

# **European Airborne Collision Avoidance System (ACAS) Xa Change Proposal (CP)1 validation report**

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## Executive summary

This document describes the evaluation of Airborne Collision Avoidance System (ACAS) Xa change proposal 1 (CP1) using representative European close encounters. It is intended for use by EASA (European Union Aviation Safety Agency) in the validation of ACAS Xa CP1 in Europe. Representative European close encounters equivalent to about thirty billion flight hours, were used in fast-time simulations to compare the performances of ACAS Xa CP1 and Traffic alert and Collision Avoidance System (TCAS) version 7.1. Encounters were generated by the EUROCONTROL Collision Avoidance Fast-time Evaluator (CAFE) Revised Encounter Model for Europe (CREME). The model is based on the US Lincoln Laboratory Correlated Encounter Model (LLCEM) with adaptations for Europe. The main differences are:

- Over 12 million flight hours of European radar data collected in the period 2015-2016 plus a day in 2018 from six Air Navigation Service Providers in the Czech Republic, France, Poland, Switzerland, UK and EUROCONTROL Maastricht which controls the upper airspace of Belgium, Germany, Luxembourg and the Netherlands.
- For encounters fed into the model, the effect of Resolution Advisories (RA) was removed where an RA downlink message was recorded. This allowed the model to construct trajectories without built-in responses to TCAS RAs.
- Adjustments to model network order, bin sizes and nodes (addition of aircraft class, controlled status, proximity, vertical separation from ATC level).
- An aircraft model instead of airspace model with aircraft performance classes.

The above data and tools were used to produce two CREME variants:

- *CREME safety*: Horizontal miss distances (HMD) are less than Near Mid Air Collision (NMAC) 0.082 NM (500 feet).
- *CREME ATM*: HMDs are less than 5NM.

The variants produce close encounters that are representative of European traffic in the period 2015-2016 plus a day in 2018. No explicit modelling of future operations was incorporated. Nevertheless, current total traffic levels in 2022 are comparable to that period due to the Covid pandemic and lack of growth and inherently some variability around currently observed encounters is built into the models. To mitigate unknown risks present in future operations but absent from encounters used in this validation, operational monitoring of ACAS Xa should be put in place.

Encounters are aircraft trajectory pairs where at least one of the aircraft in each encounter is under Air Traffic Control. Trajectory durations are from about a minute before the closest point of approach (CPA) to about 10 s after. Encounters from the model variants have been analysed by EUROCONTROL using statistical and graphical tools and an ACAS simulator to check:

- Encounters are operationally realistic.
- Distributions are reasonably representative of real encounters.
- Safety metric values are similar to a previous European encounter model (AVAL 2008);

Sample encounter sets have been analysed by the following organisations using independent ACAS simulators:

- Egis Avia, Toulouse, France (*CREME ATM*, *CREME safety*).
- Lincoln Laboratory, Massachusetts, USA (*CREME safety*).

Additionally, a set of close encounters observed in radar data was selected for assessing operational acceptability. Each of these radar encounters generated an RA in simulations with either TCAS II V7.1 or ACAS Xa CP1 or both. Close encounters that did not generate an RA were excluded.

Fast-time simulations of ACAS Xa CP1 were performed with the EUROCONTROL Collision Avoidance Validation and Evaluation Tool (CAVEAT V3.2). A standard ICAO pilot model [16] was used to simulate three sets of encounters: Radar, *CREME safety* and *CREME ATM*. The same simulations were repeated using TCAS V7.1 as a benchmark. Safety and operational acceptance performance metrics were calculated using the 'Single European Sky Air traffic management Research (SESAR) vision of European acceptability criteria for ACAS Xa development' (2015) as a guide for comparison. Scenarios of equipped aircraft versus equipped aircraft and equipped aircraft versus unequipped aircraft were performed in four altitude bands broadly corresponding to Approach, TMA, Transition and En-route airspace. A 1,000 feet level-off subset of encounters was also simulated to investigate the main cause of operationally undesired RAs in Europe. ACAS Xa CP1 was simulated for both passive and active surveillance. The number of encounters simulated depended on the desired statistical significance. A confidence level target of 95% was used which was not always met due to resources but many were met with more than 99% confidence. Difference values in the text below are the expected differences; statistical confidence ranges are shown in the results section.

The main conclusions of the study are:

Overall there are several benefits from ACAS Xa CP1 compared to TCAS II V7.1:

- When pilots follow their RAs, ACAS Xa CP1 logic provides an increased safety benefit of between 16% and 24% (depending upon whether or not the intruding aircraft have ADS-B out).
- When one pilot does not follow their RA, ACAS Xa CP1 provides an increased safety benefit of about 47% (indistinguishable results whether or not the intruding aircraft have ADS-B out).
- ACAS Xa CP1 reduces the overall number of RAs by about 60%.

In some areas ACAS Xa CP1 did not perform quite as well as TCAS II V7.1:

- For encounters where both aircraft have collision avoidance systems between 5,000 and 13,500 feet (Layer 2), both ACAS Xa CP1 and TCAS II V7.1 are very effective, but TCAS II V7.1 is more effective. This difference is an order of magnitude smaller than the overall benefit provided by ACAS Xa CP1 and is compensated by the better safety performance of ACAS Xa CP1 when one pilot does not follow their RAs.
- 85% of Very Close Encounters (VCE) trigger RAs rather than 97% with TCAS II V7.1. These VCEs without RAs occur only in very slow convergence encounters. Safety simulations show that this does not have a negative safety impact and is intimately linked with the reduction in alert rate.
- There were more vertical deviations exceeding 300 feet with ACAS Xa CP1. Based on the relatively low frequency of multi-threat encounters, these vertical deviations are expected to only rarely trigger RAs on proximate aircraft.
- There was a greater RA alert rate on board aircraft climbing/descending below 1,500 feet per minute in single 1,000-feet level-off encounters. (6 encounters observed with ACAS Xa CP1 vs 1 observed with TCAS II V7.1).
- ACAS Xa CP1 did not issue a TA at least 5 s before an RA in 104 equipped versus unequipped encounters compared with 71 for TCAS II.

In summary, ACAS Xa CP1 brings greater safety benefits than TCAS II V7.1 even if this benefit is less than TCAS II V7.1 for a few sub-classes of traffic.

Based on the conclusions above it is recommended:

1. That ACAS Xa CP1 is considered acceptable for European operations,
2. To assess whether the use of ADS-B out should be encouraged on smaller aircraft to improve ACAS II effectiveness.
3. To support RTCA / EUROCAE develop a revision to the ACAS Xa MOPS (Minimum Operational Performance Standards), incorporating all accepted change proposals.
4. To monitor the impact of ACAS Xa in service within the Single European Sky.
5. ACAS II training material for ACAS Xa should note that some very close encounters will not result in RAs and RAs are not always preceded by a timely TA.



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# 1. Introduction

## 1.1. Purpose

This document is intended for use by EASA in the validation of ACAS Xa in Europe.

This document describes the European evaluation of Airborne Collision Avoidance System (ACAS) Xa including change proposal 1 (CP1). The ACAS Xa CP1 logic was simulated in a set of close encounters observed by radar and a larger synthesised set of very close encounters representative of European airspace. Work was performed by EUROCONTROL in the period 2020-22 using the EUROCONTROL Collision Avoidance Fast-time Evaluator (CAFE) partly funded by the Single European Sky Air Traffic Management Research (SESAR) programme.

## 1.2. Scope

ACAS II systems have two main sub-systems: surveillance and threat resolution.

European and US air traffic environments are sufficiently different that they require different encounter models to assess expected operational and safety performance. Stressing encounter models, including multi-threat models, that ensure the robustness of collision avoidance in a wide range of potential future environments may be considered as equally appropriate for both European and US environments.

This document focusses on the results of simulations to compare ACAS Xa CP1 and TCAS II V7.1 in close encounters representative of European airspace. Safety performance was assessed using the equivalent of about thirty billion flight hours of close encounters. Operational performance was principally assessed using encounters observed in radar data.

Encounters were generated by the CAFE Revised Encounter Model for Europe (CREME) based on twelve million flight hours of radar data collected in the period 2015-2016 plus a day in 2018 from six Air Navigation Service Providers in the Czech Republic, France, Poland, Switzerland, UK and EUROCONTROL Maastricht which controls the upper airspaces of Belgium, Germany, Luxembourg and the Netherlands. Radar encounters were pairs of aircraft trajectories where at least one of the aircraft were under air traffic control. CREME generated encounters were nominally about 70 seconds in duration with horizontal miss distances up to 5 NM and altitudes from 1,000 feet up to flight level 660. Aircraft performance models were based on EUROCONTROL's Base of Aircraft Data (BADA). No wind or future scenarios were used but some variability was inherently built into the encounter construction. ACAS fast-time simulations were performed with the EUROCONTROL Collision Avoidance Validation and Evaluation Tool (CAVEAT V3.2) using an ICAO standard pilot model and passive and active surveillance. SESAR (Single European Sky Air traffic management Research) European acceptability criteria (2015) were used as a guide for comparing the safety and operational performance of ACAS Xa CP1 with TCAS II V7.1. The number of encounters used depended on the level of statistical significance achieved. At least 95% confidence was targeted for all encounters.

## 1.3. ACAS Xa

ACAS Xa consists of two principal modules: The Surveillance and Tracking Module (STM) and the Threat Resolution Module (TRM). The role of the STM is to provide tracked surveillance data to the TRM. The role of the TRM is to use the surveillance data to generate necessary and effective alerts and to provide traffic information. Each module has been validated by the FAA [18], [19]. Interaction between the modules (how the safety performance is affected by surveillance performance) has been adequately validated during Minimum Operational Performance Standard (MOPS) development and is not considered to have different characteristics in different airspaces.

### 1.3.1. Surveillance and Tracking Module (STM) performance

The STM of ACAS Xa CP1 provides the information required by the TRM.

Although there are differences between the European and US surveillance environments, the only difference of concern to ACAS relates to the frequency and power of interrogations and the electromagnetic interference limiting algorithms. Since ACAS Xa CP1 uses the same interrogation mechanisms and interference limiting algorithms as TCAS II V7.1 no specific European surveillance assessment has been performed. The final version of the ACAS Xa CP1 STM logic incorporated design improvements resulting from a European surveillance performance evaluation. Since the changes were small the final US assessment of surveillance algorithms is considered adequate for European airspace. Since the STM and TRM are decoupled, there was no need to revalidate the surveillance performance following CP1 TRM changes.

### 1.3.1.1. Surveillance validation

The exchange of any signals on 1030/1090 MHz increases transponder occupancy and FRUIT (False Replies Unsynchronised In Time) in this crowded frequency band. Active interrogation of intruders is by far the main source of signals generated by TCAS II and ACAS Xa.

No formal validation was made of the impact of ACAS Xa CP1 on the electromagnetic spectrum in a European environment under this validation activity. Such validation was considered unnecessary because:

The active interrogation mechanism used by ACAS Xa CP1 is identical to that used by TCAS II.

**Hybrid Surveillance (HS) is optional for existing TCAS II designs, but ACAS Xa CP1 requires the use of Extended HS. Extended HS can reduce the transponder occupancy due to active interrogation by more than 90% (as documented in studies by Lincoln Laboratory and EUROCONTROL/SESAR [17]).**

### 1.3.1.2. Tracking validation

ACAS Xa CP1 operates two trackers in parallel; the first tracks ADS-B position reports on own aircraft and intruders, the second uses the range and bearing information provided by active interrogations. Both trackers provide a relative Cartesian representation of the intruder.

European and US studies [10, 11] have shown that safety performance is better with the ADS-B tracker (with NIC, NACp, NACv, SIL values of 7,3,1,8 respectively) than the active surveillance tracker. By default, the ADS-B tracker results are used. Nevertheless, active interrogations continue to build an independent track and are used to validate the ADS-B reports. If and when the ADS-B reports and active interrogations do not correlate, or the ADS-B data quality is too poor, the fallback active interrogation track is used from that moment forward.

Validation of the final MOPS tracking system was not validated with European data for the following reasons:

- Previous versions of the ACAS Xa tracking software were validated within the SESAR2 programme by Honeywell with European data, and the results of that work were used to improve ACAS Xa CP1 tracking software.
- Manufacturers have some freedom when implementing surveillance for ACAS Xa. It will be the manufacturers' responsibility to demonstrate correct operation of their implementations of the ACAS Xa CP1 surveillance software against certification requirements.
- Since an active surveillance track is available as a fallback, issues associated with potential unreliability of ADS-B tracks are mitigated.
- The issues associated with tracking are the same worldwide. The FAA has validated the ACAS Xa CP1 tracker [19] and its robustness to off-nominal inputs [21].
- EUROCONTROL simulated close encounters collected from one year of radar data from six ANSPs using the MOPS definition of ACAS Xa (without CP1). No tracking problems were observed, and the STM is not changed in CP1.

### 1.3.1.3. Need for surveillance performance monitoring

Validation of the TRM involved simulation of close encounters equivalent to billions of flight hours. STM validation was performed with tens of thousands of flight hours data, often from flight trials. This leaves open the possibility of tracking issues occurring in operations that were not observed during ACAS Xa development.

Two recent bugs in TCAS II implementations were associated with HS and range tracking; they are examples of surveillance issues found with new equipment despite careful validation. Detecting and correcting these issues took more than 12 months to achieve.

Therefore, although ACAS Xa CP1 surveillance has been adequately validated, ACAS Xa performance should be monitored during its full operational life.

## 1.3.2. Threat Resolution Module performance

Close encounters were simulated with the ACAS Xa CP1 logic and compared with simulations of the same encounters with the TCAS II logic. These simulations were performed with different assumptions for: pilot response, surveillance noise, availability of ADS-B data and Mode S addresses. Calculations of Near Mid-Air Collisions (NMACs) in the presence of altimetry errors were made. These form the heart of the safety performance metrics. Operational metrics included the number, types and timing of RAs as well as deviations from clearance caused by RAs. Details of the encounters, simulations, pilot responses and metrics are given below.

## 1.4. Use of SESAR acceptability criteria

To assist in this validation, SESAR developed a set of acceptability criteria [4] for ACAS logic performance, broadly requiring new ACAS logic to have better performance than the existing system, TCAS II V7.1 [2]. The acceptability criteria have four main components: encounter models, simulation parameters, metrics and acceptability thresholds.

### 1.4.1. Encounter models

When the acceptability criteria document was written, the known European encounter models were: AVAL [5], PASS [6] and SA01 based on AVAL data [7]. All were created more than a decade ago. Since then, operations in European airspace have changed considerably. Maastricht Upper Area Control Centre identified the following differences:

- Aircraft generally seem to fly at higher flight levels: FL390+ used to be exceptional, now it's common. This is linked to the introduction of new types of aircraft.
- Widely varying speed profiles, especially for the low-cost airlines. In the descent, airspeeds can be as low as M0.65, where previous expectations were at least M0.75. Even in cruise, they tend to be slower than 'normal'. Newer turboprops make the situation even more complex.
- Several new ground-based alerts/tools (e.g. conflict probe, integration of Final State Selected Altitude (FSSA) into Short Term Conflict Alert (STCA)) change aircraft behaviour in close encounters. STCA has become more reliable and therefore more effective. Conflict probe allows earlier resolution of conflicts.
- Pilots have less of an idea of how their aircraft performs or why it does 'things'.
- Free route airspace – there are fewer fixed conflict points/patterns. The airspace complexity (number of points/routes) is growing exponentially: 10 years ago, the MUAC ATC system 'knew' about 2,000 navigation points. Today, it is close to 9,000.
- "New" airports are being used more frequently, by low-cost airlines and business jets.

