University of Waterloo
Department of Philosophy

Examining the Collision Safety System in Commercial Aviation

A Study of Cognition and Human Performance

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Introduction

This paper discusses the midair collision detection and avoidance system for commercial aircraft and highlights the cognitive demands placed on both air traffic controllers and flight crew through the use of this system. An evaluation of the types of controller and flight crew error in the context of human performance may yield operational suggestions to improve the current collision detection and avoidance system.

The area of collision detection and avoidance receives significant attention in the aviation industry because all collisions are catastrophic. Every incident directly affects the aircraft occupants and their families, reduces public confidence in the airline industry, and comes at great cost to the airline operator. Efforts by all stakeholders continue to develop better system to keep the skies collision-free.

In 2001, there were 7 near midair collisions reported in the United States involving commercial air carrier aircraft[1]. In all cases, the onboard systems successfully warned pilots, allowing time for avoidance and recovery measures. In July 1, 2002, a Tupolev-154 Russian airliner collided with a DHL cargo plane over South Germany. Error by air traffic control combined with unfortunate circumstances led to the aircrafts' fate. This paper will introduce the prominent concepts of human performance in the collision safety system, and put into perspective the causes for the July accident.

[1] Near Midair Collision System Database, Federal Aviation Administration, https://www.nasdac.faa.gov/

Components of the Collision Safety System

There are three primary components that make up the collision safety system: air traffic control services operating from ground-based radar facilities (ATC), flight crew in command of the aircraft (CRW), and the onboard Traffic Alerts and Collision Avoidance System that detects and provides non-conflicting avoidance maneuvers to the flight crews of the involved aircraft (TCAS)[2]. There is also a separate ground-based safety system that only warns ATC of impending collision threats. The high level interactions of these components are illustrated in Figure 1.

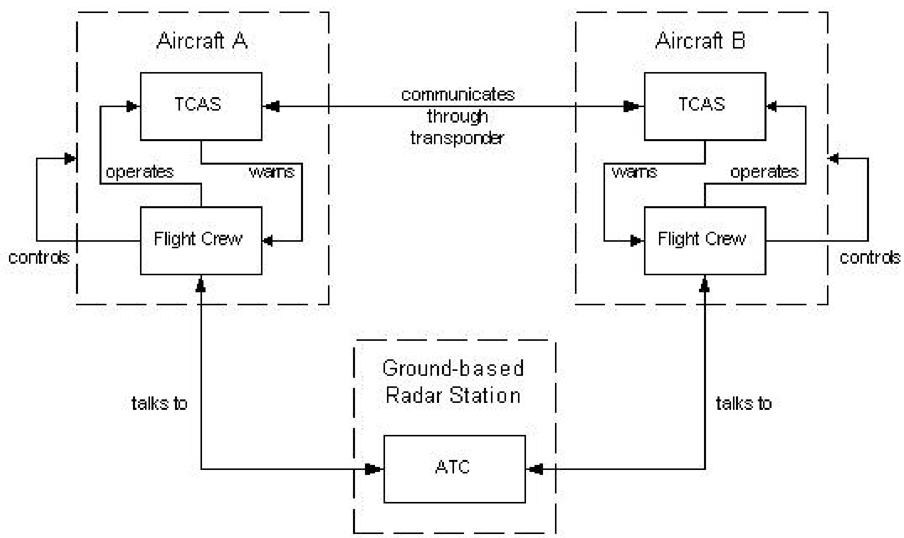

Figure 1 - Collision Safety System Interactions

[2] *Introduction to TCAS II Version 7*, U.S. Department of Transportation, Federal Aviation Administration. November, 2000

The TCAS System

The TCAS system evolved from the standards of the ACAS system of the 1970's, and was first implemented in 1981 by the Federal Aviation Administration. The latest implementation, TCAS II version 7, is widely adopted internationally and mandated by North American aviation authority[3].

TCAS operates independently of other radar and traffic management systems, ground-based or otherwise, and is responsible for detecting intruders and proposing avoidance maneuvers to pilots in threatening situations. This independence boasts operational advantages, but may lead to advice that conflicts with ATC warning systems, resulting in potentially dangerous situations.

