AN ANALYSIS OF OPERATIONAL ERRORS AND THE INTERACTION WITH TCAS RAS

Garcia-Chico, José L. & Corker, Kevin M., PhD, San José State University, CA

jgarciac@email.sjsu.edu, Kevin.corker@sjsu.edu

Abstract

This research evaluated operational errors (OEs) in Air Traffic Control (ATC). It consisted of two exploratory studies. The first one was a classification of OEs and contextual factors. The second one was an in-depth look at OEs that co-occurred with a Traffic Alert Collision Avoidance System (TCAS) Resolution Advisory (RA) onboard. The results provided a systematic characterization of OEs, with potential use to prioritize future research and interventions. Patterns of error in en route and terminal airspace were found to be slightly different. The absence of D-side controllers and the presence of developmental controllers were associated with higher proximity between aircraft. The second study found evidence of deficient pilot-controller communications during TCAS RA events in the OE reports. The results suggest that, the likelihood of receiving vertical clearances in opposite direction to the RA is higher when the information from the pilot to the controller regarding the RA is incomplete. These findings suggest the need to revisit the concept of down linking RA information to ATC.

Introduction

The prevention of the incidence of human errors in ATC becomes crucial as air transport demand increases, and the system becomes more complex. To accomplish this, the FAA has established an incident reporting system for identification and correction of incidents in ATC under the FAA Air Traffic Quality Assurance Order 7210.56 [1], [2]. It captures situations where an air traffic controller allows a separation between aircraft less than the applicable minimum standard separation criteria. These are known as operational errors.

This research and analysis has taken place in two phases. Phase one was a classification of operational error reports from January to June 2004 from both the Terminal Radar Approach Control (TRACON) and Air Route Traffic Control Center (ARTCC) facilities. The second phase was an analysis of operational error form January to June 2005, based on the full error report, form 7210-3 [2]. These analyses and classification efforts are undertaken in a broad context of error classification and identification efforts in ATC. The assumption of these analyses is that given appropriate taxonomies of human error (c.f. [3]), an understanding of both the work performance context (c.f. [4]), and the organization/system context in which the human-system performance occurs (c.f. [5]); analysts can classify "types" of error and the context of contributory factors that combine. In our broad analyses, issues of "cause," in the sense raised by Dekker [6], are not yet addressed. We are focusing on classification for the purposes of identification of trend and consistency in those classifications and in the context in which the operational errors occur. This approach has been formalized in several systems, such as, TRACEr [7], HFACS [5], and HERA-JANUS, which represents a harmonization of European and United States [8], [9]. .

The classification of human performance looks to three basic interactions to provide the basis of error identification. First, there are issues of the basic information processing elements and functions that the human operator brings to task. In these, the issue of limitations (perceptual, memorial, cognitive or motor) is provided to anticipate how humans might be overloaded by task requirements. Humans do not have infinite bandwidth and, in fact, have some unique attributes that determine what types of tasks we can and cannot do simultaneously. There are established theories that address these issues such as the Wickens' Multiple Resource Theory [10], [11]. Second, there is classification of the requisite modification of those functions in response to environmental stressors (either internal or external to the operator). These models have played a large role in human reliability analyses as "performance shaping functions" [12]. Finally, context [13] and organizational impacts [5] is accounted for in this classification framework. Ultimately, these factors are shown to be interactive in a framework for error with internal, external and psychological error modes model as influenced by context, stressors and other performance shaping factors and the flow of the activities in an air traffic mission.

In this analysis, we concentrate on one circumstance associated with operational error:

TCAS alert interjection in the course of events surrounding the operational error. The introduction of automation in complex socio-technical systems, such as in aviation, has aimed at preventing errors and its consequences, among other reasons (e.g., reducing workload of operator, replacing humans at lower cost). However, automation is not always an effective solution to solve human errors because it might introduce new error opportunities. In many situations, it does not replace the human activity, but changes human operator demands [14], [15], [3]. The TCAS system is one of these cases. Although TCAS is a cockpit alerting system and different from some more traditional automated systems (e.g., flight control systems), it retains capabilities associated with them, such as analysis and command capabilities [16]. Here, automation refers to "the full or partial replacement of a function previously carried out by the human operator" [14]. The intention of our analysis is to understand the procedural and informational context of the operational error co-occurring with the collision avoidance guidance issued to pilots by TCAS.

The problem of human error reduction/elimination is one of the most challenging in the design of complex human machine systems. Humans are included in complex systems to exploit their adaptive intelligence and interpretive inference [17]. Human operators are critical to successful performance in partially unpredictable complex and dynamic systems in which the optimization criteria are either under specified or non-stationary. The characteristic ability to deal with uncertainty, ambiguity and under-definition predisposes the human operator in a system to certain types of errors [4]. The human operator also acts in ways that are adaptive, context-responsive and where possible habitual in performance during high stress, high workload environments [13], [18]. This adaptation and development of structured response brings with it the set up for perceptual, procedural and decision biases that are effective in many or most situations, but lead the operator to error under specific contexts of operation [19]. We agree with Weigmann and Shappell [5] and Reason [3] and contend that simply concentrating on defeating the near-term "proximal cause" of an error, i.e., a miscommunication or a missed procedure does not yield the most effective design and may result in more frequent or more consequential errors. In order to avoid such unintended consequences, we have undertaken a review of TCAS-associated operational errors to support understanding of the procedural and informational aspects of these errors.

