2006

A human factors analysis of operational errors in ATC : the TCAS case study

José Luis Garcia-Chico
San Jose State University

Follow this and additional works at: https://scholarworks.sjsu.edu/etd_theses

Recommended Citation

Garcia-Chico, José Luis, "A human factors analysis of operational errors in ATC : the TCAS case study" (2006). *Master's Theses*. 2999.
DOI: <https://doi.org/10.31979/etd.zcv6-82bc>
https://scholarworks.sjsu.edu/etd_theses/2999

This Thesis is brought to you for free and open access by the Master's Theses and Graduate Research at SJSU ScholarWorks. It has been accepted for inclusion in Master's Theses by an authorized administrator of SJSU ScholarWorks. For more information, please contact scholarworks@sjsu.edu.

A HUMAN FACTORS ANALYSIS OF OPERATIONAL ERRORS IN ATC.
THE TCAS CASE STUDY

A Thesis

Presented to

The Faculty of the Graduate Program in Human Factors and Ergonomics

San José State University

In Partial Fulfillment

of the Requirements for the Degree of

Master of Science

by

José Luis Garcia-Chico

December 2006

UMI Number: 1441093

Copyright 2006 by
Garcia-Chico, Jose Luis

All rights reserved.

INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

UMI[®]

UMI Microform 1441093

Copyright 2007 by ProQuest Information and Learning Company.

All rights reserved. This microform edition is protected against
unauthorized copying under Title 17, United States Code.

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

© 2006

José Luis Garcia-Chico

ALL RIGHTS RESERVED

APPROVED FOR THE HUMAN FACTORS AND ERGONOMICS PROGRAM

Dr. Kevin M. Corker, Professor, Industrial and Systems Engineering

Dr. Kevin P. Jordan, Professor, Psychology

Dr. Kim Cardosi, Volpe Center, US Department of Transportation

APPROVED FOR THE UNIVERSITY

12/06/06

ABSTRACT

A HUMAN FACTORS ANALYSIS OF OPERATIONAL ERRORS IN ATC.

THE TCAS CASE STUDY

by José Luis Garcia-Chico

This research evaluated controller's operational errors (OEs) in the Air Traffic Control environment. It consisted of two exploratory studies. The first one was a classification of errors 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). The results provided a systematic characterization of OEs, with potential use to prioritize future research and interventions. Patterns of error in centers and terminal airspace were different. The absence of data controllers and developmental controllers were associated with higher proximity between aircraft in the incident, although the results were not conclusive. The results were not sufficient to establish any causal influence of RAs on OEs. The study found evidence of deficient pilot-controller communications during RA events increasing the likelihood of receiving vertical clearances in opposite direction to the RA. The findings suggested the need for down linking RA information.

ACKNOWLEDGEMENTS

Many people have contributed to make this project possible, in one way or another. To all of them, I would like to express my gratitude. I would like to start with the three K's, as I affectionately named my three-committee members, Dr. Kevin Corker, Dr. Kim Cardosi, and Dr. Kevin Jordan. I am highly indebted to my advisor at SJSU, Dr. Kevin Corker, for his unconditional, and generous support, intellectual and logistic, his guidance and feedback during the course of this research, and his stimulating ideas on how to conduct it. He was always ready and available to my requests and doubts. I would like also to thank Dr. Kim Cardosi and Dr. Kevin Jordan for their useful insights and assistance in previous drafts and this final document.

I am very grateful to everybody whom I share time with at the SJSUHAIL laboratory, for their help and for their friendship when I needed, making me to feel at home, when I was thousands of kilometers away. Special thanks to Samm, Elaina, and Lisa, who helped me to edit the last version in the last minute.

I have to express my gratitude to Patricia. She encouraged me to search new horizons and new challenges. Thank you for being there, in the good and hard moments.

I cannot forget mentioning LaCaixa Foundation, whose staff believed in me and unconditionally sponsored my studies in the USA, making my dream a reality.

Finally, to my dad and my mom, Domingo Garcia-Chico and Carmen Gómez, held accountable for providing me education and moral values, and giving me love. Thank you for your support along this journey. This is dedicated to them.

TABLE OF CONTENTS

INTRODUCTION.....	1
BACKGROUND.....	2
PROBLEM STATEMENT	4
GOALS OF THE STUDY	10
AN OVERVIEW OF THE ATC SYSTEM.....	11
TCAS DESCRIPTION.....	14
HUMAN ERROR VERSUS OPERATIONAL ERROR.....	24
AIR TRAFFIC OPERATIONAL ERRORS INVESTIGATION AND REPORTING PROCESS.....	27
ANALYSIS OF INCIDENT REPORTS	28
SUMMARY	29
LITERATURE REVIEW.....	31
HUMAN ERROR FRAMEWORKS AND TAXONOMIES.....	32
STUDIES OF INCIDENT AND ACCIDENT REPORT ANALYSIS IN AVIATION.....	41
A PROPOSED SOLUTION: DOWNLINK TCAS RA	45
SUMMARY	47
STUDIES PERFORMED IN THIS THESIS	48
STUDY ONE: TAXONOMIC ANALYSIS.....	49
METHOD	49
RESULTS	55
DISCUSSION	78
STUDY TWO: CASE STUDY OF TCAS RA	86
METHOD	86
RESULTS	90

DISCUSSION	119
CONCLUSIONS	125
LIMITATIONS.....	127
FUTURE WORK.....	128
REFERENCES	130
APPENDICES	137
APPENDIX A ACRONYMS	138
APPENDIX B EXAMPLE OF NARRATIVE OF A PRELIMINARY OE REPORT	142
APPENDIX C EXAMPLE OF NARRATIVE OF A FINAL OE REPORT	144
APPENDIX D DEFINITION OF ERROR TYPES (TAXONOMY)	147
APPENDIX E DEFINITION OF CONCURRENT AND CONTEXTUAL FACTORS ..	152
APPENDIX F INTRODUCTION TO JANUS METHODOLOGY AND EXAMPLE OF APPLICATION.	157
APPENDIX G RESULTS OF THE APPLICATION OF JANUS	162
APPENDIX H HUMAN SUBJECTS INSTITUTIONAL REVIEW BOARD APPROVAL	167

LIST OF TABLES

TABLE 1. NUMBERS OF ERRORS AND SUBSEQUENT CLASSIFICATIONS	56
TABLE 2. PERCENTAGE OF ERROR TYPE AND PERCENTAGE OF OE REPORTS ASSOCIATED TO EACH ERROR TYPE, IN ARTCC AND REPORTS IN TRACON.....	57
TABLE 3. DESCRIPTIVE STATISTICS OF DISTANCE BETWEEN AIRCRAFT IN OE REPORTS BY PROXIMITY CATEGORY	62
TABLE 4. FREQUENCIES AND PERCENTAGES OF PROXIMITY CATEGORIES IN CENTERS AND TERMINAL FACILITIES	63
TABLE 5. PERCENTAGE OF CONTEXTUAL FACTORS AND PERCENTAGE OF OE REPORTS ASSOCIATED TO EACH FACTOR, IN ARTCC AND TRACON	68
TABLE 6. OE REPORTS ASSOCIATED WITH EACH LEVEL OF PROXIMITY AND THE PRESENCE OR ABSENCE OF A D-SIDE CONTROLLER	74
TABLE 7. DISTRIBUTION OF OES INVOLVING TCAS AS FUNCTION OF AIRSPACE AND REVIEWED PERIOD.....	90
TABLE 8. PERCENTAGE OF ERROR TYPE AND PERCENTAGE OF OE REPORTS ASSOCIATED TO EACH ERROR TYPE, IN ARTCC AND REPORTS IN TRACON (OE REPORTS CONTAINING TCAS RAS)	92
TABLE 9. DESCRIPTIVE STATISTICS OF DISTANCE BETWEEN AIRCRAFT IN OE REPORTS BY PROXIMITY CATEGORY	97
TABLE 10. FREQUENCIES AND PERCENTAGES OF PROXIMITY CATEGORIES IN CENTERS AND TERMINAL FACILITIES WITH REPORTS THAT CONTAINED TCAS RAS	98
TABLE 11. OE REPORTS ASSOCIATED WITH EACH LEVEL OF PROXIMITY AND THE PRESENCE OR ABSENCE OF A D-SIDE CONTROLLER IN INCIDENTS INVOLVING TCAS RAS.....	103
TABLE 12. ANALYSES OF VARIANCE FOR IDENTIFIED ERROR TYPE AS FUNCTION OF CONTROLLER'S TIME ON POSITION	106
TABLE 13. OE REPORTS CONTAINING CONTROLLER'S ALTITUDE CLEARANCE AFTER TCAS RA WAS TRIGGERED ONBOARD (COMPLETE PILOT'S INFORMATION).....	116

TABLE 14. OE REPORTS CONTAINING CONTROLLER’S ALTITUDE CLEARANCE AFTER TCAS RA WAS
TRIGGERED ONBOARD (COMPLETE PILOT’S INFORMATION)..... 117

TABLE 15. DEFINITIONS OF OPERATIONAL ERROR TYPE..... 148

TABLE 16. DEFINITIONS OF CONTEXTUAL AND CONCURRENT FACTORS 153

TABLE 17. EXAMPLE OF APPLICATION JANUSTO AN OE REPORT 160

LIST OF FIGURES

FIGURE 1. EVOLUTION OF OE RATE DURING THE LAST TWELVE YEARS IN THE NATIONAL AIRSPACE	
SYSTEM	6
FIGURE 2. TIMELINE OF EVENTS IN A TYPICAL TRIGGERED TCAS RA.....	23
FIGURE 3. WICKENS' MODEL OF HUMAN INFORMATION PROCESSING.	33
FIGURE 4. REASON'S LATENT FAILURES MODEL (ALSO KNOWN AS SWISS CHEESE MODEL).	37
FIGURE 5. FLOW DECISION DIAGRAM USED TO CLASSIFY ERRORS.	51
FIGURE 6. (CONTINUATION) FLOW DECISION DIAGRAM USED TO CLASSIFY OE.....	52
FIGURE 7. PERCENT OF REPORTS CONTAINING VARIOUS ERROR TYPES IDENTIFIED PER INCIDENT REPORT. ...	59
FIGURE 8. FREQUENCY OF REPORTS THAT HAVE JOINT OCCURRENCE OF PAIR OF ERRORS.....	60
FIGURE 9. CRITERIA APPLIED TO CHARACTERIZED PROXIMITY ACCORDING TO VERTICAL AND HORIZONTAL	
DISTANCE.....	61
FIGURE 10. SEVERITY OF OPERATIONAL ERRORS ASSOCIATED WITH BOTH TRACON AND ARTCC.	63
FIGURE 11. SEVERITY OF OPERATIONAL ERRORS ASSOCIATED WITH ARTCC.	64
FIGURE 12. SEVERITY OF OPERATIONAL ERRORS ASSOCIATED WITH TRACON.	64
FIGURE 13. PERCENTAGE DISTRIBUTION OF THE ERROR TYPES LINKED TO THEIR CONSEQUENT PROXIMITY.	66
FIGURE 14. PERCENTAGE OF CONTEXTUAL AND CONCURRENT FACTORS IDENTIFIED IN THE OE REPORTS,	
WITH BASE ON THE TOTAL NUMBER OF OE REPORTS.....	71
FIGURE 15. STAFFING OF SECTOR WHEN THE OE OCCURRED.....	72
FIGURE 16. FREQUENCY OF ERRORS BY PROXIMITY IN CENTERS WHEN D-SIDE WAS PRESENT.....	73
FIGURE 17. FREQUENCY OF ERRORS BY PROXIMITY IN CENTERS WHEN D-SIDE WAS ABSENT.	73
FIGURE 18. PERCENTAGE OF OE REPORTS, SORTED BY PROXIMITY RATING FOR CPC AND	
DEVELOPMENTAL CONTROLLERS.	75
FIGURE 19. DISTRIBUTION OF OEs AS A FUNCTION OF THE CONTROLLER'S TIME ON POSITION.	76
FIGURE 20. PROXIMITY OF ERRORS AS A FUNCTION OF CONTROLLER'S TIME ON POSITION IN 5-MINUTES	
SEGMENTS.....	77

FIGURE 21. SCHEME PILOT'S MESSAGE – CONTROLLER'S ACTION DURING TCAS RA	88
FIGURE 22. FREQUENCY OF ERROR TYPES IDENTIFIED IN OE REPORTS THAT CONTAINS TCAS ADVISORIES. 91	
FIGURE 23. PERCENTAGE OF ERROR TYPES IDENTIFIED IN OE REPORTS THAT CONTAINS TCAS ADVISORIES VERSUS THOSE IDENTIFIED WITH THE FULL SET OF ERRORS.....	94
FIGURE 24. PERCENTAGE OF ERRORS IDENTIFIED IN THE OE REPORTS, WITH BASE ON THE TOTAL NUMBER ERRORS FOUND IN TRACON AND ARTCC, RESPECTIVELY.	96
FIGURE 25. SEVERITY OF OPERATIONAL ERRORS ASSOCIATED WITH THE ARTCC	98
FIGURE 26. COMPARISON OF PROXIMITY RATING BETWEEN OEs THAT TRIGGERED TCAS RA (WITH RA BETWEEN BRACKETS) AND FULL SET OE REPORTS.....	100
FIGURE 27. PERCENTAGE OF CONTEXTUAL AND CONCURRENT FACTORS IDENTIFIED IN THE OE REPORTS, WITH BASE ON THE TOTAL NUMBER OF OE REPORTS.....	101
FIGURE 28. DISTRIBUTION OF OEs WITH TCAS RA AS A FUNCTION OF THE CONTROLLER'S TIME ON POSITION	104
FIGURE 29. FAIL CONVERGING ERROR AS A FUNCTION OF THE CONTROLLER'S TIME ON POSITION, IN ENCOUNTERS WITH TRIGGERED TCAS RA.	107
FIGURE 30. FAIL IDENTIFICATION CLIMBING/DESCENDING ERROR AS A FUNCTION OF THE CONTROLLER'S TIME ON POSITION, IN ENCOUNTERS WITH TRIGGERED TCAS RA.....	107
FIGURE 31. DESCEND THROUGH ERROR AS A FUNCTION OF THE CONTROLLER'S TIME ON POSITION, IN ENCOUNTERS WITH TRIGGERED TCAS RA.	108
FIGURE 32. CLIMB THROUGH ERROR AS A FUNCTION OF THE CONTROLLER'S TIME ON POSITION, IN ENCOUNTERS WITH TRIGGERED TCAS RA.	108
FIGURE 33. OVERLOOK TRAFFIC ERROR AS A FUNCTION OF THE CONTROLLER'S TIME ON POSITION, IN ENCOUNTERS WITH TRIGGERED TCAS RA.	109
FIGURE 34. AGENT OR SYSTEM THAT DETECTED THE IMPENDING INCIDENT (WITH A TRIGGERED TCAS RA).	111

FIGURE 35. PERCENTAGE OF INCIDENTS WITH COMMANDS GIVEN BY THE CONTROLLER WITH REGARD TO THE TIME TCAS CA WAS TRIGGERED, PARAMETER OF THE CLEARANCE, AND QUALITY OF THE PILOT'S MESSAGE INFORMING ABOUT TCAS RA.....	114
FIGURE 36. CLASSIFICATION SCHEMES THAT NEED TO BE IDENTIFIED WHEN APPLYING THE JANUS METHODOLOGY.....	159
FIGURE 37. DISTRIBUTION OF ERROR TYPES OF JANUS METHODOLOGY.....	163
FIGURE 38. PERCENTAGE OF ERROR DETAIL AS IDENTIFIED BY JANUS METHODOLOGY.....	164
FIGURE 39. PERCENTAGE OF DISTRIBUTION OF ERRORS MECHANISMS AS IDENTIFIED OF JANUS METHODOLOGY.....	165
FIGURE 40. PERCENTAGE OF INFORMATION PROCESSING FACTORS AS IDENTIFIED BY JANUS METHODOLOGY.....	166

INTRODUCTION

This work presents two studies related to Operational Errors (OEs) in Air Traffic Control (ATC) within the United States (US) airspace. The first study is a classification and exploratory analysis of controllers' OEs. The second study is an in-depth look at controller OEs that co-occurred with a Resolution Advisory (RA) for at least one of the aircraft involved triggered by the Traffic Alert Collision Avoidance System (TCAS). TCAS is an onboard system independent from the ground-based air traffic services that provides collision protection and escape maneuvers to pilots. It has been asserted that the TCAS system itself may induce errors in some minor instances requiring special attention. The categorization and characterization of these kinds of errors may help prioritize interventions at error reduction. This exploratory analysis is an attempt to identify trends of OEs and contextual factors. In addition, the influence of triggering a TCAS RA on the air traffic controller's behavior was studied. The introductory chapter begins presenting the framework for the study. Further, the work developed in two phases is described, followed by the motivating problem, and the objectives that this work is pursuing. Next, the ATC environment and the TCAS system are described in general terms. Finally, the concept of human error is reviewed within the ATC framework, and the established process to investigate OEs in the US by the Federal Aviation Administration (FAA) is briefly presented, in order to understand the source of information used in this work.

Background

This study was conducted in collaboration with the John A. Volpe National Transportation Systems Center and the FAA, and conducted at the San Jose State University Human Automation Integration Laboratory (SJSUHAIL). In the spring of 2005, SJSUHAIL conducted an examination of FAA reports of air traffic controllers' OEs in the US committed during the first 6 months of 2004. These reports were a preliminary written description of incidents that occurred at the control facilities. In spring 2006, a second set of reports were received for analysis, covering the same period of 6 months of 2005. These reports were the final result of the operational error investigation by the FAA. The process for the current study was to examine in detail all the particulars of the FAA investigations, defining various characteristics in the data received that would lend further inspection.

Description of the Study

This study was a thorough investigation of OEs that take place in air traffic control from a human factors perspective. In this study, OE reports including Resolution Advisory (RA) alerts generated by the TCAS system were of particular interest. An attempt was made to characterize every error present in each report, to relate the OE type with the aircraft proximity, to determine cognitive and organizational contextual factors present in the OE report, and to study operational implications. A further step in the analysis considered situations with TCAS RA triggered on aircraft involved in the encounter, concentrating on its contribution to the air traffic controller's behavior during the incident.

The analysis was done in two phases. First, preliminary reports of OEs were collected from the FAA OE database, spanning the first six months of 2004. These reports were analyzed in order to characterize the OEs according to a classification proposed by the FAA, and amended and extended during our analysis. Relationships among OE types and contextual factors were established, when possible. The assessment emphasized the proximity rating of incidents and its relation to OE types and their concurrent and contextual factors. Analysis of additional organizational factors were made, e.g., training being conducted at the position where the OE took place, or absence of a data controller and their relation to the OE type.

Second, a case study was done, focused on those OE reports where at least one aircraft received a TCAS RA that required a deviation from the ATC clearance. For this study, final incident reports, FAA Form 7210-3, were used rather than preliminary reports. These final reports are the result of the operational error investigation done by the air traffic manager of the facility (see FAA (2002) for a description of the template report). In this second dataset, the period covered was the first six months of 2005. The aim, here, was to characterize errors and contextual factors that were present in the OE reports that included the presence of TCAS RA commands. This additional insight analysis led to recommendations for further research on areas such as ATC procedures and display design for air traffic controllers. These are covered in the discussion section. The same classification and procedure used in the first study was used in the second, which facilitated comparison between both studies. Initially, another methodology was proposed by other offices in the FAA and applied to these reports, but its application led

to speculation in some cases and to lack of criteria to assign a class to errors in others.

This methodology, named JANUS (Eurocontrol, 2003b), has been developed by the FAA and EUROCONTROL (Pounds & Ferrante, 2005; Pounds & Isaac, 2002, 2003). The results of its application are collected in the Appendix G .

Problem Statement

The main premise that motivated this study on human error in air traffic control lies in the fact that erroneous actions performed by operators in high-risk industries have been linked as the cause of accidents. This has been the case of ATC as part of the aviation system. In the early years of aviation, technological defects were the main cause of accidents, but as reliability has improved, human error has become the main factor in incidents and accidents (Wiegmann & Shappell, 2003). Hobbs (2004) suggests that human factors have been the primary cause of accidents since the early days of aviation. Depending on the specific study, the percentage of accidents and incidents attributed to human error or human factors varies between 70-80% (Wiegmann & Shappell, 2003; Reason, 1997). Boeing (2004) estimated that 70% of commercial jet airline accidents between 1959 and 2003, with aircraft heavier than 60,000 pounds maximum gross weight, involved human errors. O'Hare, Wiggins, Batt, and Morrison (1994) analyzed two sets of aviation accident reports in New Zealand, finding that 71% and 70%, respectively, were classified within one of the human error categories they used. One could argue that all accidents are caused by a human error, because "people design, build, maintain, manage, and defend hazardous technologies" (Reason, 1997, p.61). Some authors, however, warn against this pervasive idea of considering human error as the

cause of most accidents of complex systems, because looking back the causal chain to find a root cause in accidents and incidents is elusive, if not impossible (cf. Dekker, 2002, 2003; Hollnagel, 1993; Rasmussen, 1987). There is always a possibility to go one step further. How far back to seek for causes in the analysis after the facts is highly influenced by the hindsight (Wood & Cook, 2002). In addition, there are factors that influence the human action that might be hidden under the term human error (the so-called *latent conditions*), such as organizational, procedural, or design deficiencies. Regardless of the accurate percentage, what is relevant is that operators' actions sometimes fail to produce the expected result, leading to unwanted consequences, and play an important role in today aviation's accidents and incidents. This is not surprising because in aviation, as in other complex high-risk industries, the human element is retained in the system, despite the level of automation introduced (Reason, 1990). The human element is often the most vulnerable component, and, at the same time, the last safety barrier responsible for preventing accidents.

As part of the aviation system, the ATC system is in itself a complex social-technical system, where the human error has been identified as a risk factor (Pounds & Ferrante, 2005; Pounds & Isaac, 2002). The prevention of the incidence of human errors in ATC becomes crucial as air transport demand increases, and the system becomes more complex (e.g., automation is being introduced and human-machine interface is permanently evolving). To accomplish this, the FAA has established an incident reporting system to capture 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, and they capture data related to the occurrence and focused on the controller performance (Pounds & Ferrante, 2005). In 2004, the FAA Air Route Traffic Control Centers (ARTCC) managed 46,752,000 aircraft and the Control Towers registered 46,873,000 airport operations, with 1216 operational errors (FAA, 2006). Additionally, the OEs were 1041 in 2002, increasing to 1211 in 2003, 1215 in 2004, and 1506 in 2005 (FAA, 2006). Figure 1 shows the evolution of the OE rate per 100,000 facility activities during the last 12 years in the US airspace. These data reflect an increasing tendency, which eventually seems to have reached a plateau in the last three years. Therefore, there was a need to analyze OEs and to investigate contributory factors leading to them in order to develop mitigating strategies that may help to develop error recovery mechanisms in the system.

