The Human Factors Related to the Development and Incorporation of Traffic Alert and Collision Avoidance Systems (TCAS) in Commercial Aircraft

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By

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

Aviation technology is one of the most complex, fascinating, and fast-growing fields of artificial intelligence. Aircraft rely heavily on its systems in order to sustain safety both in the air and on the ground, and the ways in which the systems are constantly changing. In the case of the Traffic Collision and Avoidance Systems (TCAS) in particular, its development and incorporation into aviation has been affected substantially by the interactions between the human, social, and technical elements of the system.

TCAS, hence its name, is an aircraft computer system that helps keep aircraft separated each other in order to avoid mid-air collision. These TCAS systems receive movement data from other aircrafts' transponders and interpret that information to determine whether or not the two aircraft may be on a collision course, or dangerously close to each other. Based on the information from those sensors, the TCAS will give an alert to the pilot, and provide a recommended course of action for the pilot to perform in order to avoid the potentially hazardous situation. These recommended courses of actions are called Resolution Advisories (RA), and the pilot faces a decision every time a RA is issued. They can either accept the recommended course of action, they can take the recommendation from air traffic controllers (ATC) that sparsely, but do, conflict with RAs, or they can take effective action with what they believe is the safest course of action. After all, they are the pilot in command (PIC) and are solely responsible for the safe operation of the aircraft. As you can imagine, the multiple sources of information and potentially conflicting information may create confusion for the pilots, and the degree at which TCAS is used has varied over the course of its use.

Artificial intelligence has improved tremendously over the years, but the general population is not ready to completely trust its autonomy just yet. Whether that is an aircraft, car, or train, I believe it is safe to assume that people are not ready to completely remove humans from having control over the operation of the system. Safe operation of aircraft saves lives and increases revenue, as patrons will continue to purchase passenger tickets as long as they believe their lives are safe. Pilots and their mistakes have changed the way we fly, and the development of TCAS in aviation is a product of the interactions of its human, social, and technical elements.

Science, Technology and Society

Pilots and passengers have influenced the development of TCAS in commercial aircraft just as TCAS has influenced pilots and passengers themselves. This relationship can be viewed by the technological momentum theory, in that the relationship between technology and society is reciprocal and time dependent, so that one does not determine the changes in the other but that they both influence the other. It is important to consider how they've influenced each other because the human and social interactions involved with the need, development, and incorporation of TCAS is applicable to safety features in all aspects of technology. TCAS was researched and created because humans alone were not capable of operating aircraft safely and avoiding danger completely. However, the introduction of TCAs brought upon technological consequences, both for the better and for the worse. While many problems were solved by TCAS, such as the chance of danger and the inability for pilots and ATC to detect all nearby air traffic and collision tracks, it also brought upon new issues that were unforeseen. For example, there's four ways in which unsafe control can cause an accident. Action could be required, but not provided or implemented. There could be unsafe or incorrect action provided or implemented. The action could be provided too early, late, or without order. And lastly, the action could be performed, but ended too soon or started too late. There are many causes that can lead to those unsafe controls, but the unsafe controls are what directly cause an accident.

The socio-technical interactions of TCAS and pilots has changed the way they both operate, in order to create a safer environment. There are collisions that have occurred due to the nature in which different countries have created different procedures when TCAS comes into play. For example, in the U.S. and Europe, pilots are trained to obediently and immediately take the course of action that is recommended by TCAS right away. TCAS is considered an additional level of safety after ATC, and they view it in the sense that if ATC has already failed in putting the aircraft in dangerous proximity for TCAS to become activated and needed, the pilot should immediately do as TCAS advises in order to remedy the situation. In Russia, however, they are instructed to take ATC orders over anything else. They recognize that ATC is redundant, while TCAS is not a redundant system, and since ATC has a complete picture of the sky then the pilot should trust ATC as they can provide the most accurate safe course of action. Additionally, ATC on the ground does not receive feedback or information on any of any resolution advisories by TCAS, so Russian SOPs also prioritize ATC orders for the reason that the resolution advisories cannot be double-checked or verified by ATC. This presents an issue, as in the case of the collision at Ueberlingen in which two aircraft (one U.S., one Russian), were trained to follow different orders and it had a catastrophic result. An analysis on a case study pertaining specific to this event will be explained in more detail later, but it would be in best interest for global aviation to agree on a single methodology for these types of situations.