TCAS system

TCAS was introduced as a redundant monitoring backup for air traffic controllers and pilots to prevent midair collisions if both operators failed to detect them. It is a last-resort safety automated system [20], [21]. The impact of TCAS system on aviation safety has been beneficial, significantly reducing collision risk [22]. However, recent accidents and incidents have raised concerns on the very few circumstances where TCAS might induce new hazards [23], [24].

The objectives of the TCAS system are summarized as follows: first, it "advises" pilots visually of surrounding traffic; second, "alerts" them both visually and aurally that a collision risk exists if both aircraft keep their current course (this alert is called Traffic Advisory (TA)); and third, "issues" visually and aurally a vertical maneuver to avoid a potential collision (this alert is called Resolution Advisory (RA)) [20]. Hereafter, the acronym TCAS is used to designate the TCAS II equipment version v7, which is mandatory for most commercial carriers in the USA. TCAS II issues both TAs and RAs, in contrast to TCAS I which only provides TAs. TCAS has been mandatory for most commercial operations in the US airspace since 1991, while in Europe only since 2001. The worldwide mandate was not issued by the International Civil Aviation Organization (ICAO) until 2003 [25].

Principles of TA and RA alerts

The surveillance component of TCAS works as a Secondary Surveillance Radar (SSR). A radio transceiver interrogates the transponders carried by other aircraft, scanning the surrounding airspace. Only responses from nearby aircraft equipped with transponders that provide altitude information (Mode A/C and Mode S) allow tracking altitude, range, and bearing of intruders. The information extracted from nearby aircraft's responses (altitude, range, and bearing of intruders) is presented in a traffic display and is processed by the collision avoidance logic for threat detection and collision advice. TCAS calculates the intruder's closure rate and the Closest Point of Approach (CPA). If the distance between the two aircraft at the CPA poses a threat, the system will issue an alert. TCAS computes time to CPA rather than distance to provide protection and to issue alerts. Typically, TCAS triggers TA warnings 45 seconds before the CPA, and RAs 30 seconds before. These alarm thresholds (look ahead time, vertical distance and horizontal thresholds) increase with the own aircraft altitude [21]. No RA is issued below 1000 feet. The look-ahead time of the TA is approximately 15 s to warn the pilot of an upcoming RA and to acquire visual contact with the intruder [25], [26]. RA indicates the pilot a maneuver in the vertical plane, either passively (i.e. do not climb, do not descend) or actively (i.e. climb, descend, adjust vertical speed). In some rare occasions, TCAS can reverse the sense of an RA, after reassessing the geometry of the encounter. As soon as one TCAS issues an RA, it coordinates with the threat's TCAS equipment to ensure complementary maneuvers [21].

TCAS Procedures

TCAS procedures are executed differently across countries and airlines. In the US, the FAA has established the pilot's and controller's responsibilities and the procedures to follow in its Advisory Circular 120-55B [27]. These procedures are summarized as follows. On receipt of a TA, pilots shall respond "by attempting to establish visual contact with the intruder aircraft and other aircraft which may be in the vicinity" [21]. They shall not maneuver on response of a TA. On receipt of an RA, the pilot flying (PF) "should respond immediately by direct attention to RA displays and maneuver as indicated, unless doing so would jeopardize the safe operation of the flight or the crew can assure separation with the help of a definitive visual acquisition of the aircraft causing the RA" [21]. Aircrew takes the responsibility for separation when they decide not to follow a RA. In these cases, visual perception may be misleading, especially when the ground reference is unreliable or the horizon is masked. The traffic acquired may not be the same that triggered the RA. In addition, the FAA acknowledges that TCAS does not provide safe separation in all cases, because it does not respond to aircraft without a transponder or with a malfunction in it.

Regarding the notification of the RA to ATC, the FAA requests the pilot to "communicate with ATC as soon as practicable after responding to the RA" [21]. Pilots are required to return "expeditiously" to the previous ATC altitude clearance when the conflict is resolved. Air traffic controllers cease to be responsible for an aircraft's separation assurance as soon as the aircraft deviates from the ATC clearance in response to a RA, but they are required to provide traffic information, if "workload permitting" [21]. They do not knowingly issue instructions in opposite direction to an RA. They resume responsibility when the pilot informs them that the conflict is solved and the aircraft returns to the previous flight level or the pilot acknowledges an alternative clearance. Of special interest here is the FAA's advice of not maneuvering in the opposite direction to a given RA "based solely upon ATC instructions" [21].

Human Factors Issues related to ATC

A simplified view of pilot's actions and controller's responsibilities during a TCAS RA event is depicted in Figure1. It represents what Brooker [28] calls "desired sequence". He argued that, in reality, this sequence is not followed, and that the controller may receive one pilot's message or none informing on the TCAS RA. Eurocontrol [22] argued that because of the short time to react, the report might be issued late by the pilot, being of limited or no use for the controller.

TCAS RAs instruct pilots to maneuver in the vertical plane. They can "drastically disrupt the controller's situation awareness [SA]" [20]. Wickens et al. indicated that this disruption is amplified by the fact that the change of the flight level, the main parameter affected by those vertical maneuvers, is not evident on the ATC display as it is only included as a number in the flight data block and an arrow. The controller is not responsible for the separation of that aircraft as soon as the RA is followed and the aircraft departs from the ATC clearance [29]. However, Brooker [28] argued that the controller believes he or she is in control of separation until he receives the first voice message. The longer this period, the greater the likelihood for the controller to make an error.