Figure 1. Evolution of OE rate during the last twelve years in the National Airspace System.

A second argument to look at operational errors and the TCAS system was related to the introduction of automation in socio-technical systems. Automation has been introduced in aviation to prevent errors and its consequences, among other reasons (e.g., reducing workload of operator, replacing humans at lower cost, performing a human activity more efficiently). 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 (Parasuraman, Sheridan, & Wickens, 2000; Parasuraman, 1997; Reason 1990). The TCAS system is one of example. 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 (Pritchett, 2001). Here, automation refers to “the full or partial replacement of a function previously carried out by the human operator” (Parasuraman et al., 2000, p. 287). When looking at TCAS system, it introduces high levels of automation in three of the four levels as identified by Parasuraman et al.: information acquisition, analysis, and decision selection. The fourth level, action implementation, is not automated and it is the pilot, still in the control loop, responsible to execute the maneuver. 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 that aims at serving as a backup to visual collision avoidance and air traffic services (Wickens, Mavor, Parasuraman, & McGee, 1998; FAA, 2001) and advising pilots that a potential collision is threatening. Since the introduction of TCAS on board, a

close monitoring program to guide redesign and refinement of the system has been implemented (Wickens et al., 1998). Human factors issues related to new error forms was only one of the aspects monitored. Here, it is the impact of TCAS on controller error that is our interest. TCAS RA instructs the pilot to either “climb”, “descend”, or “adjust vertical speed” in order to avoid a possible collision. Those maneuvers are only on the vertical plane and are frequently unanticipated by air traffic controllers. They can “drastically disrupt the controller’s situation awareness” (Wickens et al, 1998, p. 130). 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. It is specified that the pilot should communicate with ATC “as soon as practicable after responding to the RA” (FAA, 2001), in reality, the controller may receive this voice message very late after the deviation from the assigned altitude or not receive it at all (Brooker , 2004), increasing the opportunity for controllers' errors in response to TCAS events. The delay in sending the voice message, or the lack of it, may be consequence of high pilot workload levels when responding to a RA (Eurocontrol, 2003a), and of a great variability of pilot behavior (Brooker, 2004; Wickens et al., 1998). As a consequence, the elapsed time between the issued RA and the pilot’s notification to ATC is highly unpredictable. 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 (FAA, 2006a). However, Brooker (2004) 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.

The impact of TCAS system on aviation safety from a holistic point of view (technical system functioning, crew and controller behavior included) has been beneficial, significantly reducing collision risk (Williams, 2004; Eurocontrol, 2003a). This system contributes to solution of hazardous situations after pilot and/or controller failure. However, recent accidents and incidents have raised concerns on the very few circumstances where TCAS might induce new hazards. The recently occurrence of two midair incidents is considered a proof of TCAS shortcomings: the collision over Uberlinguen in Germany on July 1, 2002, and the near midair incident near Yaizu in Japan on the January 31, 2001. The official report of the Uberlingen midair collision considered that “the integration of TCAS into the system aviation was insufficient and did not correspond in all points with the system philosophy” (BFU, 2004, p. 110). Nunes and Laursen (2004), in their identification of contributing factors to this accident, argued that the inability to make the controller aware of the TCAS RA issued on board and of the maneuver executed by the pilot played an important role in the accident. Furthermore, Ladkin (2004) stated that the use of TCAS played a direct causal role in the accident. Similarly, the pilot’s compliance with an ATC instruction contrary to the RA played a causal role in the incident in Yaizu. The analysis of the errors potentially induced by TCAS RA, though in marginal situations, is worth exploring with broadening operational data.

Goals of the Study

The goals of this study were threefold: first, to perform a characterization analysis of OEs and concurrent factors in ATC, second, to explore the relationship between triggered TCAS RA warnings onboard and air traffic controllers' OEs and behavior, and, finally, to propose potential mitigation measures, and future research directions.

This study attempted to characterize OEs of air traffic controllers and contextual factors in order to achieve a better understanding of underlying contributing factors and mechanisms of the error in a real-world ATC environment. It emphasized the cognitive and organizational issues present at the time the error was committed in an attempt to identify patterns of behavior. This analysis included the study of the linkage between the OE type and the severity of the encounter, defined as the vertical and horizontal distances between aircraft at the Closest Point of Approach (CPA). Ranking OEs based on the severity of the corresponding encounters provides the basis to prioritize the measures to be implemented in the near future to reduce OEs.

A further step in the analysis considered OEs involving aircraft with TCAS RAs, focusing on their possible contribution to errors, if any. It explored the potential causal effect of TCAS RA's presence and the subsequent pilot's behavior on controller's situation awareness and errors. The study investigated if TCAS RAs were present in close proximity encounters (more severe encounters) and if any particular OE was more likely to occur concurrently with TCAS RA. This helped to gain a better understanding of the TCAS-related problems found by ATC controllers.

Finally, the analyses are aimed at providing some recommendations either at the procedural or design level to mitigate the potential impact of TCAS RAs on erroneous actions. Those recommendations were made based on a structured analysis of the actual behavior of pilots and controllers after a triggered TCAS RA, its impact on controller's situation awareness, and the potential consequences of the proposed recommendations.

An Overview of the ATC System

This section describes the high-level principles and functions of the ATC system to understand the controller's role and their responsibilities. It is important to set up the context where the controller's activities take place, to understand the controllers' task demands and the opportunities to err.

Air Traffic Control Service Features

According to FAA (2006a), the primary purpose of the ATC system is to prevent a collision between aircraft operating in the system and to organize and expedite the flow of traffic. In addition to their primary functions, ATC provides additional services, e.g., weather information, if possible. Several situations may prevent these additional services, such as high volume of traffic, frequency congestion, low quality of radar, high controller workload, and the like. Air traffic controllers in three different control areas provide ATC services: tower and local control, terminal area control, and en-route control.

Tower and local controllers' are in charge of handling aircraft at taxiways, runways, and the immediate airport vicinity, and in charge of the movement of other vehicles within the airport. Depending on the dimension of the airport, the number of

controllers varies. There are typically four types of tower controllers. Ground controllers handle all vehicles within the airport movement area. Local controllers, control landing, take offs at the runway up to a few miles around the airport and clearance delivery, coordinating with the en-route areas precise departures and, in some busy airports, “apron control,” which are the non-movement areas at an airport.

Terminal Radar Approach Control (TRACON) is in charge of traffic climbing or descending between high altitude levels, or en-route area, to the airport, and vice versa. This control service only exists around some large airports, otherwise the en-route center coordinates directly with the tower at the airports that have no TRACON. Controllers need to ensure that aircraft reach the adequate altitude when departing before handing off to en-route control, and to descend, align with final approach and slow down the aircraft before handing off to tower controller.

Air Route Traffic Control Centre (ARTCC) provides control services to aircraft flying between airports, usually at high-level altitudes. Flights are guided along a net of airways across the airspace and at different altitudes. The airspace is divided into irregular shaped volumes called *sectors*, which are under the responsibility of an air traffic controller team, with horizontal and vertical boundaries. This team is made up of two controllers, radar controller or *R-side* (also known as executive controller) and data controller or *D-side* (also known as planner controller), but if the traffic is low only the radar controller is staffed, and if the traffic level is high, a third controller is added to the team, called *tracker*.

The Air Traffic Controller's Role

The main role of the air traffic controller is to operate the ATC system to assist the pilot in carrying out a safe, orderly, and expedite flight. She or he applies separation rules to the aircraft, issuing advisories to the pilot whenever appropriate to keep the minimum separation distance. A controller, based on information acquired from the system, projects and plans future aircraft movements the aircraft flies through his or her sector of responsibility until it is handed off to the next sector. The aircraft maintains voice communication with the controller all the time flying within the sector.

There are many similarities in the tasks carried out by the different controllers, but there are also differences in cognitive demands that have impact on the potential error. For example, tower controllers rely more on visual acquisition of the aircraft from the tower, en-route controllers use mainly a radar display and paper strips.

The air traffic controllers use various supporting tools to accomplish their tasks, among which radar display, flight strips, and communications systems are the more relevant. The radar display is probably the richest source of information. Traffic location is depicted in a two-dimension plane with a tag containing the altitude and other information related to the flight, accessible by the controller. The data block contains flight identification, ground speed, and altitude as minimum information. In addition, flight strips are used to strategically plan traffic that enters a sector. In the past, paper strips were used more often and updated more frequently, but currently information on a radar display is more complete. However, paper strips are used to annotate new

clearances given to aircraft or as reminders to perform other actions to an aircraft. Paper strips have been replaced in some centers by an electronic version.

Finally, the communication system is vital for the controller. They use radio frequency to communicate with pilots to issue clearance and provide information. Each sector has one unique radiofrequency assigned to communicate with all aircraft contained in it, which have to change to the next sector frequency at controller request. This action takes place after coordination between both controllers of each sector. One important aspect during the clearance delivery to pilots is that the pilot has to read back the instruction as a confirmatory procedure that he or she understood the content of the instruction. The controller has to receive this readback and to confirm that is the same instruction he or she issued.

Controller's Teamwork

Teamwork is vital for controllers. At en-route sector level, the R-side is in charge to monitor traffic to keep separation standards and make tactical decisions, to coordinate with adjacent sectors, and to communicate with pilots. The D-side controller plays a strategic role, handling flight strips and checking flights are free of conflict before entering the sector at more strategic level. He or she is responsible for coordinating changes with adjacent planner controllers. In addition, there are other actors to coordinate with supervisors and traffic flow managers.

TCAS Description

This subsection presents a description of the Traffic Alert Collision and Avoidance System (TCAS). TCAS is an airborne automatic system designed to detect

and avoid midair collisions. This system provides surveillance backup for the air traffic controller and pilot, and it issues advisories for the pilot when a potential midair collision with other nearby aircraft is imminent (Wickens et al., 1998; FAA, 2000; Williams, 2004). Wickens et al. (1998) summarized the objectives of the TCAS system: 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)). Hereafter, the acronym TCAS is used to designate the TCAS II equipment, which issues both TA and RA in contrast to TCAS I which only provides TA. TCAS II is also internationally known as Airborne Collision Avoidance System or ACAS II.

The initial motivation for TCAS development was found in a series of accidents in the US. The collision in 1956 between two airliners over the Grand Canyon raised the need of developing a collision avoidance system. Some prototypes were developed during 1960s and 1970s, but it is in 1981, after another collision over San Diego in 1978, that the FAA made the decision to develop TCAS with its current logic. Later, in 1987, a collision over Cerritos, California, resulted in a US Congress mandate that required TCAS equipment for operation of large aircraft with more than 30 passenger seats in the US (FAA, 2000; Williams, 2004). TCAS has been mandatory in the US airspace since 1991 and in Europe only since 2001. The worldwide mandate was not issued by the International Civil Aviation Organization (ICAO) until 2003 (Brooker, 2005).

The current legislation in the US, which is the same as the existing one at the time the OE reports that were analyzed in this study were created, requires the installation of TCAS II version V7 for passenger carriers, cargo haulers, commuters and air taxi operating under Part 121, Part 125, Part 129, and Part 135 (Title 14 of the Code of Federal Regulations). In other words, TCAS version V7 is mandatory for commercial carriers, but not for all aircraft operating in the US. In particular, the operation of civilian aircraft for purposes other than commercial passenger transport, including personal, business, and instructional, which is known as general aviation, does not require equipped aircraft.

Principles of TCAS Functioning

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. TCAS listens to spontaneous transmissions sent by Mode S transponders and creates corresponding interrogations. TCAS effectiveness depends on the transponder mode of nearby aircraft. TCAS cannot detect aircraft with inoperative Mode A/C or Mode S transponders, or with off or stand-by transponders. Similarly, TCAS cannot trigger RA if the transponder does not transmit altitude, either because it is a Mode A transponder or it has been selected not to transmit it.

TCAS has a minimum reliable tracking range of 14 nmi, in traffic densities of 0.3 aircraft per square nautical mile, and at least 30 aircraft simultaneously (FAA, 2000).

Interrogations and replies are sent nominally once per second, but when an intruder is identified and the range and closure rate are far from the threshold to trigger a TA, the interrogation is reduced to one every five seconds. Once the intruder is approaching and the risk of collision increases, the frequency increases again to one per second (FAA, 2000).

TA and RA Alerts

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. Using consecutive replies from a particular transponder, TCAS calculates the intruder's closure rate and the Closest Point to 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. For instance, the advisory time varies from 15 to 35 seconds; the altitude threshold varies from 300 to 700 feet, and the horizontal threshold from 0.2 to 1.1 nmi (FAA, 2000). No RA is issued below 1000 feet. RA is triggered based on the assumption that a pilot reacts within 5 s after receiving an RA, plus a maneuver time necessary to achieve a vertical speed of ± 1500 feet/minute to avoid the conflict. The look ahead time of the TA is, depending on encounter geometry, approximately 15 s to warn the pilot of an upcoming RA and to acquire visual contact with the intruder (Brooker, 2005; Rantanen, Wickens,

Xu, & Thomas, 2004; Williams, 2004). RA mandates the pilot to maneuver in the vertical plane, either passively (i.e., maintain vertical speed) or actively (i.e., climb, descend, and 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. When the conflict has passed, TCAS removes the RA and issues a "clear of conflict". The pilot should resume the previous ATC clearance and inform the controller (Williams, 2004; FAA, 2000).

Human Machine Interface

There are three main interfaces to communicate information to the crew. Two elements are visual displays, i.e., traffic display and resolution advisory display, and one element is aural, i.e., redundant prompts for the required actions. The visual displays are implemented in different ways, including a single physical unit, but they have to follow certain standards to present the same information.

Traffic display depicts surrounding traffic tracked by TCAS. Traffic is depicted using color-coded geometric symbols. Proximate traffic that is not threat and is within 6 nmi and 1200 feet below or above the own aircraft, is represented by a filled diamond in either white or cyan. If traffic evolves to cause a TA, it changes to a filled amber or yellow circle. Finally, a red square is used for traffic that generates a RA. The relative altitude of the traffic that reports altitude with its transponder is shown next to its symbol, with a + sign if the traffic is above, or with a – sign if it is below. An arrow is also

displayed to indicate that the traffic is climbing or descending at a rate greater than 600 fpm (FAA, 2000).

Resolution advisory display provides the vertical speed to fly in a green scale and the speed range of speed to avoid in red. Alternatively, it may provide pitch cue to fly or avoid. Some glass cockpit implements both pitch cue and vertical speed range (FAA, 2000).

Aural alerts are issued whenever the displays depict a TA or an RA. This redundant way of conveying information ensures pilots allocate attention on the information displayed. They reinforce the maneuver action to be taken. Thus, when a TA is triggered, it is annunciated with the message “Traffic, Traffic.” Should the conflict deteriorate, RA is aurally announced. For example, if it is a climb order, the message “Climb, Climb” is announced. Additional aural annunciation are coherent with the RA sense, e.g., “Descend, Descend”, “Increase Climb, Increase Climb”, or “Adjust Vertical Speed, Adjust” (FAA, 2000).

Procedures and Human Factors Issues Related to ATC

TCAS procedures are executed differently across countries and airlines. One of the main reasons for this is the existence of inconsistencies in the original documentation for TCAS operations defined by the International Civil Aviation Organization (ICAO), as Eurocontrol reported (2003a). Another important reason is that each country has had to ratify or to adapt ICAO’s procedures within its own airspace, which has led to variations in their implementation.

In the US, the FAA established the pilot's and controller's responsibilities and the procedures to follow in its Advisory Circular 120-55B (FAA, 2001). 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" (FAA, 2001, p. 7). They shall not maneuver on response of a TA. However, on receipt of an RA, the FAA (2001) stated:

The PF [pilot flying] 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 (p. 7).

Although the advice is to follow the RA, the possibility for the pilot to ignore it is acknowledged, and allowed. This is an important point since it accounts for the pilot's non-compliance with the RA. Wickens et al. (1998) cites studies done in the early 90's that estimate this non-compliance behavior from 30% to 50% of the time. These figures, nowadays, seem obsolete and the compliance with RA is probably higher (Eurocontrol, 2006) but no study has been found to support this statement. The FAA (2000) highlights that the 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 requires pilots to "communicate with ATC as soon as practicable after responding to the RA" (FAA, 2000,

p.9). Pilots are required to return “expeditiously” to the previous ATC altitude clearance when the conflict is resolved. Thus, they should notify to ATC that they resume the previously assigned altitude or they should acknowledge any new ATC clearance. Standard phraseology was suggested (FAA, 2000; Brooker 2004).

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, “workload permitting” (FAA, 2006a, 2000). They should not knowingly issue instructions in opposite direction to an RA. They resume responsibility for separation 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 was the FAA’s advice of not maneuvering in the opposite direction to a given RA “based solely upon ATC instructions” (FAA, 2000, p.10). Controllers should not knowingly issue instructions contrary to RAs, but they may not be aware of the RA. If an aircraft follows its RA and the other aircraft follows the direction opposite to its RA issued by controller, safe separation may be lost.

Other regulatory agencies around the world provide stronger rules for maneuvers contrary to the RA. For example, the Civil Aviation Authority in United Kingdom states that pilots should follow the advice given by TCAS if the instruction from ATC is in conflict with the RA (CAA, 2002). Eurocontrol and ICAO state “pilots shall not maneuver in the opposite sense of an RA” (Eurocontrol, 2006) regardless of the situation.

A simplified view of pilot's actions and controller's responsibilities during a TCAS RA event is depicted in Figure 2. It represents what Brooker (2004) called "desired sequence". He argued, in reality this sequence is not followed, and that the controller may receive one pilot's message or none about the TCAS RA. Eurocontrol (2003a) 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. It is also hypothesized that the RAs might be the cause of some OE. Furthermore, it is also likely that both aircraft report the RA at almost the same time, which could be highly confusing for the controller (remember that the controller has no direct indication of the RA).

Figure 2. Timeline of events in a typical triggered TCAS RA. Voice messages are represented by circles, red area covers the interval where the controller might not aware of the deviation from ATC clearance, and green area indicates when controller has been informed.

Ladkin (2004) defined socio-technical systems as “systems that contain mechanical, electrical or electronic parts but rely for their appropriate functioning on human or social organization and actions”. TCAS is a socio-technical system. Success of TCAS relies on the adequate procedures and execution by pilots and controllers (Brooker, 2004). Procedures and pilot compliance responding TCAS alerts have been issues of controversy after the near mid-air collision over Yaizu on January 31 2001 (ICAO, 2002; Brooker, 2004), and the collision in Uberlingen (Bennett, 2004; BFU,

2004). This has raised the need to advise explicitly the pilot not to maneuver contrary to RA even upon instructions of ATC, as it was described before.

Human Error versus Operational Error

The term human error is intuitively easy to understand, but when trying to classify and study in depth several difficulties arise. According to Dekker (2003), the human error in aviation has several meanings, which poses a real problem when classifying them. Human error is sometimes defined as an action that fails to meet certain standard. Changing the standard, any behavior can be relegated to error (Sheridan, 2002). Sheridan argued that the error count may be more a function of the criteria to measure than the behavior of the operator. Rasmussen (1987) recognized that errors can be caused by a “change in judgment” and what was once considered an acceptable performance turns into an erroneous act. Rasmussen described human errors as “instances of man-machine or man-task misfits,” highlighting the importance of the interaction between man and machine, and the impossibility of considering the performance of any of them in isolation. It may be argued that the erroneous behavior should be considered independently of the output and studied according to its psychological or cognitive mechanisms. To overcome this limitation on the definition, Reason (1990) defined human error as “a generic term to encompass all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency” (p. 9). Team error applies this definition to a group of people when working as a team or group (Sasou & Reason, 1999). On the other hand, if the acceptable system performance were

not known, it would be difficult to judge any action as erroneous or not (Eurocontrol, 2003a). This is more relevant when the task is highly cognitive in nature, as the air traffic controllers' tasks are.

Human error has been used as a term to describe situations where the cause of an accident or incident is attributable to some aspect of human action (Hollnagel, 1993). This adds additional ambiguity to the term human error because of the investigation process in itself. Investigation of accidents and incidents aims at finding causes and investigators try to search back in the causal chain of events. The search is not subject to any standard and, to some extent; the attribution of cause to humans depends on where to stop the search in the after-the-fact analysis (Rasmussen 1987). The search through the causal chain stops when a familiar and reasonable explanation is found and a cure is known, e.g., blame, substitute, and train. Because humans play a relevant role in complex systems, it is very likely that the causal search stops in a human action, and then assigned as human error. Another problem when attributing cause to failures and labeling as human error is the presence of hindsight bias or knowledge of outcomes (Dekker, 2002; Woods & Cook, 2002). This may lead to simplify difficulties, constraints, and pressures operators face and how they handle these factors to successfully accomplish their tasks. Dekker (2002) argued that the "old view of human error" still considers human error as the cause of most accidents. The "new view of human error", which should substitute for the old one, considers human error as an outcome of inherited interaction problems among humans, tools, tasks, and operating environments. It is crucial to understand why people did what they did, instead of

blaming them for doing it (Dekker, 2003). Norman (1990) proposed to identify the system characteristics that led operator to act in that way and change the design.

Hollnagel (2004) questioned the Western cause and effect rational model in accidents and incidents of complex systems, leading to the human error conception, which is often limited to try to fit all the facts together: “human nature is so strong that we try to find causes even when they do not exist, such in the case of misleading or spurious correlations” (p. 25). He argued that accidents happen because a number of factors come together, not because they were caused by them. Therefore, we cannot eliminate them (as causes), but only we can do is to understand the accident and try to control those conditions. He proposed a “systemic accident model,” which considers accidents and incidents as emergent phenomena that cannot be predicted. There is no direction of causality in the events. The main reasons for accidents and incidents are performance variability induced by the system complexity, as a necessary condition for a proper functioning of the system, to be constructively adaptive, but not as a fallible human characteristic. The combination of performance variability, latent conditions, technological flaws, and impaired barriers creates in the end “functional resonance” that turns out in accidents. This view includes human error as part of that variability of human behavior, but playing a less relevant role in incidents or accidents.