In addition to the way pilots and TCAS affect each other, passengers and TCAS also do. When TCAS, or the discrepancies in which it is used, fails, it projects the images that aviation is dangerous. One single accident, although rare, has the emotional effect of portraying a picture that can have significant social impact and cause passengers to avoid flying. They then drive, or take the train to places as long as they can avoid flying. As passengers neglect to purchase airline tickets, stakeholders in the aviation industry are driven to improve TCAS, the standard operating procedures pertaining to it, or both, in order to drive revenue back up. It is in the best interest of pilots, passengers, engineers, executives, and all other types of stakeholders in the aviation industry to create an environment that is most safe for people to travel via aircraft. TCAS has evolved and adapted, and will continue to as we learn from the social interactions between TCAS and pilot, TCAS and passenger, as well as the social impact of catastrophic aircraft collisions or accidents.

Case Context

The technology at hand, TCAS, is an aircraft safety system that assists pilots in avoiding mid-air collision with other aircraft. It can be considered as the “last line of defense” against preventing mid-air collisions, for there are many ways in which aircraft are separated from each other simply in the laws of the sky. For starters, all of the airspace in the word is divided up into different classifications depending on the amount of traffic that travels through there, and by the altitude. Within them are traffic flows, that are separated by the altitude and direction in which the aircraft are flying—think similarly to that of automobile traffic. The division of airspace and its standard operating procedures, along with the help of air traffic control, usually keeps aircraft separated by about one thousand feet vertically and three to five miles laterally (Federal Aviation Administration, 2017). However, humans are not perfect. TCAS helps pilots and the crew identify potential threats, and provide collision avoidance advisories if necessary. In simple terms, the system works by receiving input from aircraft transponders pertaining to the aircraft’s speed, altitude and trajectory, and determines whether or not two aircraft may be on a collision course or not (Harman, 1989). However, it there is a bit more to it than that.

After collecting and analyzing the state information gathered by the surveillance sensors, the information is processed by a set of algorithms. If the opposing aircraft also has TCAS, the response is synchronized through both systems in order to ensure that both aircraft maneuvers are correct in the sense that they are opposite in order to guarantee separation. Surveillance of the airspace is based on broadcasts once per second from the TCAS antennae, which are received and interpreted with selective interrogation. Balancing the surveillance requirements of TCAS and air traffic control ground sensors is a great challenge in its development. As more and more TCAS-equipped aircraft populate the skies, airspace has more and more TCAS data transmitted. Because of this, aircraft transponders are spending more and more time interpreting TCAS transmittals and less time responding to ground interrogations, where air traffic controllers are trying to keep in touch. In order to combat this issue, TCAS developed an interference-limiting algorithm in order to reduce the conflict between TCAS and ground sensors in order to limit the number of interrogations that transponders deal with so that they can focus on ground sensors (Harman, 1989).

However, it is a tough issue because to what extent should TCAS be the primary communicator with transponders, and to what extent should it be ground sensors which are interpreted by air traffic controllers? Currently, interference limiting ensures that no more than 2% of a transponder's time is spent dealing with TCAS units, so that the majority of its time can be with ground sensors (Harman, 1989). However, that limits the degree to which TCAS is competent and can be relied in to prevent aircraft collisions. If you take away its ability to receive and deliver data, its ability to accomplish its mission is hindered.

Threat detection and display, as well as threat resolution, are the remaining complex sub-systems of TCAS. TCAS classifies other aircraft into discrete levels, and projects an aircraft's position into the future using their position, velocity, and trajectory. All nearby aircraft are displayed in the cockpit, and are accompanied by visuals that indicate range, bearing, relative altitude, and vertical speed. This helps the pilot gather a mental image of the airspace around them. If a collision is projected to occur within the next twenty to forty-eight seconds, that is when TCAS gives an alert, accompanied by a recommended course of action. It is important to note that TCAS does not recommend turns in their resolution advisories (RAs). It gathers a sense of the trajectories of the two aircraft's course, and recommends a vertical movement to avoid each other (Kuchar & Drumm, 2007) . The entire system of TCAS will be explained more thorough, but this a good way to have a solid understanding of how it works.