EUROCONTROL recognised that validation studies would be improved if updated safety and operational validation models could be used. The CAFE project was funded to create updated European encounter models. *CREME safety* and *CREME ATM* are modern analogues of the AVAL [5] and PASS models respectively. CREME encounters have been validated for realism by operational experts using independent ACAS simulation platforms and checked for statistical representativeness against real data and past models,

### 1.4.2. Simulation parameters

Parameters used during ACAS encounter simulations include: the ICAO standard pilot response model, whether aircraft are equipped with ADS-B out and the aircraft's ACAS equipment. The potential number of simulation variations is so large that it is impractical to test all possible variations. Instead, the approach taken has been to carefully validate ideal cases and robustness against degradations.

### 1.4.3. Metrics

Although the metrics used in the acceptability criteria are well known from TCAS studies, experience has shown that they require interpretation. For example, a reduction in alerts may or may not have detrimental safety consequences.

The metrics are typically split into two categories: safety metrics and operational acceptability metrics. Safety metrics compare collision risk estimates for different ACAS. Operational acceptability metrics mostly compare the frequency of alerting between different ACAS, but can also include measures of complexity, timing and deviations. Although these metrics are not related to immediate collision risk, they can have important indirect safety consequences. For example, high false alert rates may lead pilots to ignore many RAs, thereby increasing collision risk when correct response matters. Also pilots and controllers have to be willing to work with the system.

### 1.4.4. Acceptability thresholds

Many of the thresholds for acceptable behaviour have never been used before. Some of them aim to show that ACAS Xa CP1 provides a worthwhile improvement over TCAS II V7.1 in all operating conditions. Such thresholds go beyond the requirements of acceptability and may be used for assisting design improvements.

The acceptability criteria take an idealistic view of validation that does not consider resource limitations. Furthermore, in many instances the acceptability criteria go beyond mere tests of acceptability and define requirements of improved performance. Also, since the criteria were developed, a more rigorous approach to detecting statistical significance has been adopted. This is described in section 9.3.1. The net result is that the acceptability criteria provide a frame of reference for guidance but need to be carefully interpreted. When deciding whether to allow ACAS Xa CP1 into

European airspace it is necessary to show on balance there is no average degradation with the new system and no observed areas with serious degradation.

## 1.5. Approach

The approach taken in this validation study is not to prove that ACAS Xa CP1 is better than TCAS II V7.1 in a statistically significant way, even though that has been observed for many metrics. Instead, efforts have concentrated on trying to find any metrics where ACAS Xa CP1 performs worse than TCAS II 7.1 in a statistically significant way.

Not finding cases where ACAS Xa CP1 is worse is like not finding black swans; just because no cases have been seen does not mean that they do not exist. However, by searching for performance problems, the probability and scope of their existence is diminished. This is a standard approach for scientific hypothesis testing.

## 1.6. Structure of document

Chapter 2 'Apparatus' introduces the tools and data used for this evaluation. Chapter 3 'Method' describes how the tools were used to evaluate the system under test: ACAS Xa CP1. Chapter 4 'Results' shows graphs comparing safety and operational acceptance metrics for ACAS Xa CP1 and TCAS II V7.1. Chapter 5 'Analysis of results' summarises the safety and operational performance metrics in terms of the SESAR acceptance criteria thresholds. Chapter 5 'Conclusions' highlights the strengths and weaknesses of ACAS Xa CP1 relative to TCAS II V7.1. Chapter 6 'Recommendations' lists possible further work.

## 1.7. Abbreviations

**Table 1 Abbreviation definitions**

Abbreviation	Definition
<b>ACAS</b>	Airborne Collision Avoidance System
<b>ACAS X</b>	New Airborne Collision Avoidance System under development by the FAA to support the objectives of Next Generation Transportation System (NextGen) Programme
<b>ACAS Xa CP1</b>	ACAS X – Active Change Proposal 1. ACAS Xa is functionally similar to the current TCAS II system with new surveillance and data processing techniques used to optimize the safety and suitability of the system
<b>ADS-B</b>	Automatic Dependent Surveillance - Broadcast
<b>ALIM</b>	Minimum vertical miss distance that TCAS II tries to achieve when generating an RA (values calculated to take into account errors in altimetry measurements)
<b>ANSP</b>	Air Navigation Service Provider
<b>AP/FD TCAS</b>	AutoPilot / Flight Director coupled to TCAS The safety benefits provided by TCAS II highly depend on pilot responses to triggered RAs. Operational monitoring has shown that actual reactions vary from the expected ones (e.g. too slow, too aggressive, etc.). To address this problem, a function has been developed, certified and implemented that couples TCAS II to the AutoPilot for an automatic response to RAs <sup>1</sup>
<b>ARINC</b>	Aeronautical Radio, Incorporated
<b>ASTERIX</b>	All Purpose Structured EUROCONTROL Surveillance Information Exchange
<b>ATC / ATM</b>	Air Traffic Control / Air Traffic Management
<b>AVAL</b>	ACAS on Very Light Jets and Light Jets – Assessment of safety Level
<b>CAFE</b>	Collision Avoidance Fast-time Evaluator
<b>CAVEAT</b>	Collision Avoidance Validation and Evaluation Tool
<b>CoC</b>	Clear of Conflict
<b>CP1</b>	Change Proposal 1 to ACAS Xa MOPS change 1. This is the system described in US TSO (Technical Standard Order) C219 – Airborne Collision Avoidance System (ACAS) Xa/Xo, 28 <sup>th</sup> February 2020. Appendix A details the differences from the ACAS Xa MOPS and Change 1.
<b>CPA</b>	Closest Point of Approach, i.e. the occurrence of minimum range between own aircraft and the intruder. Thus, range at closest approach is the smallest range between the two aircraft and time of closest approach is the time at which this occurs [4].
<b>CREME</b>	CAFE Revised Encounter Model for Europe
<b>CSV</b>	Comma Separated Values
<b>DDES</b>	Do not Descend
<b>EASA</b>	European Union Aviation Safety Agency
<b>EE</b>	Equipped-Equipped
<b>EU</b>	Equipped-Unequipped
<b>EUROCAE</b>	European Organisation for Civil Aviation Equipment (European standardization body)
<b>FAA</b>	Federal Aviation Administration
<b>FL</b>	Flight Level
<b>fpm</b>	Feet per minute
<b>FTD</b>	Flight Track Data
<b>FTEG</b>	Fast Time Encounter Generator – an FAA Stress testing encounter model
<b>FRUIT</b>	False Replies Unsynchronized In Time
<b>HMD</b>	Horizontal Miss Distance
<b>HS</b>	Hybrid Surveillance
<b>ICAO</b>	International Civil Aviation Organization
<b>IFR</b>	Instrument Flight Rules
<b>LLCEM</b>	Lincoln Laboratory Correlated Encounter Model
<b>LO</b>	Level Off

<sup>1</sup> EUROCAE ED-224 document [7] provides guidance to design, install and test Flight Guidance System coupling to TCAS for Automatic guidance and/or display cues to support pilot guidance upon RAs

Abbreviation	Definition
<b>LOLO</b>	Level Off Level Off
<b>MOPS</b>	Minimum Operational Performance Standards
<b>MUAC</b>	Maastricht Upper Area Control Centre
<b>NMAC</b>	Near Mid Air Collision, i.e. an encounter in which, at some point in the encounter, the horizontal separation is less than 500ft and simultaneously the vertical separation is less than 100ft
<b>OT</b>	Optimised TCAS II v7.1 RA Thresholds
<b>PASS</b>	Performance and safety Aspects of Short-term Conflict Alert – full Study
<b>RA</b>	Resolution Advisory
<b>RTCA</b>	Radio Technical Commission for Aeronautics (US standardization body) now called RTCA
<b>SARPs</b>	Standards and Recommended Practices
<b>SESAR</b>	Single European Sky ATM Research Programme
<b>SJU</b>	SESAR Joint Undertaking (Body of the European Commission)
<b>STCA</b>	Short Term Conflict Alert
<b>STM</b>	Surveillance and Tracking Module
<b>TA</b>	Traffic Advisory
<b>TCAP</b>	TCAS Alert Prevention During 1000ft level-off encounters, TCAS II triggers RAs which are often perceived as operationally undesired by air traffic controllers and flight crews. To address this problem, a function has been developed, certified and implemented which relies on new altitude capture laws taking into account TCAS II thresholds. These new altitude capture laws consist in reducing the own vertical speed automatically at the approach of the own selected flight level to avoid unnecessary RAs <sup>1</sup>
<b>TCAS</b>	Traffic alert and Collision Avoidance System
<b>TMA</b>	Terminal Control Area
<b>TRM</b>	Threat Resolution Module
<b>VCE</b>	Very Close Encounter where the aircraft come within <ul style="list-style-type: none"> <li>• 0.5NM horizontally and 400 ft vertically in TMA airspace</li> <li>• 1.0 NM horizontally and 600ft vertically in En-Route airspace</li> </ul>
<b>VFR</b>	Visual Flight Rules
<b>VMD</b>	Vertical Miss Distance

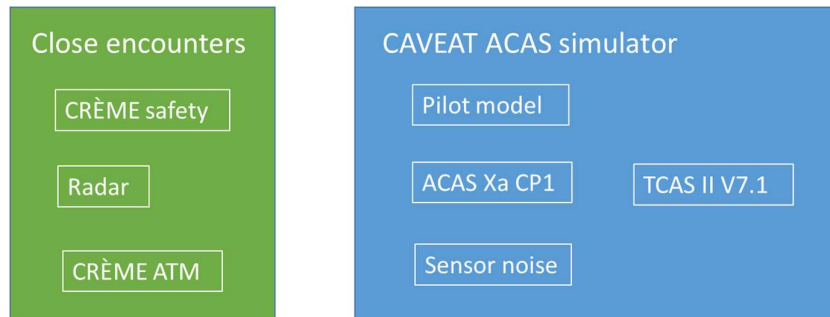
## 2. Apparatus

### 2.1. ACAS simulator: CAVEAT

#### 2.1.1. Functionality

The EUROCONTROL Collision Avoidance Validation and Evaluation Tool (CAVEAT) is a tool for the simulation and analysis of ACAS in aircraft encounters. It has recently been developed under contract by NLR (Netherlands) and Everis (Spain). CAVEAT uses an agent-based modelling and simulation (ABMS) approach. This approach is useful to conceptualise processes in complex human-machine (sociotechnical) systems, such as encounter scenarios, and it has been used for a range of safety risk analyses in air transport.

Coordination can be synchronous or asynchronous; noise can be added to any or all sensors, ADS-B can be present or absent. Monte Carlo runs can be performed, giving a restricted dithering capability.



**Figure 1 Main apparatus used for evaluation**

#### 2.1.2. System under test: ACAS Xa CP1

CAVEAT 3.2.0 supports the simulation and analysis of ACAS Xa CP1. Two implementations of ACAS Xa CP1 logic were developed by EUROCONTROL, coded in C and Julia. Both have passed all necessary MOPS tests.

#### 2.1.3. Reference system: TCAS II V7.1

CAVEAT 3.2.0 supports the simulation and analysis of TCAS II (versions 7.0 and 7.1). TCAS II logic was obtained from Mitre, coded in C. This has passed all MOPS tests. Both the TCAS II V7.1 and ACAS Xa CP1 software modules take second by second positions of aircraft and output standard ARINC 429 bus outputs which are then interpreted into RA types.

#### 2.1.4. Pilot response models

All ACAS simulations need to simulate the response (or non-response) of the pilot. This is typically characterised by three parameters: time to respond, strength of response (vertical acceleration) and extent of response (achieved vertical rate). A distinction is made between the response to first RAs and subsequent RAs.

More sophisticated models, where reactions to different RA types can be different, are possible but not used in this validation.

##### 2.1.4.1. Standard

The standard pilot response to RAs is defined in ICAO ACAS Standards and Recommended Practices (SARPS) [20]. It is the default used for simulations.

Response to 1<sup>st</sup> RA:

- Delay: 5s
- Acceleration: 0.25 g
- Achieved Vertical Rate: 1,500 fpm (feet per minute)

Response to 2<sup>nd</sup> RA:

- Delay: 2.5 s
- Acceleration 0.35 g (for increase rate and reversal RAs)
- Achieved Vertical Rate 2,500 fpm (for increase rate RAs)

##### 2.1.4.2. Non-responsive pilot

To test the resilience of the logic to non-standard pilot responses, one model in Equipped-Equipped encounters has one aircraft not responding to RAs. By default the other pilot will respond with the standard pilot model.



### 2.1.5. Sensor noise

Surveillance noise can be modelled in CAVEAT. An altimeter error model was applied post simulation– see appendix (section 9.5). The parameters used are the same as those defined for SESAR validation of ACAS Xu, but without limiting the maximum altitude bias [13].

### 2.1.6. Input format – Flight Track Data (FTD)

Initial encounter pairs from radar data and models are input into CAVEAT in FTD format described in the appendix (section 9.6.1).

### 2.1.7. Output format – modified trajectories in Comma Separated Values (CSV) File

The purpose of this file is to provide the modified trajectories and ACAS events of all aircraft in an encounter scenario, for a subset of its realisations. See appendix (section 9.6.2) for details.

## 2.2. Close encounters

### 2.2.1. Radar encounters

Over twelve million hours of radar data were collected from six air navigation service providers covering nine countries:

- ANS Czech Republic;
- DSNA (France);
- Maastricht Upper Area Control Centre (MUAC) (Belgium, Germany, Luxembourg, Netherlands);
- NATS (UK);
- PANSO (Poland);
- Skyguide (Switzerland);

The data was either collected in, or converted to, ASTERIX category 62 format (All-purpose structured EUROCONTROL surveillance information exchange). Non-disclosure agreements protect the original data. The radar data was processed with a coarse filter to produce an initial list of two-aircraft encounters that might trigger an STCA alert. Further filtering was used selecting encounters with the potential of triggering TAs (TA+ filter); this subset was used in operational acceptance simulations with radar data. A narrower RA+ filter was applied for producing the encounters from *CREME safety* and ATM models described below.

### 2.2.2. Model encounters: CREME

Encounter modelling is an established technique for generating a large set of representative test encounters for validating ACAS. CREME was built by extracting key geometrical features such as horizontal and vertical miss distance, aircraft states and state changes from the above radar encounters and storing them as counts in tables of discrete parameter bins. Monte-Carlo sampling was then applied to the bins to generate millions of representative encounters. CREME is based on the US Lincoln Laboratory Correlated Encounter Model (LLCEM) [8][9] with adaptations for Europe. The main differences are:

- For encounters fed into the model, the effect of RAs was removed for encounters where an RA downlink message was recorded. This allowed the model to construct trajectories without built-in responses to TCAS RAs.
- Adjustments to model network order, bin sizes and nodes (addition of aircraft class, controlled status, proximity, vertical separation from ATC level).
- An aircraft model instead of airspace model with aircraft performance classes including RPAS capable of lateral manoeuvres such as loitering patterns.
- A simple wind model with wind speed and direction changing with altitude is included in the CAFE tools but the functionality has not yet been exercised in CREME at time of publication.

