SAFETY ASPECTS FOR THE DESIGN OF AUTOMATIC CONFLICT RESOLUTION IN TCAS

Maurício Spiazzi Richter*, José Alexandre Tavares Guerreiro Fregnani†, Donizeti de Andrade§

* Divisão de Engenharia Aeronáutica, Instituto Tecnológico de Aeronáutica, mauriciosrichter@gmail.com
† Divisão de Engenharia Aeronáutica, Instituto Tecnológico de Aeronáutica, eng.fregnani@hotmail.com
§ Divisão de Engenharia Aeronáutica, Instituto Tecnológico de Aeronáutica, ddadonizeti@gmail.com

PAPER ID: SIT2289

ABSTRACT

There is an increasing level of automation present in every new generation of aircraft cockpits. This paper focuses the analysis on the automation of conflict resolution in traffic alert and collision avoidance systems (TCAS), bringing a discussion about the human factors related to the interaction of pilots with such systems, as well as the role-sharing between them. Grounding the discussion on relevant prior research on that topic and presenting the existing risks involving mid-air collision and in-flight loss of control, impacts in aviation safety are also evaluated, including the potential positive and negative outcomes of this extra assistance. With that, this work draws attention to the most important concerns when designing this kind of systems, in order to enhance the benefits and mitigate the side-effects aiming a development that correctly takes into account the human behavior when dealing with automated systems.

Keywords: Automatic RA; TCAS; Aircraft automation; Human factors; Aviation safety.

1. INTRODUCTION

It is no surprise that automation adds complexity in the design and operation of aircraft systems. A more challenging part, though, is to understand the specific characteristics of this complexity and propose solutions that are successful in dealing both with the functional side and performance as well as with the human side. From the transformation of input data into useful information to the automation of problems' handling in a variety of systems, this becomes even more critical to airworthiness when dealing with automated systems that are able to take control of the aircraft, as it is the case with autopilot systems, for example.

The research topic involving human factors related to systems' automation has been addressed throughout the years by authors such as Parasuraman & Riley (1997), who have analyzed several characteristics of the human-automation interaction, and Billings (1997), Ferris, Sarter, & Wickens (2010), who worked on the principles to guide the development of cockpit automation while having the human engagement as the central part of this development. Supporting human-machine analysis and design, classification of automation levels have been proposed by Save & Feuerberg (2012), on top of previous works such as (Parasuraman & Sheridan, 2000).

Closely related to that, the approach to understand accidents involving human contribution has been in constant evolution, emphasizing a more systematic analysis (Dekker, 2014) that accounts for the distribution of the cognitive processes across the human and the automated systems (De Boer & Dekker, 2017).

This research focuses on analyzing the automation of the conflict resolution stage of TCAS, *i.e.*, automatic compliance to RAs. Studies regarding tests of pilots' responses to advisories Chappell (1990) and rates of pilot compliance to TCAS RA in simulation (Pritchett & Fleming, 2013) and operational environment (Eurocontrol, 2022), as well as experiments' analysis stressing the auto-RA capability in different conflict scenarios (Pritchett, Haga, & Li, 2016), were used as the basis to evaluate the multifactorial environment in which the systems can be introduced and draw some conclusions on the most relevant impacts on safety of flight that such systems can have.

The type of accident intended to be avoided by the usage of collision avoidance systems is the mid-air collision (MAC). However, it is also important to understand the potential threats of automation contributing, for example, to loss of control in-flight (LOC-I). To address that, definitions from the International Civil Aviation Organization (ICAO, 2019) and accidents or near accidents data are brought to bring light to the discussion.

As a main objective, therefore, the present work intends to provide guidelines for the design of RA compliance automation on TCAS through recommendations that focus on the related human factors, based on a discussion that evaluates the impact of such systems on the safety of flight.

2. SETTING THE BASELINE

Automation evolution throughout the years has come with a progressive concern about the interaction of humans with systems using it. The more today's cockpits rely on automated functions providing information or actuating directly on the aircraft, the more research topics are raised to address design strategies to build safer and more efficient systems.

Parasuraman & Riley (1997), for example, contributed with a detailed analysis on how well-established ergonomics design principles can be employed to avoid misusage of automated systems and how a high-workload environment can deteriorate this interaction. The potential abuse of automation by developers and operators and the opposite situation of disuse were also investigated by the authors, stressing different expectations between designers, managers and operators for complex systems cannot be neglected and that an imbalance on that, such as operators not being actively involved in the decision of implementing an automated function often results in unanticipated problems.