Research Question

How have pilots and passengers influenced the development of Traffic Alert and Collision Avoidance Systems (TCAS) in commercial aircraft?

Methods

Data collection methods include background research on TCAS an interview with a current pilot, and analyzed case studies. The interview was conducted with Dr. Lt Col Raymond Ott (ret.) who flew the P-3 Orion in the United States Navy for seventeen years, the C-5 Galaxy in the United States Air Force for eight years, and is currently an airline pilot for United Airlines. Case studies include the Mid-Air Collision at Ueberlingen, and an analysis on the influence of TCAS on pilots and ATC, amongst others. The background research was essential to learning all the specifics of TCAS and its functions, capabilities, and limitations. The interview was helpful in gathering understanding in precisely how commercial pilots use TCAS to assist their flying and separation, the ways in which it affects their ability to fly, the frequency in which TCAS is truly needed, and the role that TCAS plays in their training.

The question of the co-influences of passengers and pilots on the development of the Traffic Alert and Collision Avoidance systems is important because the human and social interactions involved with the need, development, and incorporation of TCAS is applicable to safety features in all aspects of technology (Inagaki, 2006). TCAS was researched and created because humans alone were not capable of operating aircraft without the chance for danger. However, the introduction of TCAS brought upon technological consequences, for the better and for the worse. Many problems in the air were solved by TCAS, such as minimizing the chance of danger and providing a supplement toward the inability for pilots and ATC to detect all nearby air traffic and collision tracks, as well as increased capacity rates in airports due to the closer separation allowed. However, it also brought upon new issues that were unforeseen, to include the difference in Standard Operating Procedures from different governments, design failures of TCAS, and more (Niu, Ma, Wang, Han, 2019).

Results

TCAS has been effective in preventing midair collisions and has objectively increased the level of safety in air travel by identifying contacts to the usage of TCAS resolution advisories. TCAS prevents near midair collisions, airborne conflicts, and loss of separation between aircrafts. However, it is also known to cause a number of negative consequences as well, such as increased ATC workload, controlled flight towards terrain, and new airborne conflicts and losses of separation. There also is a large discrepancy in the manner in which pilots communicate their actions to ATC in correspondence to TCAS resolution advisories. Some communicate their intentions to comply with the resolution advisory before doing so, some ask permission from ATC, some warn ATC but comply immediately, some never communicate their actions or do so after, and some combinations thereof. There is a significant number of reports supporting the work of TCAS and its ability to reduce the threat of airborne conflicts, however, have caused confusion between pilots and ATC as to who is in control of the aircraft and its movements (Mellone, Frank, 1993).