TCAS Logic

TCAS relies on a TCAS transponder and Mode-S transponder on both aircraft to provide non-conflicting resolution advisory to both aircraft. With a Mode-C transponder, only threat traffic is conveyed to the pilots and without resolution advisory.

Based on the airspeed of ownship, the TCAS computer chooses a suitable 'protected volume' of ownship to detect for collision threats. The TCAS transponder interrogates vicinity aircraft for information, and the Mode-S transponder receives their bearing, range, and altitude information. The TCAS computer uses this data to project the aircraft trajectories and if the closest point of approach (CPA) of the intruder is within the

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[3] *Introduction to TCAS II Version 7*, U.S. Department of Transportation, Federal Aviation Administration. November, 2000

protected volume, it is considered a threat. If a breach of protected volume is within 50 seconds of occurring, a Traffic Advisory (TA) is displayed on the primary flight display with an aural announcement: ‘Traffic. Traffic.’ If a breach of protected zone is within 20 seconds of occurring, a Resolution Advisory (RA) is displayed and an aural announcement[4]. RA’s may instruct the pilot to climb or to descend.

[4] *Introduction to TCAS II Version 7*, U.S. Department of Transportation, Federal Aviation Administration. November, 2000

A Work Domain Analysis of TCAS, Flight Crew, ATC interactions

To put into perspective the cognitive demands placed on TCAS, flight crew, and ATC, it is necessary to examine them separately in the work domain. By determining the separate system inputs and outputs, unbiased evaluation of the operational procedures can be obtained. Discussion can then be performed on both what the system presently does, and what the system can possibly do to increase performance and reduce errors.

The first part of work domain analysis is presented here: means-end abstraction hierarchy. It provides sufficient review of the operational components to provide linkage to the major cognitive concepts. The abstraction hierarchy focuses on 'why-how' relationships between the system components, beginning with high level system goals and ending with low level physical form and their configuration. Means-End Abstraction Hierarchy of TCAS, flight crew, and ATC can be found in Tables 1 and 2.

Table 1 - Means End Abstraction Hierarchy - Part 1

Means- End Abstraction Hierarchy			
Abstraction Layers	**TCAS**	**ATC**	**Flight Crew**
Goals, Purposes, Constraints	- Provide safe passage to all aircraft in the vicinity	...	...
Abstract Functions and Priority Measures (measurable principles: mass, energy, etc.)	- Warn flight crew of air traffic volume in immediate vicinity (definable up to 40 nmi) - Suggest vector maneuvers to avoid projected collision scenarios	...	...
General Functions	- Detect aircraft in vicinity - Collect telemetry of all aircraft (speed, bearing, range) - Calculate resolution advisories to aircraft conflict	...	...
Physical Processes and Activities	- Display traffic advisories (45 sec. to CPA) - Dislpay resolution advisories (20 sec. to CPA) - Sound audible advisory alerts DEFINITION : CPA is closest point of approach	...	...
Physical Form and Configuration	- Mode S transponder - TCAS transponder - Antennas - Cockpit advisory dislpays	...	...

Table 2 - Means End Abstraction Hierarchy - Part 2

Means- End Abstraction Hierarchy		
Abstraction Layers	**ATC**	**Flight Crew**
Goals, Purposes, Constraints	- Provide safe passage to all aircraft in the vicinity	- Provide safe passage of their aircraft of responsibility
Abstract Functions and Priority Measures (measurable principles: mass, energy, etc.)	- Warn flight crew of air traffic volume in immediate vicinity (definable up to 40 nmi) - Suggest vector maneuvers to avoid projected collision scenarios	- Direct aircraft vector according to safe traffic regulations (flow through specified airways of travel) - Pilot aircraft within aircraft tolerances (aerodynamics, dynamics of aircraft structure)
General Functions	- Detect aircraft in vicinity - Collect telemetry of all aircraft (speed, bearing, range) - Calculate resolution advisories to aircraft conflict	- Control attitude, airspeed, altitude, heading, climb rate of aircraft - Adjust attitude, airspeed, altitude, heading, climb rate of aircraft
Physical Processes and Activities	- Display traffic advisories (45 sec. to CPA) - Dislpay resolution advisories (20 sec. to CPA) - Sound audible advisory alerts DEFINITION : CPA is closest point of approach	- Control pitch, roll of aircraft using flight stick - Control yaw of aircraft using foot pedals - Control engine power using throttle
Physical Form and Configuration	- Mode S transponder - TCAS transponder - Antennas - Cockpit advisory dislpays	- Flight stick - Throttle levers - Foot pedals - Other instrument wiz-bangs

