SAFETY BENEFITS OF ELECTRONIC CHECKLISTS: AN ANALYSIS OF COMMERCIAL TRANSPORT ACCIDENTS[1]

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ABSTRACT

Flight crew failure to follow prescribed procedures has been cited as a factor in many aviation accidents. Some of these accidents included checklist errors, such as skipping a checklist or omitting a checklist line item. Electronic checklists (ECLs) are automation-based tools that reduce or eliminate several types of errors associated with the paper checklist method. This paper presents one means of evaluating the effectiveness of ECLs in preventing accidents. Two decades of commercial accidents were searched and analyzed. A probability-based method was used to give appropriate degrees of credit to ECL as an intervention in the accident causal chain.

INTRODUCTION

Checklists are used in aircraft to ensure that critical tasks are completed by the crew in critical operational contexts. There are two distinct domains of checklists, termed normal and non-normal checklists.

Normal checklist items consist of airplane settings, such as FLAPS...SET, or crew activities, such as BRIEFING...COMPLETED, that are checked at identifiable points in a normal flight sequence. Most operators use normal checklists to confirm key steps after completion of memorized normal procedures.

Non-normal checklists, which are sometimes divided into emergency and abnormal checklists, are accomplished in response to non-normal airplane system events, such as a hydraulic system failure, or non-normal operating contexts, such as ditching the airplane at sea. The procedures correct, compensate for, or otherwise accommodate the non-normal condition to ensure continued safe flight and landing. Most non-normal checklists are used to guide procedures in real-time that the crew has not memorized, although a small subset of non-normal checklists contains memory items that the crew later confirms with reference to the checklist.

Boeing Electronic Checklist Development

In the 1980s, accident research by Boeing and others (Lautmann & Gallimore, 1987) revealed that crew procedural errors, and specifically errors in accomplishing checklists, were causal or contributing factors in a substantial number of incidents and accidents. In response to the new safety data, Boeing flight deck research and development teams began looking at methods to prevent these errors. This led to development of early prototypes of the Boeing electronic checklist.

It should be noted that while an electronic checklist tool may yield many benefits, such as shorter checklist accomplishment times, lower cognitive workload (O'Hara, et al, 2000), decreased training time and attractive marketing material, the primary design driver was simply to create an automation tool that would prevent the crew errors associated with paper checklists. A necessary derivative design goal was to absolutely avoid the introduction of new error modes related to the introduction of new automation in the flight deck. A thorough discussion of those design considerations has previously been presented (Boorman, 2000).

In 1990, the Boeing 777 program was launched and ECL moved from R&D into production design. New factors influenced the design, such as design changes to accommodate full airline modifiability of the checklist data and pilot feedback during simulator validation. ECL was certified in 1996. In the following three years, the design further evolved as several significant improvements were made based on initial service experience.

At the time of this writing, 320 Boeing 777's are in service with 27 operators, all using the ECL. Approximately 7,000 pilots have been trained in the use of ECL. In five years of service experience and over six years of training experience the tool has consistently been found to prevent errors - practically if not scientifically validating the original design objective. However, in the interest of providing more substantial validation, it was decided to circle back and revisit the accident record, examining the characteristics of the ECL tool, in the form produced by a decade of evolution, to validate its efficacy with respect to its original purpose: error prevention. This is the purpose of the present study. But first, we will take a closer look at the paper checklist error modes.

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PAPER CHECKLIST ERROR MODES

Paper checklist error modes were identified through accident/incident analysis, literature review and training observation. Table 1 lists the paper checklist error modes. Some of the error modes are effectively prevented by ECL, while others are substantially reduced in probability or severity. Mode #8 is not directly prevented or reduced by the current 777 ECL implementation.

