Part I

TCAS Development and the Federal Role

First we're going to crawl with TCAS,
then walk, then jog, then run.
— J. Lynn Helms, former FAA Administrator in announcing TCAS

BACKGROUND

Pilots are and always have been the first and foremost collision avoidance system. As pilots and aircraft became capable of flying "blind" by instruments in the 1930s, the need for air traffic control (ATC) and coordination increased. In the early days of commercial aviation (and to this day in oceanic airspace), air traffic was controlled procedurely, through reserved sections of airspace and radio reports from pilots verifying their positions. It was not until the development of radar during World War II that surveillance technology became available to assist air traffic controllers. By 1955 radar was in use at 2 of the 20 ATC enroute centers, and direct controller-pilot radio communication facilities had been established at all of them.[1] Most military and airline aircraft operated under visual flight rules, and the opportunities for collision multiplied as air traffic increased. In the wake of a catastrophic midair collision between two commercial transports over the Grand Canyon in 1956, the airline industry began the first concerted effort to develop an airborne collision avoidance system (CAS).[2] Only now, over 30 years later, are we on the verge of seeing the fruits of technology development that has continued amid industry and technical controversy.

---

1. Nick Komons, Aviation's *Indispensable* Partner Turns 50, (Washington, DC: U.S. Department of Transportation, 1986), pp. 12 and 14.
2. Frank C. White, "Where Does Aircraft Separation Assurance (or CAS) Now Stand?: An Historical Perspective and Project ion," in *Aircraft Collision Avoidance*, hearings before the Subcommittee on Transportation, Aviation and Communications of the Committee on Science and Technology, U.S. House of Representatives, June 27, 28; July 24, 1979 (Washington, DC: U.S. Government Printing Office, 1979), p. 360.

The physics of flight dictate that aircraft collisions will usually be catastrophic. Fortunately, midair collisions involving large transports are rare in U.S. airspace, having occurred just twice in the last 15 years. Thanks to continuing gradual improvements in ATC, two positively controlled airliners have not collided since 1965.[3] While the Federal Aviation Administration (FAA) followed and supported early airborne CAS efforts, it did not begin directly developing and evaluating collision avoidance technology until 1971, after congressional hearings on aircraft collisions. The Agency conducted a comprehensive evaluation of three different systems, collectively known as the Airborne Collision Avoidance System, between 1971 and 1975. FAA concluded that while the systems gave good protection in some airspace, they had severe limitations in high-density areas. Additionally, these systems required that dedicated collision avoidance equipment be installed on all aircraft.[4] Moreover, the establishment of ATC Terminal Control Areas and expanding computer automation, including conflict alert, made the ATC system much more versatile than existent airborne collision avoidance technology.

Every CAS devised for commercial aircraft requires compatible equipment installed on each aircraft to be protected or avoided. Using the radar signals from common ATC transponders installed on all commercial and military aircraft and the majority of the private fleet would eliminate the need to equip all aircraft with dedicated systems. First demonstrated in 1974, the beacon-based collision avoidance system (BCAS) relied on transponder replies for traffic data, immediately providing protection from all other transponder equipped aircraft. Aircraft without transponders were invisible to BCAS. However, BCAS development ran into difficulties. Self-contained airborne versions caused too much radio interference in high-density airspace, and solving that problem required expensive ground coordination equipment.[5]

---

3. Komons, op. cit., footnote 1, pp. 22.
4. Neal A. Blake, Acting Deputy Associate Administrator for Engineering and Development, Federal Aviation Administration, in testimony, *Aircraft Collision Avoidance,* op. cit., footnote 2, pp. 59-60.
5. U.S. Congress, Office of Technology Assessment, *Airport and Air Traffic Control*
(continued)

TCAS is Chosen

In June 1981, then FAA Administrator J. Lynn Helms announced that FAA would focus on an enhanced air-to-air version of BCAS called the Traffic Alert and Collision Avoidance System (TCAS). FAA assumed responsibility for supporting necessary research, developing prototype equipment, demonstrating the operational and technical feasibility of the TCAS concept, generating national standards for the equipment, and certificating TCAS-equipped aircraft for normal operation. TCAS is designed to:

- be compatible with the present ATC system and a logical extension of it;
- be suitable for use in high-density traffic;
- require no ground-based equipment;
- offer a range of capabilities suitable to the needs of various classes of airspace users.[6]

The 1987 Airport and Airways Capacity Expansion and Improvement Act, Public Law 100-223, established deadlines for completing development and installing the system known as TCAS II on commercial transports. By June 30, 1989, FAA must approve and validate the TCAS II performance standards. FAA finished its regulatory requirements for development on time in October 1988. The remaining FAA responsibility for establishing TCAS II is to test and evaluate TCAS II equipment that meets the latest standards. This testing is now scheduled to begin at the FAA Technical Center in early April 1989 and to be completed by Summer 1989.[7] Each passenger-carrying aircraft with more than 30 seats must be equipped with TCAS II to operate in U.S. airspace after December 30, 1991.

System, OTA-STI-175 (Washington, DC: U.S. Government Printing Office, January 1982), pp. 89-90.

6. Ibid., p. 91.

7. Joseph Fee, ACADS Program Manager, Federal Aviation Administration, in U.S. Congress, Office of Technology Assessment, “Transcript of Proceedings — Getting Collision Avoidance Airborne: TCAS Installation and Federal Deadlines,” unpublished typescript, Jan. 12, 1989.

