© MAR 2026 | IRE Journals | Volume 9 Issue 9 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I9-1715795

A Systems Engineering Approach to The Redesign of The Traffic Alert and Collision Avoidance System II

AYOKUNUMI E. OGUNSINA[1], BRENT COX[2], THOMAS AYERS[3], VITORIA R. G. SANTOS[4]
[1, 2, 3, 4]*College of Aviation, Embry-Riddle Aeronautical University*

I. INTRODUCTION

The Traffic Alert and Collision Avoidance System II (TCAS II) is an airborne system designed to prevent mid-air collisions by alerting pilots to nearby aircraft and issuing resolution advisories such as climb or descend commands. Following high-profile mid-air collisions, including the 1986 Cerritos crash, TCAS II was mandated by the Federal Aviation Administration for U.S. commercial aircraft. However, its early development and deployment during the 1980s and 1990s encountered significant challenges. Initial versions suffered from unreliable alerts, poor integration with air traffic control, and pilot confusion, which delayed full adoption until system improvements were implemented in the late 1990s.

Major issues associated with the early TCAS II design included vague requirements that failed to clearly define alert thresholds and coordination with air traffic control, as well as not clearly defined system functions that were too simplistic to handle complex operational scenarios. Usability issues further contributed to pilot confusion, as flight crews sometimes received conflicting or unclear advisories that undermined trust in the system. In addition, the lack of robust functional modeling and real-world scenario testing prior to deployment limited the system's ability to address operational complexity effectively.

The mission of TCAS II is to avoid collisions between aircraft, provide effective decision-making support to pilots and air traffic controllers, and enhance the overall safety of air traffic (FAA, 2011). The system serves as a critical safety layer to maintain safe flight operations, particularly in environments with high air traffic density. To support this mission, TCAS II must deliver timely, clear, and reliable advisories that allow rapid and correct responses to potential collision threats. This project proposes a redesign of TCAS II using systems engineering principles to address identified deficiencies through improved requirements definition, functional design, and advisory clarity. Key stakeholders include airplane pilots, air traffic controllers, system design engineers, system management organizations, and regulatory authorities such as the Federal Aviation Administration, highlighting the importance of applying systems engineering to a safety-critical aviation system.

II. MISSION STATEMENT

The mission of the Traffic Alert and Collision Avoidance System II (TCAS II) is to reduce the risk of mid-air collisions by providing flight crews with timely, clear, and reliable traffic and resolution advisories that operate independently of ground-based air traffic control. TCAS II is intended to serve as a last line of defense against airborne collisions hazards, particularly in high-density or high-workload flight environments where reliance on procedural separation alone may be insufficient.

To accomplish this mission, the system must address several critical needs, including the ability to communicate collision avoidance guidance to pilots who received advisories that were confusing, poorly timed, or appeared to conflict with air control instructions. FAA analyses have shown that unclear or inconsistent advisors can reduce pilot trust in the system and delay appropriate responses during critical situations (FAA, 2011).

As a result, TCAS II must provide standardized, intuitive, and immediately understandable visual and aural advisories that allow flight crews to rapidly

© MAR 2026 | IRE Journals | Volume 9 Issue 9 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I9-1715795

recognize collision threats and execute correct maneuvers without additional interpretation. Ensuring clarity and usability in pilot advisories is essential to support the system's mission and to prevent TCAS II from becoming a source of confusion during critical phases of flight.

Requirements

The identification of system requirements begins with understanding the stakeholders involved in the system. The primary stakeholders for the Traffic Alert and Collision Avoidance System II (TCASII) include commercial and general aviation flight crews, airline manufacturers, air traffic control organizations, regulatory authorities, and passengers. Flight crews are the direct users of the system and rely on TCAS II advisories to make immediate, safety critical decisions during potential mid-air conflict situations. Airline operators and aircraft manufacturers are key stakeholders because TCAS II must be consistently integrated with aircraft avionics and operational procedures to ensure reliable performance across different platforms.