TA’s, RA’s, and Flight Crew Interaction

Traffic Advisories inform the flight crew of intruder threats that may breach ownship’s protected volume within 50 seconds. The flight crew need not respond to TA’s, and continue to obey ATC flight instructions. However, TA’s are a positive motivator for ATC and pilots in the vicinity to confirm traffic reports and intentions with each other. TA’s are displayed on the traffic map, accompanied by aural announcement.

Resolution Advisories (RA) indicate threat traffic on the traffic map and provide critical vertical maneuver advice to avoid a disastrous incident. On the vertical speed indicator, lights will show green, yellow, and red along the vertical speed scale to indicate the climb rates that will achieve safe separation, provide potential threat, and lead to potential collision, respectively (Figure 2, right photo). Aural announcement is also produced for RA’s. The pilot responds to the RA by executing a climb rate in the green colour zone.

TCAS Symbology is explained in Figure 3, and operational description of TCAS Symbology is found in Appendix A.

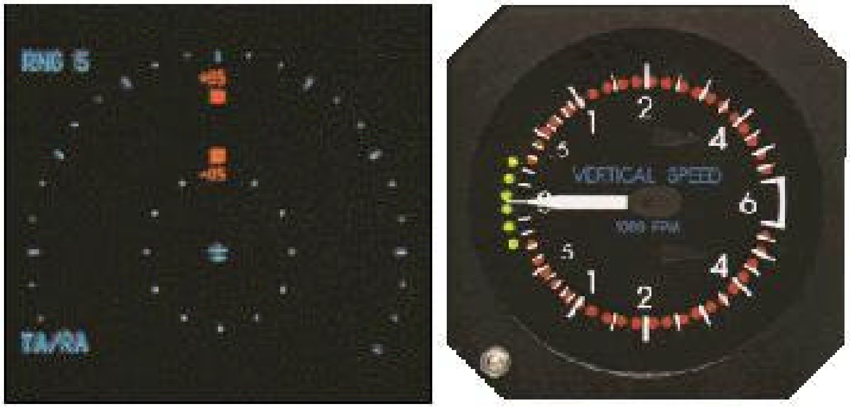

Figure 2 - TCAS Flight Displays (Traffic map, and Vertical Speed Indicator)[5]

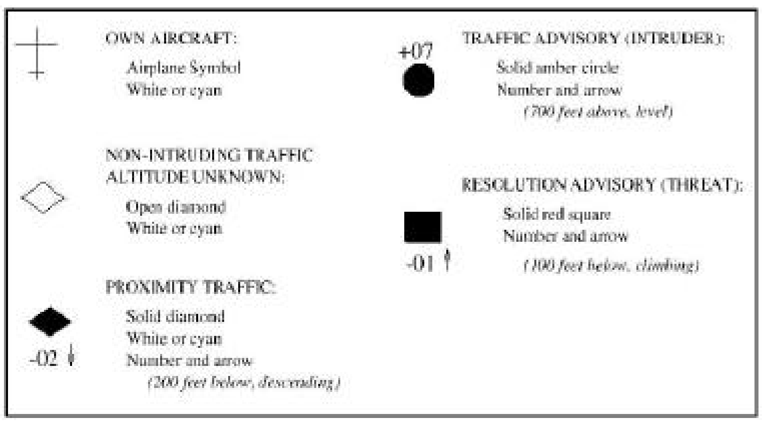

Figure 3 – TCAS Symbology[6]

[5] *Collision Avoidance System User's Manual TCAS II / ACAS II*, ACS-5059, Rev 5 - 02/2000, Honeywell Inc.
[6] Leveson N. et al, *Sample TCAS Intent Specification*, Safeware Engineering Corp.