Corroborating the concern with systems' complexity, Javaux (1998) analyzed cognitive aspects that build a gap between pilot's mental models of, for example, modal systems'

behavior, which is a simplified set of rules, and the actual human-automation interface in place. Still related to the high systems' complexity and coupling with other systems, Billings (1997) highlighted that for operators to be able to monitor automation, it requires predictability from the system. This is not something trivial when dealing with complex systems and is certainly something that needs to be considered during design to define not only the behavior but how information will be outputted. Of course, it also needs the operator to have adequate knowledge about the system and sufficient training.

Ferris, Sarter & Wickens (2010) synthetize some of these principles related to cockpit automation, combining with the analysis of lack of observability in automated systems and how to counteract it, to the illustration of lack of standardization between systems and their ever growing flexibility and complexity, and how it can be overcome by design or training.

To deal with all these intricate characteristics, Parasuraman & Sheridan (2000) have set up levels to classify automation for four generic functions, providing with this model a more complete and objective framework to examine design issues. The authors' model has been further improved by Save & Feuerberg (2012), who kept the four generic functions but developed a specific set of automation levels for each one, adapted to cover more precisely their individual aspects.

On the topic of human contribution to accidents, Dekker (2014) uses the concept of local rationality – assuming people do things that are reasonable based on their limited knowledge and perspective – to build up a sequence of steps to analyze their actions avoiding the hindsight. From a systematic approach that focuses on understanding the underlying reasons behind human actions, development of automated systems can benefit of human factors knowledge, anticipating and mitigating problems that can be created embedded to the system during the design.

Also, while analyzing que automated capabilities of a system or of an entire cockpit, much can be learned about automation complacency and bias from Parasuraman & Manzey (2010), pondering attentional factors while evaluating operational scenarios. Otherwise, De Boer & Dekker (2017) compare what they call an individual-cognition approach with a perspective focused on the effects of automation surprise and its underlying reasons, based on a distributed cognition model.

The abovementioned research, which help constituting the present knowledge supporting development and operation of important aircraft systems that humans interface with, are the foundation for the discussion presented in this work.

3. METHODS

The methodology of the paper is divided in three main stages, beginning with a literature review establishing a baseline on automation and human factors, including human-centered automation design, human factors applied to TCAS and automated conflict resolution in TCAS. Recent reports from relevant aviation institutions are also important to understand the main risks related to automation and collision avoidance.

Then, the TCAS technology is studied more deeply, understanding the mechanisms, roles and responsibilities that are involved in such systems. Data related to accidents also serve to have a more realistic scenario concerning benefits and threats of this additional automation.

From that, it is possible to develop a richer discussion over the level of automation in TCAS, human factors and impacts on aviation safety, concluding with information that can be used to develop safer systems that are able to execute their functions without posing undesirable or even unacceptable additional risks.

4. COLLISION AVOIDANCE VERSUS POTENTIAL AUTOMATION SIDE-EFFECTS

The International Air Transportation Association (IATA, 2022) states that "Mid-air Collision is an aviation accident category defined as a collision between aircraft in flight. This accident category is rare but when it occurs, it is catastrophic." The potential underlying risk explained by the high severity

makes the research and development of collision avoidance mechanisms and procedures draw so much attention. For ICAO (2011), according to the aviation occurrence categories, mid-air collision falls into the category MAC, the same one used for Airprox (air proximity), TCAS alerts, loss of separation and near mid-air collision (NMAC). Since these incidents mentioned can be considered precursors to a mid-air collision and given that actual accident data is scarce, due to the relatively low probability of happening (although with a severe impact), it is important to include these precursors (mainly NMAC) in the analysis while finding strategies to mitigate the related risks.

To illustrate the relevance of MAC prevention, ICAO (2019) classifies this type of accident as one of the High-Risk Categories (HRC) of occurrences, being one of the safety enhancement actions to "Ensure adherence to ACAS warning procedures", and EASA (2021) classifies the airborne collision as the higher risk key risk area for commercial air transport (CAT) aircraft operations and non-commercial operations with complex motor-powered aircraft (NCC), while stating as one of the actions to "Reinforce the appropriate reactions of flight crew in response to an airborne collision avoidance system (ACAS) resolution advisories (RA)".

The concern from these important actors of the aviation environment, which is based on the evaluation from groups of safety specialists, brings a relevant argument to apply a higher level of automation for TCAS resolution advisories (RA). In addition, as it has been in the past decades, the air traffic is expected to considerably grow every year, as presented in forecasts from FAA (2022) for the United States and by Eurocontrol (2022) for Europe, leading to a more crowded airspace, consequently less separation between aircraft and more complexity on its management.

