МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
ДЕРЖАВНИЙ УНІВЕРСИТЕТ “КИЇВСЬКИЙ АВІАЦІЙНИЙ ІНСТИТУТ”
ФАКУЛЬТЕТ АЕРОНАВІГАЦІЇ, ЕЛЕКТРОНІКИ ТА ТЕЛЕКОМУНІКАЦІЙ
КАФЕДРА АВІОНІКИ ТА СИСТЕМ УПРАВЛІННЯ

ДОПУСТИТИ ДО ЗАХИСТУ
Завідувач випускної кафедри
________ О.М. Тачиніна
‘___’__________2025 р.

КВАЛІФІКАЦІЙНА РОБОТА

ВИПУСКНИКА ОСВІТНЬОГО СТУПЕНЯ БАКАЛАВР

ЗА СПЕЦІАЛЬНІСТЮ 173 «АВІОНІКА»

Тема: 'Методи зниження ризиків небезпечних зближень ПС у повітрі'

Виконавець: _________Ба-173-21-2-АВ, Звонар Арсеній Іванович_________
(студент, група, прізвище, ім’я, по батькові)

Керівник: ______________ст. викл. Ситнянських Л.М.___________________
(науковий ступінь, вчене звання, прізвище, ім’я, по батькові)

Нормоконтролер: _______ Левківський В.В.
(Signature) (П.І.Б.)

Київ – 2025

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
STATE UNIVERSITY "KYIV AVIATION INSTITUTE"
FACULTY OF AIR NAVIGATION, ELECTRONICS AND TELECOMMUNICATIONS
DEPARTMENT OF AVIONICS AND CONTROL SYSTEMS

APPROVED
Head of the department
________ O.M. Tachynina
‘___’___________2025

QUALIFICATION PAPER

FOR THE DEGREE OF «BACHELOR»

SPECIALITY 173 ‘AVIONICS’

Theme: 'Methods of reducing the risks of dangerous convergence of aircraft in the air'

Done by: _________Ba-173-21-2-AV, Zvonar Arseniy Ivanovich_________
(student, group, surname, name, patronymic)

Supervisor: __________senior lect. Sytnianskykh L.M.__________________
(scientific degree, academic rank, surname, name, patronymic)

Standard controller: _______ Levkivskyi V.V.
(Signature) (surname, name, patronymic)

Kyiv – 2025

STATE UNIVERSITY "KYIV AVIATION INSTITUTE"
Faculty Of Air Navigation, Electronics and Telecommunications
Department of avionics and control systems
Specialty 173 ‘Avionics’

APPROVED
Head of the department
________ O.M. Tachynina
‘___’___________2025

TASK

for qualification paper

Zvonar Arseniy Ivanovich

1. Theme: ‘Methods of reducing the risks of dangerous convergence of aircraft in the air’, approved by order 429/ст of the Rector of the National Aviation University of 20 March 2025.

2. Duration of which is from 19 May 2025 to 22 June 2025.

3. Input data of graduation work:

4. Content of explanatory notes:

5. The list of mandatory graphic materials:

6. Planned schedule

№	Task	Duration	Signature of supervisor
1.	Validate the rationale of the graduate work theme	22.05.2025	
2.	Carry out a literature review	24.05.2025	
3.	Develop the first chapter of the graduate work	31.05.2025	

4.	Develop the second chapter of the graduate work	07.06.2025	
5.	Develop the third chapter of the graduate work	14.06.2025	
6.	Tested for anti-plagiarism and obtained a review of the graduate work	17.06.2025	
7.	Preparation of presentation and report	22.06.2025	

7. Date of assignment: '___ ' ___________ 2025

Supervisor ______________ Sytnianskykh L.M.

The task took to perform ______________ Zvonar A.I.

(Signature) (surname, name, patronymic)

ABSTRACT

Explanatory notes to graduation work 'Methods of reducing the risks of dangerous convergence of aircraft in the air' contained 51 pages, 10 figures, 3 tables, and 12 references.

Keywords: Airborne collision avoidance system, TCAS, ACAS, transponder, dangerous convergence of aircraft in the air.

The object of the research – proces of reduction of reduction of the risks of dangeorus convergence of aircraft in the air.

The subject of the research – systems of prevention of dangerous convergence of aircraft in the air based on ACAS principles.

Purpose of graduation work – to analyze the effictiveness of existing systems of dangerous convergence prevention and suggest possible improvements.

Research methods – information analysis and synthesis, expert evaluation of collision avoidance systems' effectiveness, and a comparative method for examining the characteristics of TCAS I, TCAS II, and the ACAS X family of systems.

CONTENTS

Introduction...7
Chapter 1. Understanding the risk: Dangerous aircraft convergence in flight 9
1.1 Defining dangeorus aircraft convergence in the air. 9
1.2 Causes leading to dangerous convergence events. 10
1.3 Potential dangeorus convergence events and basic approach to their resolution. 11
Chapter 2. ACAS and TCAS, and their role in preventing mid-air collisions.................14
2.1 Overview of Airborne Collision Avoidance Systems (ACAS) 14
2.2 Main components and principle of work of TCAS 17
2.3 Functional modes and alert types in TCAS 18
2.4 TCAS detection and avoidance logic 23
2.5 Limitations of TCAS and operational considerations..26
Chapter 3. Recent developments and practical steps towards improvement of existing systems 29
3.1 Application of ADS-B 29
3.2 ACAS-X family of systems 32
3.3 Performance comparison of ACAS-X and TCAS II..35
3.4 Artificial intelligence and machine learning in collision avoidance 37
3.5 The use of augmented reality...38
3.6 Certification challenges 41
3.7 Recommendations 43
Conclusion 49
Sources 50

INTRODUCTION

The relevance of the work. Ensuring the safety of aircraft in airspace is a central challenge of modern aviation. As global air traffic volumes continue to rise due to increased passenger demand, cargo operations, and the growing complexity of air navigation routes, the risk of dangerous convergence events becomes more prominent. Loss of separation incidents remains a persistent concern despite advancements in air traffic management, which highlights the need for continuous development and refinement of systems aimed at mitigating mid-air collision risks.

In this context, the study of technologies designed to prevent or minimize the risk of dangerous aircraft convergence, such as the Traffic Collision Avoidance System (TCAS) and its modern successor, ACAS X, remains highly relevant. These systems represent a critical last line of defense in the event that air traffic control fails to maintain proper separation. Their effectiveness is essential not only in preventing loss-of-separation scenarios but also in supporting the overall resilience and reliability of the global aviation system. As automation and unmanned aerial vehicles (UAVs) become more prevalent in shared airspace, the importance of scalable, adaptive, and certifiable collision avoidance mechanisms continues to grow.

Moreover, the integration of new technologies such as ADS-B (Automatic Dependent Surveillance–Broadcast), machine learning, and enhanced human-machine interfaces is gradually transforming the landscape of airspace safety. These innovations promise significant gains in predictive accuracy, pilot situational awareness, and system efficiency. However, their implementation introduces new technical, regulatory, and human-factor challenges that require thorough investigation. This includes not only performance assessments and algorithmic comparisons, but also the examination of certification processes and operational compatibility with existing systems.

This qualification paper aims to provide a comprehensive overview of the current methods used to reduce the risk of dangerous aircraft convergence in the air. Special attention is given to the development and performance of ACAS X, its comparison with existing systems, and the broader ecosystem of safety technologies in which it operates. Through this analysis, the work highlights both the progress made and the obstacles that remain in achieving safer airspace management.

The object of the research: proces of reduction of reduction of the risks of dangeorus convergence of aircraft in the air.

The subject of the research: systems of prevention of dangerous convergence of aircraft in the air based on ACAS principles.

Purpose of graduation work: to analyze the effictiveness of existing systems of dangerous convergence prevention and suggest possible improvements.

Research methods: information analysis and synthesis, expert evaluation of collision avoidance systems' effectiveness, and a comparative method for examining the characteristics of TCAS I, TCAS II, and the ACAS X family of systems.

Scientific novelty: synthesis of current approaches to assessing the risks of dangerous aircraft convergence, as well as in the comparative analysis of TCAS I, TCAS II, and ACAS X systems, with consideration of their certification and implementation prospects.

CHAPTER 1.
UNDERSTANDING THE RISK: DANGEROUS AIRCRAFT CONVERGENCE IN FLIGHT

1.1 Defining dangeorus aircraft convergence in the air.

The concept of dangerous aircraft convergence refers to a situation in which two or more aircraft come into close proximity in the airspace in such a way that the risk of a mid-air collision or other dangerous interaction is significantly increased. The monitoring and prevention of dangerous aircraft convergence in mid-air is a critical aspect of ensuring flight safety and maintaining the operational reliability of civil aviation systems. In such situations, which may develop gradually or suddenly, where dangerous aircraft convergence occurs and a possibility for collission is present, the term 'loss of separation' can be used.

According to the International Civil Aviation Organization (ICAO), a loss of separation is defined as an occurrence where the minimum required separation between aircraft, as prescribed by the applicable air traffic control procedures, is infringed. The standard minimum separation distances can vary, and are specified by the local ATS authorities, based on ICAO standards. Generally, they include a horizontal separation of 5 nautical miles (NM) and a vertical separation of 1000 feet below flight level 290, increasing to 2000 feet above that level, unless reduced vertical separation minima (RVSM) procedures are in use.

Dangerous convergence events can occur both in controlled airspace, where ATC is responsible for maintaining separation, as well as those in uncontrolled or Class G airspace, where pilots operate under see-and-avoid principles. While most commercial traffic operates under instrument flight rules (IFR) in controlled zones, general aviation and low-level operations often take place under visual flight rules (VFR), which can be prone to convergence risks, particularly near busy airports or within terminal maneuvering areas.

Thus, a reliable way of prevention of dangerous aircraft convergence as well as a universal algorythm for resolution of such situations when they do occur, is required. While procedural compliance, system capability, and situational awareness of the crew play a role in the development of such events, this paper attempts to analyze the efficiency of the system automatization specifically, aiming to propose potential improvements and new implementations for reduction of the risk of dangerous aircraft convergence in the air.