TCAS will provide independent backup to ATC and flight crews by displaying range, bearing, and when possible, altitude of nearby aircraft and alerting the crew to conflicting traffic. To serve the varied needs of the aviation community, three versions of **TCAS —** TCAS I, TCAS II, and TCAS III – are being developed, each with distinct performance characteristics.

Prototypes of each version have been flight-tested. Designed for airline use and farthest along in development, TCAS II is the system addressed in Public Law 100-223. TCAS I, appropriate for general aviation and smaller commuter airlines, will be required along with TCAS II under FAA rule making. TCAS III, the most complex and sophisticated version, will probably not be fully specified until at least 1992.[8] In any case, TCAS III may be subject to separate rulemaking procedures.

TCAS I. Primarily intended to assist the pilot in visually acquiring nearby traffic, TCAS I is the simplest and least costly TCAS. TCAS I detects and displays range, approximate bearing, and altitude of traffic that is equipped with a Mode C or S transponder[9] within 4 nautical miles of the host aircraft. Traffic equipped with Mode A transponders is displayed without altitude information. TCAS I alerts the crew with a visual and aural traffic advisory to any intruding aircraft within about 40 seconds of closest approach. TCAS I **does not** offer guidance to the pilot for maneuvering away from potential collisions.

---

8. John M. Graham, Chairman, Special Committee 147 of the Radio Technical Commission for Aeronautics, personal communication, Feb. 7, 1989.
9. Three versions of air traffic radar transponders — Modes A, C, and S — are used by civilian aircraft. Mode A transponders reply to radar interrogations with a four-digit identification code. Mode C equipment includes the aircraft’s altitude in the reply. The signal format for the newest transponder type, Mode S, allows radar interrogations and other information to be addressed to specific aircraft.

TCAS II. TCAS **II** does everything TCAS I does, but with greater range and bearing accuracies. The system also instructs the crew with a visual and aural resolution advisory (RA) on how to avoid threatening traffic, provided that the other aircraft is Mode C- or S- (altitude-encoding transponders) equipped and is typically less than 25 seconds[10] from a potential collision. Figure 1 depicts TCAS II protected airspace. TCAS II RAs are restricted to the vertical plane. Through Mode S air-to-air data links, TCAS II coordinates with other TCAS II-equipped aircraft to fly complementary avoidance maneuvers.

TCAS III. Not yet addressed directly in legislation or rulemaking, TCAS III will have all the features of TCAS II and will offer horizontal resolution maneuvers as well. To resolve conflicts with horizontal turns, TCAS III will measure the bearing of targets more accurately than required for TCAS II.

TCAS II **Components**

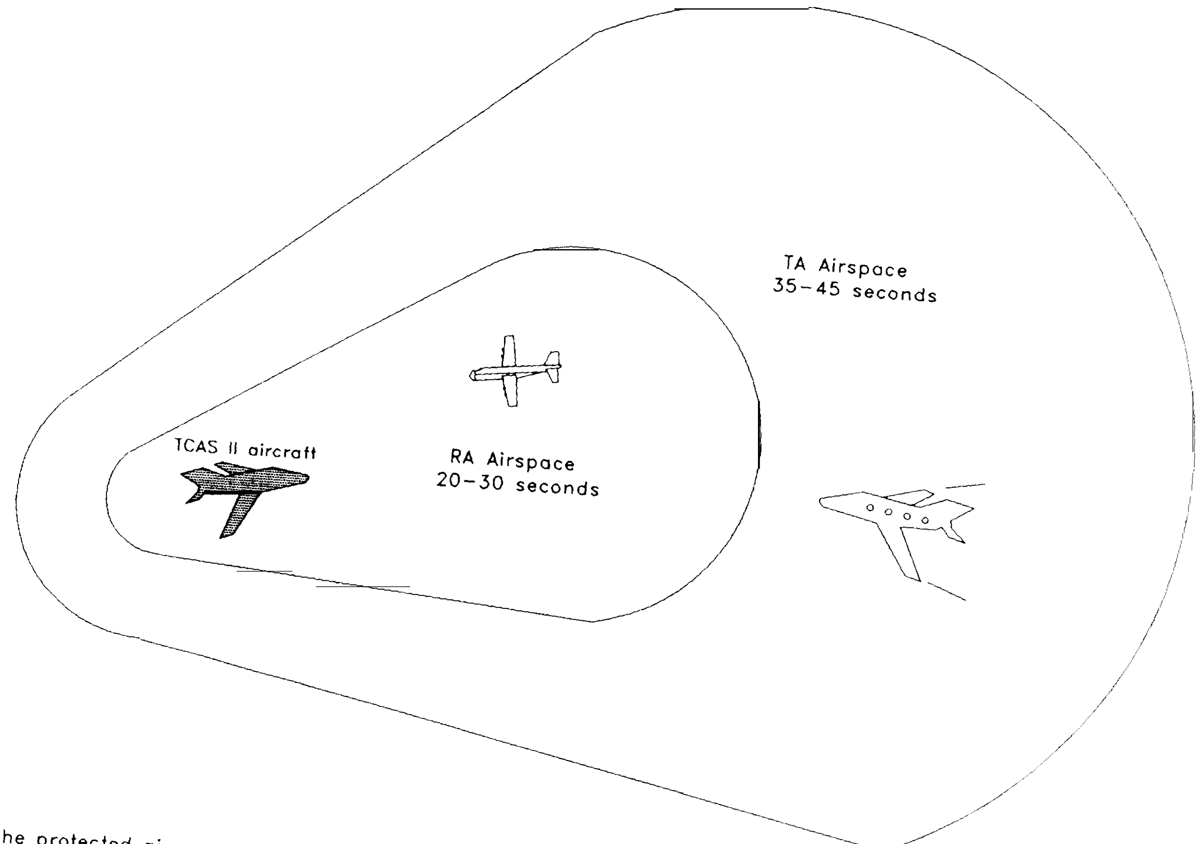
Each TCAS II unit is effectively a small, but versatile ATC-type radar station, consisting of a computer processor and software, a directional antenna system, a Mode S transponder, and cockpit displays, indicators, and controls. (See figure 2.) Although some TCAS II equipment options are still being developed, the principal features of the components as presently defined are described below.