The CAFE encounter modelling tools were developed by QinetiQ (UK), Egis Avia (France) and Polytechnic University of Catalonia (Spain) under contract in the period 2016-21. For some aspects of model testing the ACAS simulator (CAVEAT) was developed under contract by NLR (Netherlands) and Everis (Spain) in the period 2018-21.

EUROCONTROL staff used the above data and tools to produce two CREME variants where at least one of the aircraft in each encounter is under Air Traffic Control:

- *CREME safety* for safety studies of ACAS II in current traffic. Horizontal miss distances (HMD) are less than Near Mid Air Collision (NMAC) (500ft) and the encounter duration is from about a minute before the closest point of approach (CPA) to about 10s after.



- *CREME ATM* to support operational acceptance of ACAS II in current traffic. HMDs are less than 5NM and the encounter duration is from about a minute before CPA to about 10s after.

Encounters from the two model variants have been analysed by EUROCONTROL using statistical and graphical tools and an ACAS simulator to check:

- Encounters are operationally realistic;
- Distributions are reasonably representative of real encounters;
- Safety metrics are similar to a previous European encounter model (AVAL 2008);

CREME sample encounter sets have been analysed by the following organisations using independent ACAS simulators:

- Egis Avia, Toulouse, France
- Lincoln Laboratory, Massachusetts, USA

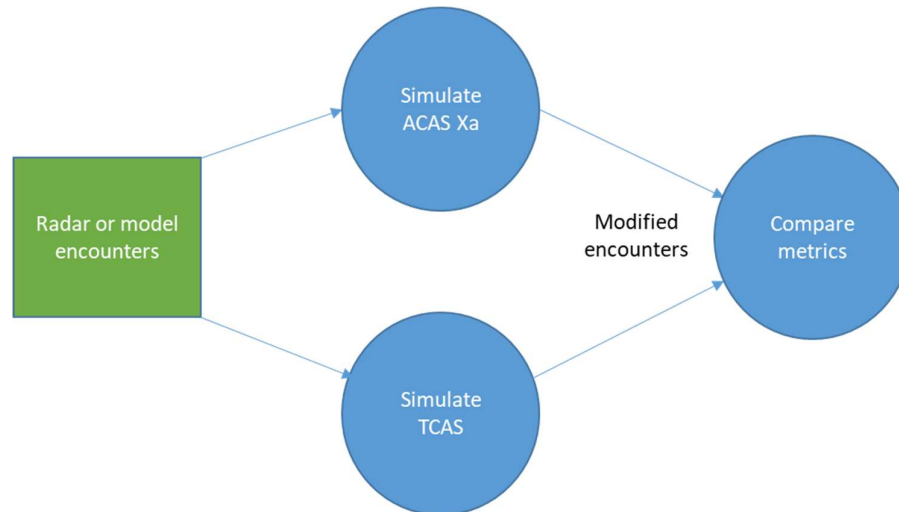
Feedback from these organisations has been used to continuously improve the quality of the model. No blocking issues have been raised on the quality of the encounters used in this validation.

## 3. Method

### 3.1. Process overview

#### 3.1.1. Safety

The *CREME* safety model generated millions of representative close encounters which were then simulated with the ACAS simulator CAVEAT configured to emulate ACAS Xa CP1. The same encounter set was also simulated with CAVEAT configured to emulate TCAS II V7.1 to act as a baseline for comparison. Safety metrics were then calculated for both ACAS Xa CP1 and TCAS II V7.1 and comparisons made with SESAR European acceptability criteria thresholds.



**Figure 2 Evaluation process overview**

#### 3.1.2. Operational acceptance

A similar process to the above was applied to radar encounters applying operational acceptance instead of safety metrics. Where statistical significance was not achieved the process was repeated using encounters generated from the *CREME ATM* model.

#### 3.1.3. Number of encounters

The number of encounters used depended on the level of statistical significance achieved. 95% confidence was targeted.

## 3.2. Encounter sets

The close encounters used for assessing collision avoidance performance are of short duration. Typically they last from less than one minute before the Time of Closest Approach (TCA) to 10 seconds after TCA. Second by second horizontal positions and altitudes of all aircraft are required by the ACAS logic. For synthetic encounters (i.e. generated and not directly observed) data is produced every second during the encounter building process. For encounters based on radar data with more than one second between plots interpolation to second by second data is required. A cubic spline was used for this interpolation using a smoothing factor based on monitoring in Maastricht Upper Area Control Centre.

#### 3.2.1. Operational acceptance

##### 3.2.1.1. Real encounters

Radar data was processed to produce a set of two-aircraft close encounters. The criteria for capturing encounters were:

- Adequate data quality;
- At least one aircraft is civil controlled;
- The encounter might cause a safety net alert.

Using these criteria, a total of 1,593,110 encounters were observed. The encounters were filtered into smaller subsets with a TA+ filter and with an RA+ filter.

### 3.2.1.2. Model encounters: CREME ATM

Where 95% statistical confidence could not be reached with radar encounters for some operational acceptance performance metrics, then synthetic encounters were generated. Radar encounters were filtered with HMD less than 5 NM and a TA+ filter to build *CREME ATM* (Table 2). Batches of encounters were generated with an RA+ filter for Equipped-Equipped and Equipped-Unequipped using the same weightings as those of radar encounters.

## 3.2.2. Safety

### 3.2.2.1. Model encounters: CREME safety

When assessing safety performance, synthetic, generated encounters must be used. There are too few occurrences of encounters having appreciable collision risk to evaluate ACAS using simulations of reconstructed radar data. The generated encounters are created by obtaining the statistical profile of encounters that were close enough horizontally that it can be considered pure chance that their Horizontal Miss Distance (HMD) was not zero. The statistical profile is then used to synthesise encounters with the same characteristics, but with the HMD set to be less than 0.082 NM (i.e. 500ft), which is the HMD threshold for NMACs. Since TCAS II and ACAS Xa only generate vertical Resolution Advisories (RAs), CPA is rarely changed significantly by vertical manoeuvres. By setting HMD to values within the NMAC range, all encounters have the possibility to become an NMAC after vertical manoeuvres.

The safety encounter sets include a wide range of Vertical Miss Distances (VMDs) to test not only the ability of the ACAS logic to resolve encounters that were originally NMACs (500ft HMD, 100ft VMD), but also to find the frequency to induce NMACs that were not present in the original (unmodified by ACAS) encounter set.

Batches of encounters were generated for Equipped-Equipped and Equipped-Unequipped, and for four altitude layers (4.2.7).

**Table 2 Filters applied on input to each CREME model variant**

Filter type	Safety model (REV11)	ATM model (REV4)
Horizontal Miss Distance (NM)	<0.5	<5
Time before CPA (s)	60	60
Time after CPA (s)	10	10
RA+ filter	Yes	Yes
Number of encounters contributing to model	22,876	191,114

## 3.3. ACAS simulations

### 3.3.1. Operational acceptance

The CAVEAT simulator was configured for the permutation of parameters specified by the SESAR ACAS Xa acceptability criteria for operational acceptance metrics. Simulations were run using a radar encounter set. Where metrics were not statistically significant, the *CREME ATM* model was used to generate representative encounters. About 800 thousand encounters were used and took about a week to simulate.

## 3.4. Safety

The CAVEAT simulator was configured for the permutation of parameters specified by the SESAR ACAS Xa acceptance criteria for safety metrics. Simulations were run using *CREME safety* model encounters until statistical significance was achieved or resources were insufficient. About 140 million combinations of safety encounters and different ACAS behaviours were needed which took about 3 months using distributed virtual machines in the cloud.

## 3.5. Statistical Significance

The following approach and assumptions were made:

- Single tailed tests are used because we are looking to see if the systems are significantly different in the direction of any observed difference.

- Matched pair comparisons are used when possible because these give the best discrimination between systems.
- Since the standard deviations of the metrics are not known a priori, the paired *t*-test is most appropriate when the variables are continuous.
- 95% confidence are sought in the results. Values better than this are displayed numerically rounded down to the nearest 1%. Values >99% are written as 99+%. Values worse than 95% are stated as low confidence.
- When the variables are discrete, McNemar's test is used. For low numbers of differences (<25), confidence values are calculated using the exact binomial formulation because this is correct and gives the most conservative estimate of confidence. For very low numbers of differences ( $\leq 6$ ), confidence will always be less than 95% - no test is needed.
- The 95% confidence bars are displayed, rather than standard error values. These values are calculated where possible. However, an acceptable alternative is to use the observed confidence and the observed difference in values to calculate error bars as if using a Z-test because that is what most people are likely to think of when they see error bars. In practical terms this means the size of the error bars is: (number of standard errors for 95% confidence i.e. about 1.64)  $\times$  (observed difference) / (number of standard errors for the calculated confidence value).
- Error bars that go below 0 are truncated to 0 because negative values don't make sense for the metrics.

## 3.6. Previous encounter model

### 3.6.1. AVAL

The AVAL model [5] was based on radar data collected before the end of 2006. It creates encounters with zero HMD, limited correlations between aircraft parameters at TCA and allows a single vertical acceleration and a single turn during the encounter. (CRÈME is built on an order of magnitude more radar data than AVAL).

### 3.6.2. SA01

Following the Überlingen accident, TCAS II V7.0 was found to have very poor behaviour in vertical chase encounters when one aircraft did not respond to RAs (or had no ACAS on board). This issue, known as SA01, was investigated in depth in both Europe and the USA. To help with this investigation, EUROCONTROL developed the SA01 model [7] based on the AVAL data and model. The model only generates vertical chase encounters with negligible VMD. These are very stressing for any ACAS, including ACAS Xa CP1.

ICAO SARPS and European law both require effective responses to SA01 encounters when one aircraft does not respond to its RAs. The AVAL SA01 model was used by the FAA for testing robustness of ACAS logics in such encounters. This testing is considered adequate from a legal point of view.

In 2021 a new SA01 model was created based on CAFE data and models. VMDs up to 200 ft were included in the model (compared to 100 ft with AVAL SA01) to allow some assessment of induced NMACs in vertical chase encounters. There was not enough time and resources to use the CAFE SA01 model in this assessment but it may be used in future assessments.

## 3.7. Multi-aircraft encounters

Operational monitoring has detected some encounters where one aircraft receives RAs against two intruders, either in short succession or simultaneously. Simultaneous RAs against two intruders are rare and consist of less than 1% of observed RAs either in Europe or the US. Only one case of an RA with 3 simultaneous intruders has ever been observed, and that involved only military aircraft.

Too few European multi-aircraft encounters have been recorded to create a reliable statistical model of their nature.

Although a multi-aircraft model can be derived from the AVAL or *CRÈME safety* models by adding an additional aircraft with similar characteristics close to TCA, there is no knowledge of their representivity. In such circumstances, it is reasonable to look at the results from simulating stressful and 'typical' models of multi-aircraft encounters performed for the ACAS Xa MOPS acceptance. These results show better performance than TCAS II V7.1 and are acceptable.

No European simulations of multi-aircraft encounters were performed with ACAS Xa CP1

## 4. Metrics

### 4.1. SESAR acceptance criteria

The main metrics are derived from the SESAR acceptance criteria. The criteria were originally intended for ACAS Xa development to help freeze the design iterations and the document explicitly states "**At this stage acceptability criteria for ACAS Xa deployment are not specifically addressed**". Therefore, the criteria should only be used as a guide in this report. Some metrics are not used because they have already been covered by the US validation work. Some additional metrics are suggested.

### 4.2. Definitions

#### 4.2.1. Level of priorities

Table 3 shows the original SESAR development priority definitions.

**Table 3 Metric priority definitions**

Priority	Definition
<b>Priority 1</b>	The metrics and associated thresholds to be absolutely satisfied from SESAR perspective, i.e. showstoppers or requirements which ACAS Xa <i>shall</i> meet to be acceptable from a European perspective
<b>Priority 2</b>	The metrics and associated thresholds to be satisfied from SESAR perspective. If a threshold is not satisfied, adequate mitigation must be shown through improvements in similar areas or sufficient improvements in other areas, i.e. requirements which ACAS Xa <i>should</i> meet to be acceptable from a European perspective

#### 4.2.2. Sources of data

The metrics provided in this document are recommended to be computed using appropriate sources of data (depending on the metrics to be calculated, e.g. more safety or operational acceptance oriented). These sources of data have to be both:

- **European encounter modelling**, i.e. safety<sup>2</sup> and/or day-to-day<sup>3</sup> encounter models; and
- **European radar data** (with an appropriate sampling), i.e. either TCAS II monitoring data and/or more generally radar data that have not been filtered by the detection of a TCAS II alert.

#### 4.2.3. Encounter subsets

The metrics in this document are provided by encounter subsets to permit a focus on some specific encounter types or operations:

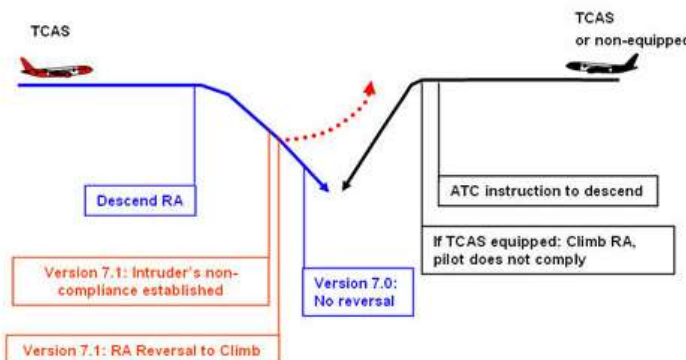
- **Overall airspace subset**: to have a full picture of ACAS Xa behaviour on all types of European encounters;
- **Equipped-equipped subset**: for its specific interest for Europe and for TCAS II / ACAS Xa interoperability studies;
- **Überlingen-like subset**: the reason for mandating TCAS II v7.1 in Europe; and
- **1,000ft level-off subset**: the main cause of operationally undesired RAs in Europe.