1.2 Causes leading to dangerous convergence events.

Dangerous convergences can vary significantly in complexity and severity depending on the specific flight conditions, aircraft speeds and trajectories, environmental factors, and the quality of situational awareness among both pilots and air traffic controllers. Causes for dangerous convergence events can originate from any number of four main categories: technical, organizational, operational, and human-related.

Technical convergence risks arise from malfunctions or failures in onboard systems, navigation equipment, transponders, autopilot mechanisms, or other avionics critical to spatial awareness and flight control. A failure in the aircraft's ability to broadcast or receive positional data can cause a breakdown in communication with other aircraft or ground-based systems, increasing the risk of conflict. The detection and reduction of such risks depend heavily on pre-flight diagnostics, routine maintenance procedures, and the integration of modern onboard fault-monitoring systems.

Organizational causes are linked to lack or low quality of planning, coordination, or resource management. These may include poor scheduling of flight paths, overlapping airspace assignments, lack of synchronization between air traffic controllers, or inadequate coordination between different airlines and service providers. Organizational errors can also involve systemic issues such as staff shortages, overextended shifts, fatigue, and overall stress, all of which may lead to reduction of performance and thus safety in high-density airspace.

Operational convergence events develop during the execution of a flight. These may include deviations from the assigned flight route due to adverse weather, communication loss with air traffic control, navigational errors, or unexpected changes in traffic. Such situations require immediate response from both pilots and ATC, often relying on conflict detection and resolution systems like radar, ADS-B, or TCAS, the latter of which this paper is focused on. Accurate and timely interpretation of these systems' warnings and instructions is crucial in determining whether a convergence remains safe or becomes dangerous.

Human factors are the most common contributor to incidents. Errors in decision-making, miscommunication, situational misjudgment, and lack of adherence to standard operating procedures can significantly compromise flight safety. Human errors may stem from fatigue, cognitive overload, stress, or lack of training of the crew. It's important to emphasize the need for continuous crew resource management (CRM) training, health and fitness monitoring, and rigorous qualification standards for both pilots and air traffic controllers in order to reduce the chance of human error occuring.

A proper understanding of the definition and classification of dangerous aircraft convergence provides the foundation for risk assessment methodologies, and conceptualization as well as implementation of preventive technologies and methods. Analyzing such events in detail allows for refinement of existing protocols, improvement of automation systems, and increase in the safety within the aviation industry.

1.3 Potential dangeorus convergence events and basic approach to their resolution.

Events where dangerous aircraft convergence occurs typically result from a deviation in one or more of the fundamental elements that ensure safe aircraft separation: vertical, horizontal, or longitudinal distance, as well as time-based separation in controlled airspace (eg. aircraft circling above the airport, waiting for clearance to land).

Two broad categories of events can be distinguished:

- Convergence caused by both aircraft maintaining course at a similar altitude (Fig 1.1 a)
- Convergence caused by one or both aircraft changing altitude in a way that causes their course to intersect (Fig 1.1 b)

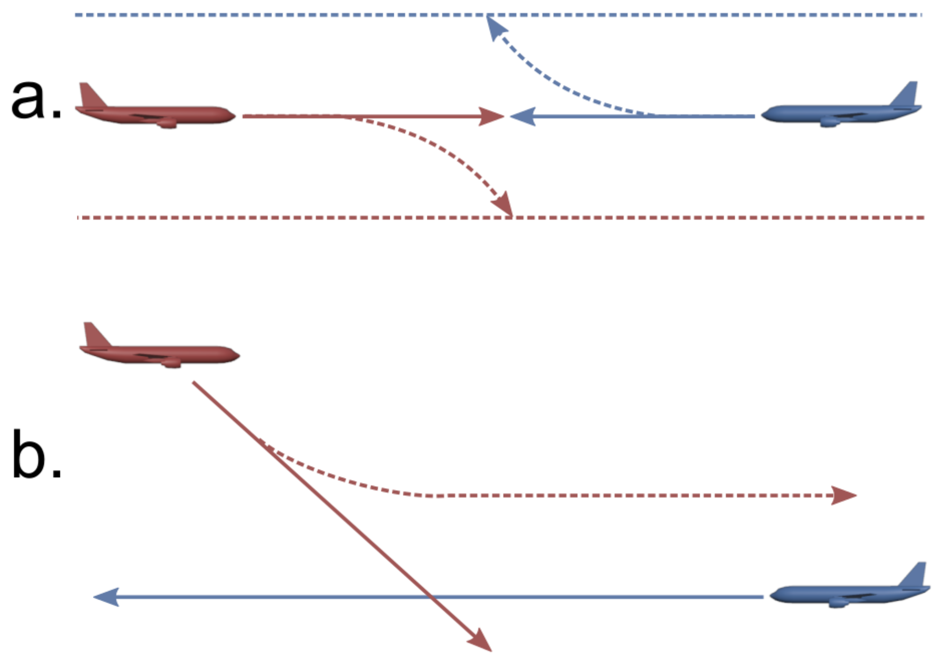


Fig. 1.1 Potential convergence scenarios of aircraft in the air

Convergence during level flight at similar altitudes.

This category involves two or more aircraft flying at comparable flight levels without vertical maneuvering. Dangerous proximity may develop as a result of parallel or intersecting trajectories that bring the aircraft into close range, particularly when their longitudinal or lateral separation is insufficient. An example of this type includes convergence of aircraft on crossing airways at the same altitude. Even minor inaccuracies in speed estimation or heading can result in a convergence scenario over time, especially under high-altitude cruising conditions where aircraft are traveling at high velocities.

Convergence involving altitude changes.

This type includes events in which one or both aircraft are climbing or descending through altitudes that intersect with the other aircraft's flight path. Such situations can occur during departure, arrival, or when aircraft are issued altitude changes en route. A dangerous convergence may occur when vertical separation is not re-established in time, either due to delayed climb/descen, wrong altitude assignment, or failure to follow the clearance properly.

It is important to note that in both categories, convergence may occur despite varying course headings or dissimilar speeds. The primary factor that will determine how soon each pilot needs to act is the speed of convergence. Two aircraft moving towards each other will have a high speed of convergence, and thus will need to act quickly, as opposed to a scenario where one aircraft is following the other, with the former aircraft moving faster than the latter. In such a scenario, the convergence speed will be the lowest, allowing both crews greater time to make a decision and change course or altitude.

Due to the predictability and precision of vertical maneuvers compared to horizontal course changes, in the vast majority of convergence scenarios, the primary method of conflict resolution involves adjusting the aircraft's altitude or rate of climb/descent, rather than attempting to resolve the situation through lateral maneuvering.

A number of reasons can be outlined for this choice of approach:

- First, heading changes that are imprecise over short timeframes, especially at cruising speeds.
- Second, horizontal maneuvers typically require more time to perform compared to change in climb/descent rate.

Thus, with altitude being an easily measurable and precise variable, altitude-based maneuvers are the desired approach when possible.

CHAPTER 2

ACAS AND TCAS, AND THEIR ROLE IN PREVENTING MID-AIR COLLISIONS

2.1 Overview of Airborne Collision Avoidance Systems (ACAS)

The research of potential ways to implement an airborne collision avoidance system, prompted by tragic accidents, began in year 1956, and remained a concept until early 1970s first prototype systems were equipped onto aircraft. Initial concepts of such systems included the Beacon Collision Avoidance System (BCAS), which used reply data from the Air Traffic Control Radar Beacon System (ATCRBS) transponders to determine an intruder's range and altitude.

The development of Airborne Collision Avoidance Systems (ACAS) was driven by the need for an independent onboard mechanism that could assist pilots in detecting and responding to potential mid-air collision threats, even in cases where ground-based air traffic control (ATC) systems might be insufficient. ACAS operates as a last line of defense, providing real-time situational awareness to flight crews and issuing advisories when an aircraft enters a potentially dangerous proximity to another. The system is designed to function autonomously, relying solely on information obtained from onboard sensors and communication with other transponder-equipped aircraft.

At its core, ACAS is built to monitor the airspace surrounding an aircraft, identify any nearby aircraft that may pose a threat, and issue alerts if a potential conflict is predicted based on their relative positions and trajectories. This task is performed without requiring input from or coordination with air traffic control, which proves crucial in areas of limited radar coverage or during periods of controller workload saturation. Unlike ATC-based conflict detection, which is subject to human limitations and communication delays, ACAS ensures a rapid and automated response to dynamic changes.

Over time, ACAS evolved into more sophisticated iterations, leading to the development of the Traffic Collision Avoidance System (TCAS), which became the internationally standardized implementation of ACAS principles. TCAS incorporates the essential functions of ACAS, such as detecting transponder signals from other aircraft and determining their range, altitude, and bearing, but enhances these capabilities with structured alerting logic and resolution advisories (RAs) that suggest specific vertical maneuvers to avoid a collision. These RAs are computed based on predictive algorithms that factor in the speed, climb/descent rates, and flight paths of both aircraft involved.

TCAS I was developed as a more basic version primarily intended for general aviation and smaller commercial aircraft. It provides Traffic Advisories (TAs), which alert the pilot to nearby transponder-equipped aircraft that may present a conflict. However, it does not offer Resolution Advisories (RAs) - instructions for vertical maneuvering to avoid collisions. The system functions mainly as an awareness tool, leaving conflict avoidance decisions to the pilot's discretion. TCAS I is mandated in several countries, including the United States and members of the European Union, for commercial aircraft with seating capacities of 10 to 30 passengers, or aircraft over a certain weight threshold

TCAS II is the most widely deployed and currently the only version that satisfies ICAO's ACAS II standards. It includes both TAs and RAs, actively advising pilots on vertical maneuvers, such as climbs or descents, to avoid mid-air collisions. The system also coordinates advisories with nearby TCAS II-equipped aircraft to prevent issuing conflicting instructions. TCAS II has undergone several updates, with Version 7.1 currently being the global standard. Version 7.1 differs in its improvement of safety logic, replacing the "Adjust Vertical Speed" RA with a more effective "Level Off" RA.

The FAA mandates TCAS II for turbine-powered airplanes with more than 30 seats or a maximum payload capacity of over 3,400 kg operating under 14 CFR Part 121 in U.S. airspace. Similarly, EASA regulations in Europe require TCAS II on all turbine-powered aircraft with more than 19 passenger seats or exceeding 5,700 kg MTOW when flying in controlled airspace.