By looking at data related to MAC occurrences from the Aviation Safety Reporting System (ASRS) and UK Department of Transport, the reasons for the position of the mentioned institutions regarding mid-air collision risks and prevention become clearer. Although not directly correlated with TCAS alerts, the following figures indicate the importance of continuously improving collision avoidance mechanisms.

Figure 1 shows ASRS NMAC data from 2000 to 2020, evidencing that although dropping until 2010, occurrences haven't neither kept this tendency nor have stabilized. Figure 2, on the other hand, shows AIRPROX events an increasing until 2018/2019, followed by a reduction but also not stabilizing. Note that the 2020 reduction on both graphics can be at least partially explained by the reduction in air traffic due to COVID-19 pandemic.

On both of them, however, the critical or potential events (where safety cannot be assured) follow approximately proportionally the trend of total occurrences, suggesting there is still room for improving aids that can increase safety margins. It is also possible to see that NMAC occurrences are lower in commercial air transport.

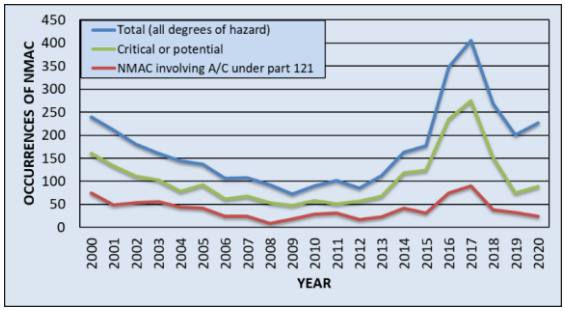


Figure 1. NMAC reporting from 2000 to 2020 in ASRS database (ASRS, 2022) – figure extracted from (Richter, 2022).

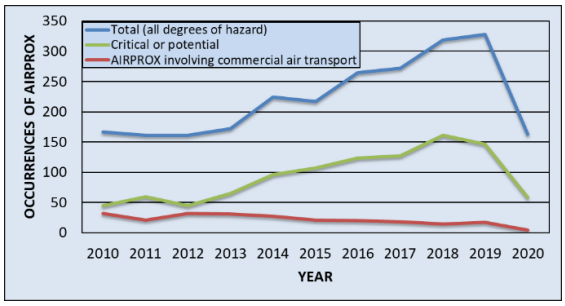


Figure 2. AIRPROX from 2010 to 2020 in the United Kingdom (UK Department for Transport, 2021) – figure extracted from (Richter, 2022).

Nevertheless, even though more automation on TCAS can serve as a mitigation for mid-air collisions on one side, there are potential side-effects related to human factors that need to be carefully taken into account. An example worth being mentioned is the cognitive overhead, which accounts for the increased mental workload related to the decision of using or not the automation

(Parasuraman & Riley, 1997). This, in critical situations such as an automatic TCAS RA, may lead to wrong decisions and cause safety to be reduced instead of reinforced. Furthermore, if human factors is not taken into account adequately, automatic TCAS RA can become an additional source of mode confusion since this is an automation that closely involves vertical AP modes coupled with speed, which according to Albano (2021) are potentially the most complex and less understood modes.

These undesired effects on pilots can lead, for example, to a loss of control in-flight (LOC-I), one of the most common types of accident with a high number of fatalities (Boeing, 2021, p. 13). This type of event is brought here considering some of the strong contributors to an aircraft upset (another classification for loss of control in-flight), as reported by EASA (2021, p. 56) in its Annual Safety Review, are "Handling of technical failures" and "Monitoring of flight parameters and automation modes", two of the most important safety issues for large aircraft.

These factors represent issues that can be related to automated functions and their interface with human behavior. In this regard, Gawron (2019) reviewed previous research on the topic, analyzing the relationship between automation characteristics and the occurrence of incidents and accidents. Items related to monitoring and vigilance, as well as improper use or poor understanding of complex systems and lack of mode awareness are likely to contribute to automation-induced accidents.

5. TCAS AND LEVELS OF AUTOMATION

Airborne Collision Avoidance Systems (ACAS) are an additional protection layer against violation of the separation minima between aircraft, independent from ground-based control, being the air traffic control (ATC) the primary layer (Kuchar & Drumm, 2007). Both of them aid the pilot who is the responsible to ensure a safe continuation of the flight, who should also apply the "see and avoid" principle for collision avoidance.

Currently, ICAO recommends through the Annex 6 *Operation of Aircraft* (ICAO, 2006) that "all aeroplanes should be equipped with an airborne collision avoidance system (ACAS II)" and "an airborne collision avoidance system shall operate in accordance with the relevant provisions of Annex 10[1]. More specifically, the installation of TCAS II is mandated by certification authorities for certain types of aircraft based on weight and number of passengers.