#	Paper Checklist Error Mode	777 ECL Feature
	Both Normal and Non-normal Checklists	
1	One or more items skipped in checklist	Current line item box jumps to incomplete item. "CHECKLIST COMPLETE" indication will not display until all items complete
2	Place lost in checklist when crew distracted by higher priority task or checklist	Automatic place holding when returning to an incomplete checklist
3	Incorrect switch selected	Sensed line items will not turn green
4	Item incorrectly confirmed complete	Sensed line items will not turn green. "CHECKLIST COMPLETE" indication will not display
5	Excessive psychomotor workload due to holding, turning/marking pages, recovering dropped or misplaced paper checklist	Panel mounted display and one-hand cursor controller
6	Checklist unreadable due to poor illumination	Display readable in any lighting condition
	Normal Checklists (NC) Only	
7	NC skipped (subsequent checklist accomplished before critical flight phase)	Next normal checklist in sequence always displayed
8	NC omitted (all checklists related to critical flight phase are omitted)	Not prevented. Checklist is displayed later when ECL next accessed, providing error feedback
	Non-normal Checklists (NNC) Only	
9	Incorrect NNC accomplished for the annunciated condition	Correct NNC automatically placed in queue when airplane system fault message displayed
10	NNC skipped or left incomplete	Checklist queue lists incomplete or unaccessed checklists. Amber "NON-NORMAL" indication displayed
11	Incorrect steps accomplished in a branching checklist	Current line item box moves to next step in correct branch. Incorrect branch displayed in cyan
12	Steps to be accomplished later in flight not accomplished	Deferred line items automatically attached to Approach or Landing checklist
13	Operational notes or revised limitations following a malfunction forgotten	Notes automatically collected for review at any time; must be reviewed to complete Approach checklist
14	Wrong steps accomplished when multiple related failures have conflicting actions	Correct steps are collected in single checklist. Consequential checklists inhibited
15	Omitted NNC or other errors due to excessive cognitive workload in multiple failure case	ECL cognitive workload and accomplishment times lower than paper

Table 1 - Paper Checklist Error Modes

ERROR MODES AND ACCIDENT EXAMPLES

Two accidents are described below, illustrating two common paper checklist error modes in the normal checklist domain. The impact of ECL in the non-normal domain is discussed elsewhere (Boorman, 2001).

One or More Items Skipped in Checklist (Mode #1)

An example of this error mode occurred in 1996 in Houston, Texas (NTSB, 1997). The DC-9 flight crew was on approach with the first officer (FO) as pilot flying (PF). The captain accomplished the In-Range checklist (Figure 1) but skipped over the item HYDRAULICS...ON & HI. This item ensures that both engine-driven hydraulic pumps are set to high-flow, enabling normal operation of landing gear and flaps.

The flaps did not extend normally nor did the landing gear. The approach speed (216 knots at 500 feet AGL) was far above normal, and the captain became over-focused on the goal of landing instead of executing a go-around. Ground proximity and configuration aural warnings sounded due to the gear-up condition, but the pilots were saturated by the airplane control task and failed to attend to and identify the meaning of the alerts. The Landing checklist was neither called for nor accomplished. On short final, the FO questioned the decision to land. The captain responded by taking control and landing the airplane gear up. Fortunately, the airplane avoided impact with ground obstacles, and the passengers and crew evacuated safely.