TCAS III was proposed as an extension of TCAS II to include horizontal maneuvering capabilities in addition to vertical RAs. However, due to limitations in sensor accuracy and reliability, particularly in determining precise horizontal bearing to intruder aircraft, TCAS III was never fielded beyond experimental phases. It was eventually discontinued in favor of other systems.

TCAS IV was the following attempt after TCAS III to incorporate accurate horizontal resolution advisories, using Mode S transponders to transmit more detailed positional data. However, the required technology to support it with adequate reliability was not yet present, and the project was eventually overtaken by **ACAS Xa**, which uses a different approach based on ADS-B data and probabilistic modeling rather than fixed geometry-based logic.

ACAS Xa is the latest development among the airborne collision avoidance systems, intended as a replacement for TCAS II. As mentioned above, it relies on probabilistic, risk-based logic that takes into account a broader range of encounter variables. This allows the system to better distinguish between genuinely hazardous situations and those that present only a minimal collision risk, thus reducing the number of unnecessary or nuisance resolution advisories (RAs).

It's important to note that while the terms ACAS and TCAS are often used interchangeably, they are not entirely synonymous. ACAS II refers specifically to the technical standard and conceptual framework established under international regulation, whereas TCAS II denotes the actual system implementation that is currently deployed on a global scale in commercial aviation.

At present, TCAS II version 7.1 is the only operational system that fully complies with the Standards and Recommended Practices (SARPs) outlined by ICAO for ACAS II. However, ICAO is actively working on updating its guidance to incorporate the next-generation system known as ACAS Xa.

A key design goal behind ACAS Xa was to enhance collision avoidance capabilities while simultaneously reducing the frequency of unnecessary alerts. Data gathered from real-world operation of TCAS II showed that the system often issued Resolution Advisories (RAs) even when the actual risk of collision was minimal.

ACAS Xa is intended to replace existing TCAS II systems while maintaining full interoperability, meaning that aircraft equipped with either ACAS Xa or TCAS II can still exchange and coordinate advisories.

2.2 Main components and principle of work of TCAS

The Traffic Collision Avoidance System (TCAS) is designed to monitor nearby aircraft using radio-based surveillance. In situations where potential mid-air conflicts are identified, TCAS provides the pilot with both visual cues on cockpit displays and audible alerts. The system continuously scans for nearby aircraft by sending out interrogation signals at regular intervals—typically once every second—and listens for replies from aircraft equipped with transponders. From these responses, TCAS compiles situational data using three primary parameters:

- Range, or distance between aircraft, is calculated based on the time elapsed between the system's interrogation and the reception of the transponder's response.
- Altitude of the detected aircraft is extracted from a coded message included in the reply, which is based on barometric measurements made on the responding aircraft.
- Azimuth, the horizontal direction or bearing relative to the nose of the aircraft carrying TCAS, is determined through directional signal reception using a specialized antenna capable of identifying the angle of the incoming response signal.

2.3 Functional modes and alert types in TCAS

TCAS implements multiple functional modes: Stand-by, Transponder Only (XPNDR or ON), Altitude Reporting Off (ALT RPTG OFF), TA only, and TA/RA. The table below shows how each mode reflects on the operation of the transponder, own aircraft ACAS, intruder ACAS, and ATC detectability.

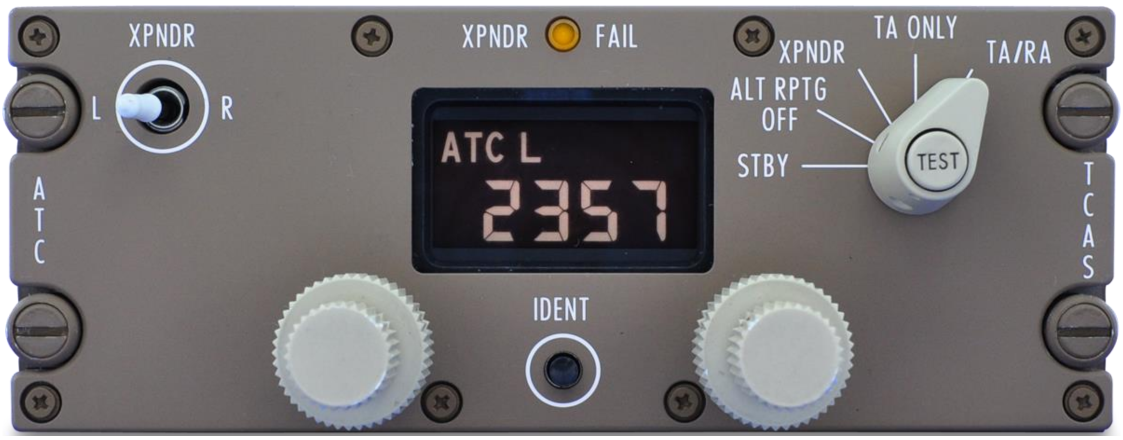


Fig. 1.2 ATC/TCAS control panel of Boeing B737 airliner, showing the TCAS mode control know (top-right).

Fig. 1.3 ATC/TCAS control panel of Airbus A320 airliner, showing the TCAS mode control know (bottom-right).

Operating mode	Stand-by (STBY)	XPNDR	ALT RPTG OFF	TA-only	TA/RA or AUTOMATI
Transponder	Off	On	On, but no altitude reporting	On	On
ACAS	Off	Off	Off	On	On
Own aircraft	No alerts	No alerts	No alerts	TA only	TA &. RA
Intruder	No alerts	TA & RA (uncoordinated)	NAR TAs[46]	TA & RA (uncoordinated)	TA & RA
ATC	No detected	Full detection	Detected, without altitude info	Full detection	Full detection

Fig. 1.4 ACAS and transponder modes of operations.

Stand-by

In the stand-by mode, the Traffic Collision Avoidance System (TCAS) remains powered but does not participate in any surveillance or interrogation activity. In this state, the system does not issue any traffic alerts (TAs) or resolution advisories (RAs), and the transponder is not transmitting replies to interrogations from external radar sources or other aircraft. The purpose of standby mode is to preserve system integrity and prevent unnecessary transmission activity when the aircraft is not airborne or not in active flight phases. This setting is typically selected while the aircraft is parked at the gate, undergoing maintenance, or during power-up procedures before takeoff. While in standby, the TCAS display remains inactive, and no situational awareness data regarding surrounding traffic is available to the flight crew.

Transponder Only (XPDR or ON)

The transponder-only mode enables the aircraft's transponder to respond to interrogations from Air Traffic Control (ATC) radar systems and other aircraft, but without transmitting pressure altitude information. In this configuration, TCAS itself remains inactive—meaning it does not detect or display nearby traffic nor issue any advisories. The transponder still provides Mode A or Mode S identification signals, which are essential for ATC tracking and aircraft identification, but the absence of Mode C (altitude) data limits the usability of this information for separation assurance. This mode is used during ground operations or in certain airspace classifications where altitude data is not required or when the aircraft is awaiting ATC clearance to operate with full surveillance capabilities.

Altitude Reporting Off (ALT RPTG OFF)

When the altitude reporting off mode is selected, the aircraft's transponder continues to respond to surveillance interrogations, but the transmission of altitude information is intentionally suppressed. In this state, although the aircraft is visible to ATC radar systems via Mode A or Mode S replies, it does not provide the essential vertical position data needed for precise separation management. From a TCAS perspective, this mode disables the system's ability to detect relative vertical distances between the own aircraft and nearby intruders, rendering both TA and RA logic inoperative. Altitude reporting off mode is rarely used, but may be required in special operational circumstances, such as flights in certain military or privacy-restricted zones. Due to the degradation it causes in both ATC situational awareness and TCAS surveillance capability, the use of this mode is discouraged unless explicitly mandated. As vertical proximity is a critical factor in collision avoidance, and as such, disabling this parameter significantly increases operational risk.

TA-only

The TA-only mode configures TCAS to monitor surrounding airspace and issue traffic advisories, while deliberately suppressing resolution advisory outputs. In this setting, the system continuously interrogates nearby transponder-equipped aircraft, processes their relative positions and velocities, and alerts the flight crew when another aircraft appears to be approaching within a proximity that warrants attention. However, no automatic vertical maneuver guidance is provided—even if the threat level would normally trigger an RA. This mode is used in specific flight operations where full RA capability may be undesirable or restricted. Examples include flights in Reduced Vertical Separation Minimum (RVSM) airspace with known equipment limitations, or operations in proximity to non-cooperative traffic that cannot respond to coordinated RA logic. TA-only mode preserves the situational awareness function of TCAS without introducing potential conflicts between automated advisories and ATC instructions.

TA/RA

The TA/RA mode, also known as "Automatic" or "Normal" mode depending on manufacturer labeling, activates the full functional spectrum of the TCAS system. In this configuration, the system not only identifies and displays potential traffic threats but also calculates and issues vertical maneuver instructions when a risk of collision is assessed to be significant. These Resolution Advisories provide real-time guidance to maintain or restore safe separation. TA/RA mode is the default operational setting for most phases of flight, especially during cruise and approach, and is mandatory in controlled airspace where TCAS-equipped aircraft are expected to operate with full anti-collision capability. In this mode, TCAS also engages in RA coordination with other TCAS II-equipped aircraft, ensuring that both aircraft receive complementary instructions to avoid converging in the same vertical path.

Type	Audio	Meaning	Required action
TA	Traffic, traffic	Intruder is close both horizontally and vertically	Attempt visual contact and be prepared to manoeuvre if an RA occurs
RA	Climb, climb	Intruder will pass below	Begin climbing at 1500–2000 ft/min
RA	Descend, descend	Intruder will pass above	Begin descending at 1500–2000 ft/min
RA	Increase climb	Intruder will pass just below	Climb at 2500 – 3000 ft/min
RA	Increase descent	Intruder will pass just above.	Descend at 2500 – 3000 ft/min
RA	Adjust vertical speed, adjust	Intruder is probably well above or below	Descend or climb at a slower rate
RA	Climb, climb now	Intruder that was passing above will now pass below	Change from a descent to a climb
RA	Descend, descend now	Intruder that was passing below will now pass above	Change from a climb to a descent
RA	Maintain vertical speed, maintain	Intruder will be avoided if vertical rate is maintained	Maintain current vertical rate
RA	Adjust vertical speed, adjust	Intruder is considerably away or the initial RA is weakening	Begin to level off
RA	Monitor vertical speed	Intruder is ahead in level flight, above or below	Remain in level flight
RA	Crossing	Passing through the intruder's level. Usually added to any other RA.	Proceed according to the associated RA
RA	Level off, level off	Intruder is no longer a threat while maintaining this level	Maintain current level (no climb, no descent)
CC	Clear of conflict	Intruder is no longer a threat	Return promptly to previous ATC clearance

Table. 1.1 List of TCAS advisories.