It is also relevant to mention that important characteristics and guidelines for certification for TCAS are given by FAA through Advisory Circular (AC) 20-151C and AC 90-48D, which states that TCAS has the purpose of "alerting all pilots to the potential hazards of midair collisions and near midair collisions (NMAC), and to emphasize those basic problem areas related to the human causal factors".

A possible improvement for the system is a hybrid surveillance using ADS-B (Automatic Dependent Surveillance Broadcast) data to decrease the number of active interrogations, reduce unnecessary advisories (considering more accurate information) and integrate the best available traffic data on a single display. Increased accuracy and range can enhance both situational awareness aid and airborne conflict management (Wichgers, 2015). Another new related technology that could benefit from ADS-B improvements is the ACAS X, removing current limitations in TCAS such as using a complex set of rules with limited outcomes (Kochenderfer, Holland, & Chryssanthacopoulos, 2012). Both of these technologies, when incorporated in current or new collision avoidance systems, can also serve to improve the efficiency of automated compliance functions.

Turning the attention to the automation present in TCAS, based on the automation functions classification proposed by Parasuraman & Sheridan (2000), which associated levels from 1 to 10 – lower to higher automation authority, Richter (2022) got the following results:

[1] Annex 10 *Aeronautical Telecommunications* provides technical characteristics and requirements for surveillance performance for intruders for TCAS equipment.

- *Information Acquisition*: Level 10 ‘the computer decides everything, acts autonomously, ignoring the human’;
- *Information Analysis:* Level 7 ‘executes automatically, then necessarily informs the human’ (however, internal calculations are not informed to the pilot, leading to a possible ambiguity on this classification);
- *Decision Selection:* Level 7 ‘executes automatically, then necessarily informs the human’ (With the focus only on TCAS aid);
- *Action Implementation:* Level 4 ‘suggests one alternative’ (without auto-RA). When dealing with the Airbus TCAS AP/FD Mode, for example, with auto-RA if the autopilot is engaged, Level 6 ‘allows the human a restricted time to veto before automatic execution’.

This scale, though, has some limitation to describe a system that has a combination of a highly automated decision and action selection with a relatively low automation in action implementation (Save & Feuerberg, 2012). With that, as previously mentioned the authors have proposed a new classification, LOAT. As a result, in the *Decision Selection* and *Action Implementation* generic functions are the differences in their level of automation: whereas in the *Decision Selection* both are classified as ‘Low-Level Automatic’, adding the auto-RA implies passing the *Action Implementation* level from ‘Step-by step Action Support’ to ‘Medium-Level Automation of Action Sequence Execution’.

There is an important aspect of the TCAS to which the effectiveness of both the design and operation are subject to: pilot compliance. Chappell (1990) carried out three studies to test pilots’ responses, evaluating adequate aircraft separation with and without the aid of TCAS II. This work has helped the beginning of TCAS II implementation at a critical time by providing relevant feedback. For example, it concluded that a display containing a green target vertical speed zone in addition to the red avoidance zone leads to more accuracy. In addition, that pilots were 85% successful in strengthening maneuvers, while 15% for reversal maneuvers (Chappell, 1990).

Still regarding the compliance rates, Pritchett & Fleming (2013) observed that pilots fully complied with 68% of the RAs, for an average of 96.6% of their duration. Zooming in the analysis, they concluded that there was lower compliance to climb than to descent RAs in arrival/approach phases of flight and also that a training program significantly impacted pilots’ response in the presence of conflicting ATC guidance in relation to TCAS alerts. On the reasons for the non-compliance, the authors found out one of the main aspects was “whether the pilots achieved the commanded vertical rate within the five second response time and ¼ g pitch maneuver”, also concluding that “pilots took longer to achieve compliance when given an explicit communication suggesting controller awareness of the situation (callout or conflicting guidance) than when only partyline information was available in the background.”

On its turn, Eurocontrol (2022) confirms pilot compliance to RA brings safety benefits by increasing Vertical Miss Distances (VMDs) between conflicting aircraft. Being in-line with previous similar evaluations, the study highlights non-compliance to RAs is one of the top 5 ATM operational risk priorities. The assessment was done using radar data from the European airspace to evaluate RA compliance over 12 months, assessing mainly pilot’s reaction time (within 5 seconds), achievement of (and not exceeding) the anticipated vertical speed for RAs of 8 seconds or longer and 12 seconds or longer, and the sense of the maneuver (upward or downward as instructed by the TCAS). The results indicated a low level of compliance to TCAS RAs, particularly the climb and descend, which did not exceed 33%. Also, in more than 50% of reversal and strengthening RAs, pilots did not react as promptly and correctly as expected.