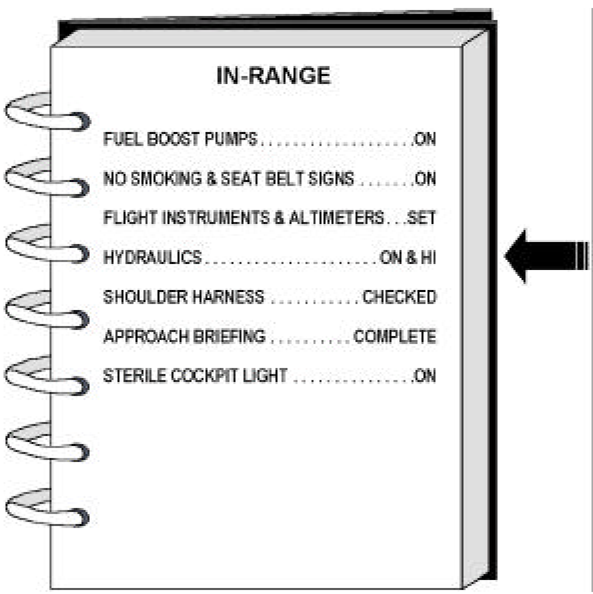

Figure 1 - In-Range checklist, paper version

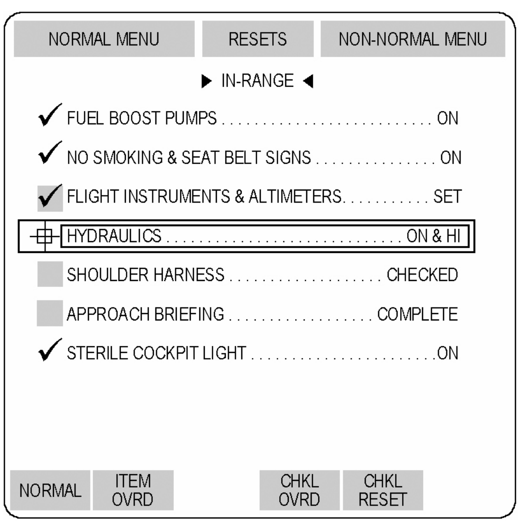

Figure 2 - In-Range checklist, ECL version

How would this scenario have transpired if all else was equal but the airplane had an ECL on board? Figure 2 shows the In-Range checklist as it would appear in ECL. The current line item box moves down the checklist, preventing the pilot from skipping a line item. The entire accident scenario, which originated with a procedural error, would have been averted from the beginning.

Normal Checklist Skipped (Mode #7)

This error occurs when a crew skips a checklist and accomplishes the subsequent checklist in the normal series, never realizing that the first checklist was skipped. The best example of this error occurred in 1987 in Detroit, Michigan. (NTSB, 1988 and Lauber, 1989). The MD-80 crew accomplished the After Start checklist, then were subject to many distractions during taxi-out due to errors in communication and navigation on the airport surface. They failed to set the flaps for takeoff. They skipped the Taxi checklist, but the FO read the items of the Before Takeoff checklist prior to beginning the takeoff roll. However, only the Taxi checklist included the item FLAPS...SET (Figure 3).

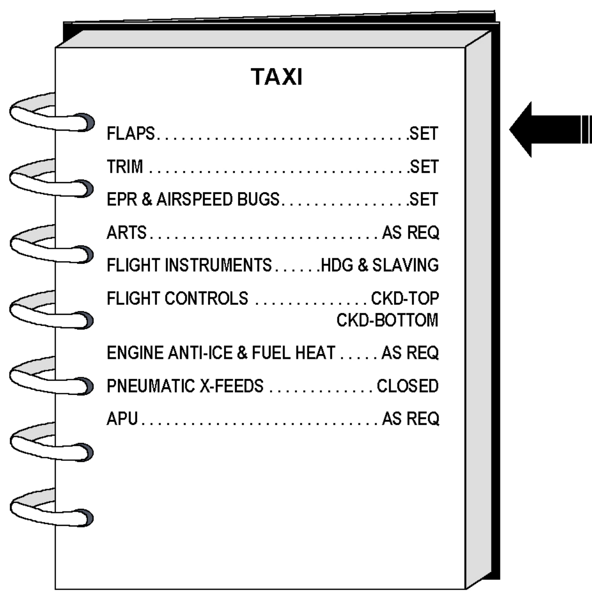

Figure 3 - Taxi checklist, paper version

The takeoff warning system should have alerted the crew to the unsafe configuration, but did not function for undetermined reasons. The airplane took off in a nearly stalled condition, struck obstacles and crashed, killing 154 on board and two on the ground. The NTSB found the probable cause to be the flight crew's "failure to use the Taxi checklist".