Processor. The heart of each TCAS II is its processor, which contains the hardware and software for connecting all the components. The processor transmits and receives radar signals through the antennas, measures range, bearing, and altitude of nearby traffic, watches for conflicts, computes escape paths if necessary, and sends this information to the cockpit indicators. During an RA, the processor coordinates the maneuver through Mode S transponder datalink if the other aircraft is TCAS II equipped.

---

10. Resolution advisory sensitivity varies with own aircraft altitude: 20 seconds below 2,500 feet above the ground; 25 seconds between 2,500 feet and about 10,000 feet; and 30 seconds above 10,000 feet.

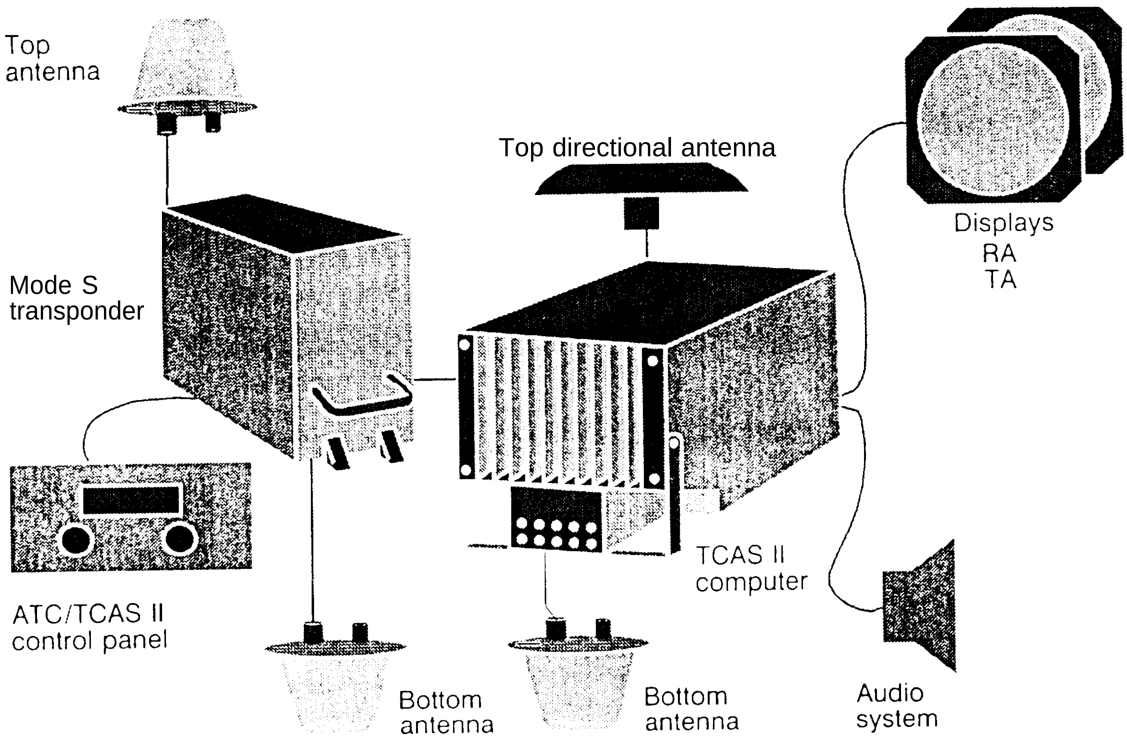
Figure 1.–TCAS Protected Airspace



[a] The protected airspace shown is for a TCAS II aircraft above 500 feet.

SOURCE: Office of Technology Assessment.

FIGURE 2. -- BASIC COMPONENTS OF A TCAS II SYSTEM



SOURCE: Boeing Commercial Airplane Co.

Antennas. Some TCAS II manufacturers are offering electronically-steered antennas accurate to about 3 degrees, far better than the 15 degree FAA minimum performance requirement.[11] Each aircraft must have two antennas, typically mounted on the top and bottom of the fuselage, although the bottom one need not be a directional antenna. The TCAS II processor does not use bearing information in generating RAs, so directional antennas are needed only for cockpit traffic displays and for reducing radar interference.

Cockpit indicators. TCAS II provides two types of traffic-related information to the cockpit: 1) a representation of nearby traffic and its status, and 2) resolution advisories to prevent potential collisions. Each airline, depending on its aircraft types and cockpit configurations, will have a number of options for displaying TCAS II information to the flight crew.