Air traffic control organizations and regulatory authorities, particularly the Federal Aviation Administration (FAA), are also major stakeholders, as TCAS II operates in shared responsibility with ATC separation services and must be compatible with existing airspace management practices. Research conducted by MIT Lincoln Laboratory highlights that TCAS II was designed as an independent airborne safety layer that complements. Rather than replaces, air traffic control, making coordination between airborne systems, controllers, and regulatory oversight essential to overall effectiveness (Kuchar & Drumm, 2007). Passengers represent indirect stakeholders whose safety depends on the successful interaction of these technical and organizational elements.

To meet user needs, the TCAS II key performance parameters (KPPs) listed in

Table 1 were defined to establish quantitative constraints for the system requirements.

Table 1 Key Performance Parameters

KPP ID	KPP / Parameter	Target Value	Why it matters
KPP_1	Detection Range	>14 NM	Provides early threat awareness
KPP_2	Update Rate	>1 Hz	Ensures accurate tracking
KPP_3	Altitude Accuracy	(+/-) 100 feet	Supports vertical separation evaluation
KPP_4	TA Trigger Time	< 40 sec	Early warning for pilot awareness
KPP_5	RA Trigger Time	< 25 sec	Ensures collision avoidance
KPP_6	RA Response Time	< 5 sec	Prevents delayed advisories
KPP_7	Availability	> 99.9%	Safety critical function
KPP_8	False Alarm Rate	< 1 per 100 flight hours	Prevents pilot distrust
KPP_9	Ground Estimation	≤1750 ft AGL	Threshold below which TCAS checks for targets on the ground
KPP_10	Intruder aircraft on ground	≤360ft	Threshold below which is determined that the intruder aircraft is on ground

Table 2 lists the TCAS II requirements. Each requirement defines a specific system capability, its rationale, hierarchical relationship to parent requirements, and its association with Key Performance Parameters (KPPs). Together, these requirements establish the functional, performance,

© MAR 2026 | IRE Journals | Volume 9 Issue 9 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I9-1715795

and operational constraints necessary to support safe and reliable collision avoidance operations.

Table 2
TCAS II Requirements

Requirement ID	Requirement Definition	Rationale	Parent ID	Related KPP
REQ-1.0	The Collision Avoidance Subsystem (CAS) shall detect and track intruder aircraft within a minimum range of 14 NM (Nautical Miles).	Provides sufficient time for threat detection and advisory generation		KPP_1
REQ-1.1	The CAS shall update intruder tracking information at a minimum rate of 1 Hz.	Accurate altitude data is required to calculate vertical separation risk.	REQ-1.0	KPP_2
REQ-2.0	The CAS shall generate a Traffic Advisory (TA) when loss of separation is predicted within 40 seconds.	It gives pilots early awareness to visually acquire traffic.	REQ-2.0	KPP_4
REQ-2.1	The CAS shall issue TA alerts using both visual cockpit display and audio communication.	Ensures pilots receive warning under high workload conditions.		KPP_4
REQ-3.0	The CAS shall generate a Resolution Advisory (RA) when loss of separation is predicted within 25 seconds	Provides pilots immediate maneuver guidance when collision risk becomes imminent.		KPP_5
REQ-3.1	The CAS shall generate an RA command within 5 seconds of reaching the RA trigger threshold.	Prevents delayed maneuver instructions that reduce reaction time.	REQ-3.0	
REQ-3.2	The CAS shall not issue an RA requiring vertical acceleration exceeding 0.25 G (gravity force).	Ensure maneuver commands remain safe and within aircraft capability.	REQ-3.0	KPP_6
REQ-4.0	The CAS shall support advisory coordination to prevent conflicting RAs between aircraft.	Prevents unsafe maneuvers where both aircraft respond incorrectly.		KPP_5; K

© MAR 2026 | IRE Journals | Volume 9 Issue 9 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I9-1715795