Flight Crew and ATC Interaction

According to North American air safety regulations, the flight crew must exercise all measures necessary to insure flight safety. In the case of RA's, the flight crew is expected to execute all RA's, with the understanding that they are overriding ATC flight instructions[7]. Additionally, it is the flight crew's responsibility to inform ATC of the RA incidents, and confirm execution of the maneuvers. ATC is required to release responsibility of the aircraft's route in the event of an RA, reinstating control after the RA maneuver is executed. However, should an RA be advised to flight crew and they fail to inform ATC, the system exhibits communication breakdown[8]. ATC may continue to issue instructions, sometimes conflicting with TCAS recommendations. This was the case in the July 1, 2002 midair collision.

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[7] *Introduction to TCAS II Version 7*, U.S. Department of Transportation, Federal Aviation Administration. November, 2000

[8] *TCAS II: Genie Out of the Bottle?,* ASRS Directline, Aviation Safety Reporting System, June 1993.

Human Performance and Error Analysis

Fault tree analysis[9] was conducted in 1983 by MITRE Corporation, a contractor that contributed to the TCAS efforts. In it, they created a branch of fault circumstances leading to an incident of near midair collision (NMAC). A summarized fault tree relating to human performance criteria is shown in Figure 4.

Root Fault: Maneuver is required to avoid NMAC, but pilot does not maneuver

- Controller instructions (if any) do not lead pilot to maneuver to avoid NMAC
  - Controller issues an instruction that the pilot does not receive
  - Controller does not issue any instruction
    - Controller perceives conflict, but cannot devise a resolution advisory
    - Controller perceives conflict, but has no time to calculate resolution advisory
    - Controller does not perceive the conflict
      - Controller does not perceive conflict from his flight information
      - Conflict alert does not cause controller to perceive conflict
        - No conflict alert is displayed
        - Controller believes alert is a false alarm
- Pilot does not maneuver the aircraft so as to avoid the NMAC based on his perception (if any) of the conflict
  - Pilot does not realize there is a conflict
    - Pilot does not perceive that there is a conflict form monitoring voice communications
    - Pilot does not realize there is a conflict (by visual awareness, without TCAS)
      - Crew may be looking, but threat not in view
      - Crew sees threat, but does not perceive it as conflict
      - Crew is not looking for the threat
        - Crew is relying on TCAS to identify potential threats
        - Crew is preoccupied
    - Pilot does not realize that there is a conflict from TCAS TA
      - Crew does not perceive the traffic advisory
      - Crew does not perceive the conflict the traffic advisory indicates
  - Pilot realizes there is a conflict but does not maneuver aircraft to avoid NMAC
    - Pilot cannot select a maneuver
      - Inadequate visual conditions
    - Pilot does not make a maneuver in time to avoid NMAC
      - Has not visually acquired the threat
      - Selects and execute maneuver too late
    - Pilot takes an action that does not avoid NMAC
      - Pilot did not avoid NMAC because he visualized the situation incorrectly
      - Pilot did not avoid NMAC because he misinterpreted voice communications
- TCAS RA is issued, but pilot does not avoid NMAC
  - TCAS displays a RA that the pilot does not follow
    - Pilot does not execute RA at all
      - Crew does not believe RA is correct
      - Crew does not perceive RA alarm
        - Inadequate alarm design
        - Crew is preoccupied
    - Pilot executes RA but inadequately
      - Pilot stops before RA is removed
      - Pilot continues beyond point RA is removed
      - Pilot delays execution beyond time allowed

Figure 4 - Summarized Fault Tree Analysis

[9] Leveson N. et al, *Sample TCAS Intent Specification*, Safeware Engineering Corp.