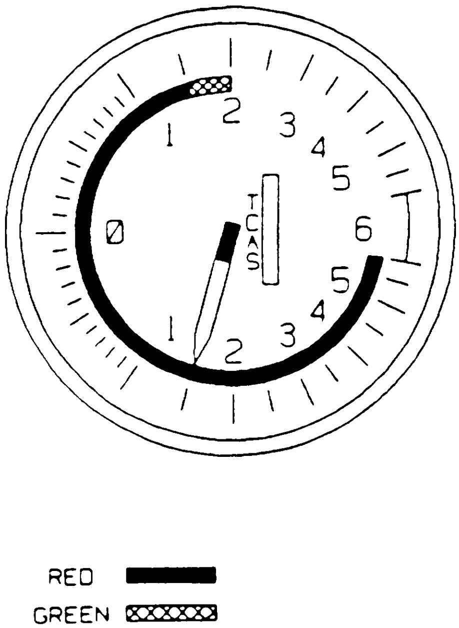
TCAS II will provide aural and visual advisories for all aircraft configurations. Visual RAs will be presented on modified instantaneous vertical speed indicators (IVSIs) for most existing aircraft. Red and green arcs appear during an RA, indicating vertical speeds to avoid (red) and to fly safely (green). (See figure 3 for an example.) Still under development are the RA indicator formats for “glass” cockpits, where many instruments are displayed on cathode ray tube (CRT) systems.

Four basic display options to indicate traffic location and threat status will be available. Airlines may install a dedicated TCAS II traffic display, modify weather radar display or an electronic flight instrument system, or replace the IVSI with one that will not only indicate RAs, but will also present traffic on a liquid crystal display in the center of the IVSI dial. Figure 4 shows a combined traffic display and IVSI, and figure 5 represents a traffic display for a CRT system. Human factors consideration are of crucial importance in the design of these links between TCAS II and the flight crew.

---

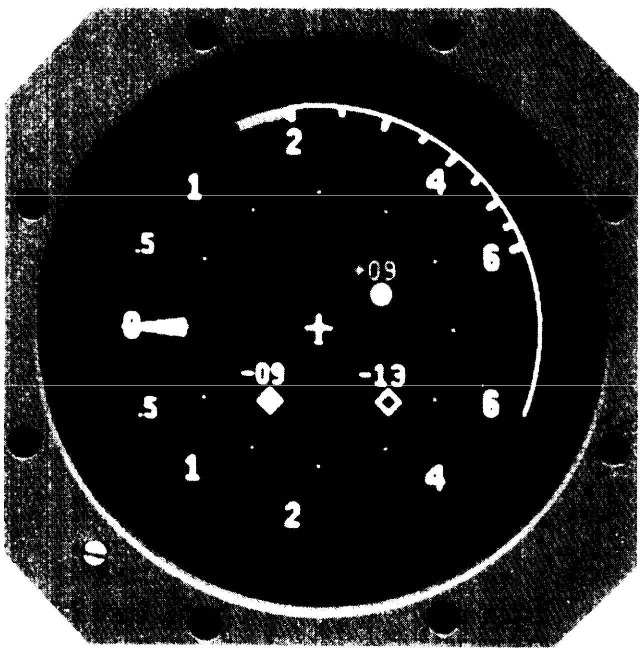
110 Federal Aviation Administration, “Airworthiness and Operational Approval of Traffic Alert and Collision Avoidance Systems (TCAS II) and Mode S Transponders, ” Advisory Circular 20-131, Oct. 3, 1988, p. 18.

FIGURE 3. -- TCAS II RESOLUTION ADVISORY EXAMPLE



This instantaneous vertical speed indicator shows a corrective resolution advisory; the pilot should reverse the present 1,500 feet per minute (fpm) descent rate to a 1,500 to 2,000 fpm climb (the green area on the dial).

SOURCE: Federal Aviation Administration.



TCAS II traffic display symbols

−03
Resolution advisory
(solid red)

+09
Traffic advisory
(solid yellow)

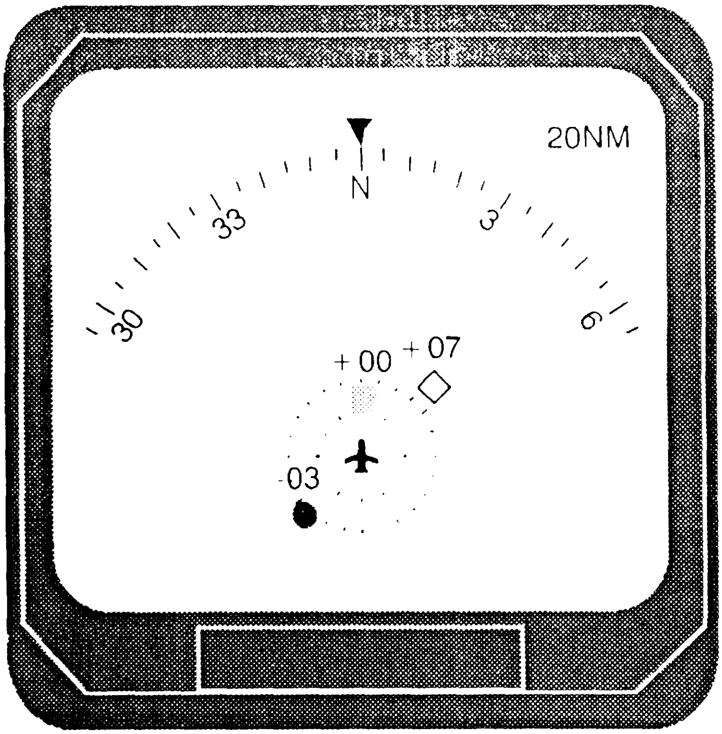
−09
Proximate traffic*
(solid white or solid blue)

−13
Non−threat
(hollow white or hollow blue)

* **Within 6 nautical miles and 1200** feet **relative altitude**

ı
ımbers).