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<sup>2</sup> which captures the properties of real risk bearing encounters

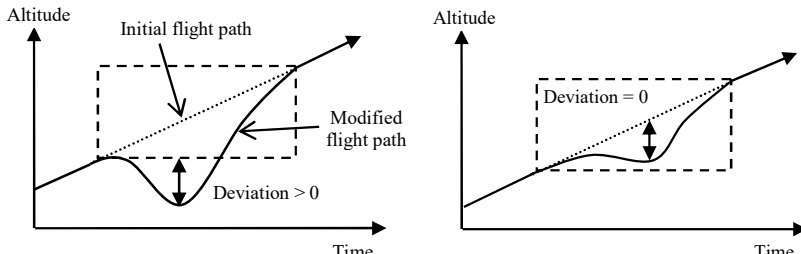
<sup>3</sup> which captures the properties of real encounters that occur in current ATM operations

**Table 4 Encounter subset definitions**

Subset	Definition
<b>Overall airspace</b>	Operationally realistic environment including all types of equipped-equipped and equipped-unequipped encounters as observed in the European airspace
<b>Equipped-Equipped (EE)</b>	Equipped-Equipped encounters only, i.e. encounters in which both aircraft are equipped with ACAS (according to the current ACAS mandate)
<b>Überlingen-like</b>	<p>Vertical chase geometry encounters with one pilot not following the RAs. These encounters have high probabilities of producing NMACs (Near Mid-Air Collisions) in the context of Überlingen-like scenarios.</p> <p>Following a series of mid-air encounters in which safety margins have been lost, including accidents in Yaizu (Japan) in 2001 and in Überlingen (Germany) in 2002, TCAS II v7.1 was developed and mandated (forward and retro fit) in European airspace (cf. Implementing Rule 1332, 2011).</p> <p>One of the two safety issues addressed by TCAS II v7.1 is an inappropriate reversal logic operation, referred to as the SA01 issue. This issue corresponds to a failure of ACAS to reverse some RAs on time when a reversal RA is required to avoid an NMAC.</p> <p>This issue typically occurs when two aeroplanes are flying at the same Flight Level and are converging in range. A very late ATC instruction then induces the intruder to manoeuvre, thwarting the initial RA (if ACAS equipped). In this situation, TCAS II v7.0 often fails to reverse whereas TCAS II v7.1, thanks to a feature which monitors RA compliance, reverses in time and thus succeeds in avoiding an NMAC.</p> <p>This issue was shown to exceed the tolerable rate for catastrophic events caused by equipment related hazard in Europe.</p> <p>Refer to the figure below for an illustration of this issue and of the behaviour expected by ACAS to avoid the NMAC:</p> 
<b>1,000ft level-off (LO)</b>	<p>Subset including:</p> <ul style="list-style-type: none"> <li>• <u>Single 1,000ft LO</u>: An aircraft in vertical evolution levelling-off 1,000ft apart from a level aircraft (with no crossing in altitude); and</li> <li>• <u>Double 1,000ft LO</u>: Two aircraft in opposite vertical evolution both levelling-off 1,000ft apart from each other (with no crossing in altitude)</li> </ul>

#### 4.2.4. Metric definitions

**Table 5 Metric definitions**

Metric	Definition
<b>Asymmetrical Crossing RA encounter</b>	An equipped-equipped encounter where the Crossing RAs are not triggered simultaneously (i.e. within 3 seconds) on-board the both aircraft
<b>Crossing LOLO RA</b>	A 'Level Off Level Off' RA requiring a crossing in altitude with the intruder aircraft (i.e. LOLO RA labelled crossing by ACAS logic)
<b>Early Clear of Conflict</b>	A Clear of Conflict triggered at least more than 3s <sup>4</sup> before CPA.
<b>Efficient Reverse RA</b>	<b>An efficient Reverse Climb / Descend RA brings own aircraft at least 100ft above / below the intruder (i.e. permits the avoidance of an NMAC)</b>
<b>Encounter with high vertical deviation</b>	<p>The deviation is computed as shown in the figures below:</p>  <p>A box is modelled between the point where the aircraft deviates from and then resumes to its original flight path. The deviation corresponds to the distance from the box to the furthest point of the modified trajectory. If the modified trajectory doesn't exit the box, the deviation is considered of zero feet.</p> <p><i>Note: The objective of this metric is to identify only deviations that have an impact on ATC. An aircraft that is levelling-off does not deviate from its original flight path in the ATC general sense.</i></p> <p>An encounter with high vertical deviation is an encounter where the vertical deviation exceeds:  300ft, or  600ft  (Source: ICAO Annex 10 Vol. 4 chap. 4.4.4.3 for the threshold values)[16]</p>
<b>RA alert rate</b>	<p>The number of RAs triggered by the logic.</p> <p>This metric can be computed from an:</p> <p><u>Aircraft perspective</u>: i.e. the number of ACAS equipped aircraft receiving any sequence of RAs (i.e. one or more RAs). If an aircraft receives two RAs, it is still counted as only one RA sequence; and/or</p> <p><u>Encounter perspective</u>: i.e. the number of encounters in which at least one of the two aircraft received an RA. If RAs are generated on-board both aircraft, it is still counted as only one RA encounter.</p>
<b>RA encounter with large horizontal separation</b>	<p>An RA encounter in which the horizontal separation at CPA between the two aircraft is:</p> <p>Above 1.2NM in TMA airspace; or  Above 2NM in En-Route airspace.</p> <p>(Source: ICAO Annex 10 Vol. 4 chap. 4.4.4.1 for the threshold values)</p>
<b>RA sequence</b>	The succession of TCAS alerts (RAs and Clear of Conflicts) on board the own aircraft during a conflict against one or more intruders.

<sup>4</sup> The time for a fast pilot to react

Metric	Definition
<b>Reverse Crossing RA</b>	A Reverse RA that requires a crossing in altitude with the intruder aircraft
<b>Risk Ratio</b>	The risk of Near Mid-Air Collisions (NMACs) of an ACAS logic calculated by dividing the NMAC rate with ACAS by the NMAC rate without ACAS. There are two types of NMACs (and thus of Risk Ratio): <u>Induced NMACs</u> : i.e. encounters where there were no NMAC without ACAS and where ACAS induced an NMAC; and <u>Unresolved NMACs</u> : i.e. encounters where there were already an NMAC without ACAS and where ACAS failed to resolve the NMAC.
<b>Split RA sequence</b>	An RA sequence with more than one Clear of Conflict against the same intruder
<b>Strengthening RA sequence</b>	An RA sequence with at least two successive RAs and where the second triggered RA strengthens the sense of the initial RA. For example, a LOLO DDES ('Don't Descend') RA followed by a Climb RA or a Climb RA followed by an Increase Climb RA.
<b>Unnecessary Reverse RA</b>	A Reverse RA for which the same level of safety (i.e. at least achieve ALIM) would have been accomplished if the Reverse RA was not triggered.
<b>Very close encounter</b>	An encounter where the distance without ACAS contribution between the two aircraft at CPA is: Below 400ft (VMD) and 0.5NM (HMD) in TMA airspace; or Below 600ft (VMD) and 1NM (HMD) in En-Route airspace.
<b>Very complex RA sequence</b>	An RA sequence including at least 3 RAs (excluding any last weakening RA before any Clear of Conflict)

#### 4.2.5. Transversal areas

This section provides the list of transversal areas that have to be considered throughout this document (i.e. for Priority 1 and 2 metrics).

#### 4.2.6. ACAS Xa / TCAS II interoperability

The performance in mixed ACAS Xa / TCAS II operations being at least as important as the performance in full ACAS Xa / ACAS Xa operations, all metrics shall not be degraded in mixed environment. The minimum list of metrics that shall not be degraded in mixed environment are tagged with <sup>(INTEROP)</sup> throughout the document.

The tagged metrics shall be tested on **equipped-equipped encounters with always a TCAS II-equipped aircraft encountering an ACAS Xa-equipped aircraft**. Indeed, this scenario shall enable to identify any benefits or drawbacks whatever the hypothesis of ACAS Xa deployment in European airspace.

*Note: The 'no degradation' value corresponds to the lowest acceptable value from SESAR's perspective. SESAR wishes to achieve greater benefits with ACAS Xa in mixed environment (e.g. at least half of the benefits obtained in Full environment).*

#### 4.2.7. Acceptability by altitude bands

Degrading safety at some altitude bands is not desirable (even though benefits are obtained at other altitude bands). The minimum list of metrics that should not be degraded at any altitude bands are tagged with <sup>(ALT)</sup> throughout the document.

It is recommended to test the tagged metrics on the following altitude bands:

- Below FL50 (very low altitude),
- Between FL50 and FL135 (TMA),
- Between FL135 and FL285 (Intermediate altitudes); and
- Above FL285 (En-Route).

**If there is a substantial overall benefit, a marginal degradation may be tolerated in some altitude bands.**



### 4.3. Priority 1

This section provides the list of metrics and associated thresholds to be absolutely satisfied from the SESAR perspective (i.e. showstoppers or requirements which ACAS Xa *shall* meet to be acceptable from a European perspective).

The metrics are presented in two separate sub-sections depending on the acceptance objective of each metric (i.e. safety or operational acceptance oriented).

There is a difference in this document between what SESAR '*requires*' (i.e. priority 1 metric) and what SESAR '*wishes to achieve*':

- **SESAR '*requires*' at least minor safety and operational improvements** (e.g. at least 5% reduction in Risk Ratio and RA alert rate); yet,
- **SESAR '*wishes to achieve*' substantial safety and operational improvements** (e.g. at least 25% reduction in Risk Ratio & RA alert rate<sup>5</sup>).

The metrics are provided for two scenarios of pilot response to RAs:

'Nominal cases', i.e. when **pilots follow the RAs**; and

'Non-nominal cases', i.e. when **one pilot does not follow the RAs** (in Überlingen-like encounters but also in all types of Equipped-Equipped encounters).

#### 4.3.1. Safety perspective

**Table 6 Priority 1 safety metrics**

ID	Metric	Rationale	Qualitative Threshold	Guidance Value
<b>Pilots follow the RAs</b>				
<b>Overall airspace</b>				
<b>P1s1</b>	<b>Risk Ratio</b> <sup>(ALT)</sup>	To be safer (from a statistical point of view)	At least a minor improvement	Minor = at least -5% <sup>6</sup>
<b>P1s2</b>	<b>Induced Risk Ratio</b>	Inducing more collisions is not acceptable	At least no increase	Improvement or no significant difference
<b>P1s3</b>	<b>Unresolved Risk Ratio</b>	To be at least as efficient as TCAS II in resolving NMACs	At least no increase	Improvement or no significant difference
<b>P1s4</b>	<b>Very close encounters</b>	To avoid very close encounters without Corrective RAs where pilots would want to have a Corrective RA	Corrective RAs triggered in nearly all very close encounters	Nearly all = at least 95% <i>(same order of magnitude as TCAS II)</i>
<b>EE subset</b>				
<b>P1s5</b>	<b>Risk Ratio in EE encounters</b> <sup>(INTEROP) (ALT)</sup>	To be safer (from a statistical point of view)	At least a minor improvement	Minor = at least -5%

<sup>5</sup> SESAR OT solution permits to obtain up to 40% reduction in RA alert rate

<sup>6</sup> 1. The official SESAR target expressed in terms of reduction of Mid-Air Collisions is -4%. Therefore, the reduction of the number of Near MACs (the value used in the Risk Ratio) shall be of at least -4%

ID	Metric	Rationale	Qualitative Threshold	Guidance Value
	<b>One pilot does not follow the RAs<sup>7</sup></b>			
<b>P1s6</b>	<b>Risk Ratio in Überlingen-like encounters</b> (INTEROP) (ALT)	To be safer (from a statistical point of view)	At least a minor improvement	Minor = at least -5%
<b>P1s7</b>	<b>Risk Ratio in EE encounters when one pilot does not follow the RAs</b> (INTEROP) (ALT)	To be safer (from a statistical point of view)	At least a minor improvement	Minor = at least -5%

### 4.3.2. Operational acceptance perspective

**Table 7 Priority 1 operational acceptance metrics**

ID	Metric	Rationale	Qualitative Threshold	Guidance Value
	<b>Pilots follow the RAs</b>			
	<b>Overall airspace</b>			
<b>P1o1</b>	<b>RA alert rate (aircraft &amp; encounter perspective)</b>	Statistically assured improvement for operational acceptance (pilot & ANSP perspective)	At least a minor improvement	Minor = at least -5%
	<b>Single 1,000ft LO subset</b>			
<b>P1o2</b>	<b>RA alert rate in single 1,000ft LO encounters (aircraft &amp; encounter perspective)</b> (INTEROP)	To be significantly fewer (from a statistical point of view) to improve compatibility with ATC and avoid disruption to pilots	At least a minor improvement	Minor = at least -5%
<b>P1o3</b>	<b>Climb / Descend RA alert rate on-board the level aircraft in single 1,000ft LO encounters (aircraft perspective)</b> (INTEROP)	To favour RAs on-board climbing / descending aircraft rather than on the level aircraft (i.e. to not reintroduce the Dallas bump-up issue)	Not more than a minor increase	Minor increase = maximum +5%* (*threshold to be discussed with a wider operational community)

Note: The interoperability study shall focus only on the Equipped-Equipped encounters of the 1,000ft level-off subset.

<sup>7</sup> The first metric focuses on Überlingen-like scenarios (i.e. one pilot does not follow the RAs in the vertical encounter chase geometry). The second metric examines the robustness of ACAS Xa in Equipped-Equipped encounters when one of the two equipped aircraft does not follow the RAs whatever the encounter geometry.

## 4.4. Priority 2

This section provides the list of metrics and associated thresholds to be satisfied from SESAR perspective. If a threshold is not satisfied, adequate mitigation must be shown through improvements in similar areas or sufficient improvements in other areas (i.e. requirements which ACAS Xa *should* meet to be acceptable from a European perspective).

**The purpose of 'Priority 2' metrics is to assess the general balance (rather than compliance with each individual threshold).** For example, a trade-off on the Reversal RA alert rate can be accepted if a limited increase is balanced by an improved Risk Ratio.

In this section, the metrics are presented by encounter subset rather than by acceptance objectives, as some metrics are intended to address both safety and operational acceptance aspects (e.g. Crossing and Reverse RA alert rates).

As for 'Priority 1' metrics, the metrics are provided for two scenarios of pilot response to RAs:

'Nominal cases', i.e. when **pilots follow the RAs**; and

'Non-nominal cases', i.e. when **one pilot does not follow the RAs**.

### 4.4.1. Overall airspace

**Table 8 Priority 2 overall airspace metrics**

ID	Metric	Rationale	Qualitative Threshold	Guidance Value
<b>Pilots follow the RAs</b>				
P2s1	<b>Risk Ratio in multi-aircraft encounters</b>	To be at least as safe	At least no increase	/
P2o1	<b>RA alert rate in encounters with large horizontal separation (encounter perspective)<sup>8</sup></b>	To keep the same level of compatibility with ATC and avoid disruption to pilots by triggering operationally unnecessary RA alerts	At least no increase (in number)	/
P2o2	<b>Rate of encounters with high vertical deviations</b>	To keep the same level of compatibility with ATC and reduce the likelihood of induced conflicts with a third aircraft by triggering RAs requiring unnecessarily high vertical deviations	At least no increase (in number)	/
P2o3	<b>Reverse RA alert rate (aircraft perspective)</b>	To favour the resolution of encounters which does not involve reversing the initial RA sense (e.g. robustness to uncertainty of response to these secondary RAs)	At least no increase (in number)	/
P2o4	<b>Crossing RA alert rate (aircraft perspective)</b>	To favour the resolution of encounters which does not involve a crossing in altitude (e.g. robustness to uncertainty of vertical tracker)	At least no increase overall & at least no increase in Crossing LOLO RAs <sup>9</sup> (in number)	/

<sup>8</sup> Operationally undesired RA encounters are mainly of two types: 1,000ft level-off RA encounters and large horizontal separation RA encounters.