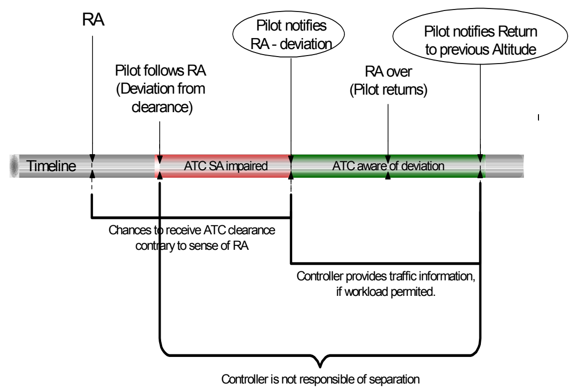

Figure 1. Timeline of events in a typical triggered TCAS RA event. Circles represent voice messages. *Note.* Adapted from [28].

Study 1: Taxonomic Analysis

Methods

A total of 539 OE reports, spanning the period from January 2004 to June 2004, were collected. From these reports, 54 reports classified as runway incursions and five as oceanic, were excluded. A total of 480 OE reports resulted to be included in the final analysis. Reports were divided between the two authors to be reviewed. For each OE report, reviewers assigned one or more error type, from a list of 24 error types, according to the flow decision diagram depicted in Figure 5 in the Appendix. A classification of contextual or concurrent factors that might have played a contributory role in the incident was also recorded in the study. An inter-reliability test was performed to ensure the two reviewers applied the same criteria by calculating Cohen's Kappa index on ten reports exchanged in a double blind between reviewers.

In addition to the counts of errors, a measure of "proximity" was calculated for all OEs. Three categories of proximity resulted: A, B, and C, based on the relative distance of aircraft from each other in horizontal and vertical planes at the CPA. Table 1 provides the criteria to calculate the index.

Vertical (ft) \ Horizontal CPA (nm)	0	0.5	1	2	2.5	>2.5
250	A	A	A	B	C	C
500	A	A	B	B	C	C
1000	B	B	B	C	C	C
1500	B	B	C	C	C	C
2000	C	C	C	C	C	C
>2000	C	C	C	C	C	C

Table 1. Proximity index calculation criteria

Results

The Kappa statistic was 0.83, which is considers a satisfactory level of agreement. The reviewers were applying the same criteria for assigning reports. Because each OE report could have multiple error types associated, the total number of errors was 810. Of those, 560 were in ARTCC and 250 in TRACON.

The top-12 errors accounted for the 87.5% of the errors identified. Overall, the most frequently reported error, *failure to notice converging aircraft*, was reported in 23.3% of all of the reports in the data set, 26.4% in ARTCC and 17.3% in TRACON. In these cases, the controller was aware of both aircraft, but failed to notice that they were on converging courses. The most frequently recorded type of error in the TRACON reports was *inadequate coordination among controllers* (either within or between facilities). This was the second more frequent error cited in 15.8% of the reports overall, 19.8% of the TRACON reports, and 13.8% of the ARTCC reports. Another common type of controller error is *readback/hearback*. In these cases the pilot reads back a different instruction that the controller issued, but the controller fails to notice and correct the discrepancy. This type of error was cited in 13.5% of the OE reports (12.9 %, of the ARTCC reports and 14.8% of TRACON reports). Approximately 25% of the reports noted that the controller issued an instruction that climbed or descended the aircraft through the path of another aircraft with less than the required separation. There are interesting differences in the patterns of these errors between ARTCC and TRACON OEs. ARTCC OEs are much more likely to cite losses of standard separation involving an aircraft instructed to descend through (20.8%) than climb through (11.3%) another aircraft's altitude. Such errors were also much more common in the ARTCC environment (total of 32%) than in the TRACON environment (12% total, with 5.6% descents and 6.2% climbs). An additional 11.7% of the reports noted that the controllers issued altitude that climbed or descended aircraft toward (but not through) the other aircraft's altitude. This type of error was also more common en route than in the terminal environment (15.4% of the ATRCC reports and 4.3% of the TRACON reports. Table 2 presents the percentages of each error type.

	Total		**ARTCC**		**TRACON**	
Error Category	#	%	#	%	#	%
Fail Converging	112	23.3	84	26.4	28	17.3
Control coordination	76	15.8	44	13.8	32	19.8
Descend through	75	15.6	66	20.8	9	5.6
Overlooked Traffic	70	14.6	48	15.1	22	13.6
Vector inadequate	68	14.2	43	13.5	25	15.4
Hearback/Readback	65	13.5	41	12.9	24	14.8
Altitude Inadequate	56	11.7	49	15.4	7	4.3
Fail Altitude Climb/Descend	54	11.3	32	10.1	22	13.6
Climb through	46	9.6	36	11.3	10	6.2
Fail Overtaking Traffic	31	6.5	23	7.2	8	4.9
Instruction no-intended	30	6.3	17	5.3	13	8.0
Temporal error-issue	26	5.4	16	5.0	10	6.2
Misapplication Procedure	16	3.3	8	2.5	8	4.9
Datablock miss enter info	15	3.1	13	4.1	2	1.2
Airspace	15	3.1	3	0.9	12	7.4
Transpose a/c	11	2.3	7	2.2	4	2.5
Others	11	2.3	6	1.9	5	3.1
FPS miss enter	10	2.1	9	2.8	1	0.6
Speed inadequate	6	1.3	5	1.6	1	0.6
Wrong a/c	5	1.0	1	0.3	4	2.5
a/c overlap	4	0.8	3	0.9	1	0.6
Misread info	3	0.6	3	0.9	0	0.0
LOA misapplication	3	0.6	2	0.6	1	0.6
Cleared below minimum	2	0.4	1	0.3	1	0.6