Requirement ID	Requirement Definition	Rationale	Parent ID	Related KPP
				PP_6
REQ-5.0	The CAS shall maintain operational availability of 99.9% during flight operations.	Collision avoidance is safety critical and must remain operational.		KPP_7
REQ-6.0	The CAS tracker shall estimate the approximate elevation of the ground above mean sea level.	The elevation estimate is one of the thresholds for triggering functions.		KPP_8
REQ-6.1	When the CAS tracker estimates an elevation ≤ 1750 ft above ground level (AGL), the Ground Determination Logic shall be activated.	The ground determination logic will prevent false alarms for the flight crew.	REQ-6.0 REQ-7.0	KPP_8
REQ-6.1.1	The CAS tracker shall estimate the elevation of each Mode C equipped intruder aircraft by subtracting the ground level (GL) from the received pressure altitude (PA). $PA_{intruder} - GL$= Estimated Altitude	This logic will be used to determine if the intruder aircraft is declared on ground or airborne.	REQ-6.1	KPP_8; KPP_9
REQ-6.2	The Ground Determination shall declare the intruder aircraft “On Ground” when the estimated altitude is ≤ 360ft.	This determination will avoid false alarms.	REQ-6.0 REQ-7.0	KPP_9
REQ-6.3	The Ground Determination shall declare the intruder aircraft “Airborne” when the estimated altitude is ≥ 360ft.	This determination ensures the safety of the alarm.	REQ	KPP_9

© MAR 2026 | IRE Journals | Volume 9 Issue 9 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I9-1715795

Requirement ID	Requirement Definition	Rationale	Parent ID	Related KPP
			-6.0	
REQ-7.0	The TCAS shall inhibit the generation of advisories against intruder aircrafts that are declared "On Ground".	The determination of intruder aircraft on ground will avoid false alarms.		KPP_9

Functional models

The functional models for the redesigned TCAS II system were developed from the system requirements to represent the operational functions necessary to accomplish the system mission. Functional Flow Block Diagrams (FFBDs) illustrate the logical sequence of system operations, from aircraft detection and tracking to the generation of traffic and resolution advisories. These models translate the requirements into functional processes and provide a structured representation of how the TCAS II system performs collision avoidance operations.

Figure 1 provides the top level FFBD, while Figures 2, 3, 4 and 5 detail the interrogation, ground targets filter, avoidance logic and flight crew alerting functions respectively.

Figure 1
Top Level Functional Flow Block Diagram

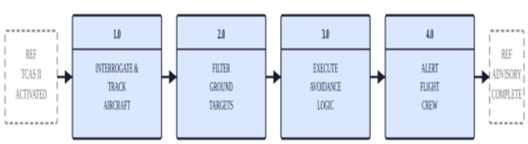


Figure 2
2.0 - Interrogate & Track Aircraft

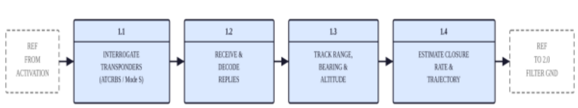


Figure 3: 2.0 Filter Ground Targets

Figure 3
3.0 - Execute Avoidance Logic

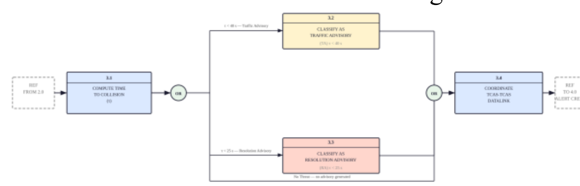
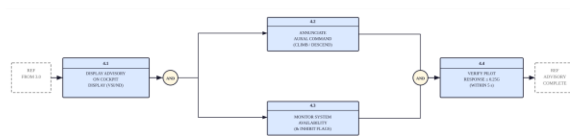


Figure 4
4.0 - Alert Flight Crew



III. TECHNICAL PERFORMANCE MEASURES (TPMS)

Technical Performance Measures (TPMs) are used throughout system development to evaluate whether a system meets its intended performance requirements. For a safety critical aviation system such as TCAS II, TPMs are essential to ensure that the system maintains reliable performance and effectively supports collision avoidance operations.