Replaying the scenario with an ECL installed, we focus on what would have happened when the FO decided to accomplish the Before Takeoff checklist. Since ECL always displays the next checklist in the

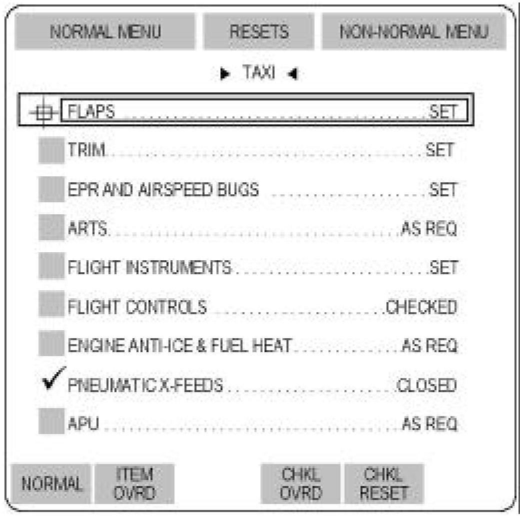

Figure 4 - Taxi checklist, ECL version

normal sequence, the Taxi checklist (Figure 4) would have been displayed instead of the Before Takeoff checklist. The Taxi checklist would clearly indicate the incomplete status of the FLAPS...SET item until the flaps and slats were in the planned takeoff position. It is highly probable that an ECL would have prevented this accident.

ACCIDENT STUDY

The goal of the accident study was to supplement the anecdotal evidence and face validity elements of ECL to further establish its validity as an effective error-preventing tool. This information was hoped to be useful to support future decisions by Boeing and others regarding the implementation of checklist tools.

The method, in general, was to find accidents in which checklist errors occurred, and evaluate how ECL might have affected the outcome. This process involved several steps, concluding in a numerical summation of the number of accidents that would have been prevented by three different variants of an ECL.

Accident Search

Only *accidents*, by the ICAO definition, were included in this study. These are events in which fatalities, serious injuries or substantial aircraft damage occur as a result of aircraft operation (ICAO, 1970). The accidents in the search group occurred between late 1978 and 2001. The accidents searched involved western-built turbojet transport aircraft of 100 seat or greater capacity (or cargo aircraft of equivalent size) in worldwide civil revenue, training and ferry operations.

Significantly, only airplanes with two-crew flight decks were included in the search. Because of the experience in designing, validating and training pilots on the 777 ECL, Boeing experts have a thorough understanding of the interpersonal dynamics of two crewmembers using both paper and ECL. The same cannot be said for the three-crew environment, so there would not be a basis to predict the effect of an ECL on such accident scenarios. Thus, accidents involving aircraft with three-crew flight decks were excluded.

Several sources of accident data were utilized. A Boeing worldwide accident database was searched. An NTSB search and various web searches were used. Keywords were used in the initial searches. Since accident summaries use inconsistent terminology, simply using the keywords *checklist* and *procedure* misses many accidents in which checklist errors occurred. Therefore, other keywords were used that presupposed the types of checklist errors that would be found. Some examples are: *non-normal, abnormal, irregular, flap, spoiler, gear, briefing, hydraulic* and *engine*. Although the goal was to find all accidents with checklist errors, some were undoubtedly missed.

Several hundred accidents were given an initial review to determine whether checklist errors might have occurred. Of those, 81 accidents were chosen for careful analysis. Information on the accidents came from official government agency reports, press accounts, web-based resources, Boeing accident files and interviews with Boeing accident investigators. A large spreadsheet was used to systematically record many variables related to each accident.

ECL Variants Studied

Three variants of electronic checklist tools were considered in the study and are shown in Table 2. Only Variant 2 actually exists. Variants 1 and 3 were postulated for purposes of the study.

Variant 1 - Non-integrated ECL. This variant might someday be incorporated in a stand-alone "electronic flight bag" tool or installed on an older technology airplane such as a DC-9 or 737 without a sophisticated alert message system. It is similar to the 777 ECL except non-normal checklists cannot be linked to the aircraft's alert message system (EICAS). Therefore, pilots must select non-normal checklists from menus, and could commit errors in this task with no feedback from the ECL. Also, the non-integrated ECL does not feature checklist line items that automatically turn green when they are complete (sensed line items). Therefore, pilots may accidentally select the wrong

Vn	Variant Name	Description	Error Modes Addressed (numbers refer to Table 1)
V1	Non-integrated ECL	No EICAS link to non-normal checklists; No sensed items	#1, 2, 5, 6, 7, 10 (partial), 11, 12, 13, 14 (partial)
V2	Integrated ECL	Same as 777	All except #8
V3	Integrated ECL with alerting	777 plus alerting for incomplete Takeoff or Landing checklist	All

Table 2 - ECL Variants

switch or incorrectly identify an item as complete with no error feedback from the ECL.