Fig. 1.5 Traffic display examples - IVSI combined with traffic display (left) and Electronic Flight Instrument System (right).

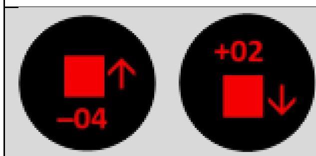
Symbol	Appearance	Meaning
	White or cyan (light blue) aircraft-like symbol or a triangle	Own aircraft
	Hollow cyan (light blue) or white diamond	Other aircraft
	Solid cyan (light blue) or white diamond	Proximate traffic Aircraft within 6 NM and 1200 feet of own aircraft
	Solid yellow or amber circle	Traffic advisory Typically generated 20-48 seconds before CPA
	Solid red square	Resolution advisory Typically generated 15-35 seconds before CPA

Table 1.2 Traffic display symbology.

2.4 TCAS detection and avoidance logic

TCAS follows a certain process in how it operates and provides informatoion and advisory. The process can be divided into 5 stages: observation, air traffic advisory, threat detection, resolution advisory, as well as coordination and communication, as shown in Fig. 1.6.

Observation of TCAS is built upon active surveillance of the surrounding airspace. TCAS transmits interrogations at 1030 MHz and receives replies from nearby aircraft transponders at 1090 MHz. These transponders must be set to either Mode C (altitude-reporting) or Mode S (selective, with aircraft-specific identity).

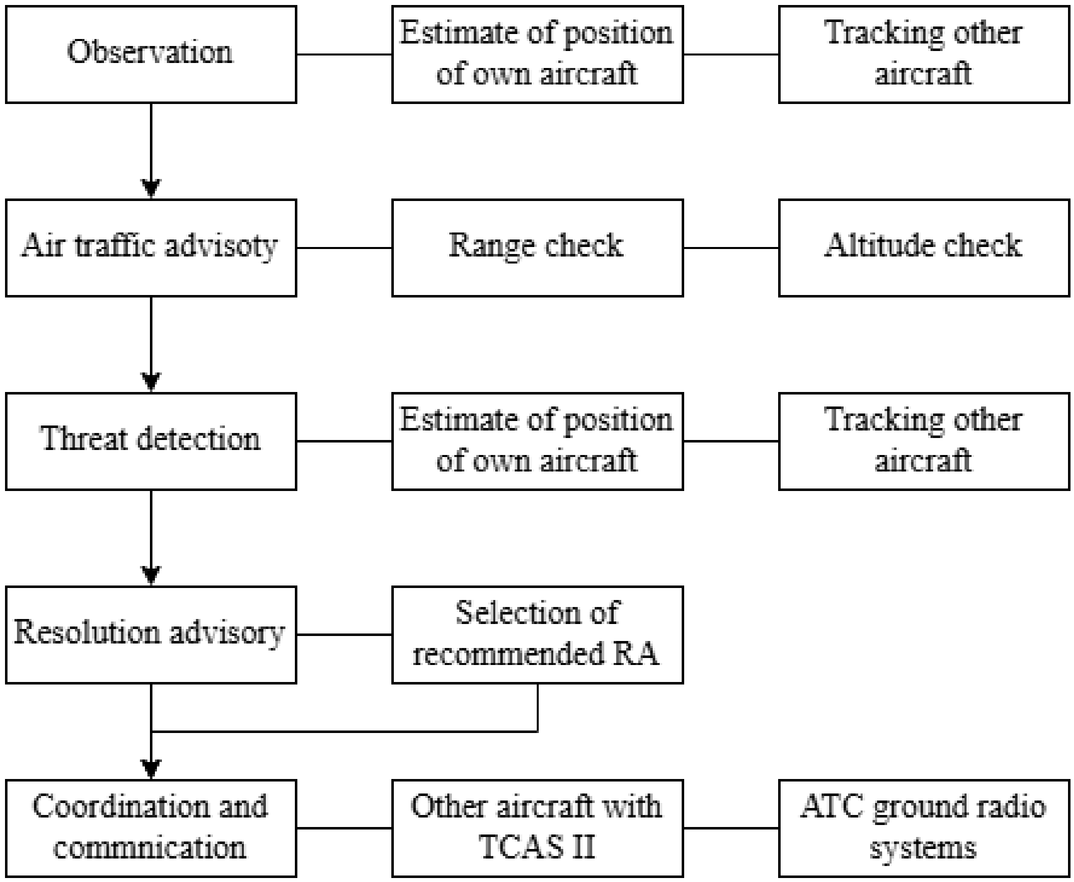


Fig. 1.6 Diagram of TCAS II logic.

Using the time delay between transmission and reply, TCAS determines the slant range (i.e., the three-dimensional distance) to nearby aircraft. If the replying transponder is Mode C or Mode S, TCAS also receives altitude data, allowing it to calculate relative vertical separation. This surveillance is updated several times per second. The frequency of interrogation adapts dynamically depending on the density of surrounding traffic

When a tracked aircraft enters a predefined proximity boundary TCAS issues a Traffic Advisory (TA), which is the forst-level alert of the system that informs the flight crew of nearby traffic that may become a threat if current trajectories are maintained. TAs are typically issued when the time to closest point of approach (CPA) is between 20 to 48 seconds, depending on altitude and closure rate. TA and RA generation times and their relation to altitude are shown in Table 1.3 below.

Altitude (more than)	Nominal TCAS II TA generation times	Nominal TCAS II RA generation times
0 – 500 ft AGL (no aural alerts below 500 ft)	20 sec.	No RAs
1,000 ft AGL	25 sec.	15 sec.
2,350 ft AGL	30 sec.	20 sec.
5,000 ft AGL	40 sec.	25 sec.
10,000 ft AGL	45 sec.	30 sec.
More than 20,000 ft AGL	48 sec.	35 sec.

Table 1.3 TCAS II nominal warning times and sensitivity levels.

TAs are intended to prompt increased visual scanning and situational awareness but do not recommend any evasive maneuvers. The information is shown on cockpit displays (such as the ND or TCAS-specific interface), and accompanied by an aural alert: “Traffic, traffic.”

TA thresholds are not fixed values but are dynamically calculated based on tau (τ), which is the predicted time until closest approach. TCAS uses range-rate and closure rate algorithms to estimate tau for each tracked target.

If the system determines that a potential collision may occur, it transitions from TA to Resolution Advisory (RA) mode. This is based on more stringent thresholds involving predicted separation minima and closure trajectories. RAs are usually triggered when the time to CPA is reduced to 15–35 seconds (depending again on altitude and configuration).

An RA provides specific vertical guidance to the pilot, either to climb, descend, or maintain altitude, in order to avoid violating the safe separation minima. A full list of possible TA, RA, and CC advisories is shown in Table 1.1. in section 2.3.

In cases where both aircraft are TCAS-equipped, the systems coordinate their advisories automatically via Mode S data link. This process, called RA coordination, ensures that both aircraft receive complementary advisories, i.e., one is told to climb while the other is told to descend.

The communication occurs within milliseconds and is fully automated, without requiring pilot input. This bi-directional link is a fundamental improvement introduced by TCAS II, and it's a critical reason why it is only certified for use when both aircraft have Mode S transponders capable of supporting coordination.

If the intruder aircraft is not equipped with TCAS or has a non-compatible transponder, the RA is still issued, but without coordination, which increases the uncertainty and potential complexity of the response.

TCAS logic also includes threat filtering algorithms that prevent unnecessary or misleading advisories. For example, TCAS will inhibit alerts about aircraft that are clearly on the ground (based on their barometric altitude and rate of climb) or those climbing through the aircraft's altitude but projected to cross safely.

There are also RA inhibition modes, such as during takeoff or landing. These modes are either manually selected by pilots or automatically triggered based on radar altitude or configuration. In such cases, TA-only mode is used to prevent unnecessary or unsafe vertical maneuvering near terrain.

2.5 Limitations of TCAS and operational considerations

Despite the demonstrated effectiveness of the Traffic Collision Avoidance System (TCAS) in reducing the risk of mid-air collisions, numerous studies and operational reports have highlighted a range of limitations associated with both TCAS I and TCAS II systems. These limitations, both technical and procedural, influence the reliability of TCAS-generated advisories and must be taken into account when assessing the system's role in the broader context of airborne collision avoidance.

TCAS I, typically installed on smaller commercial aircraft and business jets, provides only Traffic Advisories without Resolution Advisories. Its function is limited to alerting the flight crew to the presence of nearby transponder-equipped aircraft within a predefined proximity threshold. As such, TCAS I does not actively suggest vertical maneuvers to avoid potential collisions. Research has shown that while TCAS I improves situational awareness, it lacks the predictive logic required to manage imminent collision threats effectively, especially in high-density airspace (ICAO, 2018). This limitation renders TCAS I insufficient for ensuring vertical separation in dynamically evolving conflict scenarios, relying entirely on pilot judgment and visual acquisition of traffic, which is subject to human error and environmental constraints such as poor visibility.

TCAS II, which provides both TAs and RAs, is mandated for larger commercial aircraft operating in controlled airspace. While more capable, TCAS II also presents critical limitations. One of the principal constraints is its dependency on Mode S transponders. Aircraft not equipped with transponders or with transponders that are malfunctioning or turned off remain invisible to the system. Consequently, TCAS II cannot detect or issue advisories against such traffic. This creates a significant safety risk in regions with high volumes of general aviation or in conflict zones where military or irregular aircraft may not broadcast altitude or identity information.