<sup>9</sup> Refer to Appendix 9.7 for an explanation and an illustration of a crossing LOLO RA

<i>ID</i>	<i>Metric</i>	<i>Rationale</i>	<i>Qualitative Threshold</i>	<i>Guidance Value</i>
P2o5	<b>Strengthening RA sequence alert rate (aircraft perspective)</b>	To favour the direct triggering of the appropriate RA	At least no increase (in number)	/
P2o6	<b>Very complex RA sequence alert rate (aircraft perspective)</b>	Confidence in the system	At least no increase (in number)	/
P2o7	<b>Time between TA and initial RA</b>	For the flight crew to have appropriate time to prepare to follow the RA	Fewer RAs are triggered less than 6s after the TA	/
P2o8	<b>Time between initial and secondary RA</b>	Confidence in the system (i.e. wait for pilot to respond to the initial RA before triggering a secondary RA)	Fewer secondary RAs are triggered less than 3s after the initial RA	/
P2o9	<b>Early Clear of Conflict alert rate (aircraft perspective)</b>	Confidence in the system (i.e. wait for aircraft to be in horizontal divergence to trigger a Clear of Conflict)	At least no increase (in number)	/
P2o10	<b>Split RA sequence alert rate</b>	Confidence in the system	At least no increase (in number)	/

#### 4.4.2. Equipped-Equipped subset

**Table 9 Priority 2 equipped-equipped subset**

<i>ID</i>	<i>Metric</i>	<i>Rationale</i>	<i>Qualitative Threshold</i>	<i>Guidance Value</i>
<b>Pilots follow the RAs</b>				
P2o11	<b>Crossing RA alert rate in EE encounters (encounter perspective)</b> (INTEROP)	To favour the resolution of encounters which do not involve a crossing in altitude (e.g. robustness to uncertainty of vertical tracker)	At least no increase overall & at least no increase in asymmetrical Crossing RA <sup>10</sup> alert rate (in number)	/
P2o12	<b>Reverse RA alert rate in EE encounters (encounter perspective)</b>	To favour the resolution of encounters which does not involve reversing the initial RA sense (e.g. robustness to uncertainty of response to these secondary RAs)	At least no increase overall & at least no increase in unnecessary Reverse RA <sup>11</sup> alert rate (in number)	/

<sup>10</sup> Refer to Appendix 9.8 for an illustration of asymmetrical crossing RA

<sup>11</sup> Refer to Appendix 9.9 for an illustration of unnecessary reverse RA

<i><b>ID</b></i>	<i><b>Metric</b></i>	<i><b>Rationale</b></i>	<i><b>Qualitative Threshold</b></i>	<i><b>Guidance Value</b></i>
	(INTEROP)			
<b>P2o13</b>	<b>Reverse Crossing RA alert rate in EE encounters (encounter perspective)</b> (INTEROP)	Robustness to uncertainty of response to Reverse Crossing RAs	Some increase tolerated in Reverse Crossing RA alert rate but Reverse Crossing RAs should be avoided when aircraft are largely apart at the time of the Reverse Crossing RA	Largely = More than 300ft <i>(only 150ft allowed with TCAS II)</i>

#### 4.4.3. Überlingen-like subset

**Table 10 Priority 2 Überlingen-like subset**

ID	Metric	Rationale	Qualitative Threshold	Guidance Value
	<b>One pilot does not follow the RAs</b>			
<b>P2o14</b>	<b>Efficient Reverse RA alert rate in Überlingen-like encounters (encounter perspective)</b> <small>(INTEROP)</small>	In SA01 type encounters a Reverse RA must resolve the NMAC	Reverse RAs are at least as efficient	<i>(98% efficiency of Reverse RAs with TCAS II)</i>
<b>P2o15</b>	<b>Rate of RA sequences with more than one Reverse RA on-board the same aircraft in Überlingen-like encounters (aircraft perspective)</b> <small>(INTEROP)</small>	Confidence in the system	At least no increase	/

#### 4.4.4. 1,000 feet level-off subset

**Table 11 Priority 2 1,000 ft level-off subset**

ID	Metric	Rationale	Qualitative Threshold	Guidance Value
	<b>Pilots follow the RAs</b>			
	<b>Single 1,000ft LO subset</b>			
<b>P2o16</b>	Climb / Descend RA alert rate on-board descending / climbing aircraft in single 1,000ft LO encounters (aircraft perspective)	To favour LOLO RAs rather than Climb / Descend RAs (i.e. to limit deviations from the current aircraft clearances)	At least no increase (in number)	/
<b>P2o17</b>	RA alert rate on-board aircraft climbing / descending below 1,500fpm in single 1,000ft LO encounters (aircraft perspective)	To avoid triggering RAs when ICAO recommendation on "high vertical rate (hvr) encounters" is followed	At least no increase (in number)	/
	<b>Double 1,000ft LO subset</b>			
<b>P2o18</b>	RA alert rate in double 1,000ft LO encounters (encounter perspective) <small>(INTEROP)</small>	To improve compatibility with ATC and avoid disruption to pilots by triggering operationally unnecessary RAs	At least no increase	/
<b>P2o19</b>	Climb / Descend RA alert rate in double 1,000ft LO encounters (aircraft & encounter perspective) <small>(INTEROP)</small>	To favour LOLO RAs rather than Climb Descend RAs (i.e. to limit deviations from the current aircraft clearances)	At least no increase (in number)	/

## 5. Results

### 5.1. Number of encounters

The following tables show the number of encounters used for each type of simulation:

**Table 12 Number of safety model encounters (CREME safety) used in simulations**

Altitude layer	Equipage	Number of encounters
1	EE	600,000
	EU	100,000
2	EE	6,600,000
	EU	300,000
3	EE	600,000
	EU	100,000
4	EE	600,000
	EU	100,000
		Total = 9,000,000

Where:

- EE = Equipped versus Equipped
- EU = Equipped versus Unequipped

**Table 13 Number of operational acceptance encounters used in simulations**

Scenario	Equipage	Number of radar encounters	Number of CREME ATM encounters
All layers	EE	813	81,228
All layers	EU	815	118,772
Double level off	EE	158	2,944
Double level off	EU	12	1,288
Jump geometry <sup>12</sup>	EE	21	8,974
Jump geometry	EU	163	22,698
Single level off	EE	264	7,900
Single level off	EU	19	3,481
		Total EE + EU = 1,628	Total EE + EU = 200,000

### 5.2. Notation in graphs and metrics

Where feasible, graphs incorporate 95% confidence interval bars on the ACAS Xa results. The uncertainty is relative to the baseline system TCAS which therefore does not have error bars.

The following abbreviations are used:

- ACAS Xa CP1 active surveillance: CP1a
- ACAS Xa CP1 passive surveillance: CP1p
- TCAS version 7.1: T7.1
- Unequipped: Uneq

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<sup>12</sup> A jump geometry is a type of level off encounter. One aircraft is level and the other aircraft climbs (or descends) through the altitude of the level aircraft before levelling off typically 1000 ft above (or below) the level aircraft.

The following are highlighted by underlining

- Items out of scope
- Numbers outside acceptance criteria
- Statistical confidence < 95%

Results with statistical confidence < 95 % are displayed in grey italics.

## 5.3. SESAR acceptance criteria priority 1 results

### 5.3.1. Safety perspective

#### 5.3.1.1. Pilots follow the RAs

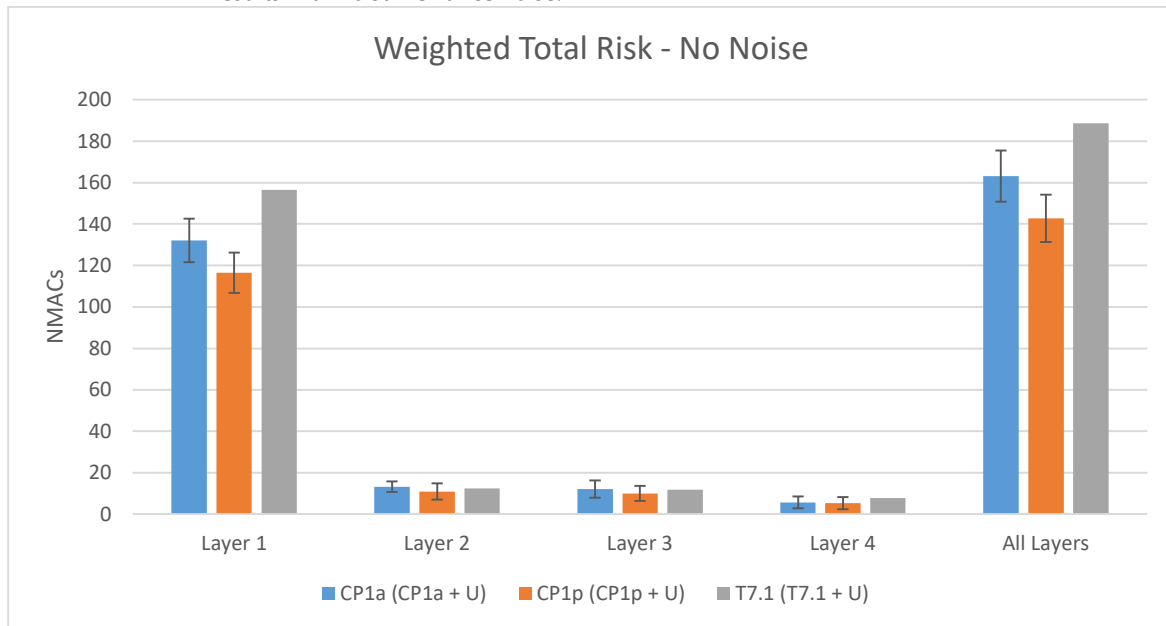
Pilots respond to RAs according to the standard ICAO pilot response model

##### 5.3.1.1.1. Overall airspace (EE + UE)

Note that results do not include mixed equipage values (these are in the EE subset)

##### 5.3.1.1.1.1. P1s1 Risk ratio (Alt)

Results with no surveillance noise:



**Figure 3 Safety model – Weighted Residual Risk (EE+EU) Without Surveillance Noise**

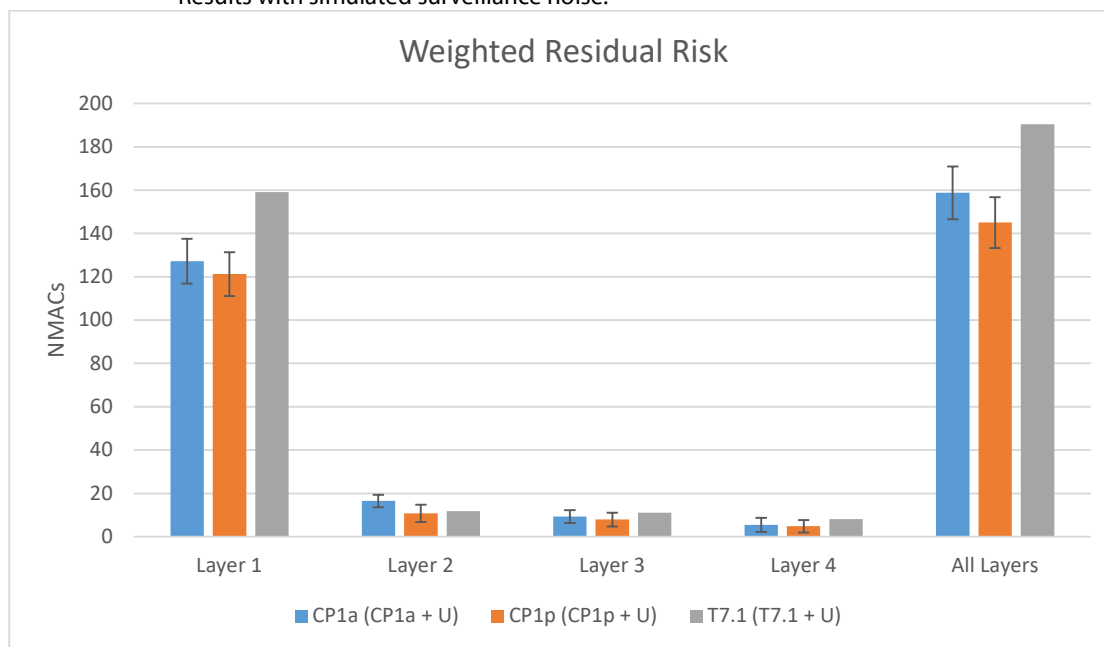
**Simulations without surveillance noise show with confidence >99% that ACAS Xa CP1 logic is safer than TCAS II V7.1 in the lowest altitude layer and the whole airspace.** Results in other layers did not show a significant difference in safety performance between ACAS Xa CP1 and TCAS II V7.1

The original simulated risk in the airspace was 3835 NMACs. In other words, more than 1000 years of close encounters were simulated. **The logic risk ratio of ACAS Xa CP1 in the whole airspace against all intruders is between 3.7% and 4.2% and about 4.9% for TCAS II V7.1.**

ACAS Xa CP1 provides an expected safety improvement of about 16% compared to TCAS II V7.1 if intruders do not have ADS-B out, and about 24% when intruders have ADS-B out.



Results with simulated surveillance noise:



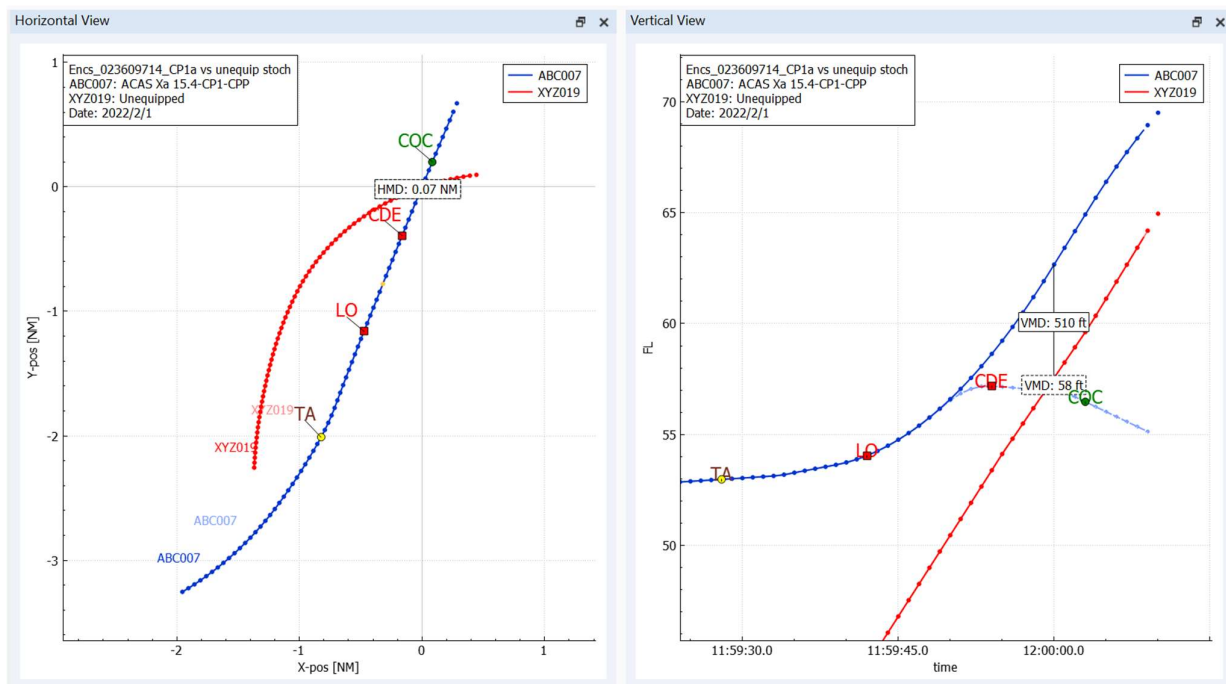
**Figure 4 Safety model – Weighted Residual Risk (EE+EU) With Surveillance Noise**

**Results with surveillance noise show broadly the same trends as those without surveillance noise.<sup>13</sup> However, in layer 2, with intruders that do not have ADS-B out, there is 94% confidence that ACAS Xa CP1 has worse safety performance than TCAS II V7.1 by 39%. It should be borne in mind that in layer 2 (FL50 – FL135) there is likely to be a mix of intruders with and without ADS-B out. Also, the surveillance noise used was the maximum allowed by ACAS MOPS and the actual figure may be lower, with results closer to those without noise.**

Detailed analysis has traced this degradation to increased induced risk in vertical chase encounters where ACAS Xa CP1 issues a crossing level off RA. This occurs for both EE and EU encounters. An example of this behaviour is shown below. In the case of EE encounters, this only occurs when ACAS Xa is the master. In the case of EU encounters, this is mostly observed when intruders have large vertical rates (>5000 fpm).

