

ACAS safety studies

Ken Carpenter, QinetiQ, 4 Feb.2004

1. Introduction

- 1.1 This paper is written at the request of the Eurocontrol ACAS Programme Manager, who saw a need for a short paper summarising ACAS safety studies and results.

Section 2 is an historical review, covering the main decisions from an ICAO perspective, and referencing the safety results at each stage.

Section 3 discusses the role of ACAS in ATM.

Section 4 discusses the scope of ACAS safety studies to date.

Section 5 discusses encounters involving several aircraft. The rest of the paper discusses exclusively encounters between two aircraft.

Section 6 introduces risk ratio and discusses methods.

Section 7 discusses the various ACAS safety studies, and summarises their results.

2. Background on the international standardisation of ACAS

- 2.1 ACAS was developed over several decades. [1, 2] The concept tended to be unpopular with ATS providers, and it was thus, at any time, either 'dead' or extremely urgent. It is a matter of record that the spells of urgency followed mid-air collisions. This has persisted, recent examples being the Indian mandate for equipage by 1999 following the Indian mid-air collision in 1996, and the US military mandate following the US military mid-air collision in Namibia in 1997. The European mandate is noteworthy for being the product of due, considered, process, rather than a reaction to an incident. The sober point is that there are collisions in the absence of ACAS, and the most telling question is whether there are more collisions with or without ACAS.

- 2.2 In November 1981, the Air Navigation Commission (ANC) established the SSR Improvements and Collision Avoidance Systems Panel (SICASP) with the following terms of reference:

“ To undertake specific studies ... with a view to developing Standards, Recommended Practices (SARPs), procedures and, where appropriate, guidance material concerning ... [*inter alia*] collision avoidance systems.”

- 2.3 In August 1987, the FAA issued formal notice that it intended to require the installation and use of ACAS in the USA. The final requirement was for all aircraft carrying more than 30 passengers to be fitted with TCAS II by 30 December 1993.
- 2.4 At this time, MITRE had completed two studies into the efficacy of ACAS, each called a 'System Safety Study'. [3, 4] These studies reported very optimistic conclusions about the extent to which ACAS would reduce the risk of collision. They also made it clear that there are circumstances in which ACAS can cause collision. The nature of these studies is discussed below in section 7.2.
- 2.5 During 1987-1989, there was debate concerning the efficacy of ACAS. Simulations of the collision avoidance logic in real encounters, captured by processing saturation radar data, seemed at odds with the MITRE studies. [5] Certain statistical properties of real encounters differed from the assumptions made (and tested) by MITRE, as discussed in paragraph 7.2.5. Contemporaneously, the logic was modified in a way that addressed these concerns. By the fourth meeting of SICASP (SICASP/4), the consensus was that the design considered at SICASP/4

(referred to as version 6) would lead to a significant reduction in the risk of collision. [6, 7] This was based on results showing that the logic works, in an average, overall sense and when the RAs are followed promptly, and on field trials and the earlier MITRE safety studies.

- 2.6 Following SICASP/4, ICAO decided, in November 1989, that the then draft SARPs should serve as guidelines during an operational evaluation of ACAS. Other documents were amended:
- Annex 11, Air Traffic Services: “The carriage of [ACAS] by aircraft in a given area shall not be a factor in determining the need for air traffic services in that area.”
 - PANS-RAC, Doc 4444 ; “The procedures to be applied for the provision of air traffic services to aircraft shall be identical to those applicable to non-ACAS equipped aircraft. In particular, the prevention of collisions, the establishment of appropriate separation and the information which might be provided in relation to conflicting traffic and to possible avoiding action shall conform with the normal ATS procedures and shall exclude consideration of aircraft capabilities dependent on ACAS equipment.”
 - ATS Planning Manual, Doc 9426: “The planning of air traffic services and the determination of the level needed for these services should not be influenced by considerations relevant to the deployment of ACAS in a specific airspace.”
- 2.7 SICASP/4 formulated certain safety objectives for ACAS II. These specified upper limits for the rate of unresolved and induced collisions as a proportion of the pre-existing risk, and long term upper limits on the absolute rates of unresolved and induced collisions. However, in 1993, SICASP/5 “considered that many factors influence the effect of ACAS on the safety of any particular airspace and the performance of ACAS depends on the design and management of the airspace.” The objectives “constrain the way that air traffic is managed rather than the design of ACAS.” For that reason, it effectively set the safety objectives to one side, on the grounds that they were not useful. The objectives were not and are not met.
- 2.8 During the period of the operational evaluation, 1989 - 1993, the design of the collision avoidance logic was again considerably revised. These revisions reflected operational experience and continuing studies of the efficacy of ACAS. At the time of SICASP/5, November 1993, the only implementation of ACAS was colloquially referred to as TCAS version 6.04A.
- 2.9 The version 6.04A collision avoidance logic was known to be safer (i.e. more effective) than that of version 6 considered at SICASP/4. This had been shown in the same way as the earlier version was evaluated, in particular assuming that pilots respond accurately, but understanding of the methods used to evaluate ACAS safety had also advanced.
- 2.10 Version 6.04A was mandated in the US, in particular because it addressed a repeated problem in encounters between two ACAS equipped aircraft. About once per month, in particular geometries, close encounters between ACAS equipped aircraft were resulting when one pilot followed an ACAS RA and the other pilot followed ATC. Thus, these could be attributed to a pilot not following the RA. However, it was found, from theoretical analysis, that the same could happen even when both pilots obeyed the RA, and this seems to have caused the issue to be regarded seriously.
- 2.11 SICASP/5, 1993, recommended that Annex 10 be amended to include ACAS SARPs. It had received a report on safety [8, 9]. This report and another on the operational evaluation were reported to States, as were guidelines for controller and pilot training on ACAS and guidelines relating to implementation. Further amendments were recommended to PANS-RAC, Doc 4444, concerning the actions of controllers during RAs and the phraseology to be used.
- 2.12 The safety report to SICASP/5 will be discussed below in section 7.3. All the material consistently emphasised the imperative that pilots follow RAs.