Several TPMs can be used to evaluate the performance of the redesigned TCAS II system. These include system reliability, false alert rate, advisory response time, and aircraft tracking accuracy. Reliability is particularly important because the TCAS II system must remain operational throughout all phases of flight. A failure during operation could significantly increase the risk of mid-air collisions.

Another key TPM is the false alert rate. Excessive false alerts can reduce pilot trust in the system and may cause pilots to ignore advisories during critical situations. The redesigned system therefore aims to minimize unnecessary alerts while still maintaining sufficient sensitivity to detect potential collision threats.

Advisory response time is also an important performance measure. The system must detect potential conflicts and generate advisories quickly enough to allow pilots sufficient time to respond safely. Additionally, aircraft tracking accuracy must remain within defined tolerances to ensure reliable threat detection and resolution advisory generation.
Monitoring these TPMs during development and operational testing ensures that the redesigned TCAS II system meets the required safety and reliability standards.

Human Factors

Human factors play a significant role in the effectiveness of airborne collision avoidance systems. Because TCAS II advisories directly influence pilot decision making during critical flight situations, the system must present information in a clear and intuitive manner.

Early implementations of TCAS II experienced usability challenges that contributed to pilot confusion. In some cases, pilots received advisories that appeared to conflict with the air traffic control instructions, which created uncertainty about which directive should be followed. These issues highlighted the importance of designing collision avoidance systems that integrate effectively with human operators.

The redesigned TCAS II system places a strong emphasis on improving the clarity and usability of advisory information. Visual displays must present advisory commands clearly, while audio alerts provide immediate notification to ensure that pilots are aware of potential threats. Standardized advisory language such as “CLIMB” or “DESCEND” allows pilots to quickly interpret and execute the required maneuver.

In addition, reducing unnecessary alerts helps prevent alarm fatigue and minimizes pilot workload during high stress aims to improve confidence and ensure effective response to collision avoidance advisories.

Project Management

Effective project management is essential for the successful development of complex aerospace systems. The redesign of TCAS II requires coordination among multiple stakeholders, including aviation regulators, system engineers, aircraft manufacturers, and airline operators.

Project management activities include defining project scope, allocating resources, managing technical risks, and ensuring that system development progresses according to schedule. Because the TCAS II system involves both hardware and software components, careful coordination between engineering teams is required throughout the development lifecycle.

Risk management is also an important aspect of project management for critical safety systems. Potential risks include software errors, sensor inaccuracies, and integration challenges with existing avionics systems. Identifying and mitigating these risks early in the development process helps ensure that the redesigned system meets safety and reliability requirements.

Through effective project management practices, the development team can maintain alignment between system requirements, engineering activities, and regulatory certification requirements.

Systems Engineering Management Plan (SEMP)

The Systems Engineering Management Plan (SEMP) provides a structured framework for managing the development of the redesigned TCAS II system. The SEMP outlines how system engineering processes will be applied throughout the system lifecycle to ensure that the final system meets operational requirements and safety standards.

The development process begins with concept definition and stakeholder analysis to identify the operational needs of pilots, air traffic controllers, and regulatory agencies. This is followed by requirement analysis, where system requirements are defined and documented. Functional analysis and system architecture design are then performed to establish how the system will mee these requirements.

Following the design phase, system integration and testing are conducted to verify that individual components function correctly and interact properly within the overall system architecture. Verification ensures that the system meets technical specifications, while validation confirms that the system satisfies operational needs and improves aviation safety.

By following the SEMP framework, the redesign process maintains traceability between requirements, system design, and testing activities. This structured approach helps ensure that the redesigned TCAS II system meets both technical and operational objectives.