Our study dealt with incidents reported in ATC in the US airspace, which, in its turn, depend on the standard that imposes operator’s action to be considered as an error or not. Therefore, the definition of human error in the context of ATC has to be operationalized. Human error in ATC was defined by Isaac and Ruitenberg (1999) as

“intended actions which are not correctly executed” (p. 11), but this definition is too vague. An operational error was defined verbatim by the FAA (2002), Order 7210.56C, as:

an occurrence attributable to an element of the air traffic system in which: 1) less than the applicable separation minima results between two or more aircraft, or between an aircraft and terrain or obstacles (e.g., operations below minimum vectoring altitude (MVA); equipment / personnel on runways, as required by FAA Order 7110.65 or other national directive; or 2) an aircraft lands or departs on a runway closed to aircraft operations after receiving air traffic authorization; or 3) an aircraft lands or departs on a runway closed to aircraft operations, at an uncontrolled airport and it was determined that a NOTAM [Notice To Airmen] regarding the runway closure was not issued to the pilot as required.

The object of this study was operational errors as defined by the FAA, because those were the ones reported in the incident reports. Despite the fact that usually operational errors are the natural consequence of an erroneous action, as defined by Hollnagel, there is not always a cause-effect relationship. A controller may miss a pilot's incorrect readback without necessarily leading to an operational error (e.g., the error is detected by the data controller and it is corrected before the separation decreases below the minimum one). The reported errors may not gather all committed human errors. We need to keep in mind the limitations and data source that were used in this study when interpreting the results.

Air Traffic Operational Errors Investigation and Reporting Process

The FAA has implemented a formal reporting process of OEs that aims at identifying and correcting performance deficiencies in the air traffic services provided since its early initial evolution and by 1965 (Pounds & Ferrante, 2005). Current process

for the identification and correction of incidents was described by the FAA Air Traffic Quality Assurance Order 7210.56C (FAA, 2002).

The reporting and analysis process starts with the identification of the OE by any employee who has to report it to a supervisor. The supervisor initiates the preliminary investigation gathering the flight progress strips, reviewing the system data and conducting preliminary interviews with the involved employees. As a result, the preliminary OE investigation report, FAA form 7210-2 (FAA, 2000) is completed and the supervisor notifies the air traffic manager at the facility and the safety investigation headquarters of its existence.

Next, the air traffic manager designates the investigator-in-charge who is responsible for the investigative process (fact-findings, interviews, collection of voice recordings and pertinent data). He fills in Part I of the final OE report FAA form 7210-3 (FAA, 2000). Then, the air traffic manager analyzes the data provided and fills in Part II of the same report with causal factors and recommendations and corrective actions. Finally, the report is submitted to the Air Traffic Division (ATD) manager and headquarters. The ATD fills in Part III of the final report and ends the investigation process. All forms are periodically reviewed by the Office of Investigations to identify system deficiencies, to follow-up corrective action recommendations, and to evaluate the effectiveness of the program.

Analysis of Incident Reports

This study reviewed incident reports result from the FAA reporting and analysis process. We used OE reports because, first, incident reports reproduce faithfully the

operational safety conditions since they are based on real-life scenarios and, second, they provide a large number of data. Laboratory based research and simulations have more difficulty in reproducing states of impaired situation awareness (Brooker, 2004) or surprising events (Wickens, 2001) that may be needed to study erroneous behavior. However, incident reports and their interpretation might be affected by analysts' biases (Wood & Cook, 2002; Dekker, 2003). Dekker argued that the lack of a common human error definition poses difficulties to differentiate between causes versus consequences, making error classifications illusory means for managers' interventions. He argued that this procedure removes context that influence in the error manifestation, "error classification disembodies data" (p. 98). However, other authors supported the importance of analysis of incident and accident reports using classification taxonomies in helping to understand underlying processes of human error (cf. Pounds, 2003; Sarter and Alexandre, 2003; Shorrock and Kirwan, 2002; Wiegmann and Shappell, 2001, 1997; Reason, 1990; Rasmussen, 1983, 1987). In conclusion, we thought they were an excellent starting point to study human error behavior, keeping in mind the limitations of this methodology.

Summary

This chapter has provided the rationale for the study of OEs. The analysis was done in two phases reviewing OE reports generated after the investigation process defined by the FAA. First, preliminary OE reports were collected and analyzed to obtain an OE classification, and concurrent and contextual factors. Second, final OE reports were analyzed in order to assess the impact of TCAS RAs warnings in OE. In the last

years, the rate of OE (as measured by error rate per 100.000 facility operations) in the US has increased from 0.66% in 2002 to 0.79% in 2004. Additionally, recent accidents and incidents have raised the questions about the TCAS lack of integration into the ATM system and its impact in the pilot and controller behavior. The goals of the study was been reviewed.

The ATC and TCAS systems were described, emphasizing the demands imposed on the controller. ATC tasks are of highly cognitive nature and require high level of coordination among operators and pilots, based in voice communications. TCAS system alerts pilots of maneuvers to avoid imminent risk of collisions, with swift of separation of responsibility from controller to pilot, as soon as the pilot deviates from the clearance. The controller situation awareness might be impaired during that maneuver.

The following chapter introduces the human error frameworks and taxonomies more relevant for error analysis. It summarizes the applications of these taxonomies to various incidents and accidents databases, and introduces a discussion about the impact of downlinking TCAS RAs to present them to the controller.

LITERATURE REVIEW

A review of literature about human error theories and taxonomies was required to understand how errors are currently classified, what were the underlying cognitive mechanisms leading to degrade human performance, and the causal factors behind them. Extensive research has been done to develop a theoretical framework of human error and taxonomies (cf. Endsley 1999; Rasmussen, 1982, 1987; Reason, 1990, 1997; Sasou & Reason, 1999; Shappell & Wiegmann, 1995; Wickens 2000). Numerous techniques have incorporated these frameworks to analyze human error in various contexts. For example, the Human Factors Analysis and Classifications System (HFACS) has been used by the Federal Aviation Administration (FAA) to analyze the civil aviation accident and incident databases (Shappell & Wiegmann, 2003) and the model for Human Error Reduction in ATM (HERA) has been developed by Eurocontrol to increase efficiency of error identification in ATM (Eurocontrol, 2003b). Elements of both approaches were integrated in a harmonized approach, named JANUS, which is currently in its validation phase (Pounds & Ferrante, 2005; Pounds & Isaac, 2003). A review of available approaches applied to ATM has been done by Shorrock, Kirwan, and Smith (2005) concluding that although it appears to be working, “there may be the need to develop a more specialized error of commission approach for ATM” (p. 379). At present, there is no unique accepted human error taxonomy to study errors in incidents in the ATM system.

In addition, various research studies were examined where one or several of these taxonomies were applied to aviation accidents and incidents databases (Bliss, 2003;

O'Hare et al., 1994; Pape, Wiegmann, & Shappell, 2001; Sarter & Alexander, 2000).

Particularly relevant here were the studies applied to OE occurrence (Rodgers, Mogford, and Mogford, 1998). It was found that very little research has been done with the OE database to address the relationship among type of OE, contextual factors and proximity of aircraft involved in OEs.

Finally, studies of analysis of TCAS incidents were reviewed to help to identify major problems with the use of this system and its impact on controller performance and error (Bliss, 2003; Brooker, 2005; Eurocontrol, 2003a, 2004; Rantanen et al., 2004).

Human Error Frameworks and Taxonomies

Information Processing Model

The information-processing model describes humans by using the metaphor of a computer. As computers possess information in several stages, mental operations are modeled as processes that transform information. The model described by Wickens and Hollands (2000) is representative of this information processing theory in relation to a decision-making problem. This model was not explicitly developed to address human error, but it serves to classify it according to the stage where information is presumed to be erroneously processed. External stimuli are transformed by our senses into neural signal and briefly stored, without requiring attentional resources. These patterns are recognized and given meaning at the next stage of perception. Following, a decision about "how to act" should be taken and action is selected. Information may be stored in working memory for short period of time, and transferred to long-term memory for longer periods. Alternatively, information might be recalled during the perception and

decision making processes. During the last stage, the action is executed. The execution is sensed again closing a feedback loop, either directly or through its effects. An essential element of this model is the attention resources. The last three stages compete for those limited resources, which can delay or degrade the processes. The errors are classified as perception errors, decision and response-selection errors, response execution errors and attention errors. The model is sketched in Figure 3.

Wiegmann & Shappell (1997) applied this model to classify 298 aviation mishaps of the US Navy and Marine Corp between 1977 and 1992, and found that 86.9% of the cases fit in this classification of error.

Figure 3. Wickens' model of human information processing.

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

Skills, Rules, and Knowledge Model

This model is a pioneer in the human error literature. Initially described by Rasmussen and Jensen (1974, as cited in Rasmussen, 1982) using verbal protocols, the model considers three levels of performance: skill, rule, and knowledge based behavior. The different levels of control behavior or performance depend on the degree of expertise or familiarity with the task (Reason, 1990).

Rasmussen (1982) defined these three levels of performance as follows:

Skill-based behavior is “controlled by stored patterns of behavior in a time space domain.” It involves highly automated tasks, which require little or no conscious resources. “Errors are related to variability of force, space, or time coordination.”

Ruled-based behavior “includes performance in familiar situations controlled by stored rules for coordination of subroutines.” The distinction with skill-based is that it requires some conscious involvement, activating some stored rules when stimuli are perceived. “Errors are typically related to mechanism of wrong classification or recognition of situations, erroneous associations to tasks, or to memory slips in recall of procedures.”

Knowledge-based behavior is “goal oriented, called upon unfamiliar situations for which actions must be planned from an analysis and decisions based on knowledge of the functional, physical properties of the system and the priority of the various goals.” The conscious resources required are high if the accomplishment of the task is carried out through reasoning. “Errors in this domain can only be defined in relation to the goal of the task.”

A Generic Error Modeling System

Reason (1990) proposed this model based on Rasmussen's model. There are two major error actions, unintended and intended. Within the first group are the skill-based errors (slips and lapses). Both are "errors which result from some failure in the execution and/or storage of an action sequence, regardless of whether or not the plan which guide them was adequate to achieve the objective" (p. 9). The difference lies in that slips are observable actions executed not as planned, because of attention or monitoring failure, and lapses involve failures in memory, and might be covered. Skill-based errors are attributed to either inattention or over-attention. The second group encompasses mistakes and violations, though the latter are not properly errors but unsafe acts (Reason, 1990). Mistakes "are failures in the judgmental and/or inferential processes involved in the selection of an objective or in the specifications of the means to achieve it, irrespective of whether or not the actions directed by this decision-scheme run according to plan" (p. 9). Mistakes are divided into rule-based, associated with familiar situations where a bad rule is applied or an adequate rule is misapplied, and knowledge-based, associated with unfamiliar situations where a new rule is to be developed. The human biases that are fundamental characteristics of human behavior play a key role, leading towards the commission of knowledge errors.

Wiegmann & Shappell (1997) applied this model to classify 298 aviation mishaps and they were able to classify 91.3% of the cases.

Team Errors Model

Sasou and Reason (1999) defined taxonomy for team errors, considering team errors in the same form that was defined by Reason (1990): slips, lapses, and mistakes. They argue that only lapses and mistakes can be team errors, since slips are “errors in the action process of one individual.” The taxonomy contains the error-making process with four types: individual and shared, each one divided into independent, when all correct information is available, and dependent, where part of the information is inappropriate or absent. It incorporates the error-recovery process at three stages: detection of occurrence, indication to bring attention and correction.

Reason's Model of Latent Conditions

The production system of an organization consists of a group of elements that have to work harmoniously to safely operate. Some of those elements act over the defense layers creating windows of opportunity for accidents to happen. This model considers two kinds of human contributions to cause accidents: *active failures* and *latent failures or conditions* (Reason, 1990, 1997). Active failures are the unsafe acts committed at the “sharp end” of the system by operators of the system (e.g., controllers or pilots). Latent conditions are causes that go beyond the individual act. The spectrum is wide and it might include organizational conditions, poor design, or lack of supervision. Active failures usually manifest immediately, but latent conditions can lie dormant for long time (Reason, 1997). The importance of this model lies in the fact that it encourages one to analyze factors beyond the operators and to consider other levels of the

organization. Human error, understood as the unsafe acts, is intertwined with other causes of different contextual origins that can be seen as cause of the erroneous behavior.

Figure 4. Reason's latent failures model (also known as Swiss Cheese Model).

Note. Adapted from Reason, J. T. (1990). Human error Cambridge, England: Cambridge University Press.

A Model of Internal Human Malfunction

Rasmussen (1982) built a taxonomy for the inappropriate human performance analysis including human malfunction. The model is in line with the information-processing model and the information follows some processing stages. The stages are detection, diagnosis, goal setting, strategy selection (target state and task), procedure adoption, and execution.

O'Hare et al. (1994) applied this model to two sets of aviation accidents reports in New Zealand, finding that 71% and 70% were classified according to this model. In their study, Wiegmann and Shappell (1997) increased that percentage to 91.3%.

Error in Naturalistic Decision Making

Orasanu and Martin (1998) proposed a model of error in naturalistic contexts built on Rasmussen's Skill-Rule-Knowledge model. According to Orasan and Martin, naturalistic decision making "describes decision making by individuals with some level of expertise in real world context (e.g., aviation)" (p. 100). This model contains two components: situation assessment and course of action. Situation assessment involves the mental processes required to understand the problem and assess risks, and course of action selects the most appropriate action among those available. Situation assessment error might be a wrong picture, wrong risk assessment or time available misjudged. Course of action errors can be a rule-based decision, a choice decision, and creative decisions.

Error Taxonomy for Situation Awareness

Endsley (1995; 1999) proposed a taxonomy linked to her situation awareness model in complex and dynamic environments, such as ATC. Endsley, Bolte, and Jones (2003) defined situation awareness as "a person's perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (p. 13). The taxonomy considers errors at three levels:

Level 1 error or failure to correctly perceived information. This kind of error might be caused by problems related to unavailability of data, difficulty to perceive or detect data, failure to monitor or detect data (e.g., because of external distractions), misinterpretation of data (e.g., because of prior expectations), or memory failures.

Level 2 error or failure to comprehend the situation. This kind of error might be caused by the lack of a good mental model, the use of a wrong mental model, or over-reliance on default values and expectations.

Level 3 error or failure to project situation into the future. This kind of error might be caused by the use of an incorrect or poor mental model, or over projecting current trends. “Mental projection is a very demanding task at which people are generally poor” (Endsley, 1999).

She adds two other categories: failure to maintain multiple goals in memory, which may have impact on the three-level errors, and missing environmental cues because of automatic execution of habitual schemata.

Endsley (1995) applied this taxonomy to aviation accident reports over a period of four years, finding that 88% of the accidents that could be classified with a human error component fitted in the situation awareness taxonomy.

Human Factors Analysis and Classification System

Wiegmann and Shappell (1997; 2003; Shappell & Wiegmann, 2001) developed a taxonomy aimed specifically at the aviation domain, the Human Factors Analysis and Classification System (HFACS). HFACS incorporates Reason’s theoretical framework and other taxonomies related to internal operator conditions or organizational factors.

HFACS contains four levels of error categories or failures (Shappell & Wiergmann, 2001): unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences.

The unsafe acts are classified into errors and violations, as Reason (1990) proposed, but in this case, HFACS defines three distinct categories of errors: skill-based errors, decision errors, and perceptual errors. Skill-based errors occur “without significant conscious thought” and are caused by failures of attention or memory (Shappell & Wiergmann, 2001). Decision errors are committed when the application of a plan is inadequate or inappropriate. Perceptual errors are misjudgment caused by degradation of sensory inputs or misleading situations, as in visual illusions. The other category, violations, occurs when operators routinely or exceptionally disregards the rules.

The preconditions for unsafe acts try to account for unsafe acts, focusing on conditions of the operator and practices as causes. There are three subgroups. Conditions of the operator include mental and physiological states, and limitations of the individual in certain situations. Personal factors contain Crew Resource Management (CRM) and personal readiness. Finally, environmental factors contribute to the substandard conditions of the operator, divided in physical and technological environment.

Unsafe supervision accounts for those factors on the causal chain back up the supervisory activity that impact on the operator activity. Shappell and Wiergmann

(2001) identified four subcategories: inadequate supervision, planned inappropriate operations, failed to correct a known problem, and supervisory violations.

The last layer, organizational influences, accounts for management practices that might affect supervision, conditions, or actions of operators. Categories included are resource management, organizational climate, and organizational process (Shappell and Wiegmann, 1997; 2001, 2003).

Following studies that apply these taxonomies to various data sources are reviewed and summarized.

Studies of Incident and Accident Report Analysis in Aviation

Various studies have addressed the study of human error in aviation using incidents and accidents reports. Incident databases are a great source of information about errors but they have some limitations. For example, one of the most visited databases, the NASA Aviation Safety Reporting System, is a voluntary and anonymous reporting database submitted most often by pilots, in contrast to the National Transportation Safety Board (NTSB) database where pilots are obliged to report by the FAA. Therefore, reports submitted to that database are likely to be biased (Bliss, 2003; O'Hare et al., 1994; Sarter & Alexander, 2000). They might not represent the complete spectrum of errors of the operational environment because pilots are more likely to fail to report errors (Sarter & Alexander, 2000). In addition, there is no way of ensuring how many incidents involving TCAS occur and the analyst might introduce biases in the retrospective analysis (Rantanen et al., 2004). Sarter and Alexander (2000) categorized 245 incidents according to their phenotype and genotype. Altitude and heading deviation

accounted for more than 68% of the incidents. They argue about the effectiveness of combining several error classification schemes. In their study, they determined the frequency of omission and commission of pilot's errors, with a marginally difference between frequencies. In addition, they classified errors using the GEMS framework to characterize slips, lapses, and mistakes, and they identified the performance level and its relation to error detection mechanisms. The majority of errors occurred during skill-based behavior (75.8%), as a result of more opportunities for these kind of behavior in the cockpit, involving lapses (41.4 %) and mistakes (43.7%) mainly related to attentional and memory problems. Pape et al. (2001) obtained similar results for air traffic controllers. This might be the result of early discover of slips by the operator before the situation evolves to be worth to report it.

O'Hare et al. (1994), using the accident and incident database from New Zealand, applied information process model proposed by Rasmussen (1982), which identifies the internal mental function that felt in the decision making process (e.g., information, strategy, procedure, and so forth). The results showed that the error in selection of goals is the more frequent in fatal accidents (33%), followed by diagnosis errors (16%). Mean, procedural errors were more likely to occur in minor incidents (28%).

Pape et al. (2001) and Wiegmann and Shappell (2001) applied the HFCAS classification to the NTSB database focusing on incidents and accidents attributable, at least in part, to ATC and aircrew, respectively. In the former study, they found that the most common error was skill-based (90% of accidents and 70% of incidents) and a third of them were violations. Although very few reports mentioned organizational and

supervisory factors, Pape et al. (2001) argued that they are not identified by the existing investigative procedure but the latent errors are actually present, and the high number of violations supports that statement. In the latter study, Wiegman and Shappell reached similar conclusions for aircrew-related accidents. Approximately 60% were skill-based errors, followed by 29% of decision errors, 26.9% of violations, and 14.3 % of perceptual errors. Among preconditions, CRM failure was the most frequent (29%), and only a 16% of accidents involved supervisory or organizational issues.

An exploratory study was conducted by Rodgers et al. (1998) to examine the relationship between ATC complexity factors and OEs in ATC. They collected data from 85 OEs starting in 1992 through 1995 from Atlanta's Air Route Traffic Control Center (ARTCC). Most of OEs (81%) were attributed to problems interpreting the display information, 29% of situations were attributed to communication problems, and coordination issues accounted for 11%. Traffic density was 1.5 aircraft higher at the time the OE occurred than the base rate level. Four factors were found predictor of OE count: frequency of problematic weather, radio frequency congestion, total complexity, and average complexity. More error occurred in lower and smaller sectors.

Studies of Incidents Related to TCAS

Brooker (2005) studied the interaction between TCAS and Short Term Conflict Alert (STCA) using 76 incidents, with at least one commercial aircraft involved in the encounter, from United Kingdom Airport Board Reports database. STCA is a system that continuously monitors secondary surveillance radar data and alerts air traffic controller of potential conflicting situations around 90 to 120 before the CPA. The

warning does not involve mandatory action by controller (Brooker, 2005). In the US air traffic system the equivalent function is called Conflict Alert (CA). He found that controllers were not surprised by the TCAS events most of the times. The 77% of situations controller acted and was aware of the incoming conflict before the TCAS RA was triggered: either they detected the conflict themselves or STCA warned them to act. Among the rest of situations, the controller was aware 90% of the times. Sudden climbs and descends were the more likely situations where controller is not aware of the TCAS RA, because STCA would eventually not alert of that situation.

Bliss (2003) found that the big portion of false alarm problems, TCAS alerts included, occurred during peak times of pilot workload, such as during the approach phase. This might exacerbate pilots' alarm mistrust. However, this study did not allow identifying the false alarms corresponding to TCAS to extract conclusions about this system. In addition, it included incidents before 1997, when version of TCAS II software was not V7, which was the one of interest in the present document. In the same line, Rantanen et al. (2004) determined the proportions of hits, false alarms, and misses for the 1991-1994 periods plus the year 2002, and the pilots' attitude towards TCAS. The proportion of false alarms has decreased along the years with the introduction of better TCAS logic, reaching a 2.96% in 2002 with the latest version V7. They collected a set of qualitative observations, among them it is worth to mention that negative comments about false alerts decreased and they were fewer than the authors expectations. In addition, they concluded, "TCAS' operational use has strongly supported the need for a downlink between flight decks and ATC" (p.37). This was a proposed solution to

ameliorate performance of the TCAS system advocated by some authors and organizations, whose approach is described in the following section.

A Proposed Solution: Downlink TCAS RA

Several authors have argued the appropriateness of automatically downlinking TCAS RA information to the controller's display to improve the shared situation awareness between pilot and controller (Brooker, 2004; Eurocontrol, 2003a, 2004; Wickens et al., 1998). Brooker (2004) proposed a systematic analysis approach to assess the effects of downlink the RA based on the study of actual incident categories from a controller perspective. He suggested the use of a simple way of communicating the RA information, possibly using the conflict alert data block currently used. The controller should not take any action based on that information since this information only indicates what the pilot is seeing, not what the pilot is doing. It may help to the controller to assess the situation and to inform of potential problems if he or she issues any instructions during that brief period since the RA is triggered.

Eurocontrol (2003a) argued that one principle of ATC is keep controllers aware about the situation of traffic all the time in the sector, and prevent them to know TCAS RA in a timely manner departs from that principle, as it is the case with the current voice communication procedure. Downlink RA information would remove randomness about the receiving time and ambiguity in the pilot's voice message. RA is generated between 15 and 35 seconds before the CPA, and any delay in communicating it to the controller is crucial. According to Eurocontrol, depending on the technology used, RA could be displayed to the controller before a pilot's voice report is received. However, further

feasibility evaluation from a technical standpoint, and simulations for operational validity are required to evaluate its implementation.