- 2.13 During 1993-1997, there was continuing work to refine the collision avoidance logic, and on other aspects of the system. By SICASP/6, the implementation of ACAS colloquially referred to as TCAS version 7 was nearing completion, and the SARPs changes recommended at SICASP/6 are based on this implementation.
- 2.14 SICASP/6, in February 1997, recommended that Annex 10 be amended to reflect the changes found desirable over the previous four years, in particular to standardise the new surveillance protocols and the performance of the TCAS version 7 collision avoidance logic. Version 7 had been shown to be more effective (safer) than version 6.04A, but it has not been universally mandated in the US.
- 2.15 In June 1997, ICAO circulated to States a proposal to mandate ACAS. The eventual mandates are: for “all turbine engine aeroplanes of a maximum certified take-off mass in excess of 15000kg or authorised to carry more than 30 passengers” to equip with ACAS II by 1 January 2003; and for those with a take off mass in excess of 5700kg or authorised to carry more than 19 passengers to equip by 1 January 2005.

3. Role of ACAS

- 3.1 The draft “ATM operational concept document” endorsed at ANC/11, September 2003, specifies three layers of conflict management: strategic conflict management; separation provision; and collision avoidance. [10] [2.1.7.1 and 2.7.3.1] ACAS addresses the last of these layers, and addresses only collision with other aircraft.
- 3.2 The operational concept describes separation provision as “the tactical process of keeping aircraft away from hazards by at least the appropriate separation minimum.” [2.7.5.1] “Collision avoidance is not part of separation provision, and *collision avoidance systems are not included in determining the calculated level of safety required for separation provision.*¹ Collision avoidance systems will, however, be considered part of the system safety management. The collision avoidance functions and the applicable separation mode, although independent, must be compatible.” [2.7.6.1] “The importance of collision avoidance systems ... is the additional and independent level of conflict management to that provided by separation provision. Note that collision avoidance systems are not considered as an element of the separation modes of separation provision.” [8.2.6.1]
- 3.3 Paragraph 1.1 of the SICASP/5 report on the safety of ACAS [9] states:
“ The objective of ACAS is to provide advice to air crew in order to reduce the risk of collision. This is achieved through RAs, which recommend a manoeuvre, and through TAs, which are intended to prompt visual acquisition and to act as a precursor to the RA.”
- 3.4 The draft ATM operational concept could be summarised as specifying that ACAS is a final layer of protection provided for the eventuality that separation provision fails and gives rise to a risk of collision with another aircraft. For ATM system safety management to be complete, both separation provision and collision avoidance must be separately effective. Separation provision must achieve its required level of safety without considering the beneficial effect of collision avoidance, and collision avoidance must be fully capable of operation when separation provision fails. This is consistent with current ICAO provisions (e.g., see paragraph 2.6 above).

¹ The emphasis has been added.

3.5 It follows that the first step, when considering some change in ATM procedures, is to decide whether the change is safe without considering the effect of ACAS on the risk of collision. At this stage, it is wise to ensure that the disruption to ATM caused by ACAS remains acceptable. Once it is known that the change is safe, it should be determined whether ACAS would still reduce the risk of collision in the newly constructed environment. If it does not, ACAS should not be operated in that environment. It would be irrational not to make beneficial and manifestly safe changes to ATM practice just because the fall-back collision avoidance system, which should not be called into action, is deficient in the environment resulting from the changes.

4. Scope of ACAS safety studies

4.1 The approach to ACAS safety has been to determine to what extent ACAS reduces the risk of collision. Thus, to take two examples, ACAS 'safety studies' do not address the risk of fire, nor do they demonstrate that ACAS RAs will not cause the pilot to fly the aircraft into the ground². Of course, certification authorities will have satisfied themselves about these aspects of safety before the equipment was installed.

4.2 ACAS safety studies address two questions:

- Will ACAS reduce the risk of collisions that might otherwise occur?
- Will ACAS cause collisions in encounters that it is attempting to resolve?

4.3 While there is considerable numerical variation, the overall thrust of the results has always been the same: using ACAS reduces the risk of collision; ACAS is not totally effective at eliminating the risk of collision; and ACAS can induce collision.