Table 2. Number of error type and % of reports that contained them in ARTCC and TRACON

Another frequent error was "overlooked traffic". In these instances, the controller doesn't "see" or overlooks a conflicting aircraft when issuing an instruction. This type of error was cited in 14.6% of the reports overall, 15.1% in ARTCCs and 13.6% in TRACONs.

Among the contextual factors identified in the OEs, *absence of data-side (D-side) controller* was the most frequent, cited in 40.7% of ARTCC OEs. Table 3 presents the proximity rating of errors with D-side present and absent.

	D-Side Present	D-Side Absent
Proximity A	3 or 1 %	8 or 3%
Proximity B	13 or 4%	27 or 12%
Proximity C	278 or 95 %	195 or 85%

Table 3. Proximity rate of errors linked to the absence to D-side controller

Another interesting contextual factor we looked at was the fact that a *developmental*[1] controller was working the sector. We did find that 7.9% of OEs involved a developmental working the sector. Figure 2 illustrate the proximity observed when there was a developmental working in the sector. A Chi-square test of independence did not support statistically significance at the 95 % degree of confidence ($\chi 2$ (2, N = 459) = 5.775; p = 0.057).

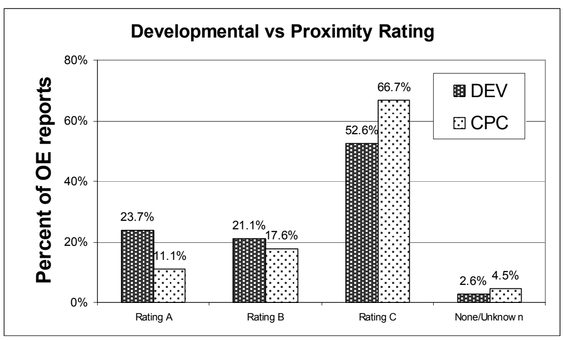

Figure 2. OEs sorted by proximity with developmental and certified controllers

Discussion

This analysis shows that there are controller errors that are common across ATC environments, such as readback/hearback errors and overlooking traffic. There are also interesting differences in the patterns of errors found in losses of standard separation between the terminal and en route environments. More detailed research into specific aspects of these errors could point to mitigation strategies.

Data related to the proximity of the encounter in those errors without D-side controller, while suggestive, have to be considered in light of the fact that we were unaware of what the base rate, or standard rate, of operations was without a D-side in the center. Nevertheless, Table 3 suggests that the severity of the error (as rated by a proximity index) is likely to be higher in both severity A and B when a D-Side is absent. The D-side assists the R-side controller when traffic reaches certain levels. This teamwork structure provides a distribution of tasks and redundancy to maintain SA [20], becoming an important element in catching errors. Changing team task into an individual one may be responsible of reduction in SA, and we argue it may be the cause of losing redundancy in some tasks, reducing the likelihood of catching R-side errors in the earlier moments of the loss of separation.

Looking at developmental as a contextual factor was equivalent to analyzing the effect of expertise. Extensive research has demonstrated that experts have superior mental models that allow them to anticipate future events [34]. The lack of the base rate of developmental operations prevented us to achieve any conclusion about the expertise effect on the occurrence of OEs. However, data suggest that developmental are associated to higher-proximity errors.

Study 2: OEs Involving TCAS RAs

Methods

The total number of reports reviewed was 104, spanning the period from January to July of 2004 and 2005. Only reports indicating that an aircraft initiated an evasive maneuver because of receiving a TCAS RA onboard were selected for the study. From those reports, 19 reports did not describe any information pertaining to the TCAS sequence within the summary, and another 23 reports were too concise for information related to the TCAS RA chain of events and subsequent controller and pilot actions to be extracted from those reports. In summary, 62 reports were analyzed for this part of the study.

We were interested to gain insights into the actual TCAS RA's chain of events and its effect on controller's behavior. Brooker [28] proposed to group incidents according to the controller's appreciation of the conflict, the action he or she was taking, and the information supplied by the aircrew. However, limitations in the interpretation of data led us to change slightly the approach. The initial question of this scheme was to be whether or not the controller was aware of an imminent TCAS RA. This information could not be determined from the reports. The second parameter to investigate was whether or not the controller issued an instruction to avoid the conflict, and if that instruction was given before or after the TCAS RA was triggered on board. Finally, the quality of the

[1] controller who has not satisfied all the training and qualification requirements in a airspace area

information report provided by the pilot was analyzed in terms of completeness and timing of the voice messages. The analysis scheme used is represented in Figure 3. The instruction issued by the controller (i.e., altitude or heading), to resolve the conflict was compared, with the direction given by TCAS RA. The quality of information that the pilot gave ATC regarding the RA was classified as complete, incomplete or none. Information was considered *complete* when the controller received two information messages from the pilot, the first one indicating the aircraft identification and the direction of the TCAS RA shortly after the pilot departed from the ATC clearance (without big delays) and a second message when the pilot received the TCAS message *clear of conflict* and he resumed previous altitude. Information was considered *incomplete* if one report was missing or lacked essential information (e.g., callsign or the direction of the deviation).