The debate of downlink RAs has been re-opened recently after two events involving pilots following ATC instructions contrary to the TCAS RA indication. The first one was a near mid-air collision over Yaizu (Japan) on January 31, 2001. The second encounter was the accident over Uberlingen on July 1, 2002, unfortunately with more tragic consequences (Brooker, 2005). Nunes and Laursen (2004) argued that “the inability of TCAS to make the controller aware of what resolution advisories were issued to the pilot or account for the execution of alternative actions by the pilot represent major limitations of the system” (p.3).

Eurocontrol (2004) conducted a study where 30 air traffic controllers were exposed to downlinked RA displayed in three different manners. The experiment collected controller questionnaires about the effect of the downlinked RA on controllers’ situation awareness and other operational and legal issues. Controllers played an observer role and they did not perform active control over aircraft. The conditions emulated the case of supervising a trainee. Although subjective, this study obtained valuable findings. Most of the participating controllers found that downlink RA might be beneficial to obtain faster and more reliable information than the pilot’s voice message, preventing controller from issuing clearance opposite to the RA. However, they expressed concerns about the increase amount of information to be acquired by the controller. Responsibilities should be kept as the current situation, and responsibility for separation should be transfer as the pilot voice message is received, rather than at the RA

downlink reception. This means that the RA should be used only for informational purposes and would not require any action by the controller. The preferred display contained a visual alert with the RA and its sense, but controllers requested to provide them in a way that allowed them to distinguish from the STCA alerts, because the implications are different. Finally, they did not perceive a significant effect on their situation awareness, but Eurocontrol argued that the experimental design might be the reason. Controllers were able to identify the situation well in advance and the RA or the pilot's maneuver did not surprise them. This fact was acknowledged by other authors, who argue that simulations and trials of display do not necessarily reproduce risky and surprising situations, and generally controllers do not lose situation awareness during these kind of studies (Brooker, 2004; Wickens, 2001).

Summary

Literature concerning human error was reviewed, as well as several taxonomies form a theoretical standpoint to more applied vision to the aviation field. There was no one taxonomy that accounted for the myriad errors and causes under the denomination of human error. The reviewed taxonomies focus on understanding cognitive processes involved in the error, not merely on describing the visible type of error. Reason and Rasmussen theoretical works are the basis of other more elaborated and applied taxonomies.

Various studies applied these taxonomies to aviation data repositories, but very little was found applied to OE. TCAS related studies addressed the number of false alarms, misses, and non-compliance by the pilot. A study in UK found that 90%, air

traffic controllers were not surprised by the TCAS because they were aware of the developing situation or the conflict alert warned them. Initial simulations showed that TCAS RA downlink might be beneficial for the controller.

Studies Performed in this Thesis

This research was exploratory and attempted to map relationships in the data obtained with the review of reports. Exploratory has to be understood as an approach to generate and test hypothesis in view of the data, rather than testing a pre-existing hypothesis derived from a model (Rodgers et al., 1998). Visual representations and graphs were useful and effective tools. The findings, even statistically tested, should be considered as tentative pending of a larger-scale studies and more powerful tests, but the results are definitively a very useful starting point for future research. This thesis was done in two parts using OE reports from FAA database. First, a taxonomic study considering a broad number of OEs was performed. Second, considering the results of the initial study, a case study was performed with focus on reports that contained TCAS RA in the description. The following sections describe materials used, procedures applied, results obtained, and a brief discussion of each experiment. The data subsection details the type and number of reports; the procedure section portrays the methodology and details about the error classification; then the results are presented, and, finally, a discussion about the implications of findings.

STUDY ONE: TAXONOMIC ANALYSIS

Method

Data

The OE reports spanned the period from January 2004 to June 2004. In this study, brief narratives summarizing the preliminary OE investigation report, FAA form 7210-2 (FAA, 2000), were used. One example of these narratives and the result of the error taxonomy and contextual factors extracted are shown in Appendix A . A total number of 539 OE reports were collected, with 323 corresponding to the en-route airspace and 216 to the terminal radar airspace. From these reports, a final selection was made based on the following considerations. The OE reports classified as surface errors, in total 54 reports, and five incidents in the oceanic airspace were excluded because the nature of the tasks and the controller's decision support tools employed are different. A total of 480 OE reports resulted to be included in the final analysis.

Procedure

Two reviewers analyzed the reports. One reviewer evaluated the reports from the first three months, and the other reviewer did the next four remaining months. For each OE report, reviewers assigned one or more error type committed from the list in Appendix C and the contextual factors, listed in Appendix E , found in the description. In addition, the following variables were recorded in a data file: (a) operational error report code, (b) vertical and horizontal separation at the CPA, (c) day and time when error occurred, (d) shift duration, (e) presence of operational supervisor, (f) presence of D-side controller, (g) presence of developmental controller in the position, (h) number of

aircraft within the sector, (i) number of sectors controlled, and (j) monitor alert parameter. These variables helped to complete the table of concurrent factors and to calculate the proximity severity rating.

The reviewers agreed an operational error classification with 24 types of errors. Appendix C presents a definition of terms of this taxonomy, together with the applied criteria to classify a given error. Figure 5 and Figure 6 represent the flow-decision diagrams used in the analysis.

Figure 5. Flow decision diagram used to classify errors.

Figure 6. (Continuation) Flow decision diagram used to classify OE.

Hollnagel (1993) suggested distinguishing between categories for observation, or phenotype, and categories for interpretation, or genotype, when systematically studying errors, in order to explain the link between them in terms of erroneous actions. He argued that the distinction between what was an observation and what was an interpretation-improved reliability of judgments and validity of the analysis. The taxonomy used in this study tried to reflect the phenotype of the error, but it did not segregate completely the genotype. Since this analysis was an exploratory study, it seemed more meaningful to use a taxonomy that included some types of error result from introspection, in the same way as used by Sarter and Alexander (2000). In summary, the errors were classified according to the observable outcome and according to the explicit causes stated in the report, avoiding as much as possible reviewer's interpretations of the facts. For example, one element of the taxonomy is named "overlook traffic," which includes those errors where the controller overlooks one of the aircraft involved in the incident. Despite the fact that many reports could be interpreted as "overlook traffic", the actual error might have been a very different one (e.g., fail to project aircraft trajectories). Only if the report explicitly stated that the controller overlooked any aircraft, the OE report was classified within this category.

A classification of contextual or concurrent factors that might have played a contributory role in the incident was also recorded in the study. Those factors were of a very different nature, ranging from contextual factors, e.g., a recent combination of sectors, to genotype error forms, such as slips or misjudgment of the situation. We used a classification of 31 elements, which is included in Appendix E .

In order to ensure that the two reviewers applied the same criteria when coding the errors, an inter-reliability test was used: the Cohen's non-weighted Kappa coefficient. Kappa provides a measure of the degree to which raters concur in their sorting of a group of N elements in k groups. It was defined as the proportion of observed agreement among raters related to the proportion of agreement expected by chance. Ten reports from each reviewer's group were randomly selected and interchanged between the two reviewers. Each reviewer coded the OE reports originally assigned to the other rater according to the proposed taxonomy, and the resulting cross-tabulation was used to calculate the Kappa coefficient.

As a step forward, the error taxonomy and the contextual factors classification were related to the proximity distance of aircraft in the encounter. This proximity rating depended on the vertical and horizontal distance between aircraft at the CPA, and it was aiming at assessing the outcome of the error. It provided an objective mean to measure the severity of the consequences of the error. Additionally, some concurrent factors were selected for further assessment. These factors are as follows: (a) D-side controller absence, (b) developmental controller, and (c) time on position. The taxonomy classifications were applied to those reports that contained these factors and the errors were examined against the proximity severity index. The result of the analysis provided frequency tabulations for each element of the taxonomy and each concurrent factor.

Results

This section will present the results of the taxonomic study. It is structured in various subsections that address one relevant topic at a time: error taxonomy and error types, proximity rating, concurrence of multiple errors, contextual factors, effect of D-side controller absence, effect of developmental controllers, and, finally the effect of controller's time on position. The first step in the analysis was to evaluate the reliability of the taxonomy when applied by different raters.

Reviewers' Inter-reliability

The inter-rater reliability of the error coding was assessed by calculating Cohen's Kappa index on ten reports exchanged in a double blind between reviewers. The Kappa statistic was 0.83, which is considered a satisfactory level of agreement. This suggests that the reviewers were applying the same criteria for assigning reports with this classification.

Error Taxonomy and Error Type Frequency

There were 480 reports analyzed with 318 assigned to en-route facilities and 162 assigned to the Terminal Radar airspace. There were 24-classification elements (taxonomy) provided to associate to OEs. Because each specific OE report could have multiple error types associated, the total number of errors for the set of OE reports was 810. Of those, 560 were in the centers and 250 in Terminal Radar airspace. Table 1 presents these data. An examination of the table revealed that the proportion between error types per OE report was 1.69, ranging from only one error type element in some reports until a maximum of four errors in a single report.

Table 1

Numbers of errors and subsequent classifications

	OE reports	Error Classification
Terminal Radar	162 (33.96%)	250 (30.9 %)
En-route Center	318 (66.04%)	560 (69.1 %)
TOTAL	480	810

Table 2 presents percentages of OE reports associated to each error category from the taxonomy. In addition, Table 2 presents the percentages of each error type with reference to the total number of error identified. This information is provided for TRACON, ARTCC, and together. An examination of the table revealed that the top-12 errors accounted for the 87.5% of the errors identified ($n = 709$).

Table 2

Percentage of error type and percentage of OE reports associated to each error type, in ARTCC and reports in TRACON

		Total		ARTCC			TRACON		
Error Category		Percent	Percent		Percent	Percent		Percent	Percent
		Errors ^a	Reports ^b		Errors	Reports		Errors	Reports
Fail Converging	(112)	13.8	23.3	(84)	15.0	26.4	(28)	11.2	17.3
Control coordination	(76)	9.4	15.8	(44)	7.9	13.8	(32)	12.8	19.8
Descend through	(75)	9.3	15.6	(66)	11.8	20.8	(9)	3.6	5.6
Overlooked Traffic	(70)	8.6	14.6	(48)	8.6	15.1	(22)	8.8	13.6
Vector inadequate	(68)	8.4	14.2	(43)	7.7	13.5	(25)	10.0	15.4
Hearback/Readback	(65)	8.0	13.5	(41)	7.3	12.9	(24)	9.6	14.8
Altitude Inadequate	(56)	6.9	11.7	(49)	8.8	15.4	(7)	2.8	4.3
Fail Altitud Climb/Descend	(54)	6.7	11.3	(32)	5.7	10.1	(22)	8.8	13.6
Climb through	(46)	5.7	9.6	(36)	6.4	11.3	(10)	4.0	6.2
Fail Overtaking Traffic	(31)	3.8	6.5	(23)	4.1	7.2	(8)	3.2	4.9
Instruction no-intended	(30)	3.7	6.3	(17)	3.0	5.3	(13)	5.2	8.0
Temporal error-issue	(26)	3.2	5.4	(16)	2.9	5.0	(10)	4.0	6.2
Misapplication Procedure	(16)	2.0	3.3	(8)	1.4	2.5	(8)	3.2	4.9
Datablock miss enter info	(15)	1.9	3.1	(13)	2.3	4.1	(2)	0.8	1.2
Airspace	(15)	1.9	3.1	(3)	0.5	0.9	(12)	4.8	7.4
Transpose a/c	(11)	1.4	2.3	(7)	1.3	2.2	(4)	1.6	2.5
Others	(11)	1.4	2.3	(6)	1.1	1.9	(5)	2.0	3.1
FPS miss enter	(10)	1.2	2.1	(9)	1.6	2.8	(1)	0.4	0.6
Speed inadequate	(6)	0.7	1.3	(5)	0.9	1.6	(1)	0.4	0.6
Wrong a/c	(5)	0.6	1.0	(1)	0.2	0.3	(4)	1.6	2.5
a/c overlap	(4)	0.5	0.8	(3)	0.5	0.9	(1)	0.4	0.6
Misread info	(3)	0.4	0.6	(3)	0.5	0.9	(0)	0.0	0.0
LOA misapplication	(3)	0.4	0.6	(2)	0.4	0.6	(1)	0.4	0.6
Cleared below minimum	(2)	0.2	0.4	(1)	0.2	0.3	(1)	0.4	0.6

Note. Numbers in table are percentages. Numbers in parentheses indicate error frequencies. Because more than one error is identified in each OE report, the percentages in the column percent error will not equal 100%.

^a Percentages of error category with base on the total number of error identified in ARTCC, TRACON, or both.

^b Percentages of reports that involved at least that error type (with a total of 480 OE reports).

Among the error categories, the most frequent error, *fail to notice converging aircraft*, accounted for 13.8% ($n = 112$). A relatively larger percentage of OE reports in ARTCC involved *fail converging* error (26.4%) than did TRACON OEs (17.3%). This might be influenced by the fact that the heading was not always specified in the report when the OE occurred in a TRACON. *Control coordination* was the second more frequent error in 9.4% ($n = 76$) of the cases. The relative proportion of OE reports with control coordination errors in TRACON (19.8%) was higher than in ARTCC (13.8%). *Descend through* accounted for the 9.3 % ($n = 75$), and here it was the relative proportion of OE reports in ARTCC (20.8 %) larger than in TRACON (5.6 %). The *overlook traffic* error accounted for 8.6 % ($n = 70$), and this percentage was relatively similar in centers and terminal areas. Giving an *inadequate vector* was found in 8.4% ($n = 68$), and again, no appreciable difference was evident when comparing the relative percentages across canters (13.5%) and terminal areas (15.4%). The next largest error was *hearback/readback*, which was equally associated to centers (12.9 %) and terminal areas (14.8 %), accounted for the 8.0% ($n = 65$). Error coded as *altitude inadequate* was founded 6.9 % ($n = 56$), and in this case the relative proportion in ARTCC (15.4 %) was larger than in TRACON (4.3 %). Finally, the last error was *fail identification altitude climbing/descending* that accounted for 6.7 % ($n = 46$) of the total errors. This was approximately equal across centers (10.1 %) and terminal areas (13.6 %).

Multiple Error Types Joint Occurrence in OE Reports.

For a proportion of the OE reports, we found that more than one error classification was necessary. This implies that more than one error was present in the

report, being possible that some error sequences could be identified. Figure 7 shows the distribution of OE reports containing more than one error type: 50 % of reports were classified with one error of the taxonomy, 36.5 % of reports were classified with two errors, 11.9 % contain three errors, and a minor number of reports had four or five errors (1.6 %). It is note worthy to remember that the reports used in this study were preliminary and often the description was too succinct as to identify more than one error per report.

Figure 7. Percent of reports containing various error types identified per incident report.

Keeping in mind the possibility of having various errors types linked, and in order to look further into the nature of these linkages, a table that plots the number of co-occurrence of two error types in the same OE report was elaborated (Figure 8). The numbers in the blocks indicate the frequency with which two errors occurred. These data suggest that some errors are related to one another, otherwise, the table would present a

more distributed joint occurrences. Further analysis needs to be done in this direction, using possibly multivariate analysis.

	a/c overlap	Airspace	Altitude Inadequ	Cleared b/w min	Climb through	Control coord	Datablock-misenter	Descend through	Fail Alt Climb/Descend	Fail Converging	Fail Overtaking-Trf	FPS-misenter	Hear/Readback	Instruc no-intended	LOA mis	Misappl Proced	Misread info	Overlooked Trf	Speed inadequ	Temp error-issue	Transpose a/c	Vector inadequ	Wrong a/c
a/c overlap			1					2		1			1					2					
Airspace			1	2									4	3		1					1		
Altitude Inadequ	1	1					2			2	1					1	6				2	3	
Cleared b/w min		2																					
Climb through						4	3	2			1		4	6				6		1	3	5	
Control coord					4		2	6		6	2		3	1	1	4		6	1	1		3	
Datablock-misenter			2		3	2		2	1	6			1					1			1		
Descend through	2				2	6	2				3	2		3						2	2		
Fail Alt Climb/Descend							1				1		3	1		2				3			
Fail Converging	1					6	6					3				2	1				1	6	
Fail Overtaking-Trf			2		1	2		3	1				2					1	1	1			
FPS-misenter			1					2		3													
Hear/Readback	1	4			4	3	1		3		2						2			6	1	2	
Instruc no-intended		3			5	1		3	1								1			2	2		
LOA mis						1																	
Misappl Proced		1				4			2	2									1		1		
Misread info			1							1			2	1						1			
Overlooked Trf	2		6		6	6	1				1											3	
Speed inadequ						1					1					1							
Temp error-issue					1	1		2	3		1		6	2			1					1	
Transpose a/c		1	2		3		1	2		1			1	2		1							
Vector inadequ			3		5	3							2					3		1			
Wrong a/c																							

Figure 8. Frequency of reports that have joint occurrence of pair of errors.

Proximity Rating

In addition to the counts of errors, a measure of aircraft proximity was calculated for all operational errors. This proximity rating is based exclusively on distance. The criteria to assign a proximity rating was proposed for the Volpe Center and can be seen in Figure 9.

		Horizontal CPA (nm)					
		0	0.5	1	2	2.5	>2.5
Vertical (ft)	250				B	C	C
	500			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

Figure 9. Criteria applied to characterized proximity according to vertical and horizontal distance. Proximity ratings for intermediate values are result of interpolation between them.

Descriptive information regarding the proximity of each OE is provided in Table

3. There was high variability in vertical separation ($M = 626$ ft, $SD = 476$ ft), and in horizontal separation ($M = 2.74$ nmi, $SD = 1.29$ nmi).

Table 3

Descriptive statistics of distance between aircraft in OE reports by proximity category

Separation	Total OE		A		B		C	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Horizontal	2.74	1.29	0.81	0.42	1.47	0.55	3.44	0.83
Vertical	626	476	243	214	565	308	713	510

The distribution of proximity rating across OE reports is presented in Table 4, and illustrated in Figure 10. Figure 11 and Figure 12 depict OEs in ARTCC and TRACON, respectively. A chi-square test of goodness-of-fit for the distribution of categories A, B, and C with the total number of reports showed that these categories differ significantly across all OE reports, $\chi^2 (2, N = 460) = 260, p < 0.001$. In addition, there were higher-proximity events in the Terminal Airspace than in the centers, as indicated in Table 4. A chi-square test of independence revealed that this difference is significant, $\chi^2 (2, N = 460) = 226, p < 0.001$. It is worth to note that 75.8% of errors identified in OE reports in TRACONs were classified as category A and B, and only the 11.6% of errors identified in ARTCCs were under those categories. This might be because of the minimum separation standard applicable in the terminal airspace were 3 nmi and 1000 feet, but in the centers this separation might increase to 5 nmi and 2000 feet.

Table 4

Frequencies and percentages of proximity categories in Centers and Terminal facilities

Category	Total		ARTCC		TRACON	
		Percent ^a		Percent		Percent
Proximity A	(58)	12.1	(7)	2.1	(51)	33.3
Proximity B	(86)	17.9	(31)	9.5	(65)	42.5
Proximity C	(316)	65.7	(285)	86.9	(21)	13.7
No Rated	(21)	4.4	(5)	1.5	(16)	10.5

Note. Numbers in table are percentages. Numbers in parentheses indicate error frequencies.

^a Percentages of OE reports, whose aircraft proximity is rated under category A, B, and C.

Figure 10. Severity of operational errors associated with both TRACON and ARTCC.

Figure 11. Severity of operational errors associated with ARTCC.

Figure 12. Severity of operational errors associated with TRACON.

The proximity rating analysis can be applied to the error type. Analyses of operational errors with respect to severity of incident (as measured by proximity) were undertaken. Figure 13 provides an overview of the percentages of proximity ratings across operational errors, which were sorted by frequency with the errors more frequent at the top of the list, and the less frequent at the bottom. Among them, *letter of agreement (LOA) misapplication* error had the highest percentage of closer proximity events (33.3%), followed by *a/c overlap* error with 25%, *misapplication of procedure* with 25%, and *instruction on-intended* error with 20%. However, those errors were among the less frequent with frequencies of 3, 4, 16, and 30, respectively.

Figure 13. Percentage distribution of the error types linked to their consequent proximity.

Concurrent and Contextual Factors

These factors described the context surrounding the error and might have influenced the controller's performance. Only factors that might have reasonably affected the controller's performance were identified. It was reasonable to assume that these factors were important to explain the error, although they might not have a direct causal relation with the error.

Table 5 presents the percentages of each factor identified with reference to the total number of factors identified in TRACON, ARTCC, and both together. In addition, it presents percents of OE reports that contain each particular factor (Figure 14 illustrate this percentage graphically). An examination of the table revealed that the two larger factors identified were associated with staffing. D-side controller was absent in 26.9 % ($n = 129$) of the times, and the Operational Supervisor (OS) was absent (or replaced by a CIC) 18.3% ($n = 88$). However, these numbers did not provide insights of a potential problem since the baseline of operations with and without D-side and OS were unknown. We cannot conclude that the absence of D-side or OS were relevant factors that increased the likelihood of having an OE. Further analysis was provided in the following section.

It is worth to highlight that the factor *mishearing* messages between pilots and controllers were found in 13.2 % of reports ($n = 63$), revealing that voice communications were still an important source of errors. Another important factor was *misjudgment*. It was found in 12.7 % of OEs ($n = 71$). This can be interpreted as a natural consequence of the cognitive nature of the air traffic controller's task.