4.4 The safety justification for ACAS is based on the evidence that there would be fewer collisions if aircraft fit ACAS than there would be were they not to. With very few exceptions, ACAS safety studies do not set out to prove that the risk of collision (either unresolved or induced) is reduced below any particular level, nor that it is acceptable in any sense other than that ACAS makes flight safer by reducing the overall risk of collision. They do not prove that ACAS reduces the risk of collision in all circumstances, still less that ACAS works in every case.

4.5 The invariable conclusion of the studies is that the more aircraft are equipped, and the more reliably and accurately pilots follow the RAs, the fewer aircraft will collide. In passing, we remark that they do not provide a basis by which the pilots can guess the particular cases in which ACAS will not work, and pilots should not attempt such a judgement.

5. Collision with third parties

5.1 By and large, ACAS safety studies have not addressed the risk of collision with third party aircraft directly. The problem is not within the scope of the main methodologies used, and has not been definitively resolved. The argument has always been that, should an ACAS RA cause a manoeuvre towards another aircraft, ACAS would operate in the encounter with the third party; in practice, this is what is observed.

5.2 Recently, ACASA [11] attempted to quantify the risk of induced collision with third parties. It sought to provide a numerical estimate of the risk of collision caused by ACAS in multiple or

² The risk that an ACAS RA could induce controlled flight into terrain was the subject of particular and heated debate during the design process. It could happen over very rapidly rising terrain, but over reasonably level terrain it could not happen other than through software or flight crew error. There have been reports of descend RAs at low level but, to date, the circumstances of each case have been consistent with the flight crew misunderstanding the annunciation. There continue to be reports of flight crew misunderstanding the sense of an RA and this is a cause of significant concern.

sequential encounters. The study proceeded in two parts. The first was to find out how frequently an RA (involving two aircraft) was close enough to a third party to consider the possibility of an induced ACAS encounter with the third party. (This is a necessary condition for induced collision involving the third party, but is much wider.) The operational record of reported multiple encounters was considered in this context, and six months' worth of radar data were exhaustively trawled. The operation of ACAS in all the multiple encounters discovered was studied. The second part of the study was to quantify the risk of induced collision using these encounters. Unfortunately, only two encounters provided material guidance, and no convincing conclusion could be drawn other than that multiple encounters in which there is any risk of collision are extremely rare.

- 5.3 Multiple ACAS encounters and ACAS encounters where a third party becomes involved occur, but infrequently. Quite properly, they cause concern, but there is no reason to doubt the expectation of ACAS experts that they will be sufficiently rare, and ACAS will be sufficiently effective in the knock-on encounter, for the risk to be well within accepted ATM safety levels. Non ACAS-experts have cited one encounter in particular as illustrating undesirable ACAS operation: the encounter involving four aircraft in UIR Switzerland on 13 September 2000. [12] This encounter is discussed in the Appendix. Far from suggesting any cause for alarm, this encounter shows ACAS sorting out the successive encounters exactly as expected.
- 5.4 The risk of induced collision with third parties is yet to be quantified. ACASA found that the frequency of multiple encounters (RAs against two aircraft in rapid succession) was of the order of $1.7 \text{ in } 10^5$ flying-hours in the busy airspace studied. As noted in 5.2, the evidence is very weak; so far as it went, it suggested that the risk of induced NMAC³ in multiple encounters is less than $1.5 \text{ in } 10^7$ flying hours.

6. Risk ratio and methods

6.1 Risk ratio

- 6.1.1 The first ACAS safety studies sought to determine the 'ACAS risk ratio', and this has remained the case ever since. [3, 4] The risk ratio expresses the benefit of ACAS in proportional terms, as follows:

$$\text{ACAS risk ratio} = \frac{\text{risk of collision with ACAS}}{\text{risk of collision without ACAS}}$$

- 6.1.2 If the ACAS risk ratio is less than 1.0, ACAS reduces the risk of collision, which is to say that it causes fewer collisions than it prevents. Various studies have obtained all sorts of values, from 0.01 to, say, 0.3⁴. *The ACAS risk ratio does not measure safety of flight*; it indicates the efficacy of ACAS.
- 6.1.3 The apparent advantage of discussing ACAS in terms of risk ratio is that it seems to become unnecessary to know the present risk of collision. Certainly, the results can be presented without having to make any statement concerning the risk of collision without ACAS; and the first estimates of risk ratio did not use data concerning the pre-existing risk. [3, 4, 7] Equally, it has always proved difficult to get clear, definitive advice concerning the risk of collision. It was

³ This is the result as given in the reference. A Near Mid Air Collision was considered to be an encounter in which the vertical miss distance is less than 100ft and the horizontal miss distance is less than 500ft (or 600ft, or 200m). Translating, the result is equivalent to saying that the risk of induced collision in multiple encounters is less than $1.5 \text{ in } 10^8$ flying hours.

⁴ Even 4.0 in the simulations discussed in paragraph 2.5, but this would have been based on treating encounters with very large miss distances (e.g. 400ft and 2NM) as the objects to be counted rather than collisions. Footnote 7 discusses the effect on calculated risk ratio of the dimensions of the box used to model collisions.

considered sufficient to 'prove' that ACAS reduces the risk of collision, and therefore makes flight safer.