ATC – Human Performance

Stress

Air traffic control is a high stress occupation. A variety of stressors influence information processing and cognition, including the visual clutter of their radar monitors, frequent auditory communication from all the aircraft in their sector, time pressure (in the case of collision avoidance routing of aircraft), and others. The high-load situation of ATC work often perpetuates stress, degrading performance[10] (Wickens, p481).

Capacity and Loss of Working Memory

Working memory is crucial to ATC work. They must keep track of all aircraft in their sector at all times and maintain minimum distance of aircraft routes. Simultaneously, they must be able to receive inbound traffic, 'handoff' their traffic to another air traffic controller in adjacent sectors, provide route instructions to pilots, and confirm aircraft maneuver status. As such, visual echo of pilot messages and recent instructions are displayed on the radar screen with visual tags beside aircraft indicating flight number and altitude to help offload working memory or stress-induced memory loss[10] (Wickens, p248)

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[10] Wickens et. al, *'Engineering Psychology and Human Performance'*, Prentice Hall, 2000.

Chunking of Memory

In the context of memory chunking, the average item capacity is 7 plus/minus 2[10]. ATC may remember aircraft call signs by chunking the alphanumeric string into a letter portion and a number portion (eg. NM007 => 'NM' and '007'). They may also chunk aircraft into groups (eg. A group of aircraft flying at altitude of 36,000 ft., 'inbound' and 'outbound' groups).

Signal Detection and Visual Search

ATC screens look similar to Figure 5. It is quickly apparent that the search task of aircraft along is a visually intensive task. ATC must first be able to perceive aircraft representations amidst flight vectors, landmarks, and other text tags. Second, ATC must be able to read the status of each aircraft and thirdly, to calculate whether to redirect them based on their desired destinations. The ATC visual search task can be a frustrating one.

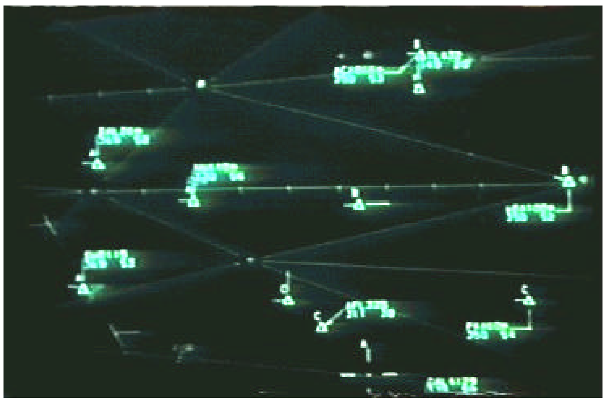

Figure 5 - ATC Radar Screen

Spatial Displays (2D vs. 3D)

Brian Fisher et. al from Simon Fraser University worked on 3D representational displays for ATC. They research issues of colour salience, feature salience, and a spatial indexing technique to produce representation techniques that provided ATC with flight status, route information, and collision detection (see Figure 6). Note the cylindrical representation of ownship protected volumes in the second image of Figure 6.

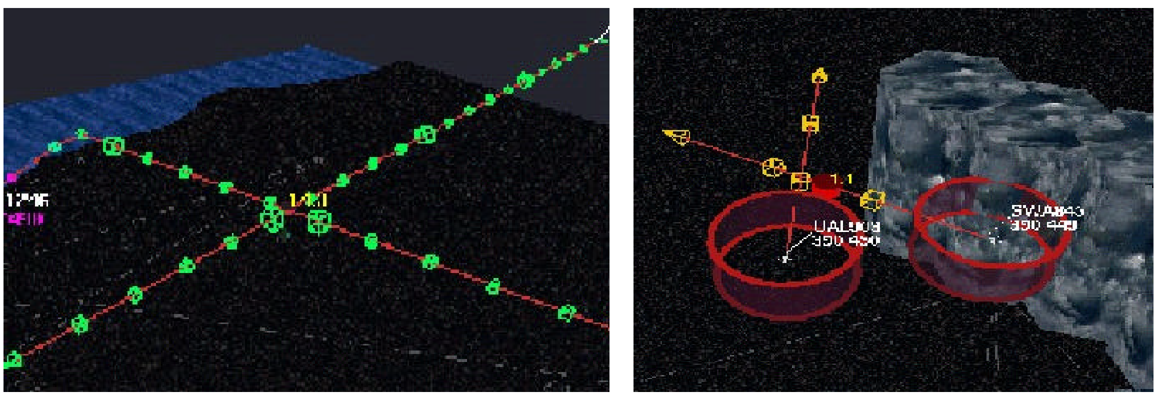

Figure 6 - Spatial ATC Displays[11]