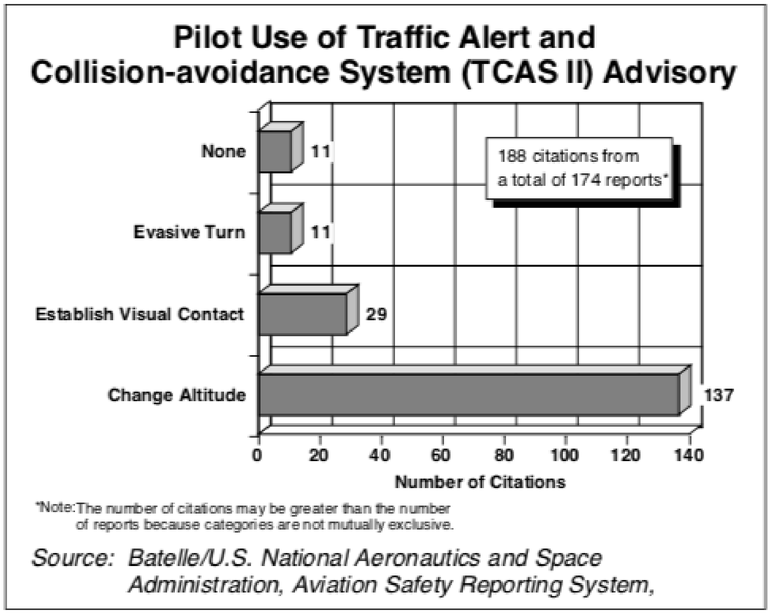

Figure 1. Pilot Use of TCAS

In Figure 1, TCAS incident reports were graphed to show the action taken by pilots to avoid airborne conflicts. It was discovered that 92 percent of these actions were performed because of resolution advisories pilots received from TCAS, and these altitude ranges ranged from 100 feet to 1,600 feet, hovering around an average of 628 feet. 81 percent of the reported altitude changes were between 300 feet and 1,000 feet, with 9.3 percent of the reported altitude changes greater than 1,000 feet. Flight levels, or the airways in the sky separated by the direction in which the aircraft is flying, are separated by 1,000 feet. Therefore, it is evident that there is an issue with pilots correcting their flight due to the resolution advisories issued, but in turn, creating a new conflict as a result of their movement. Figures 2 and 3 below depict an interesting relationship between the prevented consequences as well as the created consequences (Mellone, Frank, 1993).