The results from the abovementioned research suggest that most of these non-compliance events are caused by human factors rather than system failures during operation. And, as a potential outcome of such situations is a higher risk of mid-air collision, as it is ratified in the assessment performed by EASA (2021), which has considered an issue of “ACAS RA not followed” to be a contributor factor for an airborne collision.

Exhibiting the same concern over the risks from rates of resolution advisory non-compliance, Baroux *et al.* (2022) uses it as one of the main arguments for automatic conflict resolution, describing the TCAS integration

with autopilot done by Airbus in some of their aircraft, being it currently the only certified system operating in large aircraft with that capability.

In addition to the relatively low pilot compliance to TCAS RAs, a reduction of task execution workload for the pilots, clearly indicated by the upgrade on level of action automation, can also be understood as a benefit from implementing the auto-RA function. On a continuously denser airspace, this automation improvement is inline with a continuous search of systems that can turn operations safer, addressing risks related to airborne collision.

Another argument that can be stressed for an automatic RA is the intensity of manual maneuvers applied to comply with RAs, either not ensuring proper separation or degrading aerodynamic characteristics and eventually leading to passengers' injury in some situations. One example is the 2010 accident from report DCA10LA083 of the NTSB (2021), causing an injury to the passenger of an Embraer ERJ 170 100 SE who was at the lavatory when a TCAS RA occurred, being the compliance maneuver classified as abrupt.

Pritchett & Fleming (2013) also studied and tested an auto-RA function, with pilots leaving the autopilot engaged in 83% of the RAs (crossing-climb RAs were the least compliant). Mode confusion was also reported after clear of conflict. This capability was examined more closely by (Pritchett, Haga, & Li (2016). By stressing different conflict scenarios with Part 121 and Part 135 pilots, the authors acknowledge an increased compliance rate when using the function, but point out some possible drawbacks: when the autopilot was disengaged during an RA, it took longer for the pilots to achieve the target vertical rate; also, considering the auto-RA function only shifted the compliance rate from 53% to 76%, they conclude this technology can help, but not guarantee full compliance. In addition, pilots' acceptance of the function depend on several additional factors such as traffic, etc., so the authors suggest it could improve compliance in generally complying events and worsen it when pilots do not generally comply, being the impact of this automation only situational.

From the work of Olszta & Olson (2010), who evaluated real-world TCAS RA encounters in the United States from 2008 to 2009, using data from different airports (and different timeframes for each airport), it is relevant to add another dimension in this analysis: the differences of TCAS RA occurrences between different types of operation. The authors found a considerable variation: "RA rates for business jets were 4.5 times higher than major air carriers and 2.5 times higher than regional air carriers" (Olszta & Olson, 2010, pp. 4.A.1-1), which is at least partially explained by operation environment factors, *e.g.*, in opposition to business jets, major air carriers mostly under Instrument Flight Rules (IFR) and ATC service providing separation from other traffic in Class B airspace during low-altitude terminal operations. Figure 3 shows exactly this influence of the rules and aircraft operating at each class of airspace. Of course, it is important to note most of business jets operations occur at least restricted airspace and also that, independently of type of operation, class B has lower RA rates than classes C and D, for example (Olszta & Olson, 2010).

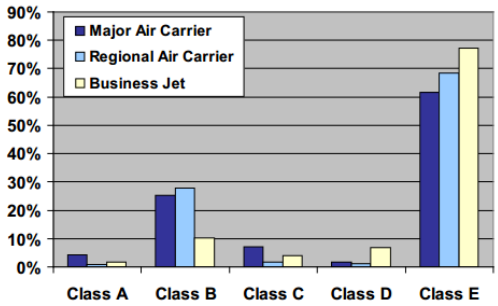


Figure 3. Percentage of RAs by Airspace (Olszta & Olson, 2010).

Also as a finding of Olszta & Olson (2010), "Pilot non-compliance is relatively uniform among operational categories and appears to be a major contributing factor in low separation events", which although needs to take into account that in many cases either the pilots might have visually acquired the intruder or had incorrectly identified the threat aircraft, is in-line with other studies referenced herein.

Considering much is impacted by the operation environment, not only TCAS logic improvements can benefit from these findings, but also automation design, focusing further system assistance where most relevant, ensuring behavior and usage fit the purpose of establishing a safe separation between aircraft.

6. FLIGHT SAFETY IMPACTS

From the previous chapters' discussion, detailing the safety concerns that can be mitigated with the automation of TCAS RA compliance, it can be added that several systems, from displays to flight control stabilizers, contain automated functions that assist the pilot in achieving increased safety. A system for automatic RA compliance which is efficient in execution and designed accounting for the human-automation interaction can be capable of helping to reduce near mid-air collision occurrences.

