that can be anticipated like the missed approach at minimums (Figure 2).

It is also shown in Figures 4 and 5 that, as would be expected, the reaction times are longer when the pilot reaches for the aft switch first. The question for the FAA, manufacturers, and airline is whether the slower reaction time is enough to result in serious safety consequences. In this case, we included the missed approach and the rejected landing to be able to compare routine and time-critical reaction times.

Comparing Figures 4 and 5 shows that the pilots are quicker to respond in a time-critical situation like the rejected landing; however, the slower reaction times when reaching first for the aft TOGA switch make the safety ramifications of mixing these airplanes worth questioning whether there are mitigation strategies. For example, in this case a design change is one possible solution. The results of this analysis were passed on to the manufacturer and they are determining the requirements for adding the TOGA switch designed for the 767-400 to the 777.

We have shown through this study that a systematic vulnerability analysis can add significant value to the decision making required when determining the feasibility of mixed-fleet flying of any two airplane types or models. Because of the value added, the FAA and airplane manufacturer have requested that we be involved in future mixed-fleet flying assessments to perform the same type of analysis.

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