6.1.4 Ironically, the most advanced and reliable methods for estimating risk ratio (e.g. [11]) require knowledge of the risk without ACAS, and the results are very sensitive to the value assumed. The results are also sensitive to the frequency of encounters that ACAS finds difficult to handle. These factors are very variable from one airspace to another, and risk ratio varies from one place to another. It is worth remarking that an absolutely safe airspace would not need ACAS, and possibly would be better off without it. However, we have yet to identify an airspace in which ACAS is not expected to be beneficial.

6.2 *How to understand a risk ratio result*

6.2.1 Risk ratio is most easily understood when we have a very well known environment or model. For a real environment, if we knew that we regularly suffered 10 collisions a year, we would easily understand a risk ratio of 0.1 to indicate that we would suffer only 1 collision in the year after ACAS was introduced. Even if that one event could be proved to be due to ACAS, it would be easy to observe that a net 9 collisions had been avoided. This is the situation for the models used to calculate risk ratio; we can point to the collisions that do not happen when ACAS is introduced. Unfortunately, circumstances are not presented in this way in the real world.

6.2.2 Now, after the introduction of ACAS, we have to understand risk ratio in a world where there are few collisions and ACAS is present. A risk ratio of less than 1.0 says there are fewer collisions than there would be were ACAS not present. The statement is hypothetical and cannot be proved by reference to real events, although it is prudent to collect events in which it seems that ACAS prevented near misses or collisions. The difficulty lies in the need to observe and count non-events. We are forced, even when we have real experience, to rely on the theoretical work done before ACAS was introduced. The first observation to make when there is a collision is that such events are what ACAS prevents occurring in larger numbers.

6.2.3 In the real world, where ACAS exists, ACAS is likely to feature in any collision that does occur. To the extent that ACAS is to 'blame' for the collision, it is likely to be very difficult to determine whether ACAS failed to prevent it or caused it. The actual risk ratio figures discussed below make this distinction, and can do so because they are based on assumption concerning what would happen without ACAS, but the distinction is much less meaningful once ACAS is involved in an actual collision. After the event, one can only ask 'Could ACAS have done better?' In this sense, ACAS could be considered to be a cause in most collisions, and one needs no analysis to come to this rather unhelpful conclusion.

6.2.4 Risk ratio results distinguish between unresolved risk and induced risk. It is possible to use them to come to conclusions such as 'If there is a collision after the introduction of ACAS, it would be a 50-50 chance that it is caused by ACAS.' Thus, if one mandates ACAS, one is always likely to find oneself in the position of defending against the accusation that ACAS has caused a collision. However, the alternative of declining to mandate ACAS would lead, more rapidly and with higher probability, to finding oneself in a position of defending against the accusation that a collision has been allowed to occur that could have been prevented with ACAS.

6.2.5 To understand the risk ratio, one is compelled to hypothesise the world without ACAS, and it would be a world with more collisions.

6.3 *Logic⁵ or system*

6.3.1 Disregarding petty matters of equipment failure (antenna failure, transponder malfunction, display failure, etc.), which simply should not happen, the efficacy of ACAS in preventing collision depends on many factors, e.g.:

- whether ACAS tracks the intruder;
- whether the other aircraft has ACAS;
- the nature and operation of the transponders on both aircraft;
- whether or not the display and a TA enable the pilot to see the other aircraft;
- whether the pilot reacts correctly to that visual acquisition;
- whether or not the pilot speaks to the controller about the RA, or the intruder;
- whether the pilot obeys the ACAS RA;
- the manner in which the pilot obeys the RA; and
- whether the encounter geometry is such that the logic operates well.

6.3.2 Most people are interested in the global question ‘Does ACAS reduce the risk of collision?’ taking all these factors into account. Attempts to answer that question tend to use the ‘system risk ratio’, and should assess all these factors. However, the last factor is critical: ACAS can prevent collisions only if the logic works, and the logic has required more attention than any other component (other than, arguably, attempts to get pilots to follow RAs). Thus, many ACAS safety studies have concentrated on calculating the ‘logic risk ratio’, which, to over-simplify, asks ‘Does the logic work?’

6.3.3 The logic and the system risk ratios measure the same thing but under different assumptions. For the logic risk ratio, a series of assumptions, which do not need to be realistic, are stated – and they must be stated. For example, one might assume that the other aircraft does not have ACAS, and is Mode C equipped rather than Mode S, and that the pilot responds exactly as intended, i.e. with an acceleration of 0.25g, after a delay of exactly 5 seconds, until he achieves exactly the specified vertical velocity. It is required that ACAS be effective when these assumptions are correct; we also need to know the logic risk ratio when each and all of these assumptions are varied.

7. **Specific safety studies**

7.1 *Introduction*

7.1.1 This section reviews the major ACAS safety studies, particularly their methodologies and results. It does not attempt to include everything that bears on safety. For examples, it does not include early work showing that risk ratio depends on airspace, nor more recent work showing the potential safety advantage of further changes that have been proposed for the logic.

7.2 *MITRE safety studies*

7.2.1 It has not been possible to confirm the remarks made below about these two studies [3, 4] by referring to the original papers, because they have been lost during a recent office move. Some ICAO papers presenting the MITRE studies to SICASP Working Group 2 have survived the move; these report the results and make some comments on the methods that confirm the memory of this author. [13, 14, 15]

⁵ The term ‘logic’ refers to the mathematical algorithms or, differently, the computer programs that calculate that a collision is imminent, and the avoidance manoeuvre that will be recommended.