There were radar data encounters with ACAS Xa CP1 issuing crossing level off RAs that reduced VMD but none induced NMACs.

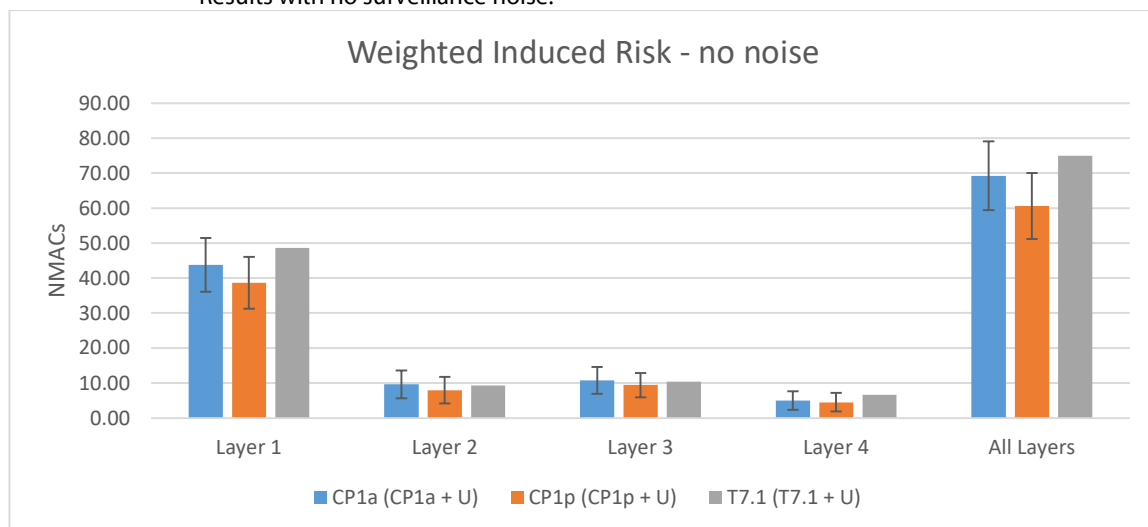
<sup>13</sup> Note that due to resource limitations, only 3.6 million Layer 2 EE encounters were simulated with surveillance noise. It would have been desirable to do more to achieve better statistical significance on the results.



**Figure 5 Safety model – example of a vertical chase encounter where ACAS Xa CP1 induces an NMAC**

### 5.3.1.1.2. P1s2 Induced risk ratio

Results with no surveillance noise:

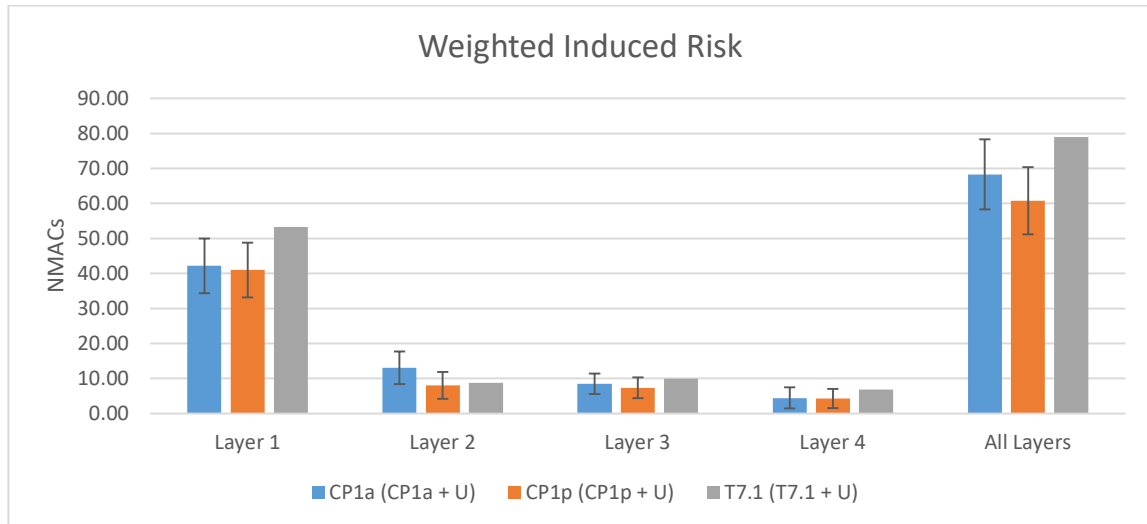


**Figure 6 Safety model – Weighted Induced Risk (EE+EU) Without Surveillance Noise**

There is confidence >95% that ACAS Xa CP1 has less induced risk than TCAS II V7.1 in the lowest altitude layer and the whole airspace against intruders with ADS-B out. Results in other layers and for intruders without ADS-B out did not show a significant difference in induced risk between ACAS Xa CP1 and TCAS II V7.1

ACAS Xa CP1 gives an expected improvement in induced risk of about 19% compared to TCAS II V7.1 if intruders have ADS-B out, and has no statistically significant difference from TCAS II V7.1 if intruders do not have ADS-B out.

#### Induced risk results with surveillance noise



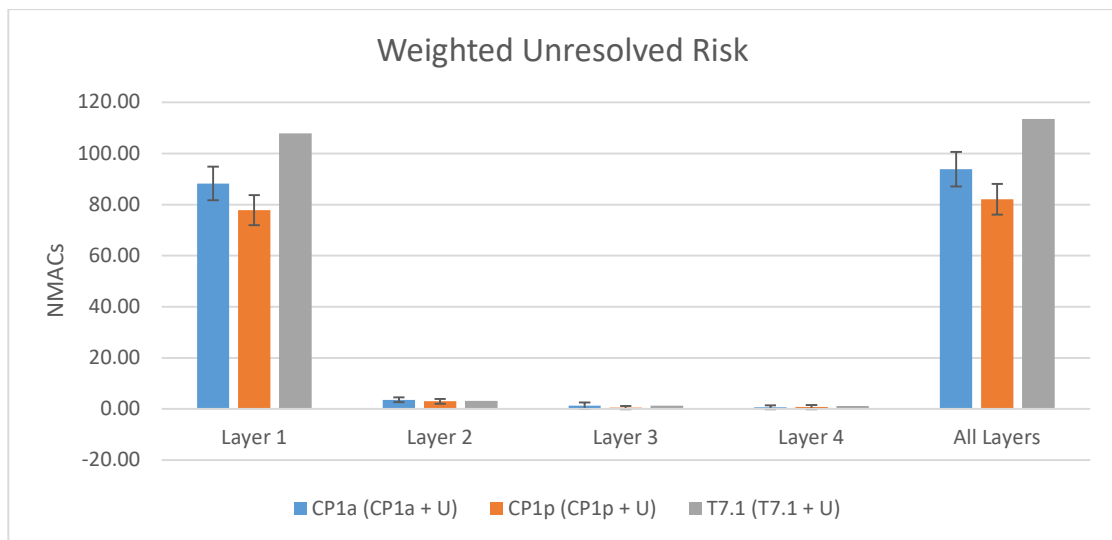
**Figure 7 Safety model – Weighted Induced Risk (EE+EU) With Surveillance Noise**

**Over all layers and equipages (EE + EU) the induced risk with simulated surveillance noise is significantly (>95%) lower for ACAS Xa CP1 than TCAS II V7.1.**

The significant (95%) increase in induced risk for layer 2 with non ADS-B out intruders is not a SESAR metric, but was used to indicate the likely source of increased risk in layer 2 encounters.

#### 5.3.1.1.1.3. P1s3 Unresolved risk ratio

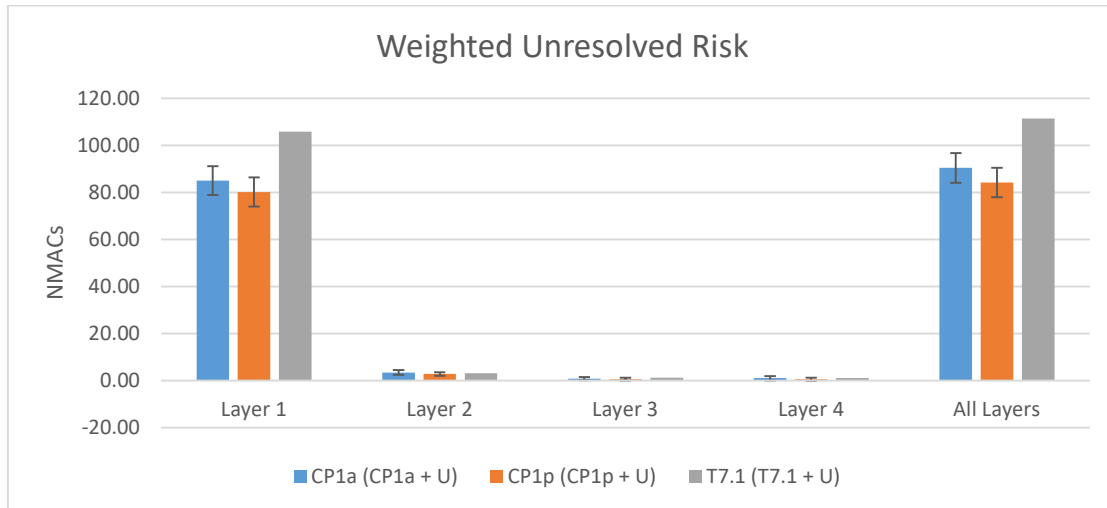
- Results with no surveillance noise:



**Figure 8 Safety model – Weighted Unresolved Risk (EE+EU) Without Surveillance Noise**

Simulation results without surveillance noise show with statistical confidence >99% that ACAS Xa CP1 has better unresolved risk than TCAS II V7.1 in the overall airspace.

#### Results with surveillance noise



**Figure 9 Safety model – Weighted Unresolved Risk (EE+EU) With Surveillance Noise**

**Simulation results with surveillance noise show with confidence >99% that ACAS Xa CP1 has better unresolved risk than TCAS II V7.1 in the overall airspace.**

#### 5.3.1.1.4. P1s4 Very close encounters without alerts

Very Close Encounters are defined as encounters where the aircraft come within

- 0.5NM horizontally and 400 ft vertically in TMA airspace
- 1.0 NM horizontally and 600ft vertically in En-Route airspace

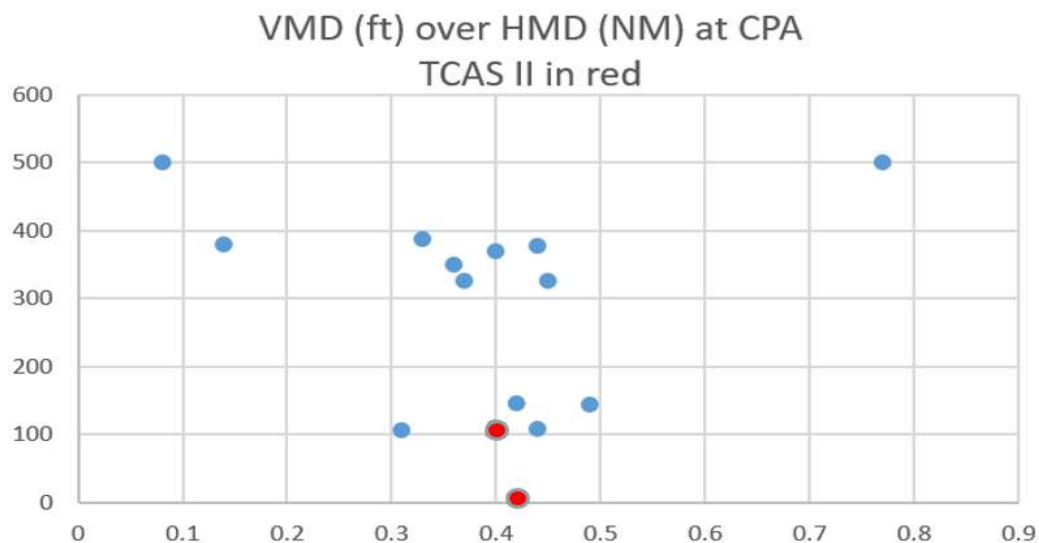
Very Close Encounters that do not result in an RA are potentially a safety concern.

A total of 86 very close encounters were observed in the radar data.

- TCAS II V7.1 had 2 very close encounters that did not issue corrective RAs.
- ACAS Xa CP1 had 13 encounters that did not issue corrective RAs.

To meet the SESAR acceptance criteria, there should be fewer than 4.3 very close encounters without alerts. TCAS II V7.1 meets this metric. Using a Poisson distribution to estimate frequency, more than 10 such alerts indicates with >99% confidence that ACAS Xa CP1 does not meet this criteria.