Table 5

Percentage of contextual factors and percentage of OE reports associated to each factor, in ARTCC and TRACON

Contextual factor	Total			ARTCC			TRACON		
	(Factors ^a)	Percent	Percent	(Errors)	Percent	Percent	(Errors)	Percent	Percent
		Factors ^a	Reports ^b		Errors	Reports		Errors	Reports
No pilot response/deviation	(36)	4.2	7.5	(26)	4.2	5.4	(10)	4.1	2.1
Climb-Descend slow/fast	(17)	2.0	3.5	(14)	2.3	2.9	(3)	1.2	0.6
Turn wide/sharp/early	(5)	0.6	1.0	(2)	0.3	0.4	(3)	1.2	0.6
TCAS RA	(1)	0.1	0.2	(1)	0.2	0.2	(0)	0.0	0.0
D-side Absent	(129)	15.1	26.9	(129)	21.0	26.9	(0)	0.0	0.0
Supervisor Absent/ CIC	(88)	10.3	18.3	(43)	7.0	9.0	(45)	18.6	9.4
Combined Sectors	(77)	9.0	16.0	(50)	8.2	10.4	(27)	11.2	5.6
Mishearing	(63)	7.4	13.1	(40)	6.5	8.3	(23)	9.5	4.8
Misjudgment	(61)	7.1	12.7	(43)	7.0	9.0	(18)	7.4	3.8
Traffic complexity	(49)	5.7	10.2	(49)	8.0	10.2	(0)	0.0	0.0
Developmental controller	(38)	4.4	7.9	(13)	2.1	2.7	(25)	10.3	5.2
Distraction	(27)	3.2	5.6	(19)	3.1	4.0	(8)	3.3	1.7
Weather complexity	(22)	2.6	4.6	(19)	3.1	4.0	(3)	1.2	0.6
Pilot/Controller request	(19)	2.2	4.0	(13)	2.1	2.7	(6)	2.5	1.3
Lapse in coordination	(17)	2.0	3.5	(10)	1.6	2.1	(7)	2.9	1.5
Other complexity	(15)	1.8	3.1	(13)	2.1	2.7	(2)	0.8	0.4
Point Out Complexity	(11)	1.3	2.3	(9)	1.5	1.9	(2)	0.8	0.4
Temporal airspace Complex	(10)	1.2	2.1	(7)	1.1	1.5	(3)	1.2	0.6
Slip in clearance	(9)	1.1	1.9	(5)	0.8	1.0	(4)	1.7	0.8
D-side coordination	(8)	0.9	1.7	(7)	1.1	1.5	(1)	0.4	0.2
Recent Comb/Decomb	(8)	0.9	1.7	(6)	1.0	1.3	(2)	0.8	0.4
Turbulence Complexity	(5)	0.6	1.0	(4)	0.7	0.8	(1)	0.4	0.2
Multi-aircraft	(5)	0.6	1.0	(5)	0.8	1.0	(0)	0.0	0.0
Lapse Delivery Clearance	(5)	0.6	1.0	(2)	0.3	0.4	(3)	1.2	0.6
Misread info	(5)	0.6	1.0	(4)	0.7	0.8	(1)	0.4	0.2
Inadequate Debriefing	(4)	0.5	0.8	(3)	0.5	0.6	(1)	0.4	0.2
FPL not checked	(4)	0.5	0.8	(3)	0.5	0.6	(1)	0.4	0.2
Stuck mike	(3)	0.4	0.6	(2)	0.3	0.4	(1)	0.4	0.2

Table 5 (continued)

		Total		ARTCC		TRACON			
Contextual factor		Percent	Percent						
		Factors ^a	Reports ^b	Errors	Reports	Errors	Reports		
Transmission stepped on	(3)	0.4	0.6	(2)	0.3	0.4	(1)	0.4	0.2
Other	(42)	4.9	8.8	(31)	5.1	6.5	(11)	4.5	2.3
Not enough info	(69)	8.1	14.4	(39)	6.4	8.1	(30)	12.4	6.3

Note. Numbers in table are percentages. Numbers in parentheses indicate frequencies. Because more than one factor is identified in each OE report, the percentages in the column “percent factors” will not equal 100%.

^a Percentages of factor category with base on the total number of factors identified in ARTCC, TRACON, or both.

^b Percentages of reports that contained at least that factor (with a total of 480 OE reports).

The controller was working various sector combined in 16 % of the cases ($n = 77$). *Traffic complexity* and *D-side absence* were identified only in en-route airspace, but for different reasons. In terminal airspace, the team structure is different as the structure in centers, and the D-side role does not exist. However, the lack of information in the preliminary reports was the reason not to have traffic complexity information in terminal airspace.

We found that a developmental was working the sector in 7.9 % ($n = 38$) of OEs, either receiving on the job training (in that case the OE is assigned to the instructor) or working a sector where he or she is already certified.

Distraction was present in 5.6 % of situations ($n = 27$), and weather complexity in 4.6 % ($n = 22$). Finally, we found that 14.4 % ($n = 69$) of the reports did not provide enough information to be able to identify a relevant contextual factor that had an important effect on the controller behavior.

Figure 14 illustrates graphically the distribution in percent of contextual factors in the OE reports reviewed. They correspond to the column *Percent Reports* of Table 5.

The following sections provide further insight into the effects of three contextual factors with respect to the generation of OEs and their proximity outcome: D-side presence, developmental and controller's time on position.

Figure 14. Percentage of contextual and concurrent factors identified in the OE reports, with base on the total number of OE reports.

Absence of D-side Controller

The most frequent contextual factor was the absence of a radar associate controller working in the sector. Figure 15 shows that in 40.7 % ($n = 129$) of errors, the D-side controller was not present. Note that this analysis considers only ARTCC data, where we had formal D-side and R-side positions. However, it was difficult to conclude if working without the support of a D-side controller had an effect on the errors, because we were not aware of the base rate of operations without D-side in the center.

Figure 15. Staffing of sector when the OE occurred

If we considered the proximity of errors having a D-side present or absent, we could gain more insights about the effect of working without D-side in the center. Figure 16 and Figure 17 illustrate the severity (as rated by our proximity index) of errors when the D-side was present and absent, respectively.

Figure 16. Frequency of errors by proximity in centers when D-side was present.

Figure 17. Frequency of errors by proximity in centers when D-side was absent.

These data suggest that working without D-side controller increased the chances of having a closer encounter. If we used OE reports instead of error types, the contingency table would be made up of observations independent of each other and we would be able to use a chi-square test. However, the application of this test did not provide reliable results because two cells of the expected frequency values count less than five. Nevertheless, the data in Table 6 suggested that the severity of the error was likely to be higher in both severity A and B when a D-Side was absent.

Table 6

OE reports associated with each level of proximity and the presence or absence of a D-Side controller.

	D-side present		D-side absent	
Proximity A	3	(1.6 %)	4	(3.1 %)
Proximity B	6	(3.3 %)	15	(11.7 %)
Proximity C	175	(95.1 %)	109	(82.2%)

^a Situations where a tracker was also present are included as “D-side present”. There are 5 OE reports that were not included, either because the proximity or the D-side presence were unknown.

Effect of Developmental Controller

An analysis of the proximity of the OE reports with respect to the presence of a developmental controller working the sector indicated that in the highest proximity ratings the developmental controllers had twice the rate of errors compared to CPCs (Figure 18). A Chi-square test of independence did not support statistical significance

at the 95 % degree of confidence ($\chi^2 (2, N = 459) = 5.775; p = 0.057$), although the test was very close to support it. It is recommended to increase the sample set to be able to confirm if that difference is due to chance or there is a statistically significant difference.

Figure 18. Percentage of OE reports, sorted by proximity rating for CPC and developmental controllers.

Time on Position and its Relation to Generation of OEs

In an attempt to examine the hypothesis about trends in time-on-position with respect to the generation of operational errors, the aggregated frequency of OEs in five-minute intervals was analyzed. It must be noted that there was not a standard of the controller's time on position, being this dependant on the traffic and time of the day. Since the standard controller shift duration was not uniform and could range from one hour until various hours, therefore we considered the analysis of the OEs committed only

during the first hour. Figure 19 illustrates the distribution of OEs relative to the controller's time on position, accumulated in five-minute intervals. Time was not provided in seven reports, and they were not used in the analysis.

Figure 19. Distribution of OEs as a function of the controller time on position.

Approximately 8% of the OEs occurred within the first 5 min, 15 % within the first ten minutes, 23 % within the first 15 minutes, and 29 % within the first 20 minutes on position. A chi-square goodness-of-fit test did not provided statistically significance in the distribution of frequencies ($\chi^2 (11, N = 388) = 6.575, p = 0.832$), therefore we could not reject the null hypothesis (no effect of time on position in generation of OEs).

We analyzed the possible effect of controller's time on position on proximity rating. A chi-square goodness-of-fit test was performed to a contingency table with

proximity ratings and aggregated errors in 10-minute segments. The test did not provide statistically significance ($\chi^2(10, N = 373) = 7.27, p = 0.700$), and we could not claim that the absence of D-side controller had an effect increasing the proximity of the OE, contrary to what was claimed by Pounds and Ferrante (2005). Figure 20 illustrates the severity of OE grouped in 5-minute intervals.

Figure 20. Proximity of errors as a function of controller time on position in 5-minutes segments.

Discussion

This section covers the discussion of the results of the taxonomic study. First, we will comment on the general results of the application of the error taxonomy. Second, we will discuss the effect of error types on the proximity rating. To sum it up, we will comment on the contextual factors identified, focusing in particular on the effect of three of them: D-side absence, developmental, and controller's time on position.

Error Taxonomy and Error Type Frequency

The results of the application of this error taxonomy suggested that the error types might account for the OEs identified by FAA, even when the preliminary investigation form was used. The top-12 errors types might account for 87.5 % of errors classified. This data might be used to narrow areas for future in-depth analyses and research, and where to target budget for mitigating interventions in design, training, or skill building. Even though some error categories may be so general as to be not useful, such as the more frequent *fail to identify converging aircraft* error, a more detailed analysis as to what the proximity of aircraft or the contextual factors are is provided in the following sections. In addition, these error categories should be broken down into further error types (e.g., converging opposite courses, converging crossing courses with acute angle, etc) but the description of the incident would need to provide enough information as to discriminate them, which was not the case at the time the reports were collected. The results suggested that often more than one error was present in each report and this could help us to understand better some of these very general errors.

The error distribution was different in centers and in terminal airspace. This was result of having different standard separations, procedures, traffic patterns, and airspace structures. Therefore, interventions would need to have this into account and would have to be planned and applied differently in both types of airspace.

The results indicated that large amounts of errors were strongly linked to teamwork related issues (control coordination and hearback/readback). This was identified and studied historically as an important source of OEs (cf. Cardosi & DiFiore, 2004; Cardosi, Falzarano, & Han, 1999; Pounds & Ferrante, 2005). Another group of errors was related to the failure to identify aircraft converging and/or climbing/descending, which might be linked to perception and vigilance deficiencies, but they might be linked to failure in the projection of future aircraft position. Rodgers, Mogford, and Strauch (2000) reported 19.6% and 17.8% of failures in detection displayed data in OEs in enroute and TRACON operations, respectively. However, Pape et al. (2001) found only a 1.1% of perceptual errors in their study about ATC errors. Further decomposition of those errors could help to increase their diagnostic power of the taxonomy.

Overlook traffic seemed to be linked with memory failures, but it might be related to perceptual breakdowns. Finally, instructions non-intended were another important error type, strongly linked to slips errors (skill-based).

In conclusion, the top twelve types of the taxonomy accounted for most of the errors, which could prioritize areas of interventions. These error types were related among them. Additional decomposition would be of help to understand how to mitigate

them. Additionally, other criteria need to be considered in this process, such as the proximity of aircraft associated to each error and the contextual factors. The following section will present the results of proximity rating.

Proximity Rating and Error Type

Currently, the FAA categorizes the severity of OEs with a severity index, which ranges from 1 to 100, and group them into three categories of severity: low, moderate, and high (Bailey, Schroeder, & Pounds 2005; Cardosi, Hannon, & Sheridan, 2005; FAA, 2002). This index combines the severity of the outcome (i.e., vertical and horizontal separation, closure rate and flight paths) and the subjective judgment of the quality of the ATC service (i.e., controller aware of the error). Cardosi et al. (2005) suggested separating the severity of the outcome with any quality attributable to controllers. Here the severity of the outcome was estimated with the proximity between aircraft, i.e., the relative distance of aircraft from each other in horizontal and vertical planes at the CPA. This proximity rating was based exclusively on distance. The proximity can be used to discriminate the outcome of a particular error, and prioritize and allocate resources to mitigate them. Nevertheless, the differences among errors were not very high, at least among the top-ten.

There were significantly higher-proximity events in the terminal airspace than in the centers. Although this might be expected because the standard separation was smaller in terminal airspace than centers, and in terminal aircraft converge to airport, the difference was surprisingly high.

It is noting worth that some OEs with low overall frequency were significantly more likely to result in more severe error. This might be the result of having a sample size too small, but it might be the case that because they were infrequent, the controller reduced the number of crosschecks to detect those (Wickens & Hollands, 2001). Thus, when these errors occurred they proceeded unchecked for longer time and their output, in terms of proximity, was more severe. These infrequent, but high consequence operational errors may need to be studied to determine how controller awareness of them (and their surrounding conditions) can be heightened.

Concurrent and Contextual Factors

In the OE reports, there were factors that were mentioned in describing the context of the error. It was reasonable to assume that these factors might have influence in some way over the controller's performance. Other taxonomies have tried to collect these factors as important part of the error investigation (e.g., Eurocontrol, 2003b, Wiegmann & Shappel, 2003). These factors might help to identify latent factors (Reason, 1990; 1997), such as supervisory and organizational issues. However, as Pape et al. (2001) argued, these supervisory and organizational factors "are rarely identified using existing accident investigation processes." The contextual factors identified here have to be considered as an attempt to identify those factors, together with others of different nature (e.g., distraction, weather complexity, operations with pointed out aircraft). Several of these factors were a reinterpretation of some errors types identifies previously, such as mishearing, adding little to the explanation of the error. However, it is noting worth that some other factors added complexity to the actual controller's tasks, such as

dealing with pointed out aircraft or bad weather. We could not claim that there was a causal relation among those factors and the error, but it might be the case that either the procedures or the interface did not support adequately the controller's operations. Further in-depth investigation should be done with individual factors.

We tried to study with more detail three of these factors, which were related to organizational and staffing issues. Next sections will present a commentary on the findings about the presence of the D-side controller, the controller's expertise, as considered by a developmental in charge of the sector, and the time on position.

Absence of D-side Controller

The single most frequent contextual factor (26.9%, $n = 129$) was the absence of a radar associate or D-side controller in the center (this analysis considered only ARTCC data, where we had formal D-side and R-side positions). It replicated the results of the study of Stager and Hameluck (1990) carried out in Canada. They found that one-fourth of incident among a sample of 142 occurred at combined D-side and R-side positions. We were unaware of what the standard rate of operations was without a D-side in the center. The D-side team member assists the R-side when traffic reaches certain levels within the sector. This teamwork structure provides a distribution of tasks and redundancy to maintain situation awareness (Wickens, Mavor, & MacGee, 1997), becoming an important element for catching errors committed by the R-side controller.

We could not find statistical support for the effect of working with and without D-side over the severity ratings of OEs. However, even if this were the case (for example increasing the sample size), the analysis of these differences would need to compare the

absent/present error rates to the fraction of the time the controller's are in those configurations, which are not currently known.

A supervisor combines D-side and R-side roles when the traffic load is low, in order to use more effectively the scarce human resources, and to combat boredom. Stager and Hameluck (1990) suggested that changing a team task into an individual one may be responsible of a reduction in situation awareness, and we could argue that it may be responsible of losing redundancy in some tasks, reducing the chances to identify R-side errors. A current solution under investigation to use effectively resources without the need of two-controller teams, but keeping some short of redundancy, is through a new role, multisector planner, who could assist to several R-sides at a time (Corker et al., 2006; Herr, Teichmann, Poppe, & Suarez, 2005). However, the initial results of this research did not seem to provide support of a safety improvement in this direction.

In summary, the D-side controller absence data suggested that there was a negative effect over the proximity of the error. The base rate of operations with both positions, R-side and D-side, would be needed in order to complete a meaningful study. Alternative working arrange, such as introduction of a multisector planner, might help to use effectively human resources without paying a safety penalty, but additional research needs to be done to prove viability and effectiveness of this solution.

Developmental Operators

Developmental operators are novice controllers. This is how new trainees are called upon their arrival to a facility to further refine their skills during a training program. They learn to control traffic with field training in various sectors. They receive

on-the job training (OJT) to develop his/her skills under the supervision of an instructor. A developmental becomes a CPC in an area (group of sectors) upon receiving the field training in each sector of that area, but they can control traffic in those sectors where they are certified before reaching the CPC status in the area. Therefore, looking at the developmental controllers was similar to analyzing the effect of expertise in air traffic controllers.

Extensive research has demonstrated that experts have superior mental models that allow them to anticipate the future, a broader area of attention protecting them from cognitive tunneling, and better ability to coordinate with others, among others characteristics (Wickens & Hollands, 2001). Based on experiments with chess players and within the framework of naturalistic decision-making under time pressure, Klein (1998) concluded that experts generate solutions with greater quality and do not waste effort and attention comparing options. Experts notice patterns and anomalies, such as the absence of a key event that novices do not see, and run more easily and accurately mental simulations of a future system state. All these characteristics support the hypothesis that novice would make more errors and more severe. On the one hand, we did find that 7.9 % ($n = 38$) of the OEs involved a developmental, but we did not have the base rate of their operations to be able to achieve a conclusion about the expertise effect on the likelihood of OEs. On the other hand, the proportion of higher-proximity incidents was higher with developmental rather than with CPC, although the difference was not statistically significant. Additional data need to be analyzed with developmental controllers to determine if the effects actually exist.

Controller's Time on Position

Previous research (e.g., Pouds & Ferrante, 2003) claimed that OEs occur frequently during the first 20 minutes after the controller taking over a position. This links the tendency of making OEs with position relief briefings issues, which take place when one controller assumed responsibility for controlling a position from another controller. Our results did not support this claim. Conversely, Figure 19 and Figure 20 suggest that there was no trend on the occurrence of OE and the controller's time on position. In addition, the deficient debriefing was identified as a factor only in 0.8% of OEs ($n = 4$). This led us to believe that the position relief briefings are performed, in general terms, adequately.

However, the artifact used only the first 60 minutes to statistically test the likelihood of OEs soon after relief, needs to be validated with baseline information about how long controllers actually work a sector or position. Moreover, additional data needs to be gathered to track the tendency, or to demonstrate the claims of other research about the high tendency of OEs to occur with the controller early on position.

STUDY TWO: CASE STUDY OF TCAS RA

Method

Data

The OE reports spanned 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. For 2004 data, the same report forms used in the taxonomic study were reviewed (26 reports); for 2005 data, the final OE investigation reports (78 reports), FAA form 7210-3 (FAA, 2000), were reviewed. The total number of reports was 104. It is worth to note that on January 20, 2005 Reduce Vertical Separation Minima (RVSM) was implemented in the NAS.

Procedure

The results of the taxonomic study showed a probable causal effect of TCAS RA over the controller's OEs. We conducted a case study focused on the effects of TCAS RA. Contrary to the taxonomic study, where we used preliminary reports, the final investigation reports of the year 2005 were more comprehensive regarding the information provided. Two different fields were used to identify the TCAS RA events and to select the OE report to be included in the study: a) the description of the event within the summary, and b) the specific indication of TCAS RA presence in the incident by the investigator (block 56 of the form). One single reviewer analyzed the final OE reports. The same procedure and classification as in the taxonomic study were applied. A second methodology, named JANUS, was proposed, and initially employed, but we found it difficult to apply to these report descriptions because it left the analyst with too

much subjectivity in the interpretation of the taxonomy. A brief description of the methodology together with an example, the problems found to apply the methodology, and the gathered data are presented in Appendix F and Appendix G , respectively.

In addition, we were interested in gaining insight into the actual TCAS RA's chain of events and its effect on controller behavior. Brooker (2004) 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 whether or not the controller was aware of an imminent TCAS RA on board. The second parameter to investigate was whether or not the controller issued some 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 information report provided by the pilot was analyzed in terms of completeness and timing of the voice messages. Unfortunately, the analysis of reports did not allow us to identify the initial question: was the controller aware of the impending TCAS? This would have introduced high subjectivity and speculation in the interpretation of the majority of incidents. Therefore, the scheme was modified to reduce subjectivity, linking the quality of the pilot's message with the subsequent controller behavior during the incident.

The scheme finally used is represented in Figure 21. The difference consisted in eliminating the controller's awareness of TCAS advisory and adding what parameter was changed by the controller (i.e., altitude or heading), if he acted to solve the conflict.

Moreover, the direction of altitude change was compared, if any, with the direction given by TCAS RA. This constituted the base argument to assess the effectiveness of downlinking TCAS information to the controller's workstation.

Figure 21. Scheme pilot's message – controller's action during TCAS RA

Note. The figure illustrates only the "Complete" branch. "Incomplete" and "No reports" have the same repeated structure.

The quality of information 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). Most of OE reports did not contain a detailed description of events after the conflict was cleared, but we considered them as complete information even though the second message was not indicated in the report.

In summary, the parameters extracted from the reports were: a) the quality of the information report provided by the pilot, b) whether or not the controller issued some instruction to avoid the conflict, c) if that instruction was given before or after the TCAS RA was triggered on board, d) if the clearance aiming to change altitude or heading, and e) if the altitude change was opposite to the TCAS RA.

Results

This section describes the results of the case study focused on OEs that involved at least one aircraft with TCAS RAs and it is structured in two main subsections. First, we have presented a comparative analysis between errors that contains TCAS RAs in the cockpit and the results of the first taxonomic study. Second, we have described a characterization of TCAS incident based on the chain of events present in the incident with regard to the controller's actions and behavior.

Error Taxonomy applied to reports containing TCAS RAs

There were 104 reports analyzed with 62 assigned to en-route facilities and 62 assigned to the Terminal Radar airspace. Table 7 presents the distribution of reports within the two periods analyzed. The total number of errors identified was 202. Of those, 62 were in the centers and 42 in Terminal Radar airspace. An examination of the table revealed that the proportion between error types per OE report was 1.94, ranging from only one error type element until a maximum of four errors in a single report.

Table 7

Distribution of OEs involving TCAS as function of airspace and reviewed period

	Total	Jan-Jun 04	Jan-Jun 05
TRACON	42 (40.3%)	8 (30.8%)	34 (43.6%)
ARTCC	62 (59.7%)	18 (69.2%)	44 (56.4%)
TOTAL	104	26	78

Figure 22 depicts the frequencies of error types we identified. The pattern is qualitatively similar to the one we obtained using every report from January to July 2004 in the study one. Table 8 expands the gathered data of this classification.

Figure 22. Frequency of error types identified in OE reports that contains TCAS advisories.