Moreover, the performance of TCAS II is inherently restricted by its operational range and update rate. The standard surveillance range of approximately 14 NM (nautical miles) and update intervals of several seconds can result in delayed or incomplete tracking of rapidly closing threats. Studies conducted by Eurocontrol indicate that in high-speed closure scenarios, particularly involving crossing traffic with significant vertical speed components, TCAS II may issue advisories too late to ensure adequate time for safe resolution, especially if the conflicting aircraft is descending rapidly toward the RA aircraft's level.

Another operational concern involves nuisance advisories, where TCAS generates alerts in situations that do not pose an actual risk of collision. This typically occurs in terminal areas with dense but procedurally separated traffic, such as during Standard Terminal Arrival Routes (STARs) or holding patterns. Frequent, low-threat advisories can contribute to alert fatigue, reducing the crew's responsiveness to genuinely hazardous encounters. Simulations and real-world data have shown that false or excessive alerts may also prompt pilots to deviate unnecessarily from ATC instructions, creating downstream traffic conflicts.

Finally, it is worth noting that TCAS systems are fundamentally reactive. They do not prevent dangerous convergence events from occurring but instead attempt to mitigate the consequences once a potential conflict is detected. This reactive nature, while valuable, underscores the importance of integrating TCAS with proactive traffic management strategies, such as Performance-Based Navigation (PBN), Automatic Dependent Surveillance-Broadcast (ADS-B), and improved airspace design.

CHAPTER 3

RECENT DEVELOPMENTS AND PRACTICAL STEPS TOWARDS IMPROVEMENT OF EXISTING SYSTEMS

3.1 Application of ADS-B

As described in the previous section, ADS-B is a more modern surveillance technology which shows promise of playing a critical role in the evolution of air traffic management and collision avoidance systems. Unlike traditional radar-based surveillance methods, which rely on external ground-based tracking, ADS-B is automatic, in that it requires no pilot or external controller input. Dependent, because it relies on the aircraft's onboard navigation and position sources (typically GNSS); and broadcast, as it transmits data continuously without interrogation.

In its standard implementation, ADS-B Out enables aircraft to broadcast their position, velocity, altitude, and other flight data via Mode S transponders on the 1090 MHz frequency. These transmissions, typically occurring once every 0.5 to 1 second, are received by ADS-B ground stations and nearby aircraft equipped with ADS-B In receivers. The accuracy of the positional data in ADS-B broadcasts is notably high, with horizontal position errors typically within tens of meters. Research conducted by the FAA and EUROCONTROL has shown that ADS-B significantly improves situational awareness, particularly in regions lacking dense radar coverage, such as oceanic and remote continental airspace.

The integration of ADS-B within Airborne Collision Avoidance System – X (ACAS-X) represents a substantial technological advancement over the legacy TCAS II system. TCAS II relies on active and passive surveillance through interrogations and replies between Mode S transponders, operating independently of any external data such as precise GPS-derived position. This limits its resolution accuracy and leads to certain operational drawbacks, such as increased radio frequency (RF) congestion and less efficient avoidance maneuvers based on relative position rather than absolute aircraft states.

By contrast, ACAS-X is designed to be ADS-B compatible, meaning it is capable of ingesting state-vector information directly from ADS-B broadcasts. Studies, such as those conducted by the MIT Lincoln Laboratory and the Eurocontrol ACAS-X working group, have demonstrated that using ADS-B data allows ACAS-X to generate intent-aware collision avoidance advisories. Instead of estimating relative positions from range-bearing measurements and transponder replies, ACAS-X systems can utilize ADS-B messages that contain aircraft position, heading, horizontal and vertical velocity, and even future trajectory predictions (when ADS-B Version 2 is used with intent-based messaging).

The ability to process this additional state information enables ACAS-X to perform more accurate threat detection and resolution, reducing the frequency of false alarms and increasing operational efficiency. For instance, when two aircraft equipped with ADS-B are converging, ACAS-X can anticipate potential loss-of-separation scenarios earlier and propose maneuvers that are less aggressive and better optimized in terms of fuel consumption and passenger comfort. This contrasts with TCAS II, which often triggers unnecessary Resolution Advisories (RAs) in dense traffic environments or issues conflicting maneuvers due to limited trajectory prediction capabilities.

Moreover, the enhanced state awareness provided by ADS-B facilitates multi-threat coordination. ACAS-X algorithms, built using Markov Decision Process (MDP) frameworks, can simultaneously evaluate and prioritize multiple encounter geometries, optimizing for minimal disruption and maximal safety. Research has shown that in high-density traffic simulations, ACAS-X with ADS-B input reduced the number of required advisories by over 30% while improving resolution smoothness compared to TCAS II.

A further application of ADS-B within ACAS-X is its potential to support cooperative intent sharing, where aircraft can exchange not only their current flight state but also planned trajectory changes or avoidance maneuvers. Though still largely experimental, this function is under active investigation by ICAO and national aviation authorities. It is anticipated that, when matured, cooperative ADS-B-based coordination will eliminate many of the current limitations associated with uncoordinated RA generation.

In addition to its role in airborne collision avoidance, ADS-B is a foundational enabler for a variety of advanced surveillance and safety applications, particularly within the SURF (Surface Traffic Situational Awareness), AIRB (Airborne Traffic Situational Awareness), and VSA (Visual Separation on Approach) categories defined by the ICAO and the FAA's NextGen implementation framework.

SURF applications, which encompass surveillance of aircraft and vehicles on airport surfaces, rely heavily on ADS-B to improve situational awareness and prevent runway incursions. Aircraft equipped with ADS-B Out can continuously transmit their position and movement on taxiways and runways, enabling both air traffic controllers and nearby aircraft with ADS-B In to visualize surface traffic in real time.

For AIRB (Airborne) applications, ADS-B provides the core surveillance input for systems that support airborne spacing and sequencing. Unlike collision avoidance systems like TCAS II, which operate reactively, AIRB functions are designed to assist in strategic and tactical separation management, particularly during terminal arrival and en route phases. One prominent AIRB application is Interval Management (IM), in which aircraft use ADS-B In data to maintain specified spacing intervals relative to a lead aircraft. The precision of ADS-B-derived state vectors enables smoother sequencing and descent profiles, reducing controller workload and enhancing traffic flow efficiency.

VSA (Visual Separation on Approach) applications are another area where ADS-B shows promise, though its use is more supplemental than primary. In traditional VSA procedures, pilots maintain visual separation with preceding aircraft under visual meteorological conditions (VMC). However, in environments with limited visibility or complex airspace geometry, maintaining true visual contact can be challenging.

Fig. 1.7 Applications of ADS-B; SURF (left), AIRB (middle), and VSA (right).

However, despite its benefits, ADS-B also introduces vulnerabilities — particularly in regard to security and integrity. ADS-B messages are currently unencrypted and unauthenticated, making them susceptible to spoofing and other cyber-attacks. However, ACAS-X systems are designed to validate input data and fall back to transponder-based surveillance in the event of suspect ADS-B signals, thus preserving operational safety.

It can be concluded that ACAS-X significantly improves collision avoidance capability, reduces operational disruptions, and creates ground for future cooperative airspace systems. The integration of ADS-B into airborne safety systems is a critical enabler of next-generation air traffic management.

3.2 ACAS-X family of systems

ACAS-X represents the next generation of collision avoidance technologies, developed as a successor to the widely implemented TCAS II. Designed by the Federal Aviation Administration (FAA) in collaboration with industry and academic partners, ACAS-X leverages advances in probabilistic modeling, computational decision-making, and systems engineering to overcome key limitations of TCAS II. While TCAS II relies on deterministic logic and rigid vertical maneuver advisories, ACAS-X adopts a flexible, model-based architecture that enables adaptation to diverse operational environments and aircraft types.

Recent research and testing efforts have led to the development of several specialized variants within the ACAS-X family, each tailored for a specific operational context or aircraft performance envelope. These include ACAS Xa, ACAS Xo, ACAS Xu, and ACAS Xp. Each variant shares a common core decision engine framework, based on a Markov Decision Process (MDP), which is optimized to balance safety, operational efficiency, and alerting stability under real-time constraints.

- **ACAS Xa** (commercial aviation) is the most direct replacement for TCAS II and is designed for use aboard large commercial transport aircraft operating under instrument flight rules (IFR) in controlled airspace. ACAS Xa maintains compatibility with legacy TCAS systems through coordinated resolution advisories but significantly improves performance in several critical areas. Research published by the FAA indicates that ACAS Xa offers reduced alerting rates, fewer unnecessary reversals of advisories, and improved handling of multi-threat scenarios [Willett et al., 2015]. The system also incorporates cost-aware decision logic that accounts for the operational cost of maneuvers, such as fuel consumption and passenger discomfort.
- **ACAS Xo** (optionally equipped aircraft) is a variant developed for aircraft that may lack the full suite of surveillance and navigation capabilities found on commercial airliners. This includes helicopters, general aviation aircraft, and certain unmanned aerial systems (UAS). ACAS Xo is particularly suited for complex, congested environments such as urban air mobility corridors or low-level VFR airspace. Unlike ACAS Xa, which assumes the availability of high-fidelity ADS-B or radar surveillance, ACAS Xo is engineered to operate under less precise sensor input while still maintaining safe deconfliction logic.
- **ACAS Xu** (unmanned aircraft systems) extends the ACAS-X framework to autonomous and remotely piloted platforms, an area of growing importance given the expansion of UAS operations in civilian airspace. Because unmanned systems do not have onboard pilots to interpret and respond to advisories, ACAS Xu is

designed to interface directly with the UAS flight control system, enabling automatic execution of avoidance maneuvers. Experimental studies by MIT Lincoln Laboratory and NASA have demonstrated the feasibility of ACAS Xu for integration into UAS traffic management (UTM) systems, particularly when supported by high-integrity surveillance sources such as ADS-B or cooperative multi-sensor fusion.

- **ACAS Xp** (passive variant) is a passive-only solution developed for aircraft that do not transmit active surveillance signals such as Mode S interrogations. Instead, it relies solely on reception of broadcast data, such as ADS-B In, to derive threat trajectories and compute advisories. ACAS Xp is particularly relevant for general aviation and light aircraft where size, weight, and power (SWaP) constraints preclude installation of traditional active transponders. Although Xp lacks full bidirectional coordination with other aircraft, simulation results show that it provides a meaningful safety benefit over no collision avoidance capability, especially in VFR environments.