The distribution of the very close encounters that did not issue RAs is shown below



**Figure 10 Radar Data – Very Close Encounters without alerts**

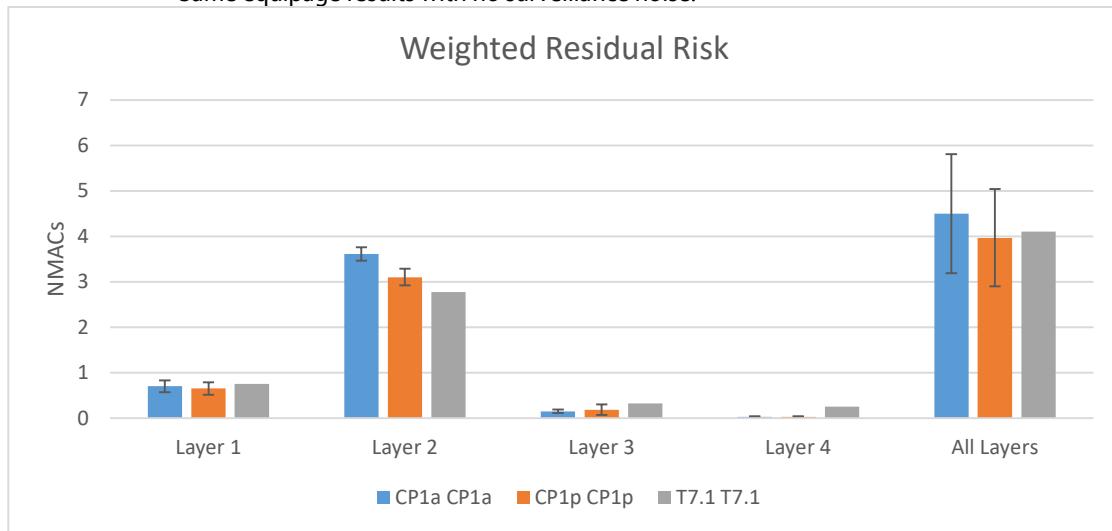
**Although ACAS Xa CP1 has more very close encounters without triggering an RA than TCAS II V7.1, these encounters do not have a substantial negative effect on the collision risk. RTCA SC147 and WG75 operational working groups discussed this SESAR metric and jointly agreed that the lack of alerting for some encounters with ACAS Xa CP1 is acceptable as part of a trade-off for reduced alert rate and collision risk.**

**Flight crew should be made aware that very close encounters can occur without triggering RAs.**

### 5.3.1.1.2. EE subset

#### 5.3.1.1.2.1. P1s5 Risk ratio (INTEROP, Alt)

Same equipage results with no surveillance noise:



**Figure 11 Safety model – Weighted Residual Risk (EE) same equipage Without Surveillance Noise**

**Over all layers, no statistically significant difference was observed between the safety performance of ACAS Xa CP1 and TCAS II V7.1 in same equipage, EE encounters.**

The ACAS logic residual risk is about 4 NMACs out of about 2280 NMACs (more than ~1000 years of encounters) in the original encounters. The logic risk ratio is less than 0.2% for both ACAS Xa CP1 and TCAS II V7.1 in equipped-equipage encounters.

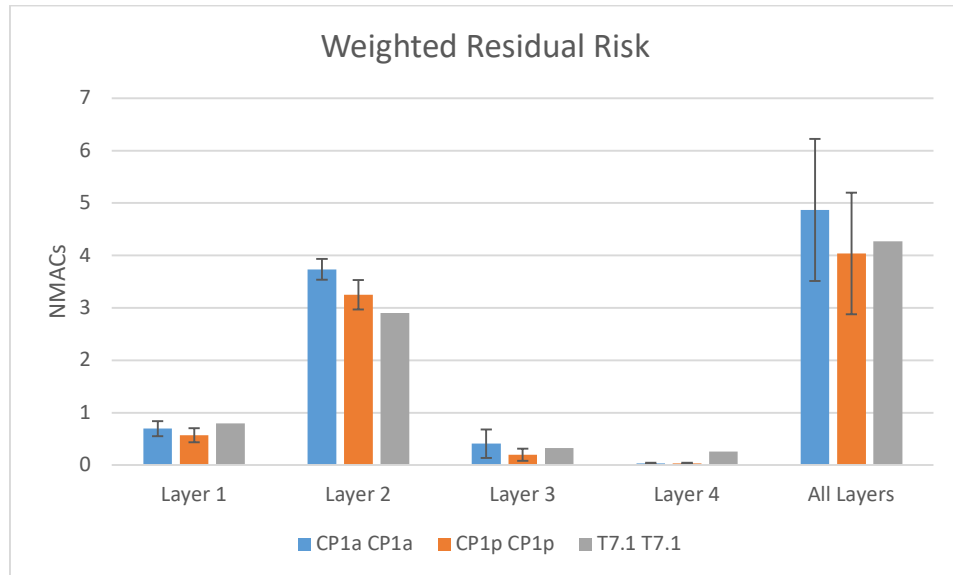
**However, in Layer 2 EE encounters, ACAS Xa CP1 has a statistically significant degradation (confidence >99%) in logic safety performance compared to TCAS II V7.1.**

The weighted figures do not show the extent of simulations performed in layer 2 EE; approximately 50 times as many NMACs were simulated and then scaled to show the layer 2 figures in perspective of the rest of the airspace.

**Despite this statistically significant degradation, it needs to be considered in the context of**

- **The very low level of logic risk compared to other risks in ACAS e.g. pilots not following RAs, and even system unavailability due to electronic failures.**
- **The uncertainties in the encounter modelling process (e.g. the previous European encounter model did not adequately account for Überlingen type encounters)**
- **The evolution of air traffic – current air traffic is very different from that 20 years ago and is likely to change as much, if not more, in the future. The better resilience of ACAS Xa CP1 to stressing encounters than TCAS II V7.1, as demonstrated by the FAA TCAS program office, is important to take into account.**
- The performance change in the presence of surveillance noise (see below).

Same equipage results with surveillance noise:

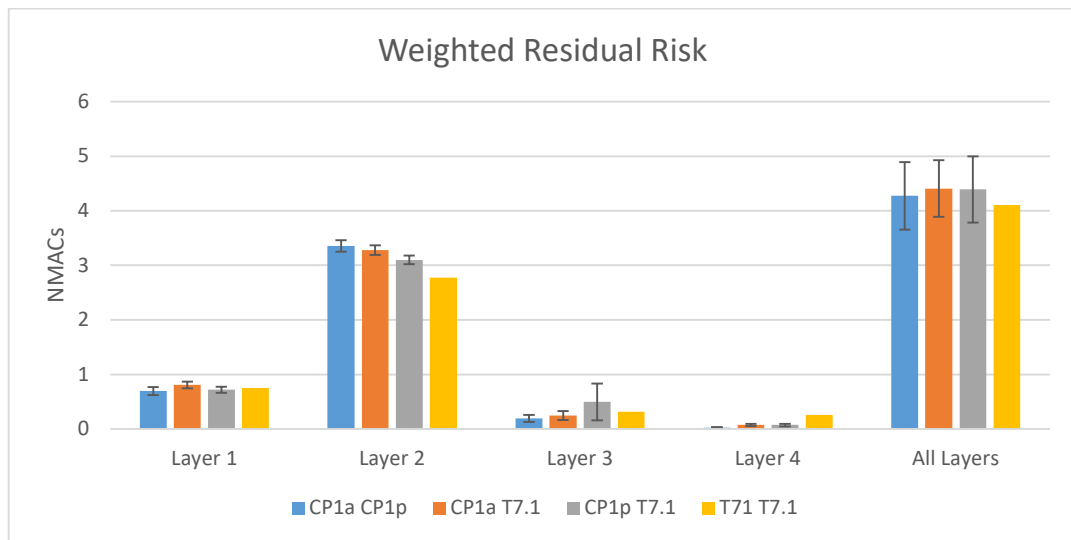


**Figure 12 Safety model – Weighted Residual Risk (EE) same equipage with Surveillance Noise**

With surveillance noise, over all layers, no statistically significant difference was observed between the safety performance of ACAS Xa CP1 and TCAS II V7.1 in same equipage, EE encounters.

The logic risk ratio is less than 0.2%. ACAS Xa CP1 has significantly better logic safety than TCAS II V7.1 against ACAS equipped intruders with ADS-B out in altitude layers 1 and 3, and against all intruders in layer 4. However, in Layer 2 EE encounters, ACAS Xa CP1 has a statistically significant degradation (confidence >99%) in logic safety performance compared to TCAS II V7.1

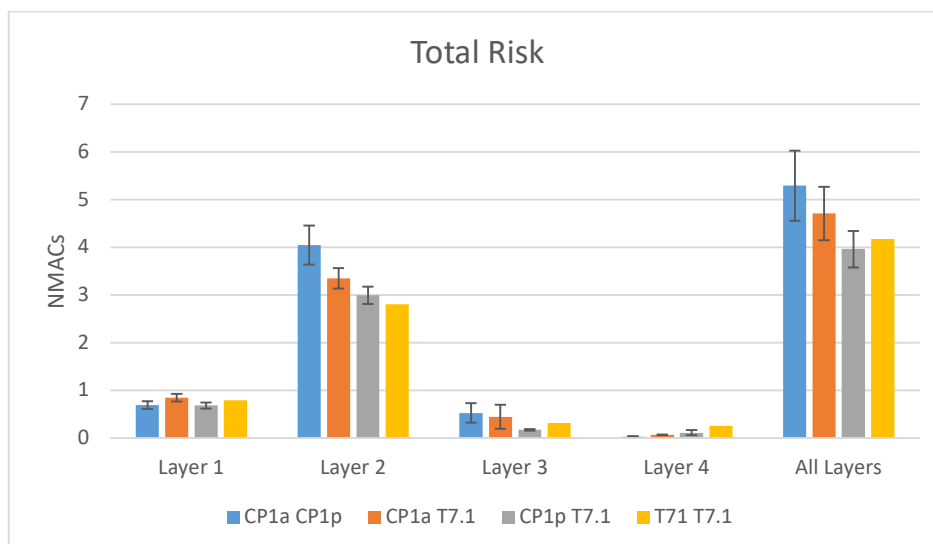
Mixed equipage results without surveillance noise:



**Figure 13 Safety model – Weighted Residual Risk (EE) mixed equipage Without Surveillance Noise**

Over all layers, no statistically significant difference was observed between the safety performance of ACAS Xa CP1 and TCAS II V7.1 in mixed equipage, EE encounters.

The risk ratio is less than 0.2%. The results for mixed equipage and same equipage are similar, ACAS Xa CP1 has significantly better logic safety than TCAS II V7.1 against intruders with ADS-B out in altitude layers 3 and 4. However, in Layer 2 EE encounters, ACAS Xa CP1 has a statistically significant degradation (confidence >99%) in logic safety performance compared to TCAS II V7.1.

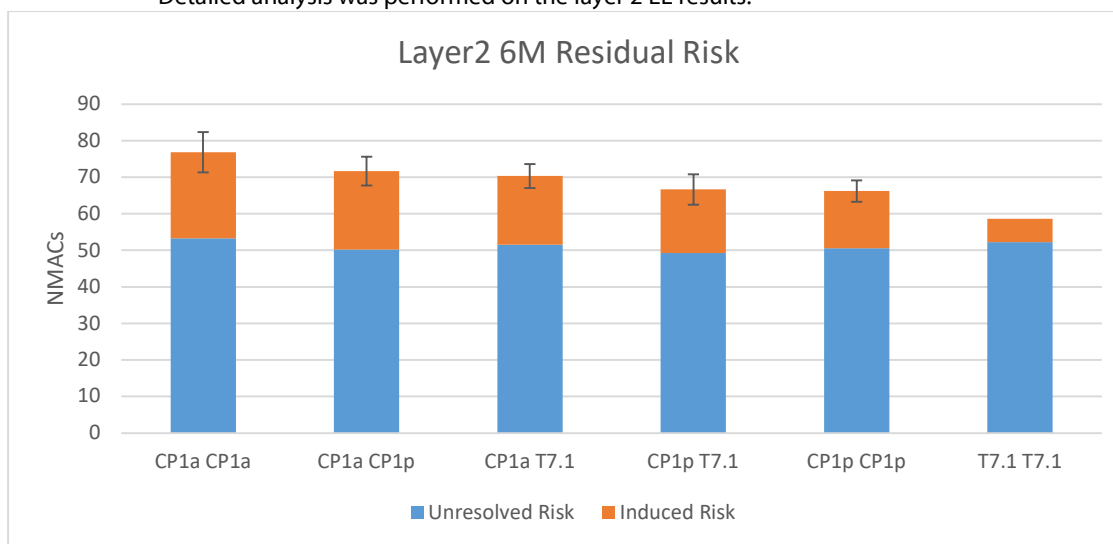


**Figure 14 Safety model – Weighted Residual Risk (EE) mixed equipage with surveillance noise**

**For simulations with surveillance noise, over all layers, no statistically significant difference was observed between the safety performance of ACAS Xa CP1 and TCAS II V7.1 in mixed equipage, EE encounters where intruders for ACAS Xa are ADS-B out equipped. Normally this will be the case. The risk ratio is less than 0.25% for both ACAS Xa CP1 and TCAS II V7.1 in equipped-equipage encounters.**

However, as with same equipage, in Layer 2 EE mixed equipage encounters, ACAS Xa CP1 has a statistically significant degradation (confidence >99%) in logic safety performance compared to TCAS II V7.1. **Degraded safety performance in layer 2 EE encounters can lead to an overall airspace degradation in safety for mixed equipage EE encounters where the intruder is not equipped with ADS-B out.**

Detailed analysis was performed on the layer 2 EE results.



**Figure 15 Safety model: Layer 2 EE unresolved and induced risk components without surveillance noise**

In layer 2 EE encounters, the differences in unresolved risk were very small between different ACAS logics. However, EE encounters involving ACAS Xa CP1 had a statistically significant (>99%) increase in induced risk compared to TCAS-TCAS encounters.

Examination of the encounters with the most induced risk showed several vertical chase encounters where ACAS Xa CP1 issued a crossing level off RA, leading to greatly reduced vertical separation at TCA.

**If ACAS Xa CP1 is considered acceptable for European operations, there should be assessment of whether induced risks in layer 2 EE encounters can be diminished, without compromising other aspects of safety and**

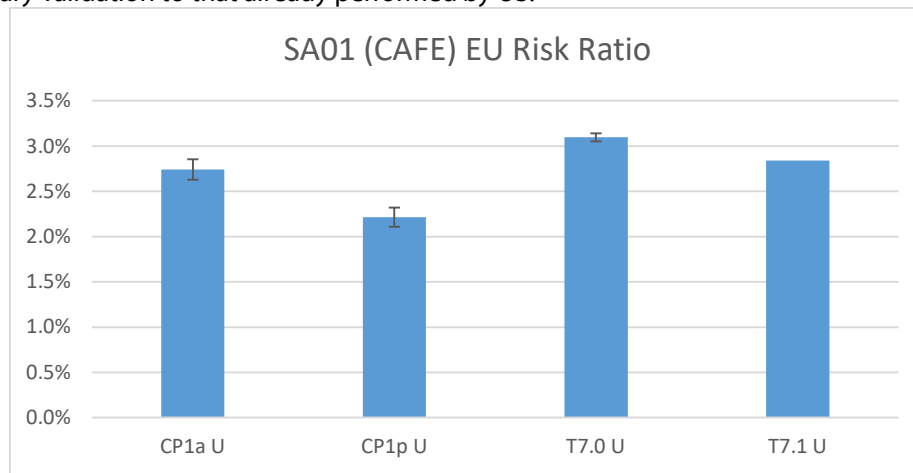


**operational acceptability. In particular, the use of ADS-B out should be encouraged and the possibility of logic improvements should be assessed.**

### 5.3.1.2. One pilot does not follow the RAs

#### 5.3.1.2.1. P1s6 Risk ratio in Überlingen-like encounters (Interop, Alt)

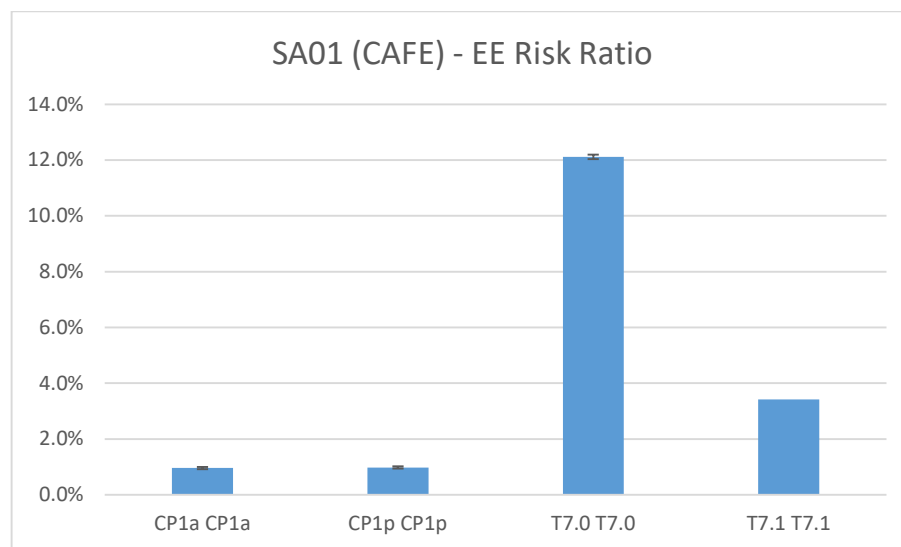
Supplementary validation to that already performed by US.