FIGURE 5. -- TCAS II TRAFFIC DISPLAY



Traffic may be displayed on a CRT system, such as a dedicated display, a weather radar, or an electronic flight instrument system.

SOURCE: Boeing Commercial Airplane Co.

While several airlines have ordered the combined traffic display/IVSI, which has not yet been used in any of the operational evaluations of TCAS II,[12] some others and some pilots, through the Air Line Pilots Association (ALPA), oppose these displays. Traffic displays for glass cockpits are still being developed.

THE FEDERAL ROLE

Much of the basic research and fundamental technology development used in the FAA's TCAS II program was completed in earlier collision avoidance projects. These set the stage for current Federal efforts requiring TCAS II on some categories of aircraft. In coordination with industry, three interrelated Federal activities to establish TCAS II have proceeded in parallel: setting national standards defining TCAS II; mandating TCAS II implementation through rulemaking; and testing and evaluating TCAS II technology.

Setting Standards

The characteristics of aircraft equipment covered under the Federal Aviation Regulations are usually defined by national standards published in Technical Standard Orders (TSOs), the ". . . minimum performance standard for a specified material, part, process, or appliance."[13] FAA has approval authority for standards governing aviation system designs. The Agency works in consort with members of the aviation community to establish the standards, often incorporating directly the findings of independent committees such as the Society of Automotive Engineers or the Radio Technical Commission for Aeronautics (RTCA). FAA does not specify design specifications in a TSO, but states the minimum performance requirement for the equipment and grants TSO "authorization" to manufacturers of articles that meet the TSO.

---

12. John O'Brien, Director, Engineering and Air Safety Department, Air Line Pilots Association, in Office of Technology Assessment, op. cit., footnote 7.
13. 14 CFR 21.601 (Jan. 1, 1988)

Since TCAS involves the application of electronics and telecommunications, RTCA developed the minimum operational performance standards (MOPS) for TCAS II, which formed the basis of the TSO[14] issued by FAA in October 1988. (See Box A for an explanation of the MOPS.) The bulk of the MOPS deal with computer algorithms and have been revised a number of times as the result of analyses, simulations, and tests. However, the latest revision of the MOPS, referred to as "Change 6," has not yet been approved by RTCA; consequently FAA's TSO is based also on an FAA report prepared by MITRE Corporation,[15] which established Change 6.

Also in October 1988, FAA released an Advisory Circular (AC)[16] which provides guidance for the airworthiness and operational approval of TCAS II. An AC is not mandatory, but following its guidance ensures compliance with the Federal Aviation Regulations.

BOX A: Minimum Operational Performance Standards for TCAS

RTCA, established in 1935 to solve aviation problems involving electronics and telecommunications, is the joint government/industry advisory committee that is developing and recommending MOPS for TCAS I, II, and III. RTCA recommendations are usually incorporated directly into TSOs or otherwise accepted by FAA.

The MOPS for TCAS II are the most mature, first published in 1983 and then followed by a series of changes. Since a large part of the MOPS deal with TCAS computer instructions, such as resolving conflicts and coordinating maneuvers between aircraft, software changes to fix problems or enhance performance are not unusual.

14. U.S. Department of Transportation, "Traffic Alert and Collision Avoidance System (TCAS) Airborne Equipment, TCAS II," TSO-C119, Oct. 14, 1988.
15. Federal Aviation Administration, "Required Modifications to the Traffic Alert and Collision Avoidance System (TCAS II) Minimum Operational Performance Standards (MOPS)," DOT/FAA/SA-88/3, October 1988.
16. Federal Aviation Administration, op. cit., footnote 11.

TCAS II MOPS including Changes 1 through 5 are incorporated into FAA's TCAS II TSO and advisory circular, and Change 6 will be added following its formal approval by RTCA, expected in June 1989. FAA will likely accept additional changes to the MOPS, but will not require them unless FAA decides they are warranted for safety. RTCA plans to include a Change 7 to enhance TCAS II.

Recently, two United and two Northwest jets were outfitted with pre-production TCAS II units, incorporating MOPS Changes 1 to 5, for operational evaluation under a limited installation program (LIP). At the same time, work continued on Change 6 to incorporate some changes identified before these evaluation flights began. The main issue was that once TCAS II issued an RA, if the other aircraft changed its path, TCAS II would not be able to resolve the new conflict and would issue a TCAS "invalid" warning, leaving the flight crew to fend for itself. Change 6 removes the invalid option and permits TCAS II to calculate additional maneuvers if the initial RA is not sufficient. Change 6 also biases against maneuvers that cross through (instead of staying above or below) the other aircraft's altitude and simplifies logic for air-to-air TCAS II coordination.

Findings from the LIPs[17] suggest further TCAS enhancements, including reducing the low-altitude traffic alert rate during approaches and in areas with many Mode A targets. By November 1989, RTCA plans to finish Change 7 addressing the LIP results. This version of the MOPS will be used for equipment purchased by most airlines. RTCA plans to make the MOPS compatible with the international collision avoidance standards now being reviewed by the International Civil Aviation Organization (ICAO) by the end of 1990.

END BOX

17. United Airlines completed its limited installation program (LIP) in October 1988; Northwest Airlines will report on its LIP in May 1989.