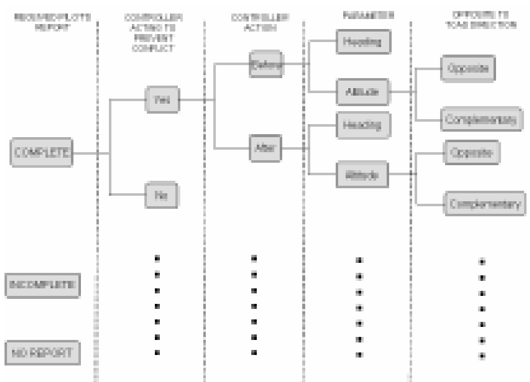

Figure 3. Scheme pilot's message – controller's action during TCAS RA.

Results

In 52 % (n = 54) of the OEs with TCAS RAs, the controller issued an instruction to resolve the conflict. Among them, 30.8 % (n = 32) of incidents contained clearances given exclusively before the TCAS RA was triggered on board, and in 21.2 % (n = 22) of the incidents the controller issued a new clearance after the TCAS RA was triggered onboard in an attempt to reestablished the standard separation. In 17.3% (n = 18) of conflicts, no action was taken by the controller. In an additional 40.4% (n = 42) the timing of the instruction relative to the RA could not be determined.

The controller received complete and timely information in 51.6 % (n = 33) of the incidents, and incomplete information (i.e., missing a pilot's message, missing aircraft call sign or TCAS direction in the message, or excessive delay) in 43.5% (n = 26) of the incidents. There were 5 % (n = 3) of reports where the controller did not receive any information. This might create opportunities for wrong decisions and errors. Figure 4 illustrates the controller's actions during encounters that had TCAS RA across situations based on the reporting pilot's voice messages about the TCAS RA deviation. The controller's action was classified according to two variables: aircraft instruction (i.e., altitude or heading) and timing of clearance compared to the triggered TCAS RA on board. The reader should note that relative timing of the controller's instruction to the RA was inferred from the narrative. Percentage is based on the number of reports with enough information about the pilot-controller interaction (N = 62).

Among OEs with received incomplete pilot's reports, 19.4 % of the reports (n = 12) contained at least a controller clearance issued after the TCAS RA was triggered. The controller should avoid issuing clearances in the vertical plane, once they had been advised that the pilot is responding to a TCAS RA, because they may interfere with the TCAS RA commands. We found that in 12.9% of incidents (n = 8), with incomplete received pilot's information, the controller gave a new vertical clearance. The pilot did not report the direction of the RA in three of these reports and he or she reported the RA after the controller's clearance in the other five reports. The controller issued an opposite altitude clearance to the TCAS RA in three reports (4.8%), and in all of them the pilot's report was given late after the controller's instruction, i.e., as response to the clearance. None clearance was in the opposite direction to the TCAS RA when the report was complete. When the controller was proper and timely informed about the TCAS RA deviation, the direction given, if any, was always complementary to the TCAS RA command. We found two reports where the controller did not receive any message because, even though the pilot who deviated from the ATC clearance contacted with the controller, he was on other frequency.

It is noteworthy to mention that if a TCAS RA alone results in a loss of standard separation (i.e., there was no concomitant controller error); the event is not recorded as a controller operational error. These encounters are not capture under this reporting and investigative process. Therefore, the number of loss of separation with TCAS RA in the NAS might be higher than the number of reports we reviewed, and we do not know how the controller behavior was impacted.