Importantly, all ACAS-X variants are designed to be modular and upgradable. The shared decision engine, based on a probabilistic model trained via extensive Monte Carlo simulation, enables consistent behavior and safety assurance across different aircraft classes. This approach marks a significant evolution from the rule-based logic of TCAS II, offering greater adaptability to future airspace configurations, including increased traffic density and the integration of autonomous platforms.

In operational evaluations and human-in-the-loop simulations, ACAS-X systems have consistently demonstrated reduced false alert rates, increased pilot trust, and smoother coordination in multi-aircraft encounters. The FAA has noted that ACAS Xa, in particular, exhibits a 30–50% reduction in nuisance alerts compared to TCAS II while maintaining or improving safety margins.

In summary, the ACAS-X family of systems represents a significant advance in airborne collision avoidance. Through modular design and variant-specific optimization, ACAS-X addresses the diverse requirements of contemporary aviation, including commercial airliners, general aviation, and autonomous aircraft. Ongoing development efforts continue to refine these systems in anticipation of evolving airspace demands and regulatory frameworks.

3.3 Performance comparison of ACAS-X and TCAS II

While both systems are developed to fulfill the same overarching purpose—preventing mid-air collisions by providing pilots with real-time advisories—their architectures, decision-making algorithms, and operational performance differ in notable ways.

TCAS II, currently mandated in most commercial aircraft, operates on deterministic logic using predefined resolution advisory (RA) thresholds and decision trees based primarily on altitude and closure rates. It has been successful in significantly reducing mid-air collision risks since its global implementation, yet it also exhibits several limitations. These include high false alarm rates, inability to coordinate maneuvers optimally with non-equipped aircraft, and a limited capacity to adapt to complex, high-density airspace environments.

In contrast, ACAS-X leverages a probabilistic, model-based approach to conflict detection and avoidance. Specifically, ACAS-X uses a Markov Decision Process (MDP) framework to select optimal advisories based on dynamic evaluation of future aircraft states, including velocity vectors, aircraft intent, and probabilistic risk assessment. This allows ACAS-X to make context-sensitive decisions that maximize safety while minimizing unnecessary or operationally disruptive advisories.

Research conducted by the FAA and MIT Lincoln Laboratory indicates that ACAS-X outperforms TCAS II across multiple operational metrics. Simulations in high-density airspace show that ACAS-X achieves a 40–50% reduction in unnecessary resolution advisories, particularly in scenarios involving vertical convergence. Additionally, ACAS-X reduces reversal rates—instances in which pilots are advised to change maneuver direction mid-response—by up to 80%, significantly improving pilot trust and compliance.

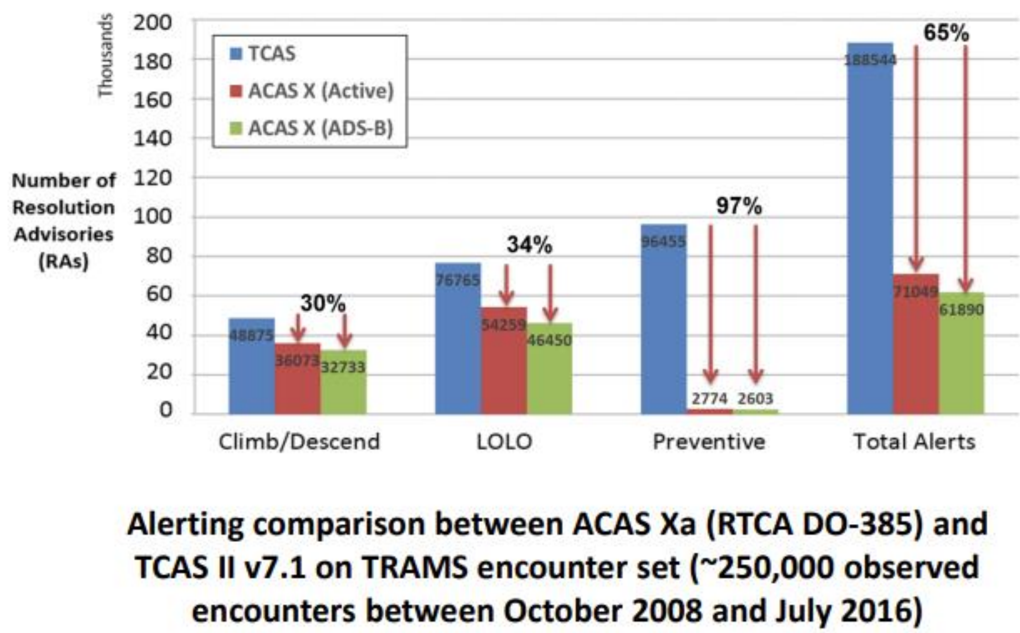


Fig. 1.8 Performance comparison between TCAS, Active ACAS-X, and ADS-B ACAS-X.

In terms of safety-critical performance, ACAS-X demonstrates improved miss distances (both horizontally and vertically) in collision scenarios. Data from joint Eurocontrol/FAA evaluations show that the average minimum vertical miss distance under ACAS-X is approximately 1120 ft, compared to 1020 ft under TCAS II, representing a statistically significant improvement in conflict resolution efficacy. Horizontally, ACAS-X maintains slightly higher miss distances due to its ability to factor in more nuanced trajectory modeling.

Another key distinction lies in their interoperability and extensibility. While TCAS II is restricted to coordinated advisories between equipped aircraft, ACAS-X has been designed as a modular system with several variants (e.g., ACAS Xa, ACAS Xo, ACAS Xu, and ACAS Xp), each tailored for different aircraft types and operational contexts. For example, ACAS Xo is optimized for operations in high-density terminal environments, while ACAS Xu is designed for unmanned aircraft systems (UAS), demonstrating the flexibility of the ACAS-X framework to adapt to emerging airspace users.

From a computational standpoint, ACAS-X benefits from a significantly more efficient advisory selection process. While TCAS II relies on hard-coded logic trees, ACAS-X precomputes policy tables offline using value iteration over large state spaces. These tables are then compressed and uploaded to aircraft systems, allowing for real-time lookup and decision-making during flight. Despite the added complexity of the design process, this architecture ensures faster advisory selection in-flight and supports easier updates in response to evolving airspace conditions or safety data.

3.4 Artificial intelligence and machine learning in collision avoidance

Recent advancements in artificial intelligence (AI) and machine learning (ML) are transforming the field of airborne collision avoidance by enabling systems to adapt more dynamically to complex, real-world scenarios. Within this context, the ACAS X family of systems has been designed from the ground up with these capabilities in mind, departing from the rule-based logic of its predecessor, TCAS II.

Unlike TCAS II, which relies on a fixed set of maneuver advisories based on a lookup-table approach, ACAS X utilizes probabilistic models and real-time optimization algorithms to evaluate a much larger range of possible encounter geometries and outcomes. Central to this is the use of aforementioned Markov Decision Processes (MDPs), which allow the system to model future trajectories of ownship and intruder aircraft under uncertainty. These models are optimized offline using machine learning techniques to generate policy tables that map sensor inputs to optimal advisories, minimizing risk and operational disruption simultaneously.

Research conducted by the MIT Lincoln Laboratory and the Federal Aviation Administration (FAA) has shown that the application of AI and machine learning in ACAS X significantly improves performance metrics compared to TCAS II. In simulation studies across a wide spectrum of encounter scenarios—including high-closing-speed, multi-intruder, and highly asynchronous situations—ACAS X demonstrated lower rates of unnecessary alerts (so-called “nuisance” alerts) while maintaining or improving safety margins.

A major advantage of incorporating machine learning in ACAS X is its ability to tailor responses to specific operational constraints. For instance, the system can generate resolution advisories that avoid unnecessary altitude changes, which is particularly beneficial in crowded terminal airspace. Moreover, variants such as ACAS Xa and ACAS Xu extend this approach to both commercial and unmanned aircraft, respectively, using AI-based models adapted to different aircraft performance profiles and sensor limitations.

Ongoing research also investigates the integration of reinforcement learning and online adaptation to further enhance system robustness in unanticipated conditions. While current ACAS X models are trained offline and verified against an exhaustive set of encounter models, future implementations may incorporate limited online learning or policy adjustment based on real-time feedback, although this raises questions regarding certification and system verifiability.

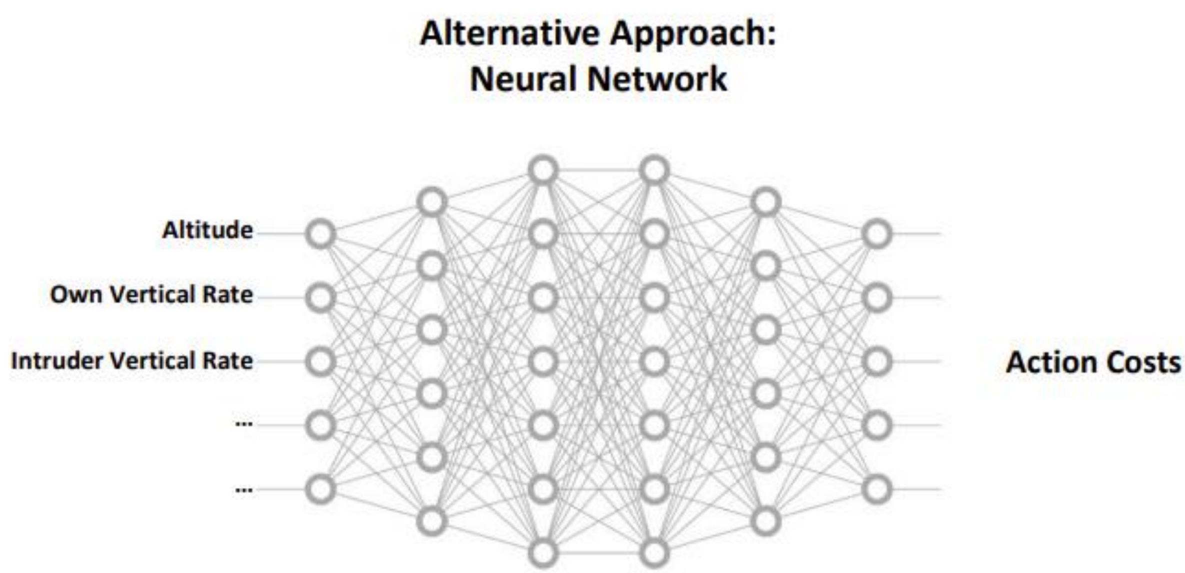


Fig. 1.9 The use of neural networks in assessing action cost

3.5 The use of augmented reality

Human-machine interaction (HMI) plays a pivotal role in enhancing situational awareness and reducing the likelihood of mid-air collisions in both civilian and military aviation. As flight decks become increasingly complex, with a growing number of digital instruments and data sources, effective HMI design has become critical in ensuring that pilots are able to process, interpret, and act upon safety-critical information in a timely and accurate manner. Augmented reality (AR), as an emerging component of HMI, offers novel possibilities for improving collision avoidance by presenting spatial and traffic data in a more intuitive and cognitively efficient manner.