Rule making

Congress gave strong guidance to FAA for implementing TCAS II in the Airport and Airway Safety and Capacity Expansion Act of 1987 (Public Law 100-223) on December 30, 1987. The Act required FAA to complete TCAS II "certification" (see Box B) within 18 months and mandated that each aircraft capable of carrying more than 30 passengers have TCAS II installed and operating in the subsequent 30 months. This implied a December 30, 1991, deadline for TCAS II installation and implementation for domestic and foreign aircraft operating in U.S. airspace.

Public Law 100-223 also required FAA to promulgate a final rule expanding requirements for aircraft to be equipped with Mode C (altitude encoding) transponders. In response, FAA adopted Amendment 91-203, "Transponder Automatic Altitude Reporting Capability Requirement, " in June 1988, [18] requiring Mode C transponder use within and above each terminal control area (TCA) and airport radar service area; within 30 miles of a TCA, and above 10,000 feet above mean sea level. Additionally, Public Law 100-223 requires that TCAS II be "upgradable" to the performance standards of the future TCAS III, although these are still being developed. FAA's final rule for TCAS states that other than air-to-air coordination logic, TCAS II may have a variety of designs, and TCAS III may be addressed through separate rulemaking. [19]

Prior to enactment of Public Law 100-223, FAA had issued Notice of Proposed Rulemaking (NPRM) 87-8[20] intending to require either TCAS I or TCAS 11 on various classes of passenger aircraft. Public Law 100-223 was generally similar to the NPRM, which proposed a 3-year deadline for TCAS II implementation on large passenger transports. At the time Public Law 100-223 was passed, the final rule was expected to be released in late 1988; it was actually issued in January 1989.

---

18. 53 *Federal Register 23356-23374* (June 21, 1988).
19. 54 *Federal Register 944* (Jan. 10, 1989).
20. 52 *Federal Register 32268-32277* (Aug. 26, 1987).

FAA received 70 separate comments to the NPRM; about half expressed concerns over the implementation schedule. Bound by Public Law 100-223, FAA could not address these concerns in the final rule and set the dates as required by the legislation. However, in response to public comment, FAA did change the requirement for 20- to 30-passenger aircraft from TCAS II to TCAS I and extended the TCAS I compliance date from 5 years to 6 years.[21]

BOX B: Certification — A Complicated Process

Public Law 100-223 requires FAA to complete ". . . certification of the collision avoidance system known as TCAS-II . . ." by June 30, 1989. The law's intent was to ensure TCAS validation, authorization, and implementation in a timely manner. Although FAA certification results in authorization, FAA can approve equipment standards, such as those for TCAS II, without certification. **Additionally, FAA may formally approve equipment performance standards, before those standards are tested and evaluated on an aircraft in flight.** Thus, FAA certification as required in Public Law 100-223 is open to interpretation.

FAA certificates the major components of the aviation system — people, such as pilots and mechanics, aircraft, and organizations, such as airlines and repair stations. Through these categories of certification, FAA approves aircraft design and production, operations, and airworthiness. For example, each specific design or make and model of airframe, engine, and propellor is manufactured under a unique Type Certificate (TC).[22] Altering an aircraft's design in a way that could affect flight safety, such as installing TCAS, requires obtaining an amended TC or a Supplemental Type Certificate (STC).[23] Extensive design changes require a **completely new TC.**[24]

21. 54 *Federal* Register 941 (Jan. 10, 1988).
22. 14 CFR Part 21, Subpart B (Jan. 1, 1988).
23. **14** CFR 21.113 (Jan. 1, 1988).
(continued)

Before the STC or TC process begins, the design requirements and performance standards for equipment such as TCAS are usually approved and validated separately. Then an engineering analysis is conducted as a basis for an STC that need only be undertaken once for each aircraft make and model to change its design. For example, an airline that receives an STC for one B727-200 will be able to use that approved procedure for modifying the rest of its 727-200 fleet, provided all its 727-200s are the same. However, additional engineering work and FAA approval are required to address individual differences among aircraft within a single make and model category. Moreover, because approved production equipment will not be available, none of the numerous varieties of aircraft equipped with TCAS II can be certificated before July 1989 at the earliest. Complicating the process, most aircraft types in airline fleets are slightly dissimilar.

STCs are proprietary, but could be shared or sold to other organizations, although doing so would require time-consuming and costly coordination. New aircraft types will likely have TCAS II installations covered by TCs.

END BOX

Testing **and Evaluation**

Much of the basic collision avoidance technology used for TCAS was developed during the past two decades by FAA at its Technical Center and by its contractors, the MITRE Corporation and the Lincoln Laboratory of the Massachusetts Institute of Technology. As for TCAS itself, limited numbers of TCAS II systems have been operated on scheduled airline flights since 1987, TCAS I will be evaluated in the operational environment later this year, and development testing is ongoing for TCAS III at the FAA Technical Center.

24. 14 CFR 21.19 (Jan. 1, 1988).