Table 8

Percentage of error type and percentage of OE reports associated to each error type, in ARTCC and reports in TRACON (OE reports containing TCAS RAs)

Error Category		Total		ARTCC			TRACON		
		Percent	Percent	Percent	Percent	Percent	Percent		
		Errors ^a	Reports ^b	Errors	Reports	Errors	Reports		
Fail Converging	(37)	18.3	35.6	(18)	14.1	17.3	(19)	25.7	18.3
Fail Identify Altitude Climbing/Descending	(24)	11.9	23.1	(11)	8.6	10.6	(13)	17.6	12.5
Descend through	(22)	10.9	21.2	(17)	13.3	16.3	(5)	6.8	4.8
Overlooked Traffic	(19)	9.4	18.3	(15)	11.7	14.4	(4)	5.4	3.8
Climb through	(18)	8.9	17.3	(12)	9.4	11.5	(6)	8.1	5.8
Altitude Inadequate	(17)	8.4	16.3	(10)	7.8	9.6	(7)	9.5	6.7
Vector Inadequate	(16)	7.9	15.4	(9)	7.0	8.7	(7)	9.5	6.7
Temporal error-issue	(10)	5.0	9.6	(5)	3.9	4.8	(5)	6.8	4.8
Control coordination	(8)	4.0	7.7	(8)	6.3	7.7	(0)	0.0	0.0
Hearback / Readback	(7)	3.5	6.7	(6)	4.7	5.8	(1)	1.4	1.0
Instruction not Intended	(5)	2.5	4.8	(5)	3.9	4.8	(0)	0.0	0.0
Misapplication of procedure	(4)	2.0	3.8	(2)	1.6	1.9	(2)	2.7	1.9
Datablock-misentered Info	(3)	1.5	2.9	(3)	2.3	2.9	(0)	0.0	0.0
Fail Overtaking Traffic	(2)	1.0	1.9	(1)	0.8	1.0	(1)	1.4	1.0
LOA misapplication	(2)	1.0	1.9	(2)	1.6	1.9	(0)	0.0	0.0
Airspace Violation	(1)	0.5	1.0	(0)	0.0	0.0	(1)	1.4	1.0
Transpose Aircraft	(1)	0.5	1.0	(1)	0.8	1.0	(0)	0.0	0.0
Wrong Aircraft	(1)	0.5	1.0	(1)	0.8	1.0	(0)	0.0	0.0
Aircraft Overlapped	(1)	0.5	1.0	(1)	0.8	1.0	(0)	0.0	0.0
Other	(4)	2.0	3.8	(1)	0.8	1.0	(3)	4.1	2.9

Note. Numbers in table are percentages. Numbers in parentheses indicate error frequencies. Because more than one error is identified in each OE report, the percentages in the column percent error will not equal 100%.

^a Percentages of error category with base on the total number of error identified in ARTCC, TRACON, or both.

^b Percentages of reports that involved at least that error type (with a total of 202 OE reports).

We compared the top-12 most frequent error types found in the OE reports with TCAS RA from Table 8 (reports of the two 6-month periods in 2004 and 2005) and the whole set of OE reports from 2004 from Table 2 to find different patterns. The comparison was made using percentages of total OE reports and is plotted in Figure 23.

Errors involving TCAS RAs seemed to be more strongly linked to altitude changes and fail to identify aircraft climbing or descending (when the clearance was given by other sector or by the current sector quite in advance to the encounter). Contrary to what one could expect TCAS RAs seemed to be less associated to hearback/readback errors and coordination errors. When considering overtaking errors, the likelihood of having a TCAS RA was reduced. These trends were not tested statistically.

On the contrary, the top-12 more frequent error types were the same in both sets of reports, and only a few of them swap the order (e.g., *Fail identification altitude climbing/descending* has become the second more frequent error, *control coordination* was ranked 8th).

Figure 23. Percentage of error types identified in OE reports that contains TCAS advisories versus those identified with the full set of errors.

Distribution of OEs in TRACON and ARTCC

The OEs with TCAS RAs in TRACONs seemed to be proportionally linked more often to error of omissions involving either a failure to identify converging conflicts on the horizontal plane (*fail to notice converging aircraft*) or the vertical plane (*fail identification altitude climbing/descending*). *Fail to notice converging aircraft* error accounted for 25.7% of errors ($n = 19$) in TRACON and 14.1% ($n = 18$) in ARTCC, as opposed to *fail identification altitude climbing/descending* that accounted for 17.6% ($n = 13$) and 8.6% ($n = 11$), respectively. However, *control coordination* and *overlook traffic* were associated more often to TCAS RA in centers, 6.3 % ($n = 8$) and 11.7% ($n = 15$), respectively, rather than they were in TRACONs, 0% and 5.4% ($n = 4$), respectively. Figure 24 illustrate this difference. No statistical test was performed with these data.

Figure 24. Percentage of errors identified in the OE reports, with base on the total number errors found in TRACON and ARTCC, respectively.

Proximity rating of the encounters with TCAS RA

The distribution of proximity rating across OE reports is presented in Table 9 and illustrated in Figure 25. The reported proximity in the horizontal plane in OEs with TCAS RA ($M = 2.10$, $SD = 1.11$) was significantly smaller than was in the OEs without TCAS RA ($M = 2.77$, $SD = 1.29$) $t(171) = 5.35$, $p < .0001$ (one-tailed). Similarly, vertical separation in OEs with TCAS RA ($M = 539$, $SD = 316$) was significantly smaller than was in OEs without TCAS RA ($M = 624$, $SD = 482$) $t(228) = 2.19$, $p = .015$ (one-tailed).

Table 9

Descriptive statistics of distance between aircraft in OE reports by proximity category

	Total OE		A		B		C	
Separation	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Horizontal	2.10	1.11	0.82	0.44	1.38	0.50	3.07	0.63
Vertical	539	316	253	244	624	220	590	338

A chi-square goodness-of-fit test applied to the distribution of categories A, B, and C (see Table 10) showed that these categories differed significantly across the OE reports that contained TCAS RAs, $\chi^2(2, N = 103) = 13.9$, $p = 0.001$. In addition, there were higher-proximity events in the Terminal Airspace than in the centers, as indicated in Table 10. A chi-square test of independence revealed that this difference was significant, $\chi^2(2, N = 103) = 24.6$, $p < 0.001$. Similarly to what was found in the first study, most errors in TRACON were under proximity A and B (78.5 %).

Figure 25. Severity of operational errors associated with the ARTCC

Table 10

Frequencies and percentages of proximity categories in Centers and Terminal facilities with reports that contained TCAS RAs.

	Total		ARTCC		TRACON	
Category		Percent ^a		Percent		Percent
Proximity A	(19)	18.3	(5)	8.1	(14)	33.3
Proximity B	(34)	32.7	(15)	24.2	(19)	45.2
Proximity C	(50)	48.1	(42)	67.7	(8)	19.0
No Rated	(1)	1.0	(0)	0	(1)	2.4

Note. Numbers in table are percentages. Numbers in parentheses indicate frequencies.

^a Percentages of OE reports, whose aircraft proximity is rated under category A, B, and C.

This pattern of low, medium, and high proximity found in the reports containing TCAS RA was similar, in both types of facilities, to the one found when using the full set of reports. The OE reports in TRACON had more severe outputs (i.e., higher-proximity events) than they had in centers. The fact that the minimum standard separation was different in TRACONs (3 nmi and 1000 ft) and ARTCCs (5 nmi and 2000ft before RVSM was implemented and 1000 ft after the implementation) had a direct impact on the number of conflicts categorized as class C. We could argue, however, that other factors were the underlying causes of the observed difference (e.g., the structure of traffic flow and aircraft maneuvers in those types of airspace).

Figure 26 illustrates the percentage of each proximity group (A, B, C) in TRACONs and centers, with the full set of OE reports and with OE reports that involved a TCAS RA. A chi-square test of independence revealed that the observed difference of higher proximity conflicts in ARTCC between both set of OE reports was statistically significant ($\chi^2 (2, N = 375) = 25.197, p < 0.001$). In TRACONs, this difference (in the same direction) was not statistically significant ($\chi^2 (2, N = 188) = 0.074, p = 0.964$), and we could not claim that the small increase of frequency of higher proximity rating was not due to chance.

Figure 26. Comparison of proximity rating between OEs that triggered TCAS RA (with RA between brackets) and full set OE reports.

Concurrent factors present in reports containing TCAS RA

The use of final investigation reports allowed us to identify a more comprehensive number of concurrent factors in each report (and more accurately as well) because the FAA investigator did identify some of those factors in the report (e.g., *distraction* or *deficient procedure*). Therefore, the observed lack of fit among study one and two has to be seen with this factor in mind. Figure 27 illustrates the percentage of contextual factors present in errors with TCAS RAs.

Figure 27. Percentage of contextual and concurrent factors identified in the OE reports, with base on the total number of OE reports.

The absence of D-side controller was notorious, being present in 26 % ($n = 27$) of OEs. This was not related specifically to the fact that the conflict triggered a TCAS RA, but it seems to follow the same pattern found when we analyzed the full set of reports in the first study. However, factors such as *distraction* in 23.1% of OEs ($n = 24$), *traffic complexity* in 25% ($n = 26$), and *other complexity factors* in 25% ($n = 26$) had higher frequency in situations where a TCAS RA was triggered. This might show an impact of complexity factors on the likelihood of triggering a TCAS RA, but it is possible that those factors were just easier to be identified in the final OE reports.

The number of OE reports where a TCAS RA might have played a causal role in the error was actually two, smaller than initially hypothesized, and always they were consequence of a previous loss of separation. The reports were coded as ZNYC04E018 in 2004 and NCTR05E006 in 2005.

ZNYC04E018 was an encounter involving three aircraft. The controller detected a first loss of separation late and the aircraft received a TCAS RA to climb, loosing separation with a third one.

NCTR05E006 occurred during the approach to an airport, where the approaching aircraft received a TCAS RA due to the presence of a VFR flight. It climbed back to 8000 feet. The controller did not realize that the aircraft had climbed and though it was at lower altitude (the report did not specified anything about pilot informing about that deviation). The aircraft was cleared to land, conflicting with another aircraft below it.

D-side controller absence and the proximity of the encounter with TCAS RA

The data suggested that there was no effect on the proximity outcome associated to the fact that the D-side was present or not. A chi-square test did not support that the distribution of frequencies in Table 11 was statistically significant ($\chi^2 = 1.981$, $p=0.371$ with two expected frequency cells less than 5, which tends to increase the χ^2 value and to reject the null hypothesis).

Table 11

OE reports associated with each level of proximity and the presence or absence of a D-Side controller in incidents involving TCAS RAs

	D-side present		D-side absent	
Proximity A	2	(5.7 %)	3	(11.1 %)
Proximity B	10	(28.6 %)	4	(14.8 %)
Proximity C	23	(65.7 %)	20	(74.1%)

Time on position and its relation to TCAS RA.

The effect of controller's time on position over the likelihood of committing an OE with TCAS RA was analyzed. A chi-square goodness-of-fit test was performed to the distribution of OEs over 15-minute intervals of Figure 28. We did not find significance results ($\chi^2 (2, N = 77) = 5.129$, $p = 1.63$) to reject the null hypothesis (i.e., there is no difference on the frequency of OE reports with TCAS RA between 15 minutes intervals) and we cannot claim that the observed difference of the Figure 28 was due to an effect of the time on position or due to chance.

Figure 28. Distribution of OEs with TCAS RA as a function of the controller's time on position.

These results were in line with what we observed with the full set of reports in the first study and suggested that the likelihood of a TCAS RA event to occur after a controller relief was not higher than at any other point in time of the shift.

We also looked at the potential effect of controller's time on position in five types of errors, the more frequent ones, with TCAS RAs: *fail converging identification*, *fail identification climbing/descending*, *descend through*, *climb through*, and *overlook traffic*. The frequencies of errors are plotted in Figure 29, Figure 30, Figure 31, Figure 32, and Figure 33, respectively.

We hypothesized that the controller's time on position had some influence in these errors, because an inadequate debriefing could impair the situation awareness of the operator, making him/her more prone to make an OE and slower to react and recover

separation. The test used was a one-way ANOVA. The results of each test are presented in Table 12. We did not find statistical significance at the level of 95 % confidence to reject the null hypothesis, i.e., no effect. The reason for the lack of statistical support might be due to an inadequate sample size and the test should be repeated with a bigger set of reports.

Table 12

Analyses of variance for identified error type as function of controller's time on position.

Error	$F(3,8)$	p
Fail converging identification	1.9	0.209
Fail identification climb/descend	3	0.095
Descend through	1.451	0.227
Climb through	3.571	0.069
Overlook traffic	2	0.193

Note. The dependent variable was the number of errors (of each type) made in five-minute intervals. The analysis of variance was performed with three observations of this variable in 15-minute segments (within each 15-minute interval the frequency of error was consider constant), allowing to test if the average of each group of three samples correspond to the same population (i.e., there is no effect of time on position and frequency of errors).

Figure 29. Fail converging error as a function of the controller's time on position, in encounters with triggered TCAS RA.

Figure 30. Fail identification climbing/descending error as a function of the controller's time on position, in encounters with triggered TCAS RA.

Figure 31. Descend through error as a function of the controller's time on position, in encounters with triggered TCAS RA.

Figure 32. Climb through error as a function of the controller's time on position, in encounters with triggered TCAS RA.

Figure 33. Overlook traffic error as a function of the controller's time on position, in encounters with triggered TCAS RA.

Analyses of TCAS RA chain of events: Controller awareness and behavior

We characterized the incidents with TCAS RAs across various dimensions: controller awareness of impending TCAS, quality of pilot's reports, controller behavior during the TCAS event and opportunities to fail, and deviations from the desired theoretical chain of events depicted in Figure 2.

The number of reports with TCAS RA increased from 26 in the 6-month period of 2004 to 78 during the same period in 2005. The increase of OEs with TCAS RA events (200 %) was higher than the increase of general OE reports (74.8 %). The TCAS RA was identified in 19 reports (24% out of the total reports with TCAS RAs), but the summary did not describe any information pertaining to the TCAS sequence onboard and, therefore, no information related to the TCAS RA chain of events and subsequent controller and pilot actions was extracted from those reports. Other 23 reports, 20 preliminary versions from 2004 and three final versions from 2004, were too concise to extract that information. In summary, 62 reports were analyzed for this part of the study.

Controller awareness of impending conflict

Although the initial objective was to identify when the air traffic controller was aware of an imminent TCAS RA, we could only identify who detected the impending conflict. Figure 34 illustrates these results. In 20.2 % of the events ($n = 21$), the pilot informed the controller about the deviation from clearance due to a TCAS RA, being the controller unaware of the impending conflict. The controller was aware of the conflict in 63.4 % of the incidents ($n = 66$), being alerted by the Conflict Alert (CA), by other

controller, or by himself/herself. The controller did not recognize and was not informed about the incident in 2% of the cases ($n = 2$).

Figure 34. Agent or system that detected the impending incident (with a triggered TCAS RA).

Controller's response to the conflict situation

The controller acted in 52 % ($n = 54$) of the situations with TCAS RAs giving a new clearance to the pilot. 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 in an attempt to reestablished the standard separation. The rest of conflicts, 48 % ($n = 50$), involved no action or the timing was not determined.

Incidents where the controller issued a clearance after TCAS RA posed risks because the ATC command might conflict with those commands provided by TCAS, creating opportunities for the pilot to heed the controller's instruction and leading the aircraft into each other (as it occurred in Uberlingen BFU (2004)). Not all of those situations were risky. For example, changing the heading might be appropriate and did not conflict with the TCAS vertical commands.

Quality of information provided by pilots

Situation awareness 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 by Endsley et al. (2003), 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 (they used the altitude field of the aircraft datablock on the display as well). Thus, the quality of the pilot's messages is crucial for controllers to gain a correct awareness of the situation. Following, we are presenting a quality analysis of pilot's messages.

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. The above figures suggested that controller might be impaired to

understand the full traffic picture. This created some opportunities for wrong decisions and errors. The next section will put together these findings with the controller's actions to resolve the conflict.

Relation between quality of pilot information about TCAS and controller behavior

Figure 35 illustrates the controller's actions during encounters that had TCAS RA across situations judged based on the reporting pilot's voice messages about the TCAS RA deviation. The controller's action was classified according to two variables: aircraft dimension (i.e., altitude or heading) and timing of clearance compared to the triggered TCAS RA on board. The reader should note that this instant was unknown and it was inferred using the timeline provided in the OE reports (see example of text description in Appendix E).

Figure 35. Percentage of incidents with commands given by the controller with regard to the time TCAS CA was triggered, parameter of the clearance, and quality of the pilot's message informing about TCAS RA.

Note. Percentage is based on the number of reports with enough information about the pilot-controller interaction ($N = 62$). In the reports with incomplete pilot' report, three incidents contained both commands with new heading and altitude, thus the sum of percentage does not equal 100%. Three reports (4.8%) had opposite altitude clearance to the TCAS RA when the pilot's report was incomplete. None was in the opposite direction when the report was complete. "None" included no action from the controller side or unknown if s/he instructed any new clearance.

We reported earlier that the controller received incomplete pilot's reports in a relatively high number of OEs with TCAS RA (43.4%). Among them, 19.4 % of the reports ($n = 12$) contained at least a controller clearance issued after the TCAS RA was triggered as opposed to the 12.9% ($n = 8$) when the pilot information was complete and timely provided. In particular, the controller should avoid issuing clearances in the vertical plane, 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, as opposed to the 8.1% of incidents ($n = 5$) with complete information. Most importantly, we found that the controller issued new vertical clearances in opposite direction to the TCAS RA in three incidents (4.8%) when he or she received incomplete pilot's TCAS RA deviation, but 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. Among them, we found two of them 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 in other frequency. In these situations the controller's situation awareness was also impaired. Table 13 and Table 14 contain a brief description of controller's actions in both conditions, with complete and incomplete information, respectively.

Table 13

OE reports containing controller's altitude clearance after TCAS RA was triggered onboard (complete pilot's information)

OE Code	Summary of facts
ZLAC05E001	Controller confirmed pilot to stop descending due to a RA command upon pilot's message reception. Controller did not receive the other pilot's message because he was in a different frequency.
ZDCC05E015	Controller confirmed the RA direction and assigned stopping FL upon pilot's message reception.
ZAUC05E009	Controller gave a new altitude clearance (in the same direction than RA)
ZTLC05E008	Controller gave a new altitude clearance (in the same direction than RA)
ZLAC05E005	Controller gave a new altitude clearance (when no deviation was required by the TCAS system). The direction was complementary with the deviation of the other aircraft in conflict. Controller did not receive any pilot's message because the aircraft that deviated form the TAC clearance was in a different frequency.

Table 14

OE reports containing controller's altitude clearance after TCAS RA was triggered onboard (incomplete pilot's information)

OE Code	Summary of facts
D01R05E001	CPC cleared the aircraft for visual approach when was descending due to a RA (pilot had not indicated the RA direction)
ZFWC05E005	CPC climbed the aircraft that received RA (opposite direction). Pilot rejected and complied with RA. Then CPC descended (again opposite direction) the other a/c, but he rectified 4 sec later and climbed it.
ZNYC05E014	CPC climbed one and descended other (both in the complementary RA direction)
ZDCC05E021	CPC expedited descent before receiving pilot's message. Pilot readback receiving a RA in opposite direction and complying with it. Then CPC turned both aircraft.
ZAUC05E018	CPC climbed the aircraft that did not deviate from ATC clearance and turned the aircraft that was deviated due to the RA.
ZNYC05E022	CPC climbed (expedite) the aircraft after receiving incomplete and late (15 sec) pilot's message about RA. He descended the other a/c.
ZTLC05E047	CPC climbed back the aircraft that was descending due to a RA (in opposite direction). Pilot questioned "what do you want us to do?". CPC rectified and gave a clearance in the same direction of RA.
ZDCC05E025	CPC confirmed the RA direction, stopping FL and turned the a/c that received RA

In addition, the percentage of situations where the controller did not issue a clearance, except maybe traffic information as ideally FAA requires (2001), was 12.3% ($n = 7$) when the pilot's message was incomplete or missed as opposed to 17.7% ($n = 11$) when the controller received full information.

This is not surprising because the TCAS RA situations are infrequent events. TCAS RAs are rare events that most of controllers do not experience in their professional lifetime, or they do a small number of times. However, even though they are very rare events, the importance of avoiding these hazards is crucial in aviation. These data suggest that keeping the controller adequate and timely informed reduces the likelihood of issuing opposite altitude clearances to the TCAS RA command, which in turn creates opportunities for the pilot to follow ATC commands, disregarding the TCAS RA message. This may jeopardize safety with catastrophic consequences, such as the accident in Uberlingen demonstrated (BFU, 2004; Ladkin, 2004; Nunes & Larsen, 2004).

Discussion

TCAS RA and the Type of Error

The application of the same taxonomy of errors used in the first study to the OE reports with TCAS RA allowed us to compare discrepancies among results of both studies to draw relationships among error types and incidents with TCAS RA. In general, there were no relative big differences among patterns in both set of reports that suggested an effect or relation between certain types of errors and the likelihood of triggering a TCAS RA. In particular, the top-12 errors were the same, with the exception of swapping the order of frequency for some of them. Errors with TCAS RAs seemed to have stronger relation to altitude changes and *fail to identify aircraft climbing or descending* errors. The frequency of TCAS RA declined with hearback/readback and coordination errors. The sample size was small to obtain any conclusive claim. It is possible that these differences were due to normal variability of the data.

OEs with TCAS RA had more frequent higher-proximity outputs than general OEs had. The average distance was significantly smaller when the OE triggered a TCAS RA. This seems a natural consequence of the fact that TCAS was a last resource barrier that should act when pilot and ATC had failed to identify the encounter, and both aircraft were approaching one another. However, the difference was not as big as one could expect (means differ in 0.67 nmi and 75 feet, respectively) and it is possible that this was a consequence of the efficiency of the TCAS system, whose performance prevented both aircraft going too closer. This was good news, and other sources seem to support the idea that the system is effective (Williams, 2004; Eurocontrol, 2003a). However, this cannot

be concluded if the study is not completed with the average separation of the full set of OEs for the year 2005, because, as it was indicated, RVSM operations were introduced in January 2005 and those OEs with separation between 1000 ft to 2000 ft were no longer considered OE. The fact that those potential situations were pulled out from our sample, reduced the average separation.

Another difference was that OEs with TCAS RA had contextual factors such as distraction and complexity factors (e.g., traffic, weather, traffic flow initiatives) with higher frequencies than we found in the general set of OEs. This suggested that distraction and complexity increased the chances of TCAS RA. In other words, lack of attention and excess of workload would play a preponderant role in triggering a TCAS RA. We have pointed that the identification of those factors was facilitated with the use of the final investigation report. We did not find support to sustain that controller's time on position had effect on the probability of a TCAS RA, similarly as we found with the general set of OE reports. Similarly, the absence of D-side controller was not related to the likelihood of triggering TCAS RA, but in contrast to the findings of the first study, the tendency was less apparent.

Finally, we did find very little support, if any, for marginal impact of TCAS RA over OEs, as initially hypothesized in view of the taxonomic results. We only found two OEs where the TCAS played a causal role. However, the following section discusses how the current use of the TCAS system might induce erroneous behavior in the controller. These errors were committed within the context of a previous loss of separation, and, consequently, they were not the cause of the OE.