Variant 2 - Integrated ECL. This is the 777 ECL implementation. It is fully integrated with the airplane's data buses, automatically selects the correct non-normal checklists based upon the annunciated condition, and senses the position of many switches and selectors in the flight deck.

Variant 3 - Integrated ECL with alerting. This is similar to the 777 ECL but has an additional feature. At critical phases of flight, specifically before takeoff and before landing, if appropriate checklists have not been completed, the pilots are automatically alerted. This is a possible "next generation" ECL that prevents error mode #8, *Normal checklist omitted*.

Accident Analysis and Results

Two Boeing employees analyzed the accident data collaboratively. One was a 777 Flight Crew Instructor with several hundred hours of experience training the ECL to airline pilots worldwide. The other was a flight deck ECL design expert. Although the analysis process was designed to be conservative, as Boeing employees involved in the ECL, the evaluators were not unbiased.

For each accident, it was determined whether any errors in checklist accomplishment occurred. In many cases, the errors were clearly documented. In other cases, it could not be determined conclusively from the available data that a checklist error had occurred. A probability value, denoted P_e, was assigned by the analysts to indicate the likelihood that a checklist error had occurred. When some other explanation for the accident circumstances could be found that was equally as plausible as a checklist error, P_e was set to 0. When, based on the clarity and completeness of the report, it was judged as probable that a checklist error had occurred, P_e was conservatively set (it ranged from .40 to .75 for these cases). When a checklist error was unambiguously documented, P_e was set equal to 1.00.

For each accident in which a checklist error occurred, or probably occurred, the accident scenario was "re-played" by the analysts with each of the ECL variants instead of a paper checklist. Assuming that the checklist error *had* occurred, and in consideration of the ability of ECL to prevent the error mode, a probability was estimated that the accident would have been prevented with the ECL variant installed. The probabilities were denoted P_{V1}, P_{V2} and P_{V3} for the three ECL variants.

The probability of a "save", in other words the overall probability that a given accident would have been prevented by the checklist tool intervention given the available information, was calculated as follows (for variant 1):

$$P_{SV1} = (P_e)(P_{V1})$$

The full or partial saves for each variant were summed. Results are shown in Table 3.

V_n	Variant Name	ΣP_{SVn}
V1	Non-integrated ECL	8.3
V2	Integrated ECL	15.2
V3	Integrated ECL with alerting	19.5

Table 3 - Summed ECL "saves" by variant

Factors limiting the accuracy and significance of these results must be discussed. Because only two-crew airplanes were considered and the accident search methods did not necessarily find all accidents with checklist errors, the actual number of saves - had ECL variants been installed in the past - may be greater. On the other hand, probability estimates by the Boeing analysts were sometimes based on incomplete accident data, and their accuracy has not been experimentally verified.

Additionally, the numbers are not being compared to similarly derived numbers for other potential accident interventions. To accomplish such a study, all potentially beneficial interventions, including crew training, airline policy changes and airplane system improvements would need to be considered and their relative probability of preventing each accident evaluated. Such a method would provide more meaningful results for use in planning intervention strategies.

Also, one must ask the philosophical question, is a measurement of the past an accurate predictor of the future? Significant changes in crew training, pilot demographics, airplane technology and the air traffic environment have and will continue to take place. Will the context of checklist errors, and indeed checklists, be significantly altered in the future? An answer to this question is available: the fundamental role of checklists, to ensure that critical crew actions are accomplished at critical points in a flight, is likely to remain valid; and decreasing the chance of errors in the accomplishment of those actions will continue to benefit flight safety. Therefore, we can use the present findings, along with the very positive but non-scientific feedback from the user population, to draw the conclusion that ECL is and will continue to be an effective tool for the prevention of accidents related to checklist errors.

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