7.2.2 The analysis was based on a comprehensive fault tree⁶. The event ‘collision’ (or, since MITRE consistently favoured NMACs as the basis of analysis, probably ‘NMAC’) was placed at the top of the tree. The circumstances or events that are required for this top event to occur were then placed below the top event and combined using ‘AND’ or ‘OR’, as appropriate. The tree was grown downwards, becoming wider and more complex as the bottom level events became easier to understand and analyse. When the probabilities of the events at the bottom of the tree can be specified, they can be combined and the probability of the top event thus estimated.

7.2.3 Even though the low-level events were ‘easier to understand and analyse’, many of them required considerable work to justify the particular probability values ascribed to them in the tree. The analysis is thorough, and thick.

7.2.4 The results were as follows. [15]

- “For overall conditions, the probability of an NMAC is reduced to 24.9% in [the 1985] traffic environment.”
- For instrument meteorological conditions, “the probability of an NMAC ... is 20.2% of that without TCAS.”
- “The biggest contribution to this residual is the fact that not all aircraft [were] equipped with transponders and Mode C altitude encoders ...”.
- Were all aircraft Mode C equipped, risk ratio would be reduced to 5.3% generally, and 4.8% for IMC.
- ACAS can induce collision, and the figures for this part of risk ratio reported in this study were 1.8% generally, and 0.8% for IMC.

The TCAS mandate was accompanied by a Mode C mandate, so it is the last two bullets that are most relevant.

7.2.5 Paragraph 2.5 above reported results based on real encounters observed in radar data that appeared to call into question the level of efficacy reported by MITRE. [5] The problems centred on the potential for ACAS to induce NMACs in traffic under tight control. MITRE anticipated such problems and looked for them. [14] At a time when the use of ATC recordings was technically difficult and politically sensitive, they examined 641 aircraft-hours of data for aircraft operating in IMC, and found no adverse effect. However, the analysis required to support the fault tree probabilities required two particular assumptions that bear on this question: MITRE assumed that horizontal miss distance and vertical miss distance are uncorrelated in close encounters; and that the probability that an aircraft will level-off is the same in a close encounter as in the absence of the close encounter. Analysis was presented to support these assumptions, but later work and experience suggests they were too simple.

7.2.6 In spite of these problems, the MITRE work was seminal and, in many details, remains definitive. The only area in which it has been questioned seriously is the operation of the logic in encounters under control. The great majority of the subsequent work centred on this question, and led to the emphasis on ‘logic risk ratio’ rather than ‘system risk ratio’.

7.3 SICASP/5

7.3.1 The report of SICASP/5 on the safety of ACAS [9] was a consensus among experts working in several different States, each using their own methods. The process of reaching agreement was complicated by the fact that the logic was evolving at this time, with the result that workers did

⁶ Paragraph 7.7.3 contains a warning that the term ‘fault tree’ as used in ACAS safety studies is not what safety experts necessarily expect to find. The author does not know whether this warning is appropriate for the MITRE fault tree; he has lost the papers.

not have a stable base-line design to judge. Nevertheless, all the results indicated that ACAS would achieve a useful reduction in the risk of collision if used correctly.

7.3.2 SICASP/5 “recognized that ACAS cannot resolve all possible collisions and may cause some risk of collision.” However, it “concluded that the use of ACAS is expected to reduce significantly the risk of collision with Mode C and Mode S transponder equipped aircraft provided that equipage with transponders is sufficiently widespread.” On this basis, the ACAS SARPs were recommended, and ACAS was subsequently mandated.

7.3.3 The report of SICASP/5 included the following.

“ 2.3.1.4 ... SICASP/4 decided that [the environmental and human factors that influence system risk ratio] should not be included in the assessment of ACAS II safety. This was because the human factors would evolve and vary from one State to another.

2.3.2.3 ... the logic can be expected to fail to resolve approximately four per cent of the expected risk of collision and to induce collisions at a rate of about four per cent of the risk of collision. ... [Paragraph 2.3.2.1 explains that the logic risk ratio gives a lower limit to the system risk ratio. In plain language, the figures given in the SICASP/5 report were based on the assumption that pilots reacted correctly to the RAs.]

2.3.2.4 ... the contribution to total system risk ratio due to failure to track [an] intruder [was estimated] to be three per cent ...

2.3.2.5 Thus ... the unresolved risk ratio is about seven per cent and the induced risk ratio is about four per cent. ... In simple terms, from 100 critical airmisses⁷ ACAS II may typically:

- resolve 93 critical airmisses,
- not resolve 7 critical airmisses, and
- induce 4 critical airmisses.

It was therefore understood that there may still remain at least 11 critical airmisses when ACAS II is fully operational.”

7.3.4 SICASP/5 went on to give advice about the factors that influence the efficacy of ACAS, including the need for flight crew to follow the RAs.

7.3.5 The numbers quoted above, and explained in 2.3.2.5, must not be regarded as precise guidance concerning the effect of ACAS on the risk of collision. Rather, they were a compromise between various estimates made for different airspaces, and using assumptions that are probably not now appropriate. (They are logic risk ratio figures based on the pilots responding to the RAs accurately, and on only one of the two aircraft in an encounter being ACAS equipped.) The message might have been rephrased thus.