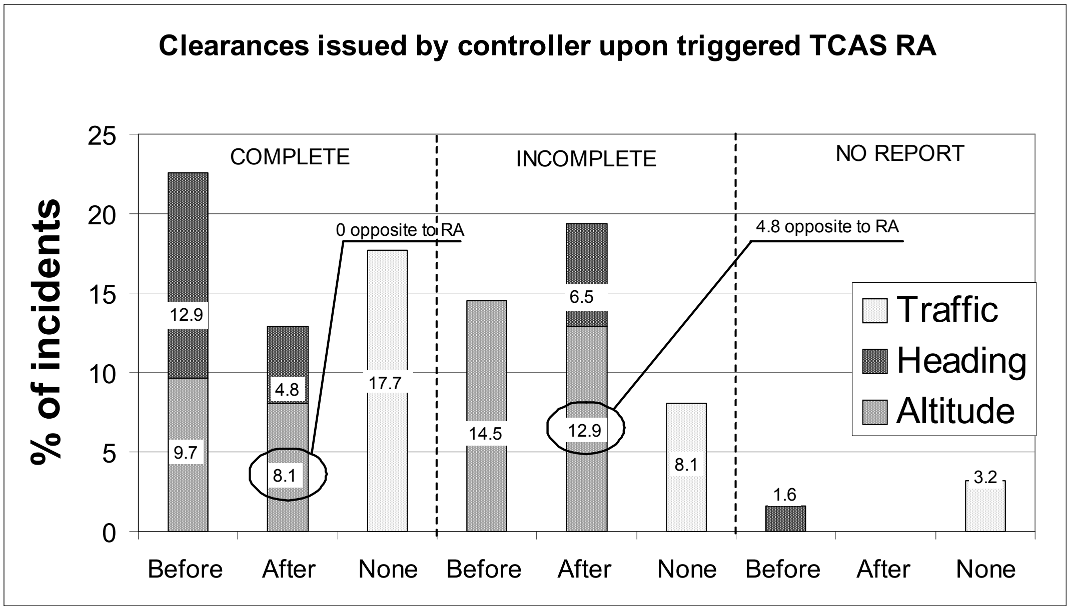

Figure 4. Clearances issued by controller with TCAS RAs involved

Discussion

SA is a key driver for decision-making and performance in many fields, but it is especially true in ATC because the tasks are highly cognitive. Within the three levels defined in [31], the perception of the status, attributes, and dynamics of relevant elements in the environment was essential to be able to comprehend the current situation, project future status and make appropriate decisions. During a TCAS RA, the controller relies completely on the pilot's message to know that the aircraft is deviating from the expected, and previous assigned, altitude. While the altitude field of the aircraft datablock will reflect changes in altitude, the delay in updating the altitude information in today's radar screens may prevent timely detection [22]. Thus, the quality of the pilot's messages is crucial for controllers to gain a correct awareness of the situation. We found that the pilot's reporting was approximately half of the times incomplete. These communications deficiencies added difficulties to the controller's understanding of the situation, impairing their SA. In a simulation study, Rome et al. [32] found similar variability in the reporting pilot's messages, creating confusion and stress among controllers.

When a TCAS RA is triggered onboard, the threat of a collision and the urgency of the actions create stress on the pilot [32]. Under such circumstances of stress, communications might be difficult to understand, and pilots usually delay reporting the deviation [22], or inform incorrectly to the controller.

In addition, we found that the controller issued vertical clearances opposite to the TCAS RA command in three incidents (4.8%) after an incomplete pilot's message. However, the direction was always complementary to the TCAS RA command when the controller was properly informed in a timely manner. If we consider only the OEs where the controller issued a clearance after the RA event in the vertical plane (21%), the percentage of contrary clearances is 23% of those reports. Vertical clearances, even in the same direction of the TCAS RA, pose hazards in the operations, because the TCAS system might reverse the RA direction after a few seconds. Rome et al. (2006) found that in four situations out of 32 scenarios, the controller issued a vertical instruction during the RA, after having been informed about the TCAS RA.

Under stress situations, decision makers may choose their most familiar responses. Therefore, abnormal events might not trigger the appropriate response because the solution is not familiar [34]. This might be the case when air traffic controllers handled incidents with TCAS RA. These events are very infrequent; therefore, when they happen, the first reaction of the controller is to act with the most familiar response, providing a clearance, either in the vertical and/or horizontal plane, to regain standard separation. The likelihood of providing a vertical command opposite to the TCAS RA was higher if the reporting was deficient because the controller's SA was impaired.

We consider two mitigation strategies to reduce the occurrence of controller's clearances after the pilot follows a TCAS RA. First, increase controller's training with simulators focused on scenarios that recreate TCAS RA events in order to increase expertise in dealing with the appropriate solutions. Second, revisit the pros and cons of downlinking TCAS RAs triggered in the cockpit in order to provide controllers with complete and timely information about the TCAS RA.

Various authors have proposed downlinking TCAS RA information (cf. [30], [22], [33], [32], [20]). In the study of Eurocontrol [33], most controllers judged beneficial the provision of RA information to the controller. They considered an improvement in SA and expected to reduce the likelihood of contradictory ATC clearances. However, some problematic issues were pointed. The first one was that the analysis of the RA information might draw too much of the controller's attention, neglecting other traffic situations. The second one was that the relevant information is the pilot deviation from the ATC clearance rather than TCAS RA, because the pilot might not comply with the RA. The third one was the operational procedures associated, controller's responsibility, and potential liability issues. It seems that the more accepted approach was to keep current responsibilities, being transferred from controller to aircrew upon reception of pilot's voice report of the RA [25], [33]. The provision of RA would be used for informational purposes. All of these need to be addressed with further research.

Conclusions

This research demonstrated the value of a systematic characterization of OEs using official record of incidents. This research helped to identify meaningful factors that merit further study. The absence of D-side controllers and the presence of developmental controllers were associated with higher proximity between aircraft.

The TCAS implementation has proven beneficial. However, its operation has had profound implications for controllers. We found evidence of a high variability in the chain of TCAS RA events, problems associated with pilot-controller communications, and harm of controller SA. Our data analysis suggests that controller often provides clearances in the vertical plane after a TCAS RA command. We found evidence (in three reports or 4.8%) of increased likelihood of receiving a clearance in opposite direction to the RA when pilot's voice information about the TCAS deviation from current clearance was incomplete. Two solutions were proposed: to increase training recreating these TCAS RA scenarios, and to downlink the RA information to the controller's workstation. The latter has implications to consider in future research.

References

[1] FAA (2002). *Air Traffic Quality Assurance* (Order 7210.56C). Washington, DC: Department of Transportation.