Research shows that poor situational awareness is a contributing factor in a significant proportion of airprox incidents and losses of separation, particularly in environments with high traffic density or complex airspace structure. Traditional displays, such as radar screens and 2D navigation panels, require constant cross-referencing and mental projection from the pilot, which can result in increased workload and delayed reaction times during time-sensitive events. In contrast, AR-based interfaces have the potential to present key information—such as traffic trajectories, separation margins, and terrain threats—directly within the pilot’s line of sight, either via head-up displays (HUDs) or head-mounted displays (HMDs), thereby reducing the cognitive load associated with maintaining situational awareness.

Augmented reality systems can integrate real-time data from ADS-B, ACAS, and onboard sensors to create a composite visual overlay of nearby aircraft and predicted conflicts. This overlay can display conflict resolution advisories, such as climb or descent commands, in a spatially contextualized format. Preliminary studies conducted by NASA and the FAA indicate that such displays significantly improve pilot response times in simulated mid-air collision scenarios, particularly under high workload conditions or degraded visibility. Furthermore, AR can assist in bridging the gap between instrument and visual flight rules (IFR and VFR), by enhancing the pilot's understanding of traffic positioning even when visual contact is impaired.

While AR technologies are still largely in the experimental stage for commercial aviation, they have already been deployed and validated in the context of next-generation fighter aircraft. Fifth-generation jet fighters, such as the F-35 Lightning II, employ advanced helmet-mounted displays that fuse data from multiple sensors to provide 360-degree awareness of both air and ground threats. These systems allow pilots to “look through" the aircraft structure and visualize nearby traffic or missiles in real time, based on data fusion and predictive algorithms. The effectiveness of such systems in reducing pilot workload and increasing survivability under high-stress conditions suggests similar benefits could be achieved in civil aviation when adapted for commercial use.

Fig. 1.10 F-35 Lightning II pilot helmet which incorporates AR technologies.

Human factors research also emphasizes the importance of designing AR systems that are non-intrusive and adaptable to varying levels of pilot expertise. Interfaces must avoid information overload by selectively filtering and prioritizing collision-related alerts. Adaptive interfaces that respond to pilot gaze, workload, or phase of flight are being actively explored as part of the broader trend toward intelligent cockpit environments. For example, experimental systems using eye-tracking have been tested to dynamically highlight traffic threats or navigation cues depending on the pilot's focus and contextual needs.

In addition to direct collision avoidance, AR can support other safety-critical tasks such as taxi guidance, runway incursion prevention, and terrain awareness—further reducing the risk of incidents that could lead to cascading traffic conflicts.

Despite its promise, the integration of AR into civilian cockpits faces several challenges, including certification hurdles, system reliability under varying lighting and weather conditions, and the need for rigorous human-in-the-loop testing. However, with ongoing development and simulation-based validation, it is expected that the next generation of airliners will incorporate AR elements as part of their safety and navigation toolset.

Human-machine interaction improvements, particularly through the use of augmented reality, hold substantial potential to enhance mid-air collision avoidance in civilian aviation. Drawing from proven military technologies and supported by emerging research, these tools represent a promising direction for increasing pilot situational awareness, reducing human error, and ultimately contributing to a higher level of safety.

3.6 Certification challenges

While the ACAS X family of systems represents a significant advancement in airborne collision avoidance technologies, their implementation within the civil aviation sector is currently constrained by the complexities of the certification process. Unlike earlier iterations such as TCAS II, which are already standardized and widely adopted, the newer ACAS X variants—such as ACAS Xa, Xo, Xu, and Xp—introduce novel algorithms, probabilistic models, and adaptive logic that require rigorous validation under diverse operational conditions. Research shows that the performance of these systems often exceeds current minimum safety thresholds, yet they remain in a pre-certification or limited deployment phase due to regulatory inertia and the inherent caution of global aviation authorities.

The ICAO and national regulatory bodies such as the FAA and EASA must ensure that any system intended for widespread use in civil airspace meets stringent reliability and interoperability standards. However, the process of validating a system as safety-critical and globally interoperable is both time-consuming and resource-intensive. For example, while ACAS Xa has demonstrated superior resolution advisory logic through large-scale Monte Carlo simulations and flight trials, translating this empirical performance into certified operational readiness requires the creation of exhaustive test cases, failure mode analysis, and formal verification models. Research indicates that this validation is further complicated by the need to preserve backward compatibility with existing TCAS II-equipped aircraft.

Another critical barrier involves harmonizing certification criteria across jurisdictions. Because ACAS X introduces probabilistic threat evaluation rather than deterministic logic, traditional certification methodologies—which are often based on rule-based logic validation—struggle to accommodate these newer paradigms. Studies suggest that regulators have not yet established a universally accepted framework for certifying machine-learning-based or probabilistic safety systems. As a result, manufacturers and developers are faced with the dual burden of proving not only system performance but also the transparency, interpretability, and auditability of their algorithms—factors that are difficult to reconcile with emerging AI-based approaches.

In addition, human-machine interaction implications associated with these new systems must also be thoroughly vetted during certification. ACAS X systems are designed to provide more intuitive and context-aware advisories to flight crews, which demands a careful evaluation of pilot response behaviors, decision-making latency, and training requirements. Certification authorities must therefore assess not only the system's technical safety but also its usability under real-world cockpit conditions. According to ongoing research, this adds further layers of complexity to the certification process, delaying the full integration of these systems into commercial aviation fleets.

In sum, while the ACAS X family and its associated technologies offer substantial improvements in collision avoidance capability, their deployment remains hampered by certification challenges rooted in regulatory conservatism, methodological constraints, and the need for cross-national standardization. Overcoming these barriers will require close collaboration between developers, regulatory bodies, and operators to develop adaptive certification frameworks that can keep pace with technological innovation without compromising aviation safety.

3.7 Recommendations

One of the most impactful advancements in modern aviation is the implementation of Automatic Dependent Surveillance–Broadcast (ADS-B). This cutting-edge system enables aircraft to automatically relay their position, altitude, speed, and other vital flight data to ground stations. Air traffic controllers and aviation services rely on this real-time information to accurately track aircraft and manage traffic flow. ADS-B dramatically enhances the precision and reliability of airspace surveillance, playing a key role in preventing collisions. A standout benefit of ADS-B is its ability to provide coverage in remote or underserved areas where traditional radar systems fall short.

Another crucial piece of the puzzle in preventing airborne conflicts is the Traffic Collision Avoidance System (TCAS). TCAS functions by interpreting signals from aircraft transponders to detect potential mid-air threats and then alerting pilots with maneuver instructions to avoid them. Especially in crowded skies, TCAS acts as a vital safety net, significantly lowering the likelihood of mid-air incidents.

Weather also plays a huge role in flight safety, and that’s where advanced meteorological technologies come in. Modern aviation weather systems—powered by radar, satellites, and automated observation stations—supply real-time data about weather conditions along flight paths. Information on turbulence, storms, icing, and other hazards allows flight crews to anticipate dangers and modify their routes proactively to ensure smoother, safer journeys.

Integrated Air Traffic Control (ATC) systems represent another major technological stride in preventing dangerous aircraft proximity. These systems utilize automation to monitor flight paths, optimize routing, and coordinate between various aviation authorities. By consolidating data from sources like ADS-B, TCAS, and weather systems, modern ATC platforms provide a comprehensive, real-time snapshot of air traffic. This holistic approach enables more informed and timely decisions, reducing the chance of conflicts.

Unmanned Aerial Vehicles (UAVs) are also making their mark in civil aviation safety. Drones are increasingly being used to inspect airport infrastructure, assess aircraft conditions, and assist in emergency response. They offer a nimble and efficient means of surveillance, especially in areas that are hard to reach or where conventional monitoring systems are lacking. Their presence enhances situational awareness and supports faster identification and resolution of potential threats.

Finally, artificial intelligence (AI) and machine learning are reshaping the landscape of aviation safety. These technologies excel at processing massive datasets—from flight logs to aircraft diagnostics and weather models—to uncover hidden patterns that might signal emerging risks. By analyzing this data, AI can anticipate potential conflicts and help devise preventive strategies. For instance, machine learning algorithms can sift through flight recorder data to detect unusual system behaviors or deviations in pilot responses, allowing authorities to act before problems escalate.

Big Data has become a vital asset in evaluating the risks of aircraft dangerously converging mid-flight. By gathering and analyzing extensive datasets on flight operations, aircraft conditions, weather patterns, crew behavior, and more, aviation experts can uncover patterns and correlations that often go unnoticed with conventional analysis techniques. Advanced analytical platforms powered by machine learning and artificial intelligence offer deep insights, predictive capabilities, and actionable recommendations—helping to proactively prevent incidents and elevate overall aviation safety and reliability.

Beyond data analytics, modern information systems and comprehensive databases play a central role in managing these risks. They enable aviation authorities to systematically collect, store, and interpret information related to incidents, technical conditions, and broader flight activities. This data-driven approach supports retrospective analysis, uncovers root causes behind conflict situations, and guides the creation of effective preventive strategies. Moreover, these systems promote transparency and data accessibility across all levels of aviation stakeholders, reinforcing a culture of safety.