Abstraction

The processing of ensuring airspace safety through directing traffic flow, and directing traffic flow through instructing aircraft, is one of cognitive abstraction that is outlined in the means-end abstraction hierarchy. In the ATC task, the controller constantly moves between the layers of 'goals', and 'general functions', as he monitors, scans, and acts on the information he sees on the screen. When a potentially dangerous situation unfolds, his objective of maintaining distance separation will provoke an instruction to deviate the intruder aircraft. At the same time, he must evaluate if the new

[11] Fisher et al., *Perceptual cognition and the design of Air Traffic Control interfaces*, 1999.

deviated course will produce a new flow of traffic that threatens the larger goal of airspace route management.

Attention switching

Cognitive workload is affected by constant attention switching of ATC. He must monitor all aircraft individually, and prioritize which aircraft to monitor based on how soon an aircraft will leave the current sector, how close aircraft are to each other, and the degree of traffic congestion throughout his sector. Mistaking the priority of tasks, and possibly confusing aircraft in the ATC's mind, can lead to wrong instructions, aircraft incidents and accidents[12] (Wickens, p446).

[12] Wickens et. al, *'Engineering Psychology and Human Performance'*, Prentice Hall, 2000.

Flight Crew – Human Performance

Redundancy

System redundancy is most apparent in the flight controls of a commercial airline by the two command seats in the cockpit with full control capability. The Caption and First Office have separate primary flight displays and flight sticks and pedals, while sharing a system status display, throttle lever, and communications equipment. The reason for redundancy is twofold. The first is for ensuring safety of the passengers. Should one of the pilots 'fail', the other can take over to recover the aircraft. Also, the task of flying a commercial plane is stressful, complex, and cognitively demanding. The First Officer helps to confirm and execute some of captain's commands, while applying a sanity check on all of the captain's actions. ATC communicates to both of the crewmembers, and there is a defined protocol of captain and first officer interaction that ensures safe and responsible operation of the aircraft. In the context of alarms and displays, aural as well as visual displays inform the crew of outstanding situations, such as the occurrence of TCAS advisory[13] (Wickens, p215), aircraft overspeed, terrain warning, and other system critical warnings. ATC and crew also exercise confirmation protocol on the radio.

[13] Wickens et. al, *'Engineering Psychology and Human Performance'*, Prentice Hall, 2000.

Signal Detection

Amongst all the display screens that appear in the command panel of a commercial airline, alarms may occur regarding any facet of the aircraft, from a collision threat to a fuel injection problem to one of the engines. Depending on severity of the problem, the status panels provide sufficient alarming mechanisms, and continuing research is helping to improve flight crew detection of alarms without affecting cognitive load. In the TCAS system, aural alarm accompanies the traffic map that shows the intruder craft, a brief text description of the type of advisory, and relevant intruder information. Given the severity of a collision alarm, ensuring signal salience will greatly improve the chances of conflict detection and recovery.

Situation Awareness

The concept of SA is well developed by Mica Endsley of SA Technologies Inc., and plays an important role in the cockpit. The pilots must be fully aware of their surroundings by monitoring their instrument displays, communicating with ATC and vicinity aircraft, as well as making visual checks of the situation outside the cockpit window. Additionally, the pilots must be fully aware of the aircraft's altitude, attitude, speed, and climb rate to assist them in the piloting task. In emergency situations, developed awareness of the current situation will quicken the assessment and execution of the required procedures to bring the situation under control.