- If you use ACAS, you will avoid most of the collisions that would otherwise occur.
- You will not avoid all the collisions that would otherwise occur.
- You will suffer collisions that would not otherwise occur.

No big surprise there!

⁷ The use of the term ‘critical airmisses’ is an outbreak of political correctness; the term ‘collision’ was considered to carry emotive overtones. That the term ‘collision’ survived in some conclusions is a triumph for plain speech.

In practice, risk ratio is usually calculated using Near Mid Air Collisions (which have a precise definition in terms of dimensions) as a substitute for collisions. ‘Critical airmisses’ was considered a more recognisable term than ‘NMAC’. It happens that risk ratio increases (gets worse) as the dimensions of the box for which it is calculated increase. Since there are no aircraft that have cross section as large as an NMAC, we can say that the risk ratio calculations are conservative in this respect. Treating aircraft as point particles would lead to answers that are too favourable.

- 7.3.6 The report of an induced risk ratio of 0.04 cannot be interpreted in terms of how often it would happen. One might attempt the argument ‘If the present collision rate (before the introduction of ACAS) is 1 in 10^6 flying hours, then presumably the rate ACAS induces collisions must be 4 in 10^8 flying hours.’ However, such an argument is not correct. The models used to calculate risk ratio had pre-existing collision rates implicit within them. These rates were not known, but it would be wrong to argue from an imagination of what they might be.
- 7.3.7 In practice we find that, when we attempt to decrease the implicit pre-existing collision rate in our models, the induced risk ratio increases. This is just what would be expected naively, from the formula for risk ratio, and illustrates that it is wrong to attempt to infer induced collision rate by multiplying risk ratio by an imagined collision rate without ACAS. The sole purpose of SICASP/7 in reporting an induced risk ratio of 0.04 was to emphasise that there is a real risk of induced collision, and to quantify the extent to which it is less than the pre-existing risk of collision.
- 7.3.8 The reader might observe that most people do indeed simply want to know ‘Does ACAS reduce the risk of collision?’ and question the reliance of SICASP/5 on logic risk ratio figures. The answer is that the system risk ratio is very much more difficult to estimate, and to some extent those involved were (without saying so) relying on the earlier MITRE work, which did examine the whole system and gave promising results. [3, 4] However, we have been able to move on since SICASP/5, and there have been subsequent estimates of system risk ratio.

7.4 *NATS full system safety study*

- 7.4.1 In 1993 UK NATS (legally, the CAA) commissioned a study on the safety of ACAS from EDS. [16] The intention was to address the full effect of ACAS (i.e. to calculate the ‘system risk ratio’), and correct the emphasis that there had been on the performance of the logic assuming ideal circumstances.
- 7.4.2 The approach adopted was to develop a fault tree for the top-level event ‘critical airmiss’. Two trees were used: one with ACAS, and the other without ACAS. The basic fault tree methodology was the same as in the earlier MITRE work.
- 7.4.3 In spite of the comprehensive aims, some simplifications were essential. Most significantly, the study did not attempt to consider ACAS-ACAS encounters. Third party aircraft were not considered, and all hardware and software components were considered to operate as designed.
- 7.4.4 There was considerable emphasis on human performance in this study, and the results took full account of a careful assessment of the potential for human error. Volume 4 of the report covers this subject.
- 7.4.5 The study reported a ‘full system risk ratio’ of 35.5%.

7.5 *ICAO standards for logic performance*

- 7.5.1 In 1997 ICAO agreed performance-based standards for the ACAS logic. [17] This was the culmination of two strands of work.
- 7.5.2 There was debate within SICASP from its inception concerning the standards for the collision avoidance logic. Initially, the intention (not welcomed by everyone) was to describe a model design (*de facto* the TCAS logic) in sufficient detail to ensure it was the only option for manufacturers. The problem with this approach was exposed by the fact that important changes were being made to the logic at precisely the time when the standards were being finalised. The alternative, which SICASP/5 decided to adopt, was to place requirements on the performance of

the logic. These standards relate to the efficacy of the logic and to the disruption it causes to air traffic control, e.g. nuisance alert rate and the magnitude of the deviations caused by RAs.

7.5.3 The second strand was an agreed approach to estimating the efficacy of ACAS.

7.5.4 The standards for the logic state a large number of assumptions under which the performance of the logic is to be judged. While these assumptions were intended to be as realistic as possible, it was not stated nor required that they are actually true. They are working assumptions required to provide the necessary tests that the logic is effective. In particular, the calculation of risk ratio requires the simulation of the performance of ACAS in very many encounters, far more than can be found in real data, and the creation of encounters for these simulations is based on a stochastic model. The statistical parameterisation of this model is based on the analysis of encounters observed in many months' worth of radar data.

7.5.5 The standards specify the logic risk ratios that have to be bettered by any proposed design for the collision avoidance logic. The actual values are based on TCAS version 7, but include a small margin. The requirement is that:

“ the collision avoidance logic shall be such that the expected number of collisions is reduced to the following proportions of the number expected in the absence of ACAS:

- a) when the intruder is not ACAS equipped 0.18;
- b) when the intruder is equipped but does not respond 0.32; and
- c) when the intruder is equipped and responds 0.04.”