For that to happen, as already reinforced, it important to evaluate carefully its downsides and possible effects on pilots during flight. Considering that, this chapter summarizes the analysis done in (Richter, 2022).

Regarding cognitive complexity in modal automation, it is extremely relevant to understand that system states won't always be readily available in operators' memory, especially in high-workload situations such as an automatic system engagement to follow an RA, creating a pilot-independent mode transition. High system complexity, as Javaux (1998) analyses, is a key factor in this sense. Another aspect that affects mode consciousness is system feedback and annunciations, which facilitate comprehension but might also suffer from possible representation inaccuracies or delays that can deteriorate precise detection, leading to undesirable situations such as operation errors and potential safety reduction (Albano, 2021).

From the work of Parasuraman & Manzey (2010), the following human factors can be highlighted as applicable to the automatic RA compliance being analyzed:

- *Higher prevalence of automation complacency in multitasking environments*: even with the autopilot conducting the RA compliance, this cannot be considered a single-task phase considering the pilots have to monitor several aircraft information and ATC communication at the same time.
- *Lower detection rate of automation failures with constant-reliability than with variable-reliability:* current certification requirements and production techniques make systems constantly highly reliable in most of the situations, requiring clear monitoring clues and specific experience in varied contexts.

With a perspective focused on the effects of automation surprise and its underlying reasons, on the other hand, it is worth to highlight, from De Boer & Dekker (2017):

- *Lack of knowledge about the automation in the context of the operation*: pilot needs to be aware of the sequence and criteria that will make the aircraft enter in this specific mode, therefore the importance of predictability and bringing operators closer to the design.
- *Quality and sufficiency of information presented:* if feedback is not clear enough, pilots are more prone to automation surprise.
- *No significant reduction in trust when experiencing an automation surprise:* for this system, it can be seen as positive, since trust is an essential characteristic to allow a proper execution with no unnecessary interventions.

Results from Balfe, Sharples, & Wilson (2018) showed that trust upon safety-critical systems arises from a good knowledge of the system in the operation context, as well as appropriate system transparency through feedback, rather system reliability itself.

The design solutions to overcome incomplete feedback leading to less mode awareness need to be evaluated to avoid causing a "fragmentation of feedback" (Ferris, Sarter, & Wickens, 2010) and, considering the criticality of a potential in-flight encounter, it is important that all the necessary information to be assessed is concentrated and harmonized. During a conflict resolution, it is desired some degree of attention tunneling to guarantee a successful conflict clearance. However, it is also important to leave some attention for enough scanning of other sources maintaining situational awareness (Brown, 2016).

In addition but not least important, as emphasized by Pritchett & Fleming (2013), is to allow pilots to disengage automatic RA to manually fly the aircraft if necessary.

7. DESIGN RECOMMENDATIONS

Still with the focus on a concern with the influence of system behavior on human performance at a development phase, a set of recommendations are drawn to support the

design of systems that have the ability to automatically comply with TCAS RAs, while avoiding as much as possible negative effects on the airworthiness and safety.

The following recommendations were proposed in (Richter, 2022) and are centered on design aspects:

- *Evaluate if automating RA compliance function is consistent with aircraft current capabilities.*
- *Maintain displays' harmonization, including colors for armed/active modes and alerts consistency.*
- *Evaluate not only the possible states of TCAS inputs, but also all possible transitions between states.*
- *Establish logical limits for autopilot RA maneuver based on aircraft operational envelope.*
- *Provide visual feedback if TCAS advisory exceeds autopilot execution limits.*
- *Provide clear and visible mode feedback, anticipating mode transitions if possible.*
- *Set a high priority for the TA and automatic RA modes, evaluating each possible transition from and to other modes.*
- *Evaluate either: automatic return to the previous active modes, automatic transition to default modes or keeping a visual indication of previous active modes during automatic RA execution.*
- *Provide different visual and aural alerts for TA and RA modes.*
- *Provide a clear feedback of RA compliance status (based on target and avoidance zones), anticipating an exit from safe zones with flight path and TCAS symbology.*
- *Include feedback cues that can assist the monitoring task using underlying logic (e.g., consistency check between TCAS input commands and actual aircraft movement).*
- *Set an acceptable maximum amount of time to reach each RA compliance for definition of acceleration command limits, taking into consideration controlled and smooth dynamic for adequate predictability and monitoring.*
- *When initiating the RA mode on autopilot, activate a display mode (preferably on a head-up display) that highlights critical TCAS information, such as target and avoidance zones, for reduction of focus on non-priority information which could cause distractions, leaving adequate resources to monitor RA execution and flight-critical parameters.*
- *Evaluate the severity of new failure conditions considering new potential mishaps, developing with adequate process assurance.*
- *Design a fail-safe architecture for incorrect compliance to RA and missing RA.*
- *Create new failure messages (visual and aural) concerning loss of automatic RA function before or during execution (higher priority) for the pilot to be aware if intervention is necessary.*
- *Review consistency between new and existing TCAS failure messages.*
- *Record internal performance data for interface, logic or feedback improvements.*
- *Make an exhaustive analysis of normal and failure scenarios, validating the solution for each one.*
- *Ensure proper testing of normal and failure scenarios (which might require exiting automatic RA mode).*
- *Involve operators in the decision-making process during development from early to late stages, acquiring feedback for developers as much as possible.*