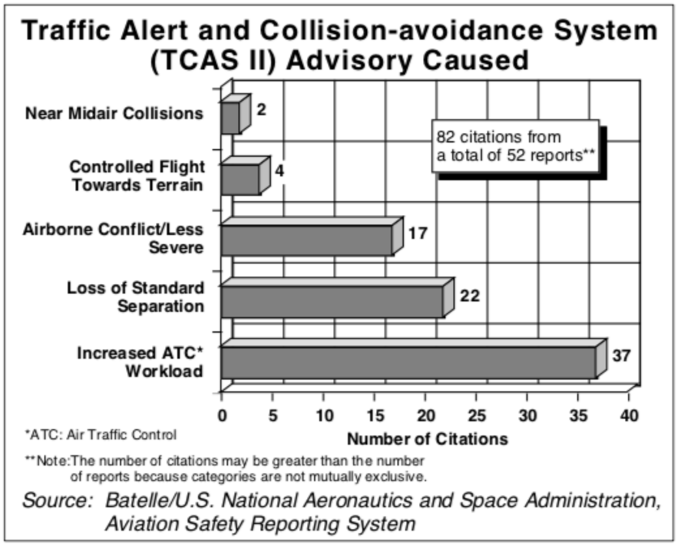

Figure 2. TCAS Advisory Caused

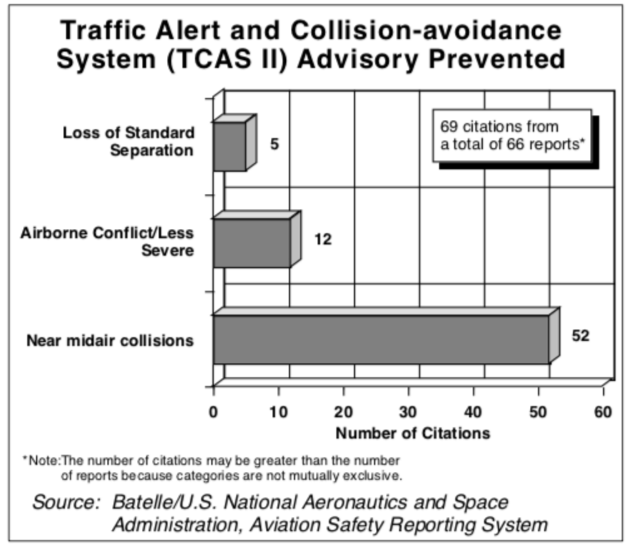

Figure 3. TCAS Advisory Prevented

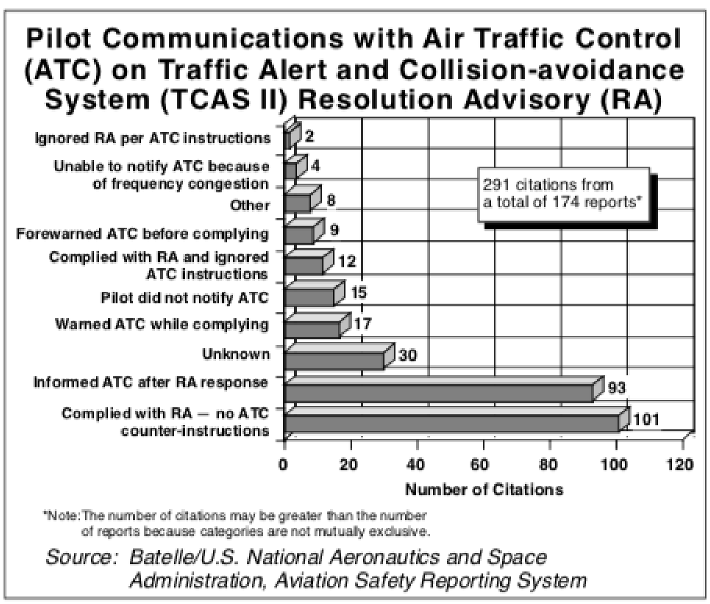

Figure 4. Pilot Communications ATC

As you can see, TCAS has its pros and cons. On the positive side, the consequences prevented are very high-stake consequences, whereas the consequences caused are generally all lower-staked, with only 6 citations of near midair collisions or controlled flight towards terrain.

Figure 4, above, shows the nonstandard usage of TCAS by pilots. Pilots should not be placed in a predicament in which they should make a split-second decision to comply with TCAS resolution advisories or ATC instructions, as well as the manner in which to communicate intentions with ATC. This discrepancy can lead to situations like the midair collision at Ueberlingen.

In the collision at Ueberlingen, TCAs was amongst the causes in which a Russian Tupolew Tu154M and a U.S. DHL cargo Boeing B757-200 collided on July 1, 2002, over southern Germany. All 71 passengers aboard were killed. U.S. and European Standard Operating Procedures (SOPs) consider TCAS to be a last-resort safety measure to come into play when pilot operation and ATC fail to maintain aircraft separation alone. Therefore, pilots are trained to immediately act on the resolution advisory given by TCAS, in order to diffuse the situation. It is considered that ATC does not have perfect information to the situation, and since TCAS operates using data from the transponders in the corresponding aircrafts, their recommendations are synchronized and will solve the near collision scenario. On the other hand, Russian SOPs are less trusting of TCAS, due to its limitations and imperfections. Russian pilots are trained and required to assume ATC orders over TCAS or any other navigational system, due to its redundant nature (Weyer, 2006).