7.5.6 The figures in 7.5.5 standardise the performance of the logic and give an indication of what is expected of TCAS version 7. They describe the best that can be achieved by ACAS; the system as a whole cannot be expected to perform better than the logic operating in ideal conditions. In particular, the figures assume that pilots respond correctly to RAs (except in (b), where it is assumed the pilot of the other aircraft ignores his RA).

7.5.7 The comparison between (a) and (b) in 7.5.5 illustrates the importance of pilots following ACAS RAs. Failure to follow an RA positively screws the ACAS on the other aircraft.

7.6 *Version 7*

7.6.1 TCAS version 7 was developed to very high standards required by the certification authorities. This had two effects:

- high standards of validation were required;
- the software developments standards were very high.

7.6.2 The validation requires studies showing that the logic is effective (risk ratio), studies of the effect on ATC and studies searching exhaustively for circumstances in which the logic will perform adversely. It is generally desirable. The only problem is that it will always be possible to find circumstances when any change will have adverse effects, and there is a tendency to regard these failures too seriously when the probability of their occurrence is lower than that of the circumstances where the change is beneficial. This is the point of using a balanced encounter model to calculate risk ratio.

7.6.3 The requirement of stringent software standards is irrational and totally counterproductive. Its purpose is to ensure that the logic does exactly what it is supposed to do; in other words, to ensure that collision (or other adverse consequence) is not caused by a software error. But ACAS is far more likely to lead to collision either because it is inherently incapable of resolving a particular geometry, or because pilots fail to follow RAs, than through software error. Placing a high requirement on the software standards positively obstructs improvements to the design.

7.7 ACASA WPI

7.7.1 The purpose of the ACASA study was to produce practical advice, and a wealth of results, most expressed as risk ratios, were presented in order to draw lessons or give advice. With regard to risk ratios given for the purpose of expressing the value of ACAS, ACASA reported as follows. These quotations start with logic risk ratios, then move on to system risk ratios.

“ E4.2.2 The [logic] risk ratio in encounters between an ACAS equipped aircraft and an unequipped intruder is 0.229, of which 0.137 is due to induced risk.

E4.2.3 The [logic] risk ratio in coordinated encounters between two ACAS equipped aircraft is 0.033, of which 0.022 is due to induced risk.

E4.3.1 The logic risk ratios quoted above (and others calculated for various non-standard pilot responses) were combined with the probabilities of other system events ... to obtain [system] risk ratios relevant to the operation of the total ACAS system.

[Thus the next two paragraphs give system risk ratio results.]

E4.4.1 ... the use of ACAS was found to reduce the risk of collision in an airspace to 0.299 of the risk that would exist in the absence of ACAS. The risk of an induced collision is 0.045 of the risk [of any collision] that would exist in the absence of ACAS.

E4.4.3 The risk ratio for an aircraft that equips was found to be 0.267 if it equips before Phase 1 [of the European mandate], 0.278 after Phase 1 but before Phase 2, and 0.272 after Phase 2. ... ”

7.7.2 The logic risk ratios were calculated using a stochastic model from which as many encounters as desired could be generated. This model was an improvement on that standardised by ICAO, and the statistical characteristics of the model were tuned to fit those of many encounters collected in about a year's worth of saturation radar recordings. Unfortunately, in spite of the large quantity of radar data used, many of the statistical characteristics of the model were based on small samples. However, the rate of collisions was not, because that was separately tuned to match general experience and expectation.⁸ Of course, this process designed a model that represented the airspace in which the data were collected.

7.7.3 The system risk ratio results were calculated using a logical diagram that broke down all the events and circumstances that are required for collision, and combined them using the operators AND and OR (and XOR). The approach was suggested by the MITRE work and the EDS study for NATS, and was commonly referred to as a 'fault tree'. However, this term has a particular and precise meaning for safety experts, and the diagram is not a fault tree in that specialised sense. This does not make it incorrect; the diagram is intended to divide up all the different circumstances in which a collision can occur, and then combine their probabilities in a correct way.⁹ A standard fault tree tool was used to produce the diagram (which covered about 50 pages of A4), which was then implemented on an Excel spreadsheet. The spreadsheet calls for more logic risk ratio values than could be calculated, so those not calculated were estimated using logic risk ratios that had been based on very similar assumptions, using the observed effect of varying those assumptions.

7.7.4 The logic risk ratio results in E4.2.2 and E4.2.3 say that the logic works given the qualifying assumptions stated in the ACASA report. The results for encounters where the other aircraft is not ACAS equipped, E4.2.2, are directly comparable with the results reported by SICASP/5, and

⁸ ACASA forced the pre-existing collision rate to equal 3 collisions in 10^8 flying hours, because the risk ratio is sensitive to this assumption. It was not suggested that this rate is correct; it was the most realistic assumption that could be made in the absence of clear and firm evidence. There has been no comment on the assumption during the year since the report was published.

⁹ ACASA did not know of a fault tree tool that achieves this, and it knew that two tools did not achieve it.

they seem less optimistic (0.229 in place of 0.08, and 0.137 in place of 0.04). The reasons are that risk ratio depends on the airspace, and also the later ACASA work is indeed giving less optimistic results.