8. FINAL CONSIDERATIONS

The present work has analyzed the impact of the automation of TCAS RA compliance, evaluating which are the main characteristics and potential effects related to human-automation interaction to be given close attention, in order to build systems that are at the same time efficient in their functions and safe in their operation. In addition, it brings relevant data from aviation accidents to justify the discussions raised and goals presented.

All that is summarized in a set of design recommendations to support a continuous enhancement of existing system safety solutions while carefully evaluating risks.

Within the next years, flight data related to this automation might become more available if more aircraft implement it, and it is essential to use it to improve system design and pilots' training.

Finally, an also continuous work on certification requirements cannot be neglected, assessing if any revision needs to be done in to advance on the comprehension and safe implementation and operation of such systems.

9. REFERENCES

Albano, L. M. (2021). *Análise da Confusão de Modo de Automação em Pilotos Brasileiros de Linha Aérea.* Instituto Tecnológico de Aeronáutica, São José dos Campos/SP, Brasil.

ASRS. (2022). *Aviation Safety Reporting System*. Retrieved August 05, 2022, from ASRS Database Online: https://asrs.arc.nasa.gov/

Balfe, N., Sharples, S., & Wilson, J. R. (2018, June). Understanding Is Key: An Analysis of Factors Pertaining to Trust in a Real-World Automation System. *Human Factors, 60*(4), 477-495. doi:10.1177/0018720818761256

Baroux, C., Cardona, F., Corral, C., Durepaire, X., Lopez Villarejo, M., & Villeneuve, C. (2022, January). Safe Handling of TCAS Alerts. *Safety First*(33), pp. 6-16.

Billings, C. E. (1997). *Aviation automation: the search for a human-centered approach.* Boca Raton, Florida, USA: CRC Press.

Boeing. (2021). *Statistical Summary of Commercial Jet Airplane Accidents: Worldwide Operations | 1959 – 2020.* Boeing Company, Chicago/IL, USA. Retrieved September 8, 2022, from https://www.boeing.com/resources/boeingdotcom/company/about_bca/pdf/statsum.pdf

Brown, J. (2016). The Effect of Automation on Human Factors in Aviation. *The Journal of Instrumentation, Automation and Systems, 3*(2), 31-42. doi:http://dx.doi.org/10.21535%2Fjias.v3i2.916

Chappell, S. (1990). Human Factors Research for TCAS. *Conference on the TCAS - Its Development, Testing, Installation and Operational Use* (p. 19). London, UK: Royal Aeronautical Society.

De Boer, R., & Dekker, S. (2017, September). Models of Automation Surprise: Results of a Field Survey in Aviation. *MDPI Safety, 3*(3 - Aviation Safety). doi:https://doi.org/10.3390/safety3030020

Dekker, S. W. (2014). *The Field Guide to Understanding 'Human Error'* (3rd ed.). Surrey, UK: Ashgate Publishing Ltd.

EASA. (2021). *Annual Safety Review 2021.* European Union Aviation Safety Agency (EASA), Cologne, Germany. doi:10.2822/071257

EASA. (2021). *European Plan for Aviation Safety (EPAS) 2022-2026 Volume I - Introduction & Strategy.* European Union Aviation Safety Agency (EASA), Cologne, Germany.

Eurocontrol. (2022). *Aviation Outlook 2050 - Main Report.* Eurocontrol, Brussels, Belgium.

Eurocontrol. (2022). *The Assessment of Pilot Compliance with TCAS RAs, TCAS Mode Selection and Serviceability Using ATC Radar Data, Edition 2.2.* Assessment, Eurocontrol, Brussels, Belgium.

FAA. (2022). *Aerospace Forecast Fiscal Years 2022–2042.* Federal Aviation Administration (FAA), Washington DC, USA.

Ferris, T., Sarter, N., & Wickens, C. D. (2010). Cockpit Automation: Still Struggling to Catch Up…. In E. Salas, & D. Maurino, *Human Factors in Aviation* (2nd ed., p. 732). London, UK: Academic Press.