Legal and Ethical Considerations
The development and implementation of TCAS II must comply with strict regulatory standards established by aviation authorities such as the Federal Aviation Administration (FAA). Certification requirements ensure that airborne safety systems operate reliably and do not introduce unintended risks into the aviation environment.

Engineers involved in the design of safety critical systems also have significant ethical responsibilities. Aviation systems directly affect the safety of passengers, flight crews, and individuals on the ground. As a result, engineers must prioritize safety reliability, and thorough testing throughout the system development process.

Failure to adequately design, test, or verify a system such as TCAS II could lead to catastrophic consequences. Ethical engineering practice therefore requires adherence to professional standards, rigorous testing procedures, and transparent documentation of system capabilities and limitations.

By addressing both regulatory and ethical considerations, the redesigned TCAS II system supports the broader goal of maintaining safe and reliable air transportation.

IV. DISCUSSION AND CONCLUSIONS

The analysis conducted in this project highlights the importance of applying systems engineering principles when designing complex safety critical systems such as the TCAS II. Early implementations of TCAS II experienced several challenges, including vague requirements, insufficient functional modeling, and useability issues that contributed to pilot confusion and reduced trust in the system.

By applying a structured systems engineering approach, the redesigned TCAS II system improves several key aspects of system performance. Clearer requirements definitions allows systems capabilities to be better aligned with operational needs. Functional modeling improves understanding of system behavior and interactions help ensure that pilots can respond quickly and effectively to potential collision threats.

The redesign also emphasizes reliability and maintainability, ensuring that the system can operate consistently throughout its lifecycle while supporting efficient maintenance and system upgrades.

Despite these improvements, certain limitations remain. Integrating the redesigned TCAS II system with existing aircraft avionics infrastructure may present technical challenges, particularly for older aircraft platforms. Additionally, the certification process required for aviation safety systems can be complex and time consuming, potentially extending development timelines.

Future work may involve additional simulation testing, evaluation of system performance under complex air traffic scenarios, and integration with emerging collision avoidance technologies such as the next generation Airborne Collision Avoidance System (ACAS X). Continued advancements in sensing technology and data processing may further improve the accuracy and reliability of airborne collision avoidance systems.

Overall, the redesign of TCAS II demonstrates how the application of systems engineering methodologies can significantly improve the development of complex aviation safety systems. By addressing requirements definition, functional modeling, reliability, and human factors, the redesigned system provides a more robust and effective solution for preventing mid-air collisions and enhancing aviation safety.

REFERENCES

[1] Kuchar, J., Drumm, A. (2007), The Traffic Alert and Collision Avoidance System, MIT Lincoln Laboratory, https://www.ll.mit.edu/sites/default/files/publication/doc/traffic-alert-collision-avoidance-system-kuchar-ja-11284.pdf

[2] FAA (2011), Introduction to TCASII, http://www.faa.gov/documentLibrary/media/Advisory_Circular/TCAS%20II%20V7.1%20Intro%20booklet.pdf

[3] Heimdah, M. (1996), Experiences and lessons from the analysis of TCASII, ISSTA '96: Proceedings of the 1996 ACM SIGSOFT international symposium on Software testing and analysis, Pages 79 – 83, https://doi.org/10.1145/229000.226304

[4] M. P. E. Heimdahl, N. G. Leveson and J. D. Reese, "Experiences from specifying the TCAS II requirements using RSML," 17th DASC. AIAA/IEEE/SAE. Digital Avionics Systems Conference. Proceedings (Cat. No.98CH36267), Bellevue, WA, USA, 1998, pp. C43/1-C43/8 vol.1, doi: 10.1109/DASC.1998.741499.

[5] Federal Aviation Administration. (2017, July 21). *Advisory Circular 20-151C: Airworthiness approval of traffic alert and collision avoidance systems (TCAS II), versions 7.0 & 7.1 and associated Mode S transponders*. U.S. Department of Transportation.

[6] Liu, D. (2015). *Systems engineering: Design principles and models* (1st ed.). Taylor & Francis Group.