By cross-mapping the measures of human performance between ATC and the flight crew, the flight crew/ATC system can be seen as a complicated and heavily cognitive interaction. This must be considered when designing for the cockpit.

Discussion of the July 1, 2002 Accident in the Context of Human Performance

In this particular accident, ATC had given conflicting instructions to the Tupolev-154 crew that conflicted with the onboard TCAS advisory. The Tupolev TCAS system produced a Resolution Advisory to “Climb, Climb”, but ATC instructed the Tupolev to descend. Meanwhile, the DHL cargo plane was advised by TCAS to “Descend, Descend”[14]. The two aircraft then collided at 35,400 feet.

From additional investigative reports, the most significant discrepancy that led to the accident is the conflicting advice of ATC and TCAS in the Tupolev-154. From a cognition/automation perspective, it is a reasonable requirement that ATC be aware of what TCAS tells the flight crew in order to make an informed judgement of whether or not to interfere with the collision avoidance maneuvers, and if so, to calculate what instructions to give to each aircraft. However, it is very likely that lack of situation awareness, workload stress, and time pressure prevented the Tupolev pilot from communicating to ATC that TCAS had given a ‘climb’ RA. Similarly, the DHL cargo plane did not inform ATC regarding its execution of the ‘descend’ RA maneuver. With ATC unaware of either aircrafts’ advisories or course of action, it gave an arbitrary instruction to the Tupolev (in this case, ‘climb’), assuming the DHL aircraft flight path remained unaltered.

This accident is a grave example of inadequate situation awareness. In this incident, the three parties were unaware of each other’s actions, leading to the midair collision.

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[14] AirDisaster.com Accident Database
http://www.airdisaster.com/cgi_bin/view_details.cgi?date=07012002&airline=DHL+Aviation

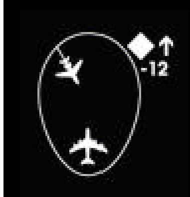
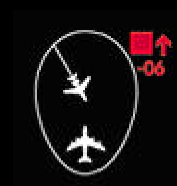
Recommendations & Conclusions

In co-ordinated collision avoidance maneuver efforts, the most useful pieces of information that help develop situation awareness are aircraft intent, plan of action, and status of execution. From this case study, further research is recommended in the following areas:

- ATC interface that increases situation awareness of overall airspace traffic
- ATC interface that communicates TCAS and other critical onboard warning systems
- Flight crew displays that convey traffic warnings AND open an active channel of communications with intruder aircraft AND their flight crew

Additionally, human performance measures must be considered during design and evaluation of new systems, ensuring that they do not reduce the effective of system operators or introduce new risks towards the safety of the airline system and its passengers.

Appendix A – TCAS Symbology[15]

TCAS Symbology			
	**Non-Threat Traffic** **An open white diamond indicates that an intruder's relative altitude is greater than plus or minus 1200 feet vertically or its distance is beyond 6 nm range.It is not yet considered a threat.** **This one is 1700 feet below your own altitude, climb-ing at 500 feet per minute or greater.**		**Traffic Advisory (TA)** **A symbol change to a filled yellow circle indicates that the intruding aircraft is considered to be poten-tially hazardous. Depending on your altitude TCAS II will display a TA when the time to CPA is between 20 and 48 seconds.** **A voice announcement is heard in the cockpit,adv ising,** "Traffic, Traffic"
	**Proximity Traffic** **A filled white diamond indicates that the intruding aircraft is within plus or minus 1200 feet vertically and within 6 nm range, but is still not considered a threat.** **This intruder is now 1000 feet below your aircraft and climbing.**		**Resolution Advisory (RA)** **A solid red square indicates that the intruding aircraft is projected to be a collision threat. The time to closest approach with the intruder is now between 15 and 35 seconds depending on your altitude.** **A synthesized voice announces a vertical maneuver command,such as, "Climb, Climb, Climb."**

[15] *Collision Avoidance System User's Manual TCAS II / ACAS II*, ACS-5059, Rev 5 - 02/2000, Honeywell Inc.