- 7.7.5 The comparison between E4.2.2 and E4.2.3 says simply that the logic works very much better in encounters where both aircraft are ACAS equipped.
- 7.7.6 E4.4.1 reports that the effect of the European mandate is to reduce the risk of collision occurring in European airspace to 30% of the risk in the absence of ACAS. It addresses the effect on an airspace, where not all aircraft will equip. E4.4.3 looks at the issue from the point of view of the aircraft required to equip, and we will return to that.
- 7.7.7 If the reader looks at the numbers in E4.4.1 (0.299 and 0.045) and compares them with those in E4.2.2 (0.229, 0.137) and those in E4.2.3 (0.033, 0.022), he might be puzzled. He might observe that the overall system risk ratio, 0.299, seems rather large, or, if that is not large, then the induced system risk ratio, 0.045, seems rather small. The explanation is that the system risk ratio takes into account aircraft that are still not equipped, and aircraft in which the pilot fails to respond to the ACAS RAs. Both these factors will make the ACAS mandate more ineffective (increase risk ratio), but they also reduce the possibility that ACAS will induce a collision (decrease induced risk ratio).
- 7.7.8 For ACASA, it was still the case (as at SICASP/5) that the main purpose in reporting an induced risk ratio was to emphasise that there is a real risk of induced collision, and to quantify the extent to which it is less than the pre-existing risk of collision. However, the situation is modified from that for SICASP/5 because, in ACASA, the pre-existing collision rate implicit in the model is known, and was forced⁸ to be 3 collisions in 10^8 flying hours. Thus we know that the induced risk ratio of 0.045, quoted in E4.4.1 for the airspace, is equivalent to 1.35 induced collisions in 10^9 flying hours. This is an average for all the aircraft in the airspace – ACAS equipped, or not. One might ask whether this result is sensitive to the pre-existing rate assumed, but there is reason to think it is not. The induced risk depends on the frequency of encounters that ACAS finds difficult to handle, and in which there is no risk of collision without ACAS. The latter suggests it does not depend on the pre-existing collision rate.
- 7.7.9 E4.4.3 gives the system risk ratio for an aircraft that equips with ACAS, as opposed to an airspace; all factors influencing the efficacy of ACAS have been addressed. One of these factors is the proportion of other aircraft equipped with ACAS II, which varies as more aircraft equip. Thus, before Phase 1, no other aircraft are equipped and the reduction in the risk of collision by a factor of 0.267 arises from the protection given by own ACAS in encounters with unequipped aircraft. After Phase 1, and more so after Phase 2, other aircraft are ACAS equipped. This provides some protection to own aircraft even before it itself fits ACAS. However, when own aircraft equips, it gets further protection in two ways: it gets ACAS protection in encounters with aircraft that are not ACAS equipped; and it gets very much better protection in encounters with ACAS equipped aircraft. Thus the result is saying that an aircraft always reduces collision risk when it fits with ACAS, and that the factor by which it is reduced is remarkably constant: 0.267, 0.278 or 0.272 depending on the number of other aircraft that are equipped.

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A. Swiss chain-reaction incident [12]

- A.1 Multiple encounters are very rare, but this was a humdinger. Whether it was a true ACAS multiple encounter, i.e. one in which an ACAS unit declares RAs against two or more aircraft at the same time is not clear. From the account, it seems plausible that it was not. In any event, the sequence of events can be understood if they are viewed as three successive ACAS encounters.
- A.2 Four aircraft were involved, hence three encounters. The first aircraft, the lowest, was initially climbing to FL260. The other three aircraft were initially at FL270, FL280 and FL290, respectively.
- A.3 The first RA occurred because of a high rate of climb approaching FL260. SICASP recognised that high rates of climb approaching cleared flight levels cause a problem as early as 1989, and recommended then that vertical speed should be moderated when approaching a cleared flight level. This was the conclusion of the investigation.
- A.4 The second aircraft climbed in response to this first RA, causing a second RA encounter with the third aircraft. The third aircraft thus climbed, in response to its ACAS RA, towards the fourth.
- A.5 The encounter between the third aircraft and the fourth, the actual airprox, was exacerbated by an excessive response to the climb RA in the third aircraft. Even so, the vertical separation between these two aircraft approximated that which ACAS aims for (400ft being achieved rather than 600ft). From an ACAS perspective, none of the three encounters was close. In the actual airprox, the horizontal miss distance was a huge 2.9NM – large enough to explain the failure to achieve the full desired 600ft of separation. (The ACAS logic is designed to operate accurately in near-collisions, and a miss distance as large as 2.9NM would invalidate the assumptions made by the logic.)
- A.6 This is a beautiful example of ACAS operating in a knock-on or domino encounter in exactly the way that has always been predicted. It has always been said (without quantitative justification) that the risk of knock-on induced collision is acceptably small because ACAS would resolve the knock-on encounter. It did.
- A.7 The most alarming thing in this complex encounter is that it contains a recorded example of flight crew obeying ATC rather than ACAS, and almost getting praised for it. (The aircraft initially at FL270 was instructed to return to FL270, possibly during its climb RA, and did so.)