[2] Pounds, J., & Ferrante, A. S. (2005). FAA strategies for reducing operational error causal factors. In B. Kirwan, M. Rodgerds, & D. Schafer (Eds.), *Human factors impact in air traffic management* (pp. 89-105). Aldershot, UK: Ashgate.

[3] Reason, J. T. (1990). *Human Error*. Cambridge University Press, Cambridge U.K., 1990.

[4] Rodgers, M., Mogford, R. and Mogford, L. (1998). The Relationship of Sector Characteristics to Operational Error. DOT/FAA/AM-98/14.

[5] Wiegmann, D. A., & Shappell, S. A. (2003). *A human error approach to aviation accident analysis: The human factors analysis and classification system.* Aldershot, UK: Ashgate.

[6] Dekker, S. (2002). *Field guide to human error investigations*. Brookfield, VT: Ashgate.

[7] Shorrock, S.T. & Kirwan, B. (1988). The development of TRACEr Technique for Retrospective Analysis of Cognitive Errors in ATM. 2nd Conference on Engineering Psychology and Cognitive Ergonomics (pp. 28-30), Oxford.

[8] Isaac, A., Shorrock, S., Kennedy, R., Kirwan, B, Andersen, H, & Bove, T (2003). The Human Error in Air Traffic Management Technique (HERA-JANUS). Eurocontrol HRS/HSP002-REP-03.

[9] Pounds, J (2006). Retrospective Human Factors Analysis Technique to Identify Factors in ATC System Error (Janus). User's Manual. Draft 1.4.4

[10] Wickens, C. D. (2002). Multiple Resources and Performance prediction. *Theoretical Issues in Ergonomics, 3*, (2), 159-177

[11] Endsley, M & Rodgers, M (1997). Distribution of Attention, Situation Awareness, and Workload in a Passive Air Traffic Control Task: Implications for operational errors and automation. DOT/FAA/AM-9713.

[12] Swain, A. & Guttmann, H. (1983). Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications. NUREG/CR-1278.

[13] Hollnagel, E. (1993). Human Reliability Analysis, Context and Control. London: Academic Press.

[14] Parasuraman, R., Sheridan, T. B., & Wickens, C. D. (2000). A model for types and levels of human interaction. *IEEE Transactions on Systems, Man, and Cybernetics, 30* (3), 286-297

[15] Parasuraman, R. (1997). Humans and automation: Use, misuse, disuse, abuse. *Human Factors, 39* (2), 230-253.

[16] Pritchett, A. R. (2001). Reviewing the role of cockpit alerting systems. *Human Factors and Aerospace Safety, 1* (1), 5-38.

[17] Anderson, J. and Lebierre, C (1998). *Atomic Components of Thought*. Hillsdale, NJ: Erlbaum.

[18] Bier, V., Caldwell, B., Gibson, N. & Kapp, E. (1996). The effects of workload, information flow, and shift length on coordinated task performance and human error. Final Report 133-Z572.

[19] Rodgers, M. (1993). An Examination of the Operational Error Database for Air Route Traffic Control Centers. DOT/FAA/AM-93/72.

[20] Wickens, C. D., Mavor, M., Parasuraman, R., & McGee, J. (1998). *The future of air traffic control: Human operators and automation*. Washington, DC: National Academy of Science.

[21] FAA (2000). *Introduction to TCAS II version7*. Washington, DC: US Department of Transportation

[22] Eurocontrol (2003). Review of ACAS RA downlink: An assessment of the technical feasibility and operational usefulness of providing ACAS RA awareness on CWP. Brussels, Belgium.

[23] BFU (2004). *Uberlingen midair collision*. Investigation Report AX001-1.2/02. Braunschweig, Germany: German Federal Bureau of Aircraft Accidents Investigation.

[24] Nunes, A. & Laursen, T. (2004). Identifying the factors that led to the Ueberlingen mid-air collision: implications for overall system safety. Proceedings of the *48th Annual Meeting of the Human Factors and Ergonomics Society* (pp. 20-24). New Orleans, LA.

[25] Brooker, P. (2005). STCA, TCAS, airproxes and collision risk. *The Journal of Navigation, 58*, 389-404.

[26] Rantanen, E., Wickens, C. D., Xu, X., & Thomas, L. C. (2004). Developing human factors certification criteria for cockpit displays of traffic information avionics. AHFD-04-1/FAA-04-1). Savoy, IL: University of Illinois .

[27] FAA (2001). *Advisory Circular120-55B*. Washington, DC: Department of Transportation.

[28] Brooker, P. (2004). Thinking about downlink of resolution advisories from airborne collision avoidance systems. *Human Factors and Aerospace, 4* (1), 49-65.

[29] FAA (2006). *Air traffic control* (Order 7110.65R). Washington, DC: Department of Transportation.

[30] Garcia-Chico, J. L. (2006). *A Human Factors Analysis of Operational Errors in ATC. The TCAS Case Study.* Master's thesis, San Jose State University, CA.

[31] Endsley, M. R., Bolte, B., & Jones, D. G. (2003). *Designing for situation awareness: An approach to user-centered design.* New York: Taylor & Francis.

[32] Rome, F., Cabon, P., Favresse, A., Mollard, R., Figarol, S., & Hasquenoph, B. (2006). Human factors issues of TCAS: A simulation study. In F. Reuzeau, K. Corker, & G. Guy (Eds.) *Proceedings of International Conference on Human-Computer Interaction in Aeronautics* (pp. 2-7). Seattle, WA.