To observe and record TCAS II performance and pilot interaction with the equipment during normal operations, FAA sponsored and partly funded four evaluation programs carried out by industry. Each participating airline and TCAS II manufacturer contributed substantial time, manpower, and financial support for these programs. Two types of data were collected in each program — electronic output from the TCAS II equipment and comments from pilots and other observers. These programs included:

Piedmont Phase I. Collision avoidance equipment developed under the BCAS program was modified to incorporate some TCAS elements and installed on two Piedmont Airlines B727 aircraft. These aircraft were flown in scheduled service from November 1981 to March 1982. The purpose of Phase I was to measure TCAS II performance; flight crews could not see or use any TCAS II-generated information.[25]

Piedmont Phase II. TCAS II prototype equipment was first operated in regular airline service in this program, whose purpose was to assess the effects of TCAS II on both the flight crew and the ATC system. However, the TCAS equipment, built by Dalmo Victor/Singer prior to full development of the MOPS and Aeronautical Radio, Inc. (A RI NC) characteristics, lacked many of the capabilities of present systems. While the pilots had TCAS displays in the cockpit, they could use the information only in visual flight conditions. Additionally, the equipment lacked Mode S capability and could not coordinate with another TCAS-equipped aircraft. A single TCAS-equipped B727 operated from March 1987 to January 1988.[26]

Assisting flight crews in visually locating nearby aircraft was found to be a major benefit of TCAS II, garnering positive acceptance by Piedmont's pilots. TCAS II had no noticeable effect on ATC or on pilot workload. Higher than expected alert rates and minor problems with aural and visual TCAS II information suggested numerous

---

25. 52 Federal Register 32271 (Aug. 26, 1987).
26. ARINC Research Corp., In-Service Evaluation of the Traffic *Alert and Collision Avoidance System (TCAS) Industry Prototype,* prepared for the Federal Aviation Administration, DOT/FAA/SA-88/2 (Springfield, VA: National Technical Information Service, May 1988), pp. vii-x.

improvements.[27] The Piedmont programs are analogous to the crawling stage described by Administrator Helms in announcing TCAS.

Limited Installation Programs. The TCAS II installations used in the LIPs are fully certified for the full range of airline operations. Incorporating the latest available MOPS (Change 5) and ARINC characteristics, the equipment used in the LIPs was intended to match closely in performance and appearance the versions to be installed fleetwide. The equipment operated on two United Airlines aircraft, a B737 and **a** DC8, from January through July 1988, were built by the Bendix/King Air Transport Division of the Allied-Signal Aerospace Company. Honeywell teamed with Northwest Airlines for the ongoing operational evaluation onboard two MD80s, which began in October 1988 and is expected to be completed in March 1989.

The Bendix/United LIP found that TCAS II substantially enhanced air traffic safety, and is highly desirable for routine airline operations, provided certain CAS logic changes are made to prevent disruptive and unnecessary advisories.[28] Additionally, United assessed TCAS II's readiness for full implementation. The final report raises concerns about:

- integrating TCAS II into glass cockpit aircraft,
- the lack of ramp test equipment for efficient installation testing,
- the fact that no airline experience with CAS logic beyond Change 5 will precede certification,
- incorporating ICAO requirements into U.S. standards,
- the engineering, mechanic, and facility resources required for full fleet retrofit, and

---

27. Ibid., pp. x-xvi.
28. George K. Schwind et al., United Airlines, Inc., "Summary User Evaluation Report on the Traffic Alert and Collision Avoidance System (TCAS II) Limited Installation Program, " prepared for Bendix/King Air Transport Avionics Division, October 1988, p. vii.

- high traffic advisory/RA rates and the need to eliminate unnecessary alerts.[29]

Other evaluation programs will begin in the near future. British Airways will begin an operational evaluation with a Bendix/King TCAS II with Change 6 in March 1989.[30] FAA is currently testing Change 6 in computer simulations and will conduct flight tests in April 1989 at the Tech Center. The three TCAS II manufacturers will begin flight tests and other certification procedures to obtain TSO and STC approval. These are now scheduled for March 1989. FAA also expects to contract for a (31 to 60 seat) turboprop commuter LIP by October 1989.[31] The LIPs are analogous to walking for TCAS.

REMAINING CONCERNS

FAA and industry agree that closely monitoring the initial implementation of TCAS II will help ensure adequate TCAS II, flight crew, and air traffic system performance. FAA has established a TCAS II Transition Program to coordinate data collection and analysis among industry and FAA certification, ATC, and the TCAS Program office.[32] However, the Agency has not yet clearly defined how the program will work, or what the scope and timing of its efforts will be.

There is widespread agreement in the aviation community that cockpit human factors and air traffic system effects need further attention. From the inception of TCAS, pilots, airlines, and manufacturers have been concerned about possible human factors implications of traffic displays, warnings, and maneuver advisories in the

29. Ibid., pp. 99-103.
30. Buzz Hefti, Allied Signal, personal communication, Feb. 9, 1989.
31. Joseph Fee, Federal Aviation Administration, in Office of Technology Assessment, op. cit., footnote 7.
32. C.R. Melugin, Jr., Executive Director for Regulatory Standards, Federal Aviation Administration, personal communication, Jan. 10, 1988.

cockpit. While pilot responses to TCAS have been studied at the National Aeronautics and Space Administration (NASA) Ames Research Center and during the LIPs, the full effect of TCAS on other pilot duties is unclear.

The reactions and interactions of pilots, controllers, and TCAS will affect the safety and operation of the entire ATC system. While the air traffic system can be modeled to include TCAS on a simple basis, the human dimension escapes prediction. Using past and predicted traffic patterns and TCAS detection and avoidance algorithms, the number and extent of TCAS alerts, warnings, and conflict resolution maneuvers can be studied along with the potential for electromagnetic interference. However, pilot and controller performance could change due to TCAS, ranging from complacency to interference with normal duties. The following issues need to be more fully addressed: 1) changes in the amount of pilot/controller communications; 2) pilot/controller attention to other duties due to workload or complacency; and 3) the effect of pilots using or reacting to TCAS information outside design boundaries — maneuvering in traffic without an RA or over/underflying an RA.