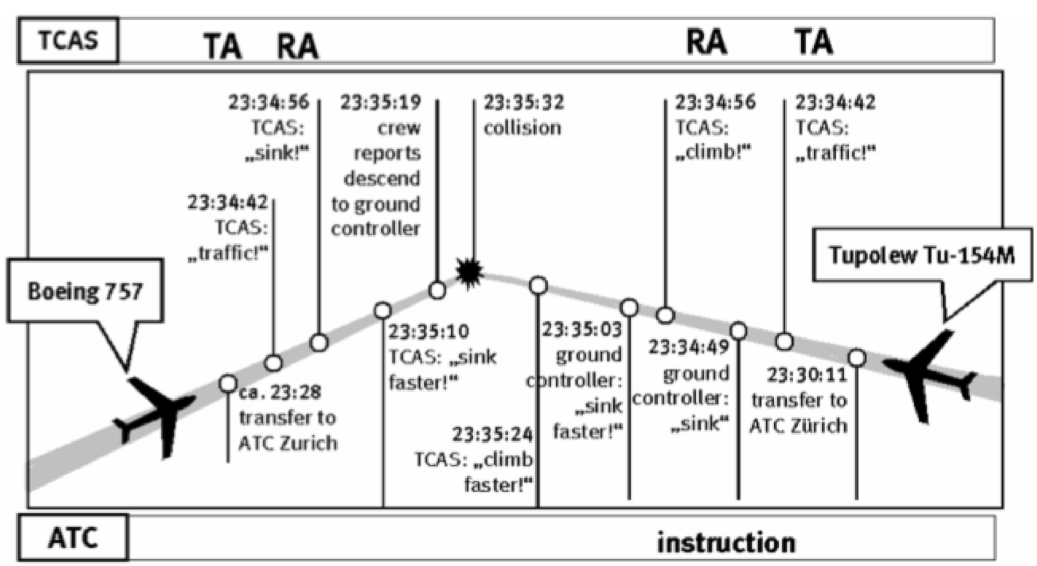

Figure 5. Ueberlingen Collision

Figure 5 illustrates the scenario in which the ATC controller at Zurich was guiding the two planes, and had taken over the two planes just a few minutes prior to the actual collision. After realizing the approaching issue, the ATC controller gave his instructions for the Russian Tupolew to descend, but at this time the two aircraft had already received resolution advisories from their TCAS systems. The U.S. Boeing obeyed the TCAS instructions to climb, and the Tupolew disobeyed the TCAS instructions to sink, and instead obeyed the ATC instructions, as he is trained and legally required to do. Unfortunately, TCAS systems are decentralized, meaning their resolution advisories cannot be seen by ground controllers or by other aircraft. Only the pilots in the aircraft can see the resolution advisories (Weyer, 2006). This communication error could have been prevented if TCAS had the function to relay their resolution advisories and information to ground controllers, which is a clear fundamental design error.

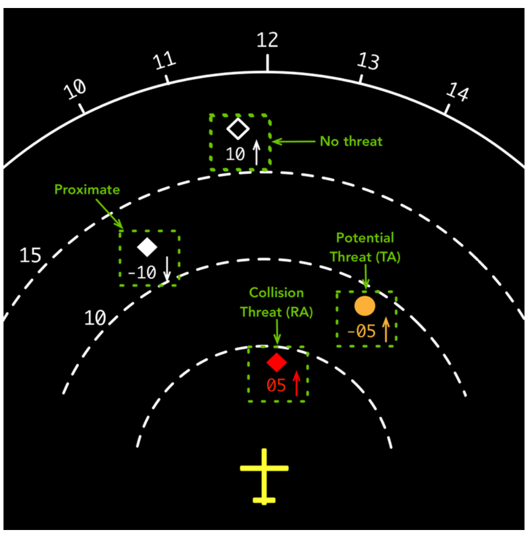

Figure 6. TCAS Normal Operating Screen

The interview with Dr. Lt Col Raymond Ott (ret.) was insightful in providing understanding towards how TCAS is used by pilots. While he only has been issued a resolution advisory 4 times in a real flight in the three years flying commercially, Dr. Ott says that he uses TCAS in every single flight in order to provide situational awareness, and gain an idea of what the traffic in the airspace around his aircraft looks like. Figure 6 provides an example as to what the normal operating screen of TCAS looks like, with the number corresponding to other aircrafts representing the vertical distance between the two, in hundreds of feet.

United Airlines pilots practice resolution advisories every 9 months in the simulator. They are taught that if you end up close enough to another aircraft, it is because ATC or the aircraft systems have failed you up to that point, so you rely on TCAS as the last layer of safety. When responding to a resolution advisory, Dr. Ott says he is trained to immediately act as directed, as your movements and separation could be very time-sensitive. Once you are clear of conflict, as TCAS will say audially, you report to ATC that you responded to a resolution advisory, and that you are returning to your originally assigned heading and altitude, to which ATC will either approve or assign you a new heading and altitude. United pilots view quarterly presentations, near mishaps, and data to show where these airborne conflicts are occurring, in order to be aware of which airports, regions, or airways are garnering the most issues.