[33] Eurocontrol (2004). *RADE1-RA downlink experiment1*. Brussels, Belgium.

[34] Wickens, C. D., & Hollands, J. G. (2000). *Engineering Psychology and Human Performance* (3rd ed.). New Jersey, NJ: Prentice Hall

Keywords

Operational error, ATC, human error, TCAS RA, error classification, contextual factors.

Biographies

Jose L Garcia-Chico

Jose Garcia-Chico is currently an ATC Research Analyst in L-3 Communications-Titan. He received his MS in Human Factors & Ergonomics from San Jose State University, CA in 2006, and MS in Aeronautical Engineering from Polytechnic University of Madrid in 1998. He has worked as technical consultant for Isdefe and Aena in the development of future ATM paradigms, and human-in-the-loop evaluations in the research arena. His major areas of research interest include development of ATC concepts of operation, traffic flow management, human error, and issues in automation and human workload.

Kevin M. Corker

Kevin Corker is currently an Associate Dean of the College of Engineering and a Professor in the Industrial and Systems Engineering Department, San Jose State University. He is Director of the Human Automation Integration Laboratory (HAIL) at SJSU. He received his Ph.D. in a joint program in Cognitive Psychology and Engineering Systems from the University of California, Los Angeles. His major areas of research interest include computational cognitive modeling, human performance, human system measurement methodologies, human automation system integration and issues in control and display in large-scale dynamic.

Appendix: Flow decision diagram

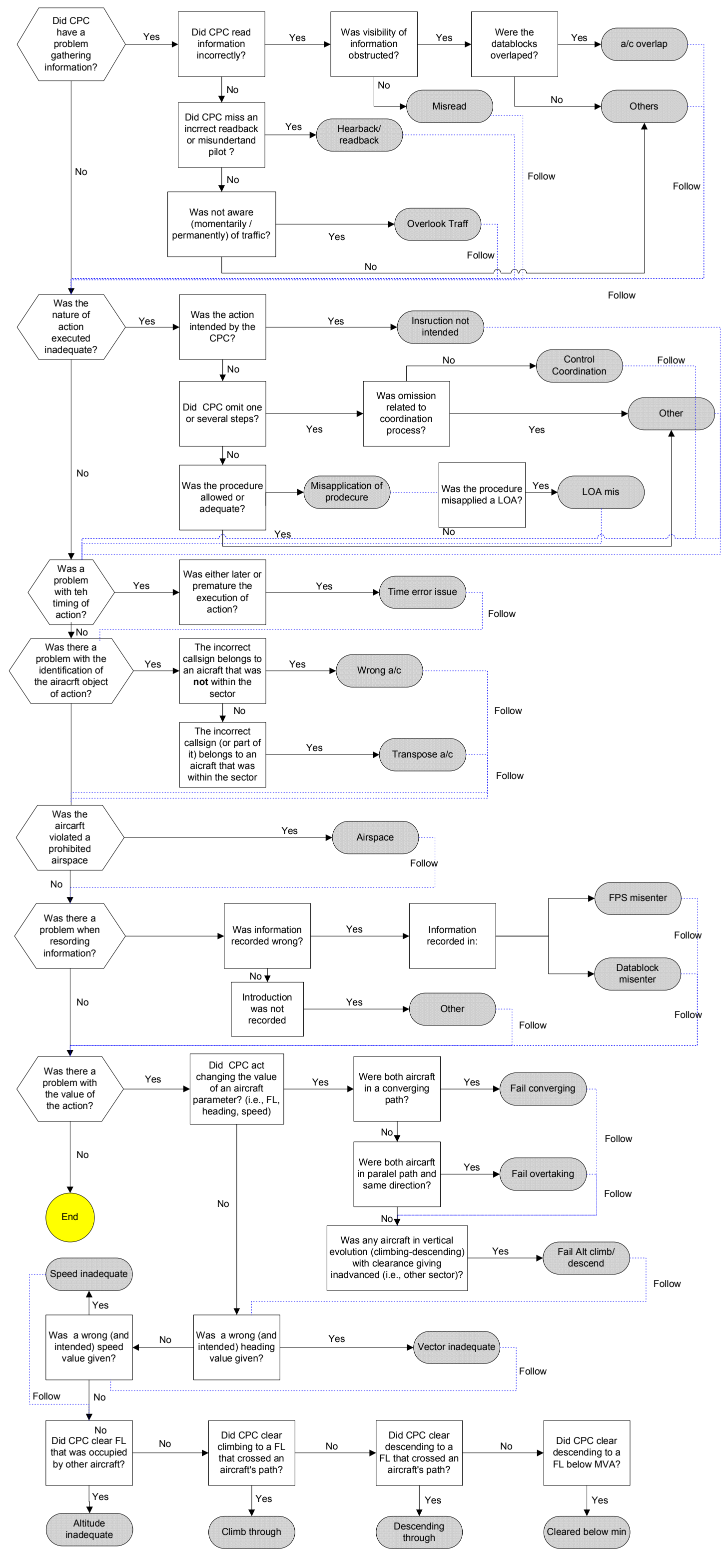

Figure 5. Flow decision diagram used to classify OEs.