Gawron, V. (2019). *Automation in Aviation - Accident Analyses.* MITRE Center for Advanced Aviation System Development (CAASD), MacLean/VA, USA.

IATA. (2022). *Mid-air Collision*. Retrieved August 01, 2022, from International Air Transport Association: https://www.iata.org/en/programs/safety/operational-safety/midair-collision/

ICAO. (2006). *Doc 9863 Airborne Collision Avoidance System (ACAS) Manual.* Manual, International Civil Aviation Organization (ICAO), Montréal/Quebec, Canada. Retrieved from https://www.icao.int/Meetings/anconf12/Document%20Archive/9863_cons_en.pdf

ICAO. (2011). *Aviation Occurrence Categories v4.2.* Commercial Aviation Safety Team/International Civil Aviation Organization, Montréal/Quebec, Canada. Retrieved from Commercial Aviation Safety Team (CAST) / International Civil Aviation Association (ICAO).

ICAO. (2019). *Doc 10004 Global Aviation Safety Plan.* International Civil Aviation Organization (ICAO), Montréal/Quebec, Canada.

Javaux, D. (1998). Explaining Sarter & Woods' Classical Results: The Cognitive Complexity of Pilot-Autopilot Interaction on the Boeing 737-EFIS. *Second Workshop on Human Error, Safety, and Software Design* (pp. 62-77). Seattle/WA, USA: University of Washington. Retrieved from https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.122.3608&rep=rep1&type=pdf

Kochenderfer, M. J., Holland, J. E., & Chryssanthacopoulos, J. P. (2012). Next-Generation Airborne Collision Avoidance System. *Lincoln Laboratory Journal, 19*(1), 17-33.

Kuchar, J. E., & Drumm, A. C. (2007). The traffic alert and collision avoidance system. *Lincoln Laboratory Journal, 16*(2), 277-296.

NTSB. (2021). *Aviation Accident Final Report DCA10LA083 / 2010.* Aviation Accident Final Report, National Transportation Safety Board (NTSB), US Department of Transportation, Washington DC, USA. Retrieved September 5, 2022, from https://data.ntsb.gov/Docket?ProjectID=76906

Olszta, J., & Olson, W. (2010). A comparative study of air carrier and business jet TCAS RA experiences. *29th Digital Avionics Systems Conference* (pp. 4.A.1-1-4.A.1-10). Salt Lake City, UT, USA: IEEE. doi:10.1109/DASC.2010.5655358

Parasuraman, R., & Manzey, D. H. (2010, June). Complacency and Bias in Human Use of Automation: An Attentional Integration. *Human Factors, 52*(3), 381-410. doi:10.1177/0018720810376055

Parasuraman, R., & Riley, V. (1997, June). Humans and automation: use, misuse, disuse, abuse. (I.

Sage Publications, Ed.) *Human Factors, 39*(2), 230-253.

Parasuraman, R., & Sheridan, T. B. (2000). A Model for Types and Levels of Human Interaction with Automation. *IEEE Transactions on systems, man, and cybernetics, 30*(3), 286-297.

Pritchett, A. R., Haga, R. A., & Li, H. (2016, December). Attempting to Automate Compliance to Aircraft Collision Avoidance Advisories. *IEEE Transactions on Automation Science and Engineering, 13*(1), 18-25. doi:10.1109/TASE.2015.2500959

Pritchett, A., & Fleming, E. S. (2013). Pilot Compliance to TCAS Resolution Advisories. *32nd Digital Avionics Systems Conference (DASC)* (pp. 6B6-1 - 6B6-13). East Syracuse/NY, USA: IEEE/AIAA. doi:10.1109/DASC.2013.6712618

Richter, M. S. (2022). Safe Automation of Aircraft Control for Conflict Resolution in Traffic Alert and Collision Avoidance Systems. *Final paper, Specialization in Flight Safety and Continued Airworthiness*, 24.

Save, L., & Feuerberg, B. (2012). Designing Human-Automation Interaction: A New Level of Automation Taxonomy. *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2012 Annual Conference* (p. 14). Toulouse, France: Human Factors and Ergonomics Society Europe.

UK Department for Transport. (2021). *UK Government Digital Service*. Retrieved August 05, 2022, from Statistical data set: Aviation (TSGB02): https://www.gov.uk/government/statistical-data-sets/tsgb02

Wichgers, J. M. (2015). Automatic Dependent Surveillance - Broadcast. In C. Spitzer, U. Ferrell, & T. Ferrell, *Digital Avionics Handbook* (3rd ed., pp. 364-380). Boca Raton, USA: CRC Press.