Emerging technologies like augmented reality (AR) are also carving out a space in risk assessment and management. AR enhances the crew's situational awareness by overlaying real-time information—such as weather updates, nearby aircraft positions, and airport conditions—onto visual displays. This immersive layer of data empowers pilots to make quicker, more informed decisions, minimizing human error and further strengthening flight safety.

Decision Support Systems (DSS) are another key technological advancement in this space. By synthesizing data from multiple sources—weather updates, traffic density, aircraft diagnostics—DSS tools provide real-time analysis and predictive guidance to both flight crews and air traffic controllers. These systems enable faster, smarter responses to dynamic scenarios, significantly reducing the likelihood of near-miss events and improving safety outcomes. For instance, by proactively optimizing flight paths based on current conditions, DSS can help prevent potential airspace conflicts.

To continue enhancing safety and operational efficiency in civil aviation, strengthening conflict monitoring systems is essential. This includes implementing cutting-edge technologies like Automatic Dependent Surveillance–Broadcast (ADS-B), which offers precise, real-time tracking of aircraft positions. Widespread adoption and integration of ADS-B into existing air traffic control infrastructures would lead to more seamless coordination between flight crews and controllers, elevating both the accuracy and responsiveness of the monitoring process.

A key step toward reducing mid-air collision risks is enhancing Traffic Collision Avoidance Systems (TCAS). Although TCAS is a standard feature in modern civil aviation, there's still plenty of room for advancement. By upgrading the underlying algorithms and embracing newer technologies, airlines can boost the system's accuracy and responsiveness. It's equally vital to ensure that flight crews are thoroughly trained to use TCAS effectively — the system only works as well as the people operating it.

Upgrading meteorological infrastructure is another crucial move. Today's weather radars, satellite data, and automated reporting stations offer real-time insights into atmospheric conditions along a flight path. For maximum safety, airlines and aviation authorities should continue investing in the expansion and modernization of these tools, making sure crews receive timely, accurate updates about weather hazards. This kind of foresight can help pilots reroute flights before encountering turbulence, storms, or other dangerous weather events.

Better integration between air traffic control (ATC) systems is also essential. By combining inputs from ADS-B, TCAS, weather systems, and more into a single interface, controllers get a full, unified view of airspace activity. With this holistic perspective, they can make faster, better-informed decisions. Aviation organizations should prioritize building and deploying these integrated ATC networks to elevate safety standards across the board.

Artificial intelligence (AI) and machine learning represent another promising frontier. These technologies can sift through massive volumes of flight data — including aircraft status, weather patterns, and previous incident reports — to detect patterns that humans might miss. With AI-powered analytics, it's possible to anticipate potential near-miss scenarios and take preventative steps well before a threat materializes.

The aviation industry can also benefit significantly from implementing Internet of Things (IoT) solutions. Connecting devices and systems in real time allows for smarter, more dynamic monitoring — capable of spotting risks and responding automatically. By incorporating IoT into aircraft and ground systems, airlines and airports can create an intelligent ecosystem that enhances situational awareness and sharpens the precision of collision risk assessments.

Finally, none of these technical upgrades matter much without skilled, confident personnel. Strengthening training and human resource management is fundamental to safety. From simulated emergency drills to ongoing education programs, crews need constant exposure to realistic scenarios and updated protocols. Airlines should treat training not as a box to check, but as a continuous investment in safety — ensuring every team member is ready to make the right call when it matters most.

An essential recommendation for enhancing flight safety is the modernization of communication systems. Seamless interaction between flight crews, dispatchers, maintenance teams, and supporting services is fundamental to safe operations. To that end, airlines should adopt advanced digital communication tools—such as Controller–Pilot Data Link Communications (CPDLC)—which enable swift and precise information exchange. Implementing such systems minimizes the risk of miscommunication and operational errors, thereby contributing to a higher standard of safety.

Cybersecurity is another critical pillar of aviation safety. As digital systems become increasingly integrated into flight operations, the threat of cyberattacks that could compromise safety continues to grow. To mitigate these risks, airlines must establish robust cybersecurity frameworks. This includes protecting sensitive data, performing routine security audits, and training personnel to respond effectively to potential cyber incidents. These measures help safeguard access to flight control systems and ensure their continued secure functionality.

Equally important is the enhancement of aircraft condition monitoring systems. The deployment of modern diagnostic tools allows for early detection of technical anomalies and supports timely maintenance interventions. By investing in state-of-the-art monitoring technologies, airlines can significantly reduce the likelihood of in-flight technical failures and bolster the overall reliability of their fleets. Consistent maintenance and real-time system oversight remain key to sustaining safe flight operations.

Incorporating augmented reality (AR) technology into cockpit systems is another forward-looking recommendation. AR can present pilots with real-time environmental data—such as weather conditions, surrounding traffic, and airport status—directly on their visual displays. This augmentation boosts situational awareness and supports more accurate, timely decision-making, thereby lowering the potential for human error and improving operational safety.

Furthermore, the integration of blockchain technology offers promising improvements in data transparency and integrity. Blockchain's decentralized and tamper-proof nature enables the secure recording of maintenance histories, flight logs, and component certifications. Its adoption reduces the risk of data manipulation and fosters greater confidence in the information used to assess and mitigate mid-air collision risks.

Infrastructure modernization is also a foundational requirement for advancing aviation safety. Upgrades to air navigation systems, airport equipment, and other critical infrastructure reduce the likelihood of safety-related incidents stemming from outdated or failing systems. Regular updates and proactive maintenance are vital to ensuring these systems operate reliably.

Finally, sustained and reliable funding is crucial to maintaining all safety initiatives. Financial instability can lead to reduced investment in essential safety programs, maintenance, and personnel training, thereby introducing additional risks. To preserve high safety standards, it is imperative that aviation stakeholders secure consistent financial support for these critical areas.

To conclude, enhancing the collision prevension systems in civil aviation requires a comprehensive and multifaceted strategy. Key recommendations include the adoption of advanced Automatic Dependent Surveillance–Broadcast (ADS-B) technologies, modernization of Traffic Collision Avoidance Systems (TCAS), enhancement of meteorological infrastructure, integration of diverse air traffic control (ATC) systems, and the incorporation of artificial intelligence (AI), machine learning, and Internet of Things (IoT) technologies. Improvements in both management frameworks and ATC operations are also essential. Implementing these measures will significantly bolster flight safety, minimize the risk of mid-air conflicts, and ensure more efficient oversight of aviation operations. A holistic approach to upgrading the conflict monitoring infrastructure is crucial for achieving a high standard of reliability and safety in civil aviation, thereby reinforcing passenger trust and supporting the overall resilience of the aviation sector.

CONCLUSION

1. **Relevance of the subject.** The issue of dangerous aircraft convergence remains one of the key safety challenges in civil aviation, especially as global air traffic continues to grow. Addressing mid-air collision risks is essential for maintaining both passenger safety and operational efficiency.

2. **Effectiveness of existing systems.** TCAS I and TCAS II have significantly contributed to the reduction of mid-air collisions by providing timely resolution advisories to pilots. However, their limitations in handling complex traffic scenarios and their reliance on predefined logic necessitate further evolution.

3. **Need for modernization.** As the density and complexity of airspace increase, the limitations of legacy systems become more apparent. There is a clear need for more adaptive, precise, and intelligent collision avoidance technologies.

4. **Promising new developments.** The ACAS X family of systems is a major advancement in collision avoidance, offering improved decision-making through probabilistic modeling and greater flexibility. Its modular architecture allows for better integration with modern surveillance systems such as ADS-B.

5. **Recommendations for improvements.** Future development should focus on integrating artificial intelligence and machine learning to enhance the predictive and adaptive capabilities of collision avoidance systems. Augmented reality may also play a role in improving pilot situational awareness by providing intuitive visual cues during potential conflict scenarios.

6. **Certification challenges.** Despite their technical promise, ACAS X and AI-driven solutions face significant hurdles in terms of international certification, particularly under ICAO regulations. These challenges delay widespread implementation and highlight the need for updated certification frameworks that can accommodate non-deterministic systems.

SOURCES

1. ACAS Guide: Airborne Collision Avoidance Systems / EUROCONTROL, 2022. 144 p.
2. Jun Tang. Review: Analysis and Improvement of Traffic Alert and Collision Avoidance System / IEEE. 2017. 11 p.
3. Harman W.H., Kennedy R.S. TCAS: A System for Preventing Midair Collisions. *The Lincoln Laboratory Journal*. Volume 2, №3. P. 437-458
4. International Civil Aviation Organization (ICAO). Annex 10 to the Convention on International Civil Aviation. Volume IV – Surveillance and Collision Avoidance Systems. Montreal: ICAO, 2014. 216 p.
5. TCAS Program Office (AJM-42). ACAS X Validation Strategy. 20 September 2023. – 27 slides.
6. Arbuckle D. Future ADS-B Applications. Automatic Dependent Surveillance – Broadcast OUT Technical On-Line Workshop for the NAM/CAR Regions (ADS-B/OUT/W), 29 January 2021. – 37 slides.
7. Lepird J. R. Multi-Objective Optimization of Next-Generation Aircraft Collision Avoidance Software. Massachusetts Institute of Technology, June 2015. – 90 p.
8. Wan Y., Tang J., Lao S. Research on the Collision Avoidance Algorithm for Fixed-Wing UAVs Based on Maneuver Coordination and Planned Trajectories Prediction. MDPI Sensors, 25 February 2019. – 20 p.
9. Julian K. D., Kochenderfer M. J., Owen M. P. Deep Neural Network Compression for Aircraft Collision Avoidance Systems. 9 October 2018. – 13 p.
10. Li S., Egorov M., Kochenderfer M. J. Optimizing Collision Avoidance in Dense Airspace Using Deep Reinforcement Learning. Thirteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2019), 20 December 2019. – 10 p.

11. Stroeve S. What Matters in the Effectiveness of Airborne Collision Avoidance Systems? Monte Carlo Simulation of Uncertainties for TCAS II and ACAS Xa. Aerospace, 2023, Vol. 10, No. 952, 11 November 2023.
12. IVAO Documentation Library. Traffic collision avoidance system – TCAS. URL: https://wiki.ivao.aero/en/home/training/documentation/Traffic_collision_avoidance_system-TCAS (accessed: 02.06.2025)