Controller Behavior during TCAS RA Events

Perhaps the most interesting relationship the data suggest was between the quality of the pilot's messages informing about a TCAS RA deviation and how the controller's was actually reacting to the conflict situation during the RA event and subsequent aircraft maneuver. The only manner for the controllers to be informed about a TCAS RA is through the communication by the pilot. Delay in updating the altitude information in today's radar screens may prevent to detect altitude updates due to RA deviation (Eurocontrol, 2003a). We found that the pilot's reporting was approximately half of the times incomplete or inexistent. There was high variability of the ideal sequence of chain of events during a TCAS advisory, as depicted in Figure 2. These communications deficiencies added difficulties to the controller's understanding of the situation, impairing their situation awareness. In a simulation study, Rome, Cabon, Favresse, Mollard, Figarol, and Hasquenoph (2006) 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. Rome et al. (2006) found a clear physiological reaction, the increase on the heart rate, related to high level of stress during TCAS maneuvers in both pilots and controllers in a simulation setting. A real situation would aggravate the stress level. Under such circumstances of stress, communications might be difficult to understand, and pilots usually delay reporting the deviation (Eurocontrol, 2003a), or inform incorrectly to the controller. We have found evidence of these factors in our review of EO reports.

In addition, we found that the controller issued vertical clearances opposite to the TCAS RA command in three incidents (4.8%) when an incomplete pilot's message about TCAS RA deviation had been sent. However, the direction was always complementary to the TCAS RA command when the controller was proper and timely informed. If we consider only the OE reports 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. Other vertical clearances, even in the same direction of the TCAS RA, placed some risk 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 (Orasanu & Martin, 1998). 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 situation awareness was impaired.

Two solutions are proposed 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 familiarity and expertise in dealing with the appropriate solutions, i.e., to provide traffic information and horizontal spacing but not vertical clearances. Second, downlink TCAS RA triggered in the cockpit in order to provide controllers with complete and timely information about the TCAS RA and subsequent deviation.

Various authors have proposed downlinking TCAS RA information (cf. Brooker, 2004; Eurocontrol, 2003a, 2004; Rome et al., 2006; Wickens et al., 1997, 1998). In the study of Eurocontrol (2004), most controllers judged beneficial the provision of RA information to the controller. They considered an improvement in situation awareness and expected to reduce the likelihood of contradictory ATC clearances. Some problematic issues for this solution were studied. The first one was that the analysis of the RA information might draw too much of the controller's attention, neglecting other traffic situations (Eurocontrol, 2004). 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. In that situation the controller would have to determine which of the two sources is correct. The third one was the operational procedures for the use of that information, i.e., how the RA information would be used, if there were any change of 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 (Brook, 2005; Eurocontrol, 2004). This means that the provision of RA information would be used for informational purposes. These issues need to be addressed with further research before implementation.

In summary, although the sample was small and no statistical significance was derived from our data, we argue that there was evidence to suggest that the likelihood of receiving a clearance in opposite direction to the RA increased when the information about deviation from clearance was not accurate or was not sent in a timely manner. The solutions proposed were twofold: 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.

CONCLUSIONS

This research demonstrated the value of a systematic characterization of operational errors using official record of incidents investigation across the NAS and across a relative extended period of time. The taxonomy used was an aggregation of those categories currently being used amended during the analysis and designed to focus on causal factors (see final classification in Table 2). This research was exploratory and lacked in-depth analysis to isolate causal factors, but this classification helped to identify meaningful factors and to focus organizational actuations to reduce OEs. Given the limitations associated with the analysis of incident database (e.g., hindsight bias), the findings need to be interpreted carefully, but they provide important initial insights.

This study examined prior research and reviewed OE investigation reports to explored relationships between causal factors of errors. We found different patterns in errors committed in TRACON and ARTCC, as Tables 2, 3, 4, and 5 reveal. The results suggested that *control coordination*, *overlook traffic*, and *hearback/readback* errors accounted for a sizable proportion of OEs (see Table 2). The combination of contextual factors and severity of the OE (as measured by proximity) was revealed as useful approach into the investigation of OEs. The study pointed out areas where the ATC service provider and regulator could invest effort and resources aiming at reducing the most frequent errors and those ones with more severe outcome.

The results of the study suggested, although not statistically as Table 6 shows, that the absence of D-side was related to higher proximity ratings of the encounter. Similarly, Figure 18 illustrates that developmentals were also associated with higher

number of high severity OEs, although it was not statistically proved. The baseline of operations would have been needed in both cases to gain further insights. This highlights the importance of monitoring performance during training and application of staffing strategies. The study, as Figure 19 illustrates, did not found support for relationship among controller's time on position and OEs, as other research reported (Pounds & Ferrante, 2005; Schoeder et al., 2006).

As noted in the literature, implementation of TCAS system has improved safety avoiding imminent risks of collisions in certain situations where controller and pilots failed to identify loss of separation between aircraft. However, its operation has had profound implications for air traffic controllers. The results of the taxonomic study suggested that the TCAS RA might be a causal factor in OEs, and we performed a thorough study on those reports with TCAS RA. The case study, as Figure 26 illustrates, did not found support to relate the presence of TCAS RA and specific types of errors in our taxonomy. However, this study revealed very important operational issues. We found evidence of a high variability in the chain of TCAS RA events, problems associated with pilot-controller communications in high-risk situations, and harm of controller situation awareness. Our data analysis suggests that controller provides clearances in the vertical plane after a TCAS RA command, although the adequate TCAS operational procedure does require not to do it. We found evidence (see Figure 35) of increased likelihood of receiving a clearance in opposite direction to the RA when pilot's voice information about the deviation from current clearance was incomplete. The analysis revealed that this situation occurred in a three situations (4.8 % of the time).

These results are consistent with some theories in air traffic operations (cf. Brooker, 2004; Eurocontrol, 2003a; Orasanu & Martin, 1998; Wickens et al., 1998) and with results in simulation settings (Rome et al., 2006).

Limitations

The main limitations of this study were associated to the use of reports result of an investigation process and to the reliability of the applied taxonomy.

On the one hand, the use of investigation reports makes results highly dependent on the interpretations of the facts described in the reports, above all if the reports are focused on the investigation of human error. Investigations of incidents are likely to stop causal searching when a familiar and reasonable explanation is found, leaving uncovered some causal factors. This is highly influenced by the hindsight bias or knowledge of outcomes (Dekker, 2002; Woods & Cook, 2002). In addition, the preliminary reports often lacked of comprehensive information that led us to identify fewer errors than those that actually might have been present. When we used the final reports, we found a great variability in the level of details provided by the investigators. This might have influenced again the interpretation of the incident and the identification of errors and contextual factors. Regarding the TCAS RA analysis, we found difficulties in several reports (42 reports with TCAS RA were pulled out of the analysis) to determine the timing of controller's action as compared to the TCAS RA message.

On the other hand, the reliability of the taxonomy was not validated. Although inter-reliability of two reviewers was demonstrated, we should expand the analysis with other reviewers and use a longitudinal analysis. There were concerns with the

completeness of the taxonomy and the level of detail of each error type and contextual factors. A review of the elements to adequately capture individual, situation, and organizational factors should be performed. We feel that the investigation and reporting process should capture the same elements as those contained in the taxonomy, in order to avoid reinterpretations.

Future Work

Based on the findings and the experience gained during this research, some recommendations are drawn for future research efforts.

First, it is recommended to obtain and record the standard or baseline operations of some contextual factors and errors. For example, it would be useful to know the baseline information about how often D-side is present in actual operations, or what is the frequency of supervisors monitoring operations.

Second, further attempts to know the interactions between multiple errors and/or contextual factors in the OE process should be pursued. We found that the probability of co-occurrence of pairs of error types differed across the taxonomy, but additional research should directed towards the analysis of the nature of these conditional probability interactions.

Third, the TCAS RA analysis should increase the time span of reports in order to study a larger sample size and to confirm the findings of this study. In addition, it would be advisable to crosscheck the FAA reports with other databases, such as NASA Aviation Safety Reporting System, to contrast information and, possibly, enrich the incident description and improve the accuracy of the study.

Finally, further research attention should be conducted on downlinking TCAS RA to the controller's workstation. The use of future data link technologies might facilitate the operational implementation of this feature, increasing controller's situation awareness of the onboard TCAS RA. However, research needs to address and discover the complex pilot-controller interactions that emerge from the use of TCAS before its implementation. Some issues to answer are the design of the controller's interface ensuring that not excessive demand is posed on attentional resources, the definition of the most adequate operational procedures and operator's responsibilities (i.e., pilots and controllers), and the liability issues that might be derived (Eurocontrol, 2004).

REFERENCES

- American Psychological Association (2001). *Publication manual of the American Psychological Association* (5th ed.). Washington, DC: Author.
- Besnard, D., Greathead, D., & Baxter, G. (2004). When mental models go wrong. Co-occurrences in dynamic, critical systems. *International Journal of Human-Computer Studies*, 60, 117-128.
- Bliss, J. P. (2003). Investigation of alarm-related accidents and incidents in aviation. *The International Journal of Aviation Psychology*, 13 (3), 249-268.
- BFU (2004). *Überlingen midair collision*. Investigation Report AX001-1.2/02. Braunschweig, Germany: German Federal Bureau of Aircraft Accidents Investigation.
- Boeing Commercial Airplanes. (2004, May). *Statistical summary of commercial jet airplane accidents: worldwide operations 1959-2003*. Seattle, WA: Author.
- Brooker, P. (2004). Thinking about downlink of resolution advisories from airborne collision avoidance systems. *Human Factors and Aerospace*, 4 (1), 49-65.
- Brooker, P. (2005). STCA, TCAS, airproxes and collision risk. *The Journal of Navigation*, 58, 389-404.
- Cardosi, K., & DiFiore, A. (2004). Metrics of communication performance. *Air Traffic Control Quarterly*, 12 (4), 297-313.
- Cardosi, K., Falzarano, P., & Han, S. (1999). *Pilot-Controller Communication Errors: An Analysis of Aviation Safety Reporting System (ASRS) Reports*. (Report No. DOT/FAA/AR-98/17). Washington, DC: Federal Aviation Administration.
- Cardosi, K., Hannon, D., Sheridan, T., & Davis, W. (2005). A method for rating the severity of runway incursions. *Proceedings of the 6th USA/Europe Seminar on Air Traffic Management Research and Development*. Baltimore, MD.
- Corker, K., Lee, P., Prevot, T., Guneratne, E., Martin, L., Smith, N. et al. (2006). *Analysis of multi-sector planner concepts in U. S. airspace* (HAIL Tech. Rep. 2006-3442-01). San Jose, CA: San Jose State University.
- Dekker, S. W. A. (2001). The disembodiment of data in the analysis of human factors accidents. *Human Factors and Aerospace Safety*, 1 (1), 39-57.

- Dekker, S. W. A. (2002). Reconstructing human contributions to accidents: the new view on error and performance. *Journal of Safety Research*, 33, 371-385.
- Dekker, S. W. A. (2003). When human error becomes a crime. *Human Factors and Aerospace Safety*, 3 (1), 83-92.
- Eurocontrol (2002). *Technical review of human performance models and taxonomies of human error in ATM (HERA)* (Report No. RS/HSP-002-REP-01). Brussels, Belgium: Author.
- Eurocontrol (2003a). *Review of ACAS RA downlink: An assessment of the technical feasibility and operational usefulness of providing ACAS RA awareness on CWP*. Brussels, Belgium: Author. Retrieve February 12, 2006, from http://www.eurocontrol.int/ra-downlink/library/Review_of_ACAS_RA_Downlink_ver_10.pdf
- Eurocontrol (2003b). *The human error in ATM technique (HERA-JANUS)* (Report No. HRS/HSP-002-REP-03). Brussels, Belgium: Author.
- Eurocontrol (2004). *RADE1 - RA downlink experiment 1*. Brussels, Belgium: Author. Retrieve February 12, 2006, from http://www.eurocontrol.int/ra-downlink/Library/RADE_1_final_report_v-10.pdf
- Endsley, M. R. (1995). *A taxonomy of situation awareness errors*. In R. Fuller, N. Johnson, & N. MacDonald (Eds.), *Human Factors in Aviation Operations* (pp. 287-292). Aldershot, England: Avebury.
- Endsley, M. R. (1999). Situation awareness and human error: Design to support human performance. *Proceedings of the High Consequence Systems Surety Conference*. Albuquerque, NM: Sandia National Laboratory.
- Endsley, M. R., Bolte, B., & Jones, D. G. (2003). *Designing for situation awareness: An approach to user-centered design*. New York: Taylor & Francis.
- Federal Aviation Administration (2000). *Introduction to TCAS II version 7*. Washington, DC: US Department of Transportation.
- Federal Aviation Administration (2001). *Advisory Circular 120-55B*. Washington, DC: Department of Transportation. Retrieved April 12, 2006, from http://www.airweb.faa.gov/Regulatory_and_Guidance_Library/rgAdvisoryCircular.nsf/0/0C02E3D02AD4011786256C1400632EF7?OpenDocument&Highlight=120-55b.

- Federal Aviation Administration (2002). *Air Traffic Quality Assurance* (Order 7210.56C). Washington, DC: Department of Transportation. Retrieved November 2, 2005, from <http://www.faa.gov/atpubs/ATQ/INDEX.htm>.
- Federal Aviation Administration (2006a). *Air traffic control* (Order 7110.65R). Washington, DC: Department of Transportation. Retrieved June 2, 2006, from <http://www.faa.gov/atpubs/ATC/ATC.pdf>.
- Federal Aviation Administration (2006b, April). *Administrator's Fact Book*. Washington, DC: Department of Transportation. Retrieved June 2, 2006, from <http://www.atctraining.faa.gov/site/factbooks.htm>.
- Herr, S., Teichmann, M., Poppe, M., & Suarez, N. (2005). The impact of multisector planning and new working procedures on controller tasks. *Proceedings of the 24th AIAA/IEEE Digital Avionics Systems Conference (DASC)*, Washington, DC.
- Hobbs, A. (2004). Human factors: The last frontier of aviation safety?. *The International Journal of Aviation Psychology*, 14 (4), 335-341.
- Hollnagel, E. (1993). The phenotype of erroneous actions. *The International of Man-Machine Studies*, 39, 1-32.
- Hollnagel, E. (2004). *Barriers and accident prevention*. Aldershot, England: Ashgate Publishing Company.
- Hutchins, E. L. (1995). How a cockpit remember its speed. *Cognitive Science*, 19, 265-288.
- Isaac, A. R., & Ruitenberg, B. (1999). Human Error. In Isaac, A. R., & Ruitenberg, B. (Eds.), *Air Traffic Control: Human performance factors* (pp. 11-37). Aldershot, England: Ashgate.
- Issac, A., Shorrock, S.T., & Kirwan, B. (2002). Human Error in European air traffic management: The HERA project. *Reliability Engineering and System Safety*, 75, 257-272.
- Klein, G. (1998). *Sources of power: How people make decisions*. Cambridge, MA: The MIT Press.

- Ladkin, P. B. (2004). Causal Analysis of the ACAS/TCAS sociotechnical system. In Cant, T. (Ed.), *Conferences in Research and Practice in Information Technology: Vol. 38. 9th Australian Workshop Safety Critical Programmable Systems* (pp. 3-12). Brisbane, Australia: Australian Computer Society, Inc.
- Love, W. D. (1997). Preview of TCAS II version 7. *Air Traffic Control Quarterly*, 6 (4), 231-247.
- Norman, D. A. (1981). Categorization of action slips. *Psychological Review*, 88 (1), 1-15.
- Norman, D. A. (1990). Commentary: Human error and the design of computer systems. *Communications of the ACM*, 33 (1), 4-7.
- Norman, D. A. (2002). *The design of everyday things*. New York: Basic Books.
- 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.
- O'Hare, D., Wiggins, M., Batt, R., & Morrison, D. (1994). Cognitive failure analysis for aircraft accident investigation. *Ergonomics*, 37 (11), 1855-1869.
- Orasanu, J., & Martin, L. (1998). Error in aviation decision making: a factor in accidents and incidents. *Proceedings of the 2nd International Workshop on Human Error, Safety, and Systems Development* (pp. 100-107). Seattle, WA: Author.
- Pape, A. M., Wiegmann, D. A., & Shappell, S. A. (2001). Air traffic control (ATC) related accidents and incidents: A human factors analysis. In R. Jensen (Ed.), *Proceedings of the 11th International Symposium on Aviation Psychology*. Columbus, OH: The Ohio State university.
- Parasuraman, R. (1997). Humans and automation: Use, misuse, disuse, abuse. *Human Factors*, 39 (2), 230-253.
- 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.

- 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, England: Ashgate Publishing Company.
- Pounds, J., & Isaac, A. (2002). *FAA strategies for reducing operational error causal factors* (Report No. DOT/FAA/AM-03/19). Washington, DC: Federal Aviation Administration.
- Pounds, J., & Isaac, A. (2003). *Validation of the JANUS Technique: Causal Factors of Human Factors in Operational Errors* (Report No. DOT/FAA/AM-03/21). Washington, DC: Federal Aviation Administration.
- Pritchett, A. R. (2001). Reviewing the role of cockpit alerting systems. *Human Factors and Aerospace Safety*, 1 (1), 5-38.
- Rantanen, E., Wickens, C. D., Xu, X., & Thomas, L. C. (2004). *Developing human factors certification criteria for cockpit displays of traffic information avionics* (Tech. Rep. AHFD-04-1/FAA-04-1). Savoy, IL: University of Illinois at Urbana-Champaign.
- Rasmussen, J. (1982). Human errors: A taxonomy for describing human malfunction in industrial installations. *Journal of Occupational Accidents*, 4, 311-333.
- Rasmussen, J. (1987). The definition of human error and a taxonomy for technical system design. In Rasmussen, J., Duncan, K., & Leplat, J. (Eds.), *New Technology and Human Error* (pp. 23-30). New York, NY: John Wiley & Sons.
- Reason, J. T. (1990). *Human error*. Cambridge, England: Cambridge University Press.
- Reason, J. T. (1997). *Managing the risks of organizational accidents*. Aldershot, England: Ashgate Publishing Company.
- Rodgers, M. D., Mogford, R. H., & Mogford, L. S. (1998). *The relationship of sector characteristics to operational errors* (Report No. DOT/FAA/AM-98/14). Washington, DC: Federal Aviation Administration.
- Rodgers, M. D., Mogford, R. H., & Strauch, B. (2000). Post hoc assessment of situation awareness in air traffic control incidents and major aircraft accidents. In M. R. Endsley & D. J. Garland (Eds.), *Situation Awareness Analysis and Measurement* (pp. 73-112). Mahwah, NJ: Erlbaum, Inc.

- 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.
- Sarter, N. B., & Alexander, H. M. (2000). Error types and related detection mechanisms in the aviation domain: An analysis of aviation safety reporting system incident reports. *The international Journal of Aviation Psychology*, 10 (2), 189-206.
- Sasou, K., & Reason, J. (1999). Team errors: definitions and taxonomy. *Reliability Engineering and System Safety*, 65, 1-9.
- Schroeder, D., Bailey, L., Pounds, J., & Manning, C. (2006). *A human factors review of the operational error literature* (Report No. DOT/FAA/AM-06/21). Washington, DC: Federal Aviation Administration.
- Sheridan, T. B. (2002). *Humans and automation: System design and research issues*. New York: Wiley
- Shappell, S.A., & Wiegmann, D.A. (1997). A human error approach to accident investigation: The taxonomy of unsafe operations. *International Journal of Aviation Psychology*, 7 (4), 269-291.
- Shappell, S.A., & Wiegmann, D. A. (2001). Applying Reason: The human factors analysis and classification system (HFACS). *Human Factors and Aerospace Safety*, 1 (1), 59-86.
- Shorrock, S., Kirwan, B., & Smith, E. (2005). Performance prediction in air traffic management: applying human error analysis approaches to new concepts. In B. Kirwan, M. Rodgerds, & D. Schafer (Eds.), *Human factors impact in air traffic management* (pp. 351-381). Aldershot, England: Ashgate Publishing Company.
- Stager, P., & Hameluck, D. (1990). Ergonomics in air traffic control. *Ergonomics* 33, 493-499.
- Wickens, C. D., & Hollands, J. G. (2000). *Engineering Psychology and Human Performance* (3rd ed.). New Jersey, NJ: Prentice Hall.
- Wickens, C. D., Mavor, A. S., & McGee, J. P. (1997). *Flight to the future: Human factors in air traffic control*. Washington, D.C. : National Academy Press.

- 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.
- Wiegmann, D. A., & Shappell, S. A. (2003). *A human error approach to aviation accident analysis: The human factors analysis and classification system*. Aldershot, England: Ashgate Publishing Company.
- Wiegmann, D. A., & Shappell, S. A. (1997). Human factors analysis of post accident data: applying theoretical taxonomies of human error. *International Journal of Aviation Psychology*, 7 (1), 67-81.
- Williams, E. (2004). Airborne Collision Avoidance System. In T. Cant (Ed.), *Conferences in Research and Practice in Information Technology: Vol. 47. 9th Australian Workshop Safety Critical Programmable Systems* (pp. 97-110). Brisbane, Australia: Australian Computer Society, Inc.
- Woods, D. D., & Cook, R. I. (2002). Nine steps to move forward from error. *Cognition , Technology, and Work*, 4, 137-144.