These issues cannot be resolved until TCAS is implemented widely; if a problem requiring TCAS modification exists, it must be uncovered early if changes are to be effected economically. An early implementation period and evaluation program (equivalent to jogging in Administrator Helms' statement) could accomplish this. The present schedule for TCAS implementation is unusual in that new technology will be introduced to the full air transport fleet over a short timespan.

DEVELOPMENT FINDINGS

TCAS II technology has been proven feasible and is sufficiently developed to justify Federal actions requiring airline implementation. Pre-production TCAS II technology has been successfully demonstrated, and airline evaluations to date have uncovered no fundamental flaws preventing industry-wide implementation. OTA concludes that TCAS **II is likely to be practical and beneficial for all transports; however, this will not be confirmed until sufficient numbers of TCAS II are installed on airliners and operated in the air traffic system.**

FAA has approved the minimum performance standards for TCAS II, and if all goes well, will complete simulation and flight test validation by June 30, 1989, thereby "certifying" TCAS by the deadline set in Public Law 100-223. The last revision of the TCAS software required by FAA, known as Change 6 to the MOPS, is being tested extensively in computer simulations and will be flown at the FAA Technical Center beginning in March 1989. No problems that would prohibit approval and validation are anticipated.

OTA **concludes that an evaluation program that includes early implementation of TCAS in a substantial portion of the fleet would benefit safety.** Without such a program, the worst case scenario is that the airlines could completely outfit their fleets only to learn that a technical glitch requires major modification of the current TCAS equipment. A structured evaluation phase would allow problems to be identified early, preventing further installation of flawed units and permitting modifications soon enough in the installation program to minimize costs.

In the best case, TCAS II works perfectly in all respects. However, most airlines will not take delivery of TCAS II equipment until 1991 (see page 35) unless early implementation is required. A monitoring program requiring early implementation for part of the fleet could provide added protection to a portion of the traveling public earlier than it would otherwise receive. As part of the program, industry and FAA will want to consider ways to incorporate modifications identified through the evaluation.

According to LIP findings, software modification is desirable; however, only some of the changes will be addressed in the baseline TCAS II requirements established by FAA. The FAA position is that Change 6 is sufficient for safety, and no information has

been provided that disproves this claim. Moreover, airlines may add changes as "enhancements" to the baseline TCAS II equipment, although absent FAA requirements or widespread industry support, such enhancements will be very costly. A monitoring program could open lines of communication within the aviation community and provide the necessary information to support TCAS II modification decisions for all parties involved.

OTA concludes that a basic requirement for a successful operational evaluation program is having a critical mass of aircraft outfitted with TCAS II at an early date. If 15 to 30 percent of the commercial fleet (about 600 to 1,200 aircraft) were equipped with **TCAS II during 1990, a reasonable operational evaluation of system effects would be possible.** Operations under the evaluation should cover the full spectrum of geographical locations and aircraft and airspace types, including sufficient numbers at hubs to address high-density issues. FAA and industry must cooperate to plan and allocate sufficient resources for collecting, analyzing, and disseminating TCAS data. A wide range of expertise is required, including certification, air traffic, aviation medicine, safety, and TCAS program officials from FAA, airlines, TCAS and aircraft manufacturers, pilots' and controllers unions, and aviation human factors experts from NASA.

Although some TCAS II technology is still being developed, this need not prevent introducing TCAS. The major technology concerns that remain unresolved include:

- Displays: Only two display option types, the dedicated display and modified weather radar, have been flight tested. The combination traffic display/IVSI incorporates liquid crystal/flat panel technology that is new to commercial aviation. The small size and combination of functions in the traffic display/IVSI is opposed by ALPA, whose members cite human factors concerns. Some new glass cockpit aircraft have only one display option available — modifying the CRT systems. The display modifications for earlier electronic cockpit aircraft (such as the Boeing 757), will be very expensive, almost doubling installation costs for TCAS.[33] The aircraft manufacturers have not defined the necessary changes and are not expected to do so until summer 1989.

- **Ground test equipment:** While not required for TCAS, acceptable ground test equipment can reduce or eliminate flight test requirements and expedite installation check-out. Such equipment may prove necessary to meet the installation deadline, and none is yet available.

- **TCAS II for commuter aircraft:** Initial production versions **of** TCAS II may not fit in some Part 121 commuter aircraft (31 to 60 passengers) and questions remain about the effect the propellers and high wings that characterize most commuter aircraft will have on **TCAS** signals. The results of FAA testing, scheduled for late 1989, may come too late to give commuter airlines any reasonable chance of meeting the installation deadline.

Public Law 100-223 requires TCAS II systems to be upgradable to the performance standards for TCAS III. These performance standards give TCAS III a more accurate surveillance capability and an alternative escape maneuver selection in the horizontal plane. Even though these performance standards are currently under development, a number of common elements between TCAS II and TCAS III have been identified. Two manufacturers are advertising their TCAS II units as upgradable. Thus, it can be assumed that there will be some hardware and software commonality between TCAS II and

---

33. Ulf Gustafsson, United Airlines, personal communication, Feb. 8, 1989.

TCAS III, and that TCAS engineers will strive for minimum aircraft modifications for TCAS III.

However, OTA finds that a Federal specification of TCAS II upgradability is inappropriate at this time. Since FAA gives wide latitude for TCAS II designs, there is no reason to expect one manufacturer's TCAS II components to be compatible with another's, except for air-to-air coordination logic. Presently, there are no regulatory requirements for TCAS III.