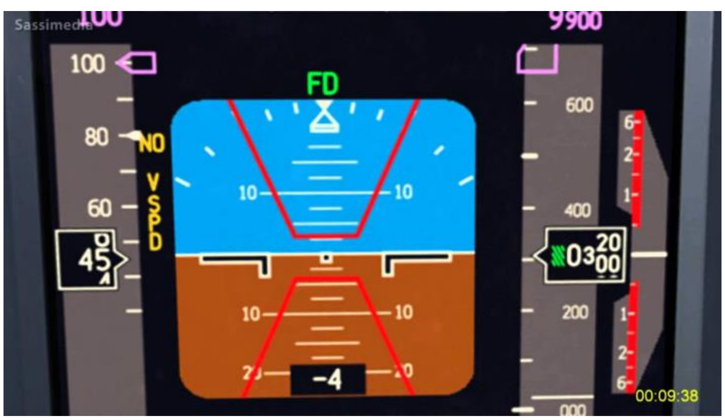

Figure 7. TCAS Resolution Advisory

Despite never being issued a resolution advisory during his time in the military due to the nature of his work, Dr. Ott says that he has always used TCAS to aid his situational awareness. Over the years, the visual picture has grown to become very clear, and describes the resolution advisories looking “like a goal post in a football game, and you just have to fly through the uprights, and if you are instructed to descend then you simply fly through the upside-down goal post.” Figure 7 illustrates this image. Older versions of TCAS had an outline directing where to fly, and in the heat of a moment it was not exactly clear whether to descend or climb. Lastly, the latest versions of TCAS also indicate if the rate of descent or climb is not fast enough, both visually on the screen and audially. TCAS has improved significantly over the years to make its functions more intuitive and the system easier to use, as a result of confusions and pilot errors in the past.

Discussion

TCAS is not perfect. A universally standard practice would prevent issues like that of the Ueberlingen collision, and other near mishaps of the like. TCAS, along with other electronic equipment with the aircraft, were created in order to aid the human pilot with the safe operation of the aircraft. Humans are not perfect and rely on technology to accomplish their mission, which is flight, in this case. The interactions between human and technology and how they co-influence each other is essential to understanding and predicting future interactions between human and technology, such as with drones and self-driving cars. Since commercial flight is one of the most technologically supported methods of transportation it can be extremely helpful to learn from the sociotechnical relationship in aircraft and apply some lessons learned to other aspects of sociotechnical transportation.

Limitations in the research of this paper has to do with the number of case studies examined. While there are collisions in commercial aviation from time to time, there is not a significant amount of case studies analyzing the mishaps from it. More case studies would bring to light more issues with TCAS and more ways in which pilots and TCAS have influenced the development of the system as well as the training of pilots. Additionally, additional interview(s) with pilots from different airlines would help create a better understanding of how different airlines train their pilots to use TCAS. To reiterate, the limitations of this research is not the types and methods of research, but rather the quantity of it.

If this research were to be continued or done differently, the author should begin by investigating more case studies and interviews, in order to increase the validity of the claims made. Additionally, this research could be used to analyze potential limitations of all autonomous vehicles, particularly that of self-driving cars. Before autonomous cars are widely produced on the road, engineers should study how aircraft, which are already largely autonomous, handle the various predicaments they find themselves in, as well as how the artificial intelligence communicates with the human user or operator.

The knowledge gained from the research is directly applicable to my future career. This summer I will begin learning aircraft systems and how to operate aircraft as a Student Naval Aviator, and it is beneficial to begin learning about how pilots and AI systems coincide. In the near future, I will be making decisions in the cockpit based off of information I gather from the aircraft systems and outside resources, and it is beneficial to know the connection, or lack thereof, between internal aircraft systems and ground controllers. The biggest takeaway I can make as a future pilot is to always communicate as much as possible with ATC and other pilots in the area your intentions and actions, to avoid any possible confusion. The stakes are high in aviation in terms of revenue and livelihood, and it is important to try and avoid all negative situations.

Conclusion

Pilot decision-making, errors, and incident reports have furthered the development of TCAS over the years. It has expanded from originally just providing traffic advisories, or notices of nearby traffic, to providing resolution advisories to correct the situation at hand, to recently adding the capability to offer horizontal movement resolution advisories. Pilot's confusion with the visual diagram of TCAS systems have generated the need for improving the graphical display, from the basic imaging to the indicators of direction of aircraft, their movement, and the direction of desired movement for resolution. Pilots and TCAS have a hand-in-hand relationship, in which its issues are constantly being renewed and brought to light as conflicts occur, and it will continue to develop until it is perfect. The lessons learned in analyzing the relationship of the human and social interactions of pilots and TCAS can be applied to all human and technology relationships, and more notably that of autonomous travel. By studying TCAS, engineers working on autonomous vehicles can learn valuable lessons in predicting situations before they happen. Insights to this paper can help create a safer environment not only for air and road travel, but for better understandings in all human and technical relationships.

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