APPENDICES

APPENDIX A ACRONYMS

ANOVA	Analysis of Variance
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
ATD	Air Traffic Division
ATM	Air Traffic Management
CA	Conflict Alert
CIC	Controller in Charge
CPA	Closest Point of Approach
CPC	Certified Professional Controller
CRM	Crew Resources Management
CWP	Controller Working Position
D-side	Data Controller
FAA	Federal Aviation Administration
FL	Flight Level
FPL	Flight Plan
GEMS	Generic Error Modeling System
HAIL	Human Automation Integration Laboratory
HERA	Human Error Reduction in ATM
HFACS	Human Factors Analysis and Classification System
ICAO	International Civil Aviation Organization

IMC	Instrumental Meteorological Conditions
LOA	Letter of Agreement
MIT	Miles in trail
MVA	Minimum Vectoring Altitude
MVA	Minimum Vectoring Altitude
NAS	National Airspace System
NOTAM	Notice to Airmain
NTSB	National Transportation Safety Board
OE	Operational Error
OJT	On-the Job Training
OS	Operational Supervisor
RA	Resolution Advisory
R-side	Radar Controller
RVSM	Reduced Vertical Separation Minima
SD	Standard Deviation
SJSU	San Jose State University
SSR	Secondary Surveillance Radar
STCA	Short Term Conflict Alert
TA	Traffic Advisory
TCAS	Traffic Conflict Alert System
TRACON	Terminal Radar Approach Control

UK	United Kingdom
US	United States
VMC	Visual Meteorological Conditions

APPENDIX B EXAMPLE OF NARRATIVE OF A PRELIMINARY OE REPORT

Following it is presented verbatim the narrative of the preliminary OE investigation coded as ZHU-C-04-007 by the FAA:

ZHU-C-04-007 Saturday May8, 2004 1:14 pm: CPC working sectors 80 and 96 radar and radar associate positions combined for less than one minute, responsible for 7 aircraft, no previous OE/D. Aircraft#1/B733 was westbound to Austin, TX at FL 230 and was descended to 17,000 ft. (The first transmission for the CPC) The pilot of Aircraft#1 readback 11,000 and the CPC missed the incorrect readback. Aircraft#2/DH8, was westbound and level at 16,000 ft. As Aircraft#1 overtook N308RD while descending, separation was lost. Closest proximity was 800 feet vertical, 1.9 lateral Moderate Category "B". Required 1,000 feet/5 miles. 1 OS on duty and working a position of operation. 1 CIC monitoring the control room. 10 CPC's on duty, 6 CPC's on position and 4 CPC's on break. The position relief briefing was recorded and met standards.

The application of our taxonomy provided the following results:

- Errors: Hearback/Readback, Fail overtaking, Descend through
- Concurrent factors: Recent combination of sectors, Pilot deviation of clearance,

Mishearing, Operational supervisor absent (CIC in room), D-side absent

APPENDIX C EXAMPLE OF NARRATIVE OF A FINAL OE REPORT

Following it is presented verbatim the narrative of the preliminary OE investigation coded as 1050518579 (ZFW-C-05-E005) by the FAA:

This error occurred on the TXK-H altitude sector. TXK-H /SLR-H 90 R/RHO combined. TXK-H airspace lies East of the DFW terminal area FL240 and above. TXK-H controllers primarily work DFW terminal departures and overflights. All synopsis times are UTC and, unless otherwise stated, are derived from the voice recording. Times are approximate.

Aircraft#1 a SHV departure proceeding West Northwest bound was at FL240. Aircraft #2 an eastbound DFW departure initiated radio contact with TXK-H (R90) climbing to FL230. R90 instructed Aircraft #2 to climb and maintain FL330. approximately 10 minutes later, a relief briefing began. During the R90 relief briefing, R90 told the relieving controller not to worry about Aircraft #2 because he had not initiated radio contact. R90 believed that Aircraft #2 had been cleared to FL230. Approximately 1 minute after the relief briefing began, R90 recognized that Aircraft #2 had climbed above FL230 and was in conflict with Aircraft#1 at FL240. R90 issued instructions to separate the aircraft but separation was lost 9 seconds later. Training was taking place on the TXK-H radar associate position (D90).

Timeline summary: (Times are UTC and approximate, transmissions are acknowledged unless otherwise stated.)

18:47:35 Aircraft#1 initiated radio contact with R90 climbing to FL230.

18:47:55 After R90 completed a point-out to an adjacent sector, R90 instructed AIRCRAFT#1 to climb and maintain FL240.

18:58:15 Aircraft#1 requested direct SPS.

18:59:06 R90 cleared Aircraft#1 direct SPS.

19:04:12 Aircraft #2 initiated radio contact with R90 climbing to FL230. R90 cleared Aircraft #2 to climb and maintain FL330.

19:04:23 Conflict alert activated.

19:05:55 R90 began a position relief briefing.

19:06:22 R90 told the relieving controller that he was not talking to AIRCRAFT#2.

19:06:55 R90 realized that Aircraft #2 had climbed above FL230 by stating "holy crap." This transmission was not on the frequency but was recorded on the relief briefing line.

19:06:57 R90 instructed Aircraft #2 to expedite climb through FL250 for traffic. Aircraft #2 advised that he was executing a RA descent.

19:07:02 R90 instructed Aircraft#1 to descend and maintain FL230, expedite.

19:07:06 R90 told Aircraft#1 to disregard and climb and maintain FL250.

19:07:06 Separation was lost. 4.13 miles and 400 feet. This was closest proximity.

19:07:15 Separation reestablished.

19:07:15 R90 told the supervisor that he had an operational error. R90 again stated that he did not think Aircraft #2 had initiated radio contact. This was also recorded on the relief briefing line.

19:07:20 R90 told Aircraft #2, "Thanks for the help I'll have higher in a minute." Aircraft #2 stated: "We've got a visual on the traffic, what's the problem with that." R90 responded, "Well Sr. I forgot that you checked on, I apologize, I forgot that I had climbed you."

Blocks 30,31,32,40

R90 was not aware that an operational error was developing because he thought that Aircraft #2 was cleared to FL230 and he thought he was not in direct communication with the aircraft. R90 contemplated taking corrective action when he became aware of the situation. R90 took action to separate the aircraft but it was to no avail. Assistance was given in the form of a D-side. Training was taking place on the D-side position.

The application of our taxonomy provided the following results:

- Errors: Fail converging, Climb through
- Concurrent factors: Combined sectors, Developmental, Training in progress,

Other complexities (head-on with departures), Lapse in delivery clearance, Inadequate relief briefing, Other (not written interim FL)

- TACS RA events: Conflict detected by himself, incomplete pilot report, clearance given after TACS RA, changed altitude, opposite direction to TCAS RA.

APPENDIX D DEFINITION OF ERROR TYPES (TAXONOMY)

This appendix collects the glossary of terms and definitions used during the analysis. It does not intend to describe concepts universally agreed among the aviation community, but to clarify conventions used in this work.

Table 15

Definitions of Operational Error Type

OE Type	Definition
Aircraft overlapped:	The label or aircraft symbols were overlapped on the radar screen, preventing the controller to perform adequately his/her duties and identify the conflict.
Airspace violation:	An aircraft penetrated airspace that was delegated to another position of operation or another facility without prior coordination and approval. Also if controller issues a clearance that violates a restricted area, e.g., military, Minimum Vectoring Area (MVA).
Altitude inadequate:	New issued FL coincides with the conflicting a/c's FL. The vertical paths do not cross each other, but both aircraft are flying towards the same altitude or one of them flying towards the other's altitude. FL change is given by the current controller.
Cleared below minimum altitude:	Aircraft cleared below minimum allowed altitude (MVA). This is always coupled with airspace violation, but not vice versa. The altitude change had to be given by the current controller.
Climb through:	The aircraft is cleared to climb to a FL that crosses other aircraft's FL path. The current sector controller issues the clearance for the level change. Changing FL to the same altitude that other aircraft has, is considered "Altitude Inadequate".
Control coordination:	Failure to correctly coordinate (incomplete or absence of coordination between controllers) either inter- or intra- facilities, e.g., dismissing coordination or passing incomplete information.

OE Type	Definition
Datablock misentered information:	The controller enters wrong information, e.g., he or she issued a FL or heading and he or she entered a different one.
Descend through:	The aircraft is cleared to descend to a FL that crosses other aircraft's FL path. The current sector controller issues the clearance for the level change. Changing FL to the same altitude that other aircraft has, is considered Altitude Inadequate.
Fail converging:	Failure to detect a conflict between aircraft with converging horizontal routes. Both aircraft need to have converging headings issued in other sectors or by the CPC in control but very in advance to the conflict. That is, the controller fails to detect the convergence. It is possible having initially both aircraft at different levels.
Fail Identification altitude climbing/descending:	Failure to identify a conflict when one of the aircraft is descending or climbing, but the clearance was issued by other sector. If it was issued by the current sector, it is classified under "climb through", "descend through" or "altitude inadequate".
Fail overtaking traffic:	Failure to separate overtaking traffic. It is included violations of standard separation when aircraft is caught behind by other with the same course or either when the CPC gives a vector to locate the aircraft in a parallel path or to resume heading (not included parallel tracks issued in other sector).
Flight Paper Strip (FPS) misentered information:	The controller writes wrong information on the FPS or omits subsequent revisions, e.g., he or she issued a FL or heading and he or she entered a different one on the FPS.
Hear/readback:	The pilot read back incorrectly the instruction given by the controller, and it goes undetected by the controller. It includes no pilot readback errors too.
Instruction not Intended:	Controller issues an instruction s/he stated as non intended (e.g., slips of tongue when giving a FL, speed, etc)

OE Type	Definition
Letter-of-agreement (LOA) misapplication:	Misapplication of letter of agreement between sectors. This is a particular case of “misapplication of procedure”. If there is a LOA to apply and the controller did not do it.
Misapplication of procedure:	Controller applies a procedure that is not longer valid or it is not possible to apply under current circumstances, e.g., apply VMC separation when aircraft are flying in IMC.
Misread information:	Controller read wrong information; either he or she read a wrong field or stated reading incorrect information in the report. It does not include short term failures when retrieving information.
Other:	Other situations/errors not contemplated in the list before.
Overlooked traffic:	Controller misses or ignores the traffic situation for some reason (e.g., distraction, preoccupation, other conflict, etc). It should be clearly stated in the OE description that the controller overlooked the traffic.
Speed inadequate:	Speed issued is not adequate to prevent loss of separation. It might be misestimated, or coupled with other OE, such as given at a wrong time (i.e., Temporal error issued)
Temporal error-issue:	Failure to issue timely the instruction, i.e., the instruction is correct, but it is not issued in time to prevent loss of separation. OE is only categorized as temp error-issue if this fact is written in the report.
Transpose information:	Alter the sequence of saying a clearance for two different aircraft, mixing callsigns, numbers, symbols and/or instructions. The confusion involves two aircraft that exists in the sector (or one was recently handed off), or same airline but wrong number (e.g AA1345 instead of AA1365, which is flying as well).
Vector inadequate:	Controller is giving an incorrect or inaccurate heading (vector) to the aircraft that creates the conflict. It is sometimes coupled with “fail overtaking”.

OE Type	Definition
Wrong aircraft:	The aircraft callsign used is wrong. There is no confusion among aircraft within the sector, but the controller uses a callsign that does not either exists or is not in the sector. .

APPENDIX E DEFINITION OF CONCURRENT AND CONTEXTUAL FACTORS

This appendix collects the glossary of terms and definitions used during the analysis.

Table 16

Definitions of Contextual and Concurrent Factors

<i>Contextual Factor</i>	<i>Definition</i>
Climb slow/fast	a/c did not climb as quickly or climb faster than controller anticipated
Combined sectors	Controller was working with combined sectors. This is not having merged both R-side and D-side roles in one position.
Descend slow/fast	a/c did not descend as quickly or descend faster than controller anticipated
Distraction	Some event attracted controller attention and diverted him/her from the evolving conflict.
D-side absent	D-side was not on duty and R-side controller assumed responsibilities of both.
D-side coordination:	D-side coordinated with other sectors a change in the a/c profile, which conflicted with other a/c in the vicinity. CPC was not able to separate, either because of lack of internal coordination or lapse on the application of further measures.
Flight plan not checked:	Controller was not aware of the FPL and a/c made an "unexpected" maneuver (it is unexpected because the controller is not aware, but it is compliant with the FPL)
Inadequate relief briefing:	Inadequate position relief briefing either coordination or communication as the result of the position relief, such as incomplete or erroneous. It must be explicitly stated.

<i>Contextual Factor</i>	<i>Definition</i>
Lapse in coordination	Controller forgot completely or partially coordinating with the adjacent sector.
Lapse in delivery clearance:	Controller forgot delivering a clearance s/he intended.
Mishearing	Either pilot or controller misheard a voice message.
Misjudgment	The maneuver was miscalculated or misjudged by the controller, because the complexity of the traffic or distraction. It is present when the OE is related with timing.
Misread information:	Some information misread trigger the sequence that leads to the error.
Multiple aircraft:	A conflict involving several a/c or the OE was created due to a cascade effect when avoiding a conflict elsewhere.
No pilot response/deviation	There was no pilot response to a controller request or his/her action did not follow the corresponding clearance, if any (e.g. due to a pilot hear back error). This includes encounters where a different a/c is responding to a controller call and the clearance was not addressed to him.
Not enough information:	Not enough information to identify any factor relevant at the time of the error.
OS absence / CIC present	OS was not in the room (e.g. in a break), s/he was engaged in other tasks at other sector, or working a radar position at the same time. The report states clearly the circumstances. It also includes when there is a CIC.
Other complexity factors:	Traffic situations that creates unusual conditions and therefore increases complexity of controller operations, which are not gathered under other category (e.g. MIT or military operations)
Other:	Other factors identified

<i>Contextual Factor</i>	<i>Definition</i>
Pilot / Other controller request a conflicting clearance	Pilot requested a conflicting clearance that was critical to lose separation, and controller did not realize.
Point out aircraft:	One controller pointed out an aircraft to other sector. It is consider that the traffic situation is more complex.
Recent combination/decombination:	Sectors were recently combined/recombined. "Recently" is considered here within 5 minutes.
Slip in clearance:	Slip on delivering either FL, callsign or heading.
Stuck mike:	The channel or the microphone failed in the transmitter mode because other microphone blocked the frequency. There was no transmission of the message.
TCAS RA maneuver	TCAS RA is present in the OE and it might have contributed to the conflict and/or increased the complexity. Not all TCAS are considered in this category.
Temporal airspace complexity:	OE occurs with some unusual airspace configuration that might have impacted on the complexity. (e.g., change of runway configuration due to weather, or use of an unusual airways due to high traffic volume)
Traffic complexity	Traffic complexity rating. This is rated by controllers, but because usually the summary report has no this information available, traffic is considered complex if the reports states the MAP number and the number of a/c in the sector is higher than 2/3 of MAP.
Training in progress	There was training being conducted at the position where the error took place.
Transmission stepped on:	Here the transmission was partially-blocked (stepped on). Part of the message was audible, and part was not.
Turbulence complexity:	Turbulence was created due to other a/c presence

<i>Contextual Factor</i>	<i>Definition</i>
Turn wide/sharp/early/late	a/c turn was wider / more sharply / was initiated earlier/later than controller anticipated
Weather complexity	Weather or conditions caused by weather increase the complexity of operations, e.g., route deviation, closure of a runway, icing affecting climb

APPENDIX F INTRODUCTION TO JANUS METHODOLOGY AND EXAMPLE
OF APPLICATION.

The JANUS technique (Isaac and Pounds, 2001; Pounds and Isaac, 2002; Pounds and Isaac, 2003; Eurocontrol, 2003b) is used to identify and to assess human errors in ATC. The JANUS technique has been developed in coordination by the FAA and Eurocontrol. It is the result of a harmonization process of both organizations' human error identification techniques, the Human Reduction in ATM technique (HERA) and the Human Factors and Analysis and Classification System (HFACS).

The JANUS technique has two main dimensions to identify and to be described by the analyst: one related to the error itself (what error did occur and how it did occur) and the other related to the context (when and where it did occur, who was involved). These dimensions consist of several classification layers, which will be identified following a series of decision-flowchart diagrams, aiming at building a more in-depth approach. This helps to explain the contributing factors and underlying causes of the error (Eurocontrol, 2003b).

In these flowchart diagrams, first, the error type is identified. This is the external manifestation of the error, e.g., action performed too late. Second, the error mechanism is identified, which is related to the internal manifestation of the error, identifying the cognitive function that failed, e.g., late visual detection. Third, the information processing level is coded, which identifies the psychological cause of the error mechanism, i.e., how the error occurred. One example might be a distraction by an external event. Finally, contextual conditions that were present when the error occurred and influenced the controller performance and, therefore, played a role in the error making process, are also identified, e.g., pilot-controller communication with other

aircraft was impaired because the frequency was blocked. These error classifications are depicted in Figure 36.

Figure 36. Classification schemes that need to be identified when applying the JANUS methodology.

Note. Adapted from Eurocontrol (2003). The human error in ATM technique (HERA-JANUS) (Report No. HRS/HSP-002-REP-03). Brussels, Belgium: Author.

Table 17 presents an example of the application of the JANUS to one of the OE reports. This example shows the difficulty to categorize the error in each layer. For example, in error#1 the information processing was classified as *slip of the tongue* and in error#2 as *intrusion of thoughts*. This decision was speculative if we consider the error description.

Table 17

Example of application of Janus to an OE report

Description of OE
<p>The incident occurred at 7:27 a.m. on February 10, 2005. Sector 21 radar and radar associate positions were staffed. Traffic was average with the controller responsible for 12 aircraft, with four on frequency. The R21 and RA21 specialists had both been on position 20 minutes prior to the incident. The aircraft involved were AIRCRAFT#1 (T/321/Q), a LAX (Los Angeles) departure. Eastbound, and AIRCRAFT#2 (BE20/Q), a see (Gillespie) departure, northwest bound. At the time of the error, both aircraft were on sector 21's frequency. (the following times are UTC)</p> <p>At 15:21:18 R21 placed a J-ring on AIRCRAFT#2's datablock.</p> <p>At 15:22:50 AIRCRAFT#1 checked on sector 21's frequency climbing through 10,500, to 17,000. R21 cleared AIRCRAFT#1 to climb to FL230 [1], and resume normal speed leaving fl180, which was acknowledged. R21 then entered an interim altitude of fl230 in AIRCRAFT#1's data block.</p> <p>From 1523:20 until 1523:48 D21 was not monitoring the frequency, as he was busy with landline coordination.</p> <p>At 15:24:27 r21 entered an interim altitude of 17,000 [2] in AIRCRAFT#1's data block.</p> <p>At 15:25:23 r21 issued traffic to AIRCRAFT#2 at ten o'clock and 15 miles, climbing through 15,000 to 17,000, an airbus, which was acknowledged.</p> <p>At 15:25:47 R21 issued traffic to AIRCRAFT#1 at two o'clock and 15 miles, northwest bound, a king air at fl180, which was acknowledged.</p> <p>At 15:27:02 R21 advised AIRCRAFT#1 that he was assigned 17,000, and cleared him to turn 30 degrees left for traffic at two o'clock and 5 miles, northwest bound, at fl180.</p> <p>At 15:27:04 conflict alert activated between the two aircraft.</p> <p>At 1527:13 OEDP activated between the two aircraft at 3.4 miles and 200 feet. At the same time, AIRCRAFT#1 stated he was descending for a TCAS RA, and that they were assigned fl230. R21 responded that awe590 was assigned fl230, then cleared AIRCRAFT#2 to turn 20 degrees left for traffic at 12 o'clock and one mile, eastbound out of 17,600.</p> <p>At 15:27:25 AIRCRAFT#2 reported the traffic in sight.</p> <p>At 15:27:27 the two aircraft passed at their closest point of 1.12 miles and 700 feet.</p> <p>At 15:27:30 AIRCRAFT#1 stated they were assigned FL230, and normal speed leaving fl180. R21 responded that swa187 was given normal speed and maintain 17,000.</p> <p>#29- the employee stated that she did not request assistance prior to the incident.</p> <p>#30- the employee stated that she was aware that an operational error was developing when she saw AIRCRAFT#1 climb above 17,000.</p>

#31- the employee stated that she contemplated taking corrective action.

#32- the employee stated that she attempted to take corrective action by issuing AIRCRAFT#1 clearance to 17,000 and a 30 degree left turn.

#40- the OSIC stated that he had just looked at sector 21 and had seen the interim altitude of 17,000 in AIRCRAFT#1's data block, indicating to him that the two aircraft were separated. Based on his observation, he did not believe assistance was required.

Description of error # 1

The controller cleared AIRCRAFT#1 to climb FL230, but we intended to send this FL to AWE590

Error Type	Selection Action – Right action to wrong aircraft
Error Detail	Response execution
Error Mechanism	Incorrect information transmitted
Information Processing	Slip of the tongue

Description of error # 2

The controller cleared to FL230, but he introduced FL 170 in the datablock

Error Type	Information Transmitted – Type wrong information
Error Detail	Response execution
Error Mechanism	Typing error
Information Processing	Intrusion of thoughts

APPENDIX G RESULTS OF THE APPLICATION OF JANUS

This Appendix will present the result of the application of JANUS to a set of 68 reports with TCAS RA. Error types and error details were identified without big problems, but the error mechanisms and information processing graphs contain are speculative because the description of the reports did not allow extracting internal information about those mechanisms. These results have to be considered as a first attempt to apply the methodology, but they might not be representative of the actual controller's mechanisms of making errors.

Figure 37. Distribution of error types of Janus methodology.

Figure 38. Percentage of error detail as identified by Janus methodology.

Figure 39. Percentage of distribution of errors mechanisms as identified of Janus methodology.

Figure 40. Percentage of Information Processing factors as identified by Janus methodology.

APPENDIX H HUMAN SUBJECTS INSTITUTIONAL REVIEW BOARD**APPROVAL**

San José State
UNIVERSITY

**Office of the Provost
Associate Vice President
Graduate Studies & Research**

One Washington Square
San José, CA 95192-0025
Voice: 408-924-2427
Fax: 408-924-2477

E-mail: gradstudies@sjsu.edu
<http://www.sjsu.edu>

To: Jose-Luis Garcia-Chico
518 Church Street
San Francisco, CA 94114

From: Pamela Stacks, Ph.D. *Pamela C Stacks*
Associate Vice President
Graduate Studies and Research

Date: October 26 2006

The Human Subjects-Institutional Review Board has approved your request to use secondary data related to human subjects in the study entitled:

"Human Factor Analysis of Operational Errors in Air Traffic Control"

This approval, which provides exempt status under Category C, is contingent upon the subjects included in your research project being appropriately protected from risk. Specifically, protection of the anonymity of the subjects' identity with regard to all data that may be collected about the subjects from your secondary sources needs to be ensured.

The approval includes continued monitoring of your research by the Board to assure that the subjects are being adequately and properly protected from such risks. If at any time a subject becomes injured or complains of injury, you must notify Dr. Pamela Stacks, Ph.D. immediately. Injury includes but is not limited to bodily harm, psychological trauma, and release of potentially damaging personal information. This approval for the human subject's portion of your project is in effect for one year, and data collection beyond October 26, 2007 requires an extension request.

If you have any questions, please contact me at (408) 924-2480.

cc. Kevin Corker, ENG 485D-0085

The California State University:
Chancellor's Office
Bakersfield, Channel Islands, Chico,
Dominguez Hills, East Bay, Fresno,
Fullerton, Humboldt, Long Beach,
Los Angeles, Maritime Academy,
Monterey Bay, Northridge, Pomona,
Sacramento, San Bernardino, San Diego,
San Francisco, San José, San Luis Obispo,
San Marcos, Sonoma, Stanislaus