**Figure 16 SA01b (CAFE) – EU risk ratios**

In SA01 EU encounters the ACAS pilot does follow their RA, but there is a risk of manoeuvres on the unequipped aircraft thwarting the RAs on the equipped aircraft. 49,000 encounters were simulated.

As expected, the model demonstrates that TCAS II V7.1 is statistically significantly (>99%) safer than TCAS II V7.0. Also ACAS Xa CP1 with active surveillance is statistically significantly safer (>92%) than TCAS II.



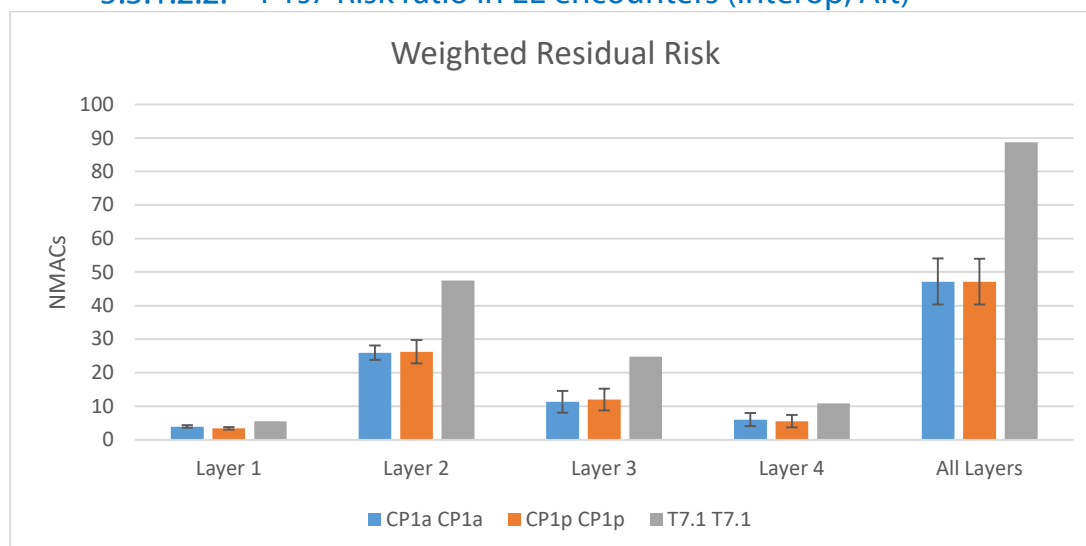
**Figure 17 SA01a (CAFE) – EE same equipage risk ratios**

100,000 encounters were simulated. As expected, the model demonstrates that TCAS II V7.1 is statistically significantly (>99%) safer than TCAS II V7.0.

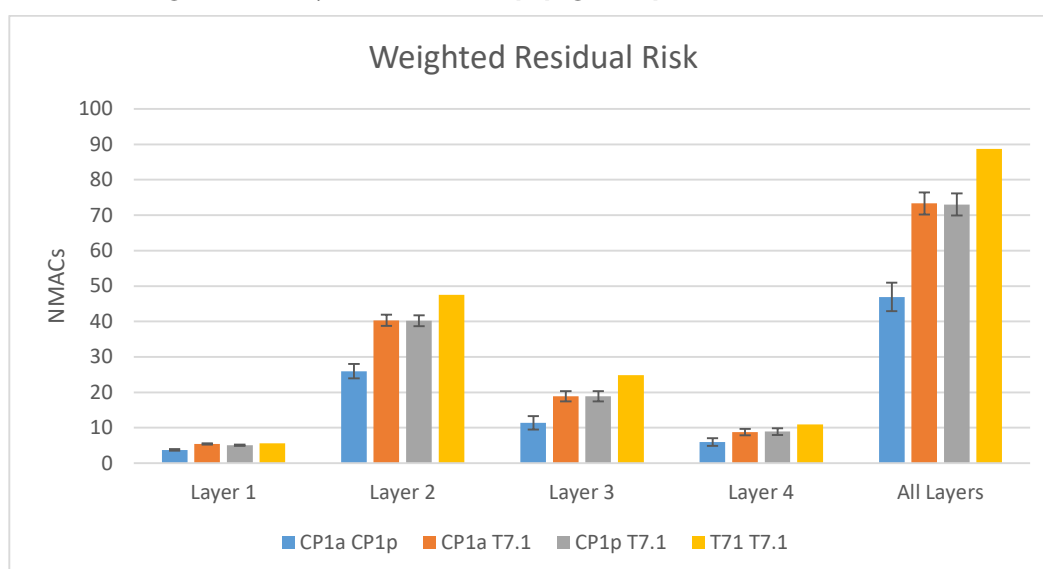
In SA01 (CAFE) same equipage encounters ACAS Xa CP1 with either active or passive surveillance is statistically significantly safer (>99%) than TCAS II V7.1.

**The CAFE SA01 model is consistent with US results showing ACAS Xa CP1 is safer than TCAS II V7.1 in AVAL SA01 encounters by a factor greater than 3.**

### 5.3.1.2.2. P1s7 Risk ratio in EE encounters (Interop, Alt)



**Figure 18 Safety model – Same equipage one pilot does not follow RA**



**Figure 19 Safety model – Mixed equipage one pilot does not follow RA**

**Overall in EE encounters when one pilot does not follow their RA, ACAS Xa CP1 logic risks are statistically significantly (>99%) lower than TCAS II V7.1 by up to 47%.**

Given the proportion of aircraft that do not adequately follow their RAs in European airspace [12] this is a substantial safety benefit.

## 5.3.2. Operational acceptance perspective

### 5.3.2.1. Pilots follow the RAs – overall airspace

#### 5.3.2.1.1. P1o1 RA alert rate (aircraft and encounter perspective)

##### 5.3.2.1.1.1. Radar data

###### Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU: >99%

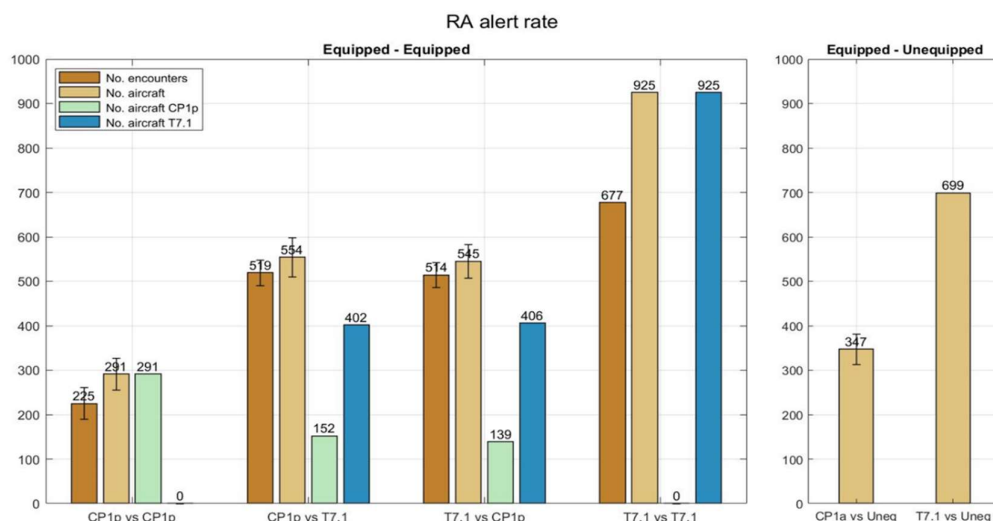


Figure 20 Radar data RA alert count

**Radar data analysis shows there is a 60% reduction in the number of RAs issued from 1624 to 638.**

There is a 58% reduction in the number of encounters with RAs from 1376 to 572. The reduction of alerts with non-ACAS equipped intruders (which probably do not have ADS-B out) is only 50%.

##### 5.3.2.1.1.2. ATM model

###### Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU: >99%

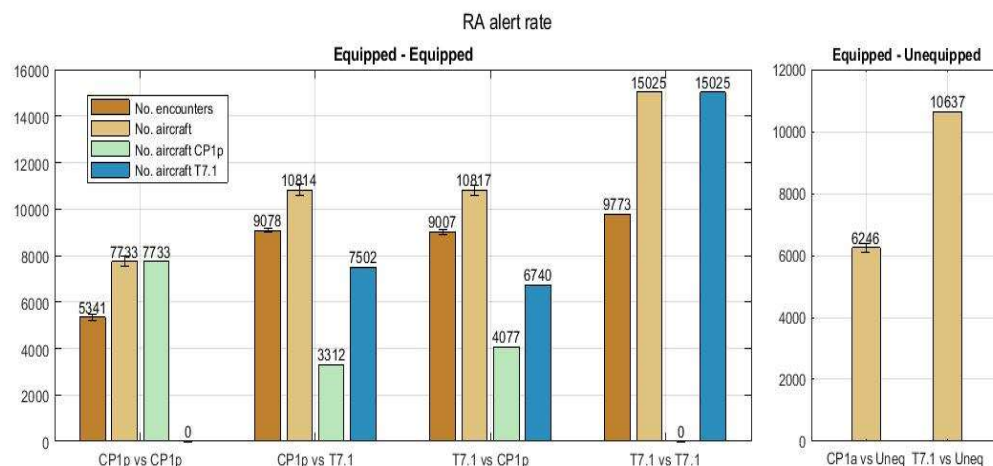


Figure 21 ATM model RA alert count

The ATM model shows a reduction in alerts by 45% and a reduction in encounters with alerts by 43%.

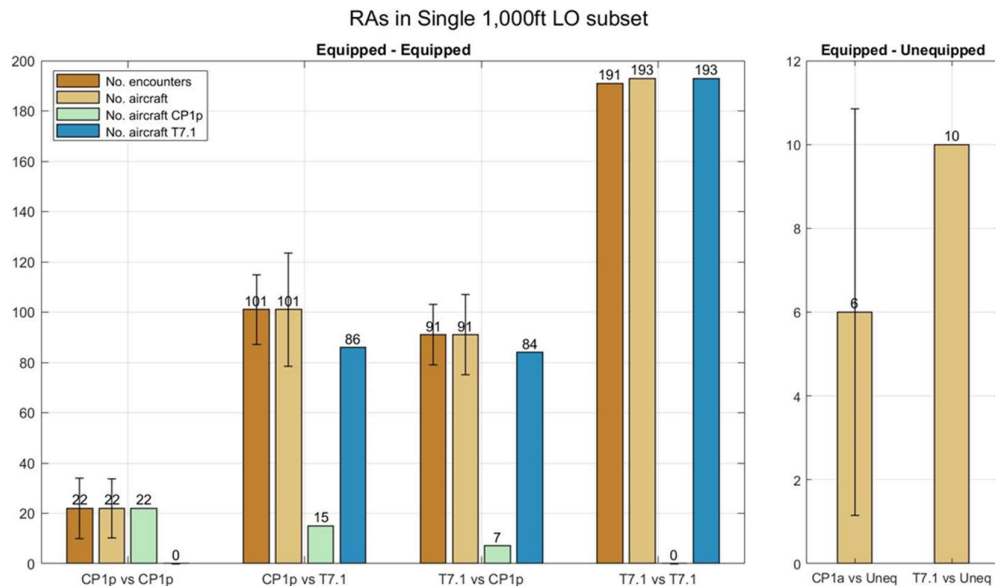
### 5.3.2.2. Pilot follows the RAs - Single 1,000 feet Level-off subset

#### 5.3.2.2.1. P1o2 RA alert rate (Interop)

##### 5.3.2.2.1.1. Radar data

###### Confidence

- EE encounters perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU 91%



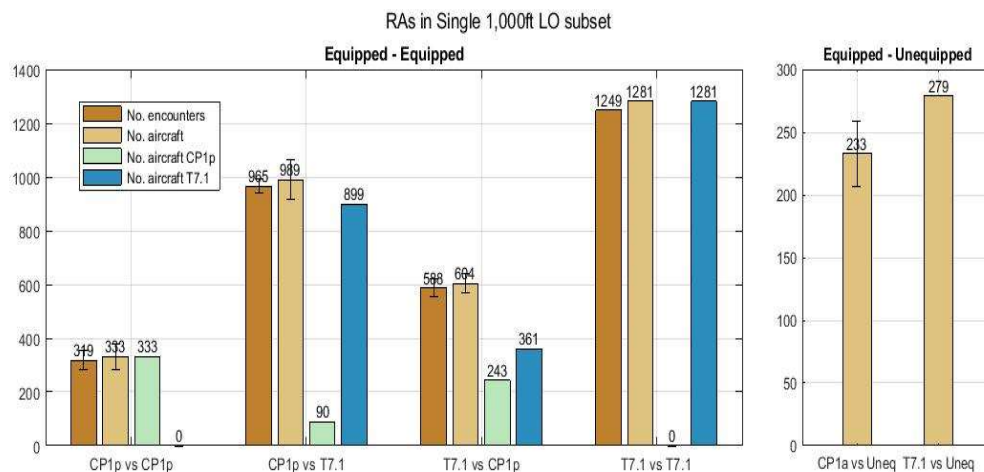
**Figure 22 Radar data RAs in single 1,000 ft level off subset**

**In encounters where a single aircraft is levelling off 1000ft from another aircraft in level flight, radar data simulations show ACAS Xa CP1 reduces the number of RAs by 86%.**

##### 5.3.2.2.1.2. ATM model

###### Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU 99.8%



**Figure 23 ATM model RAs in single 1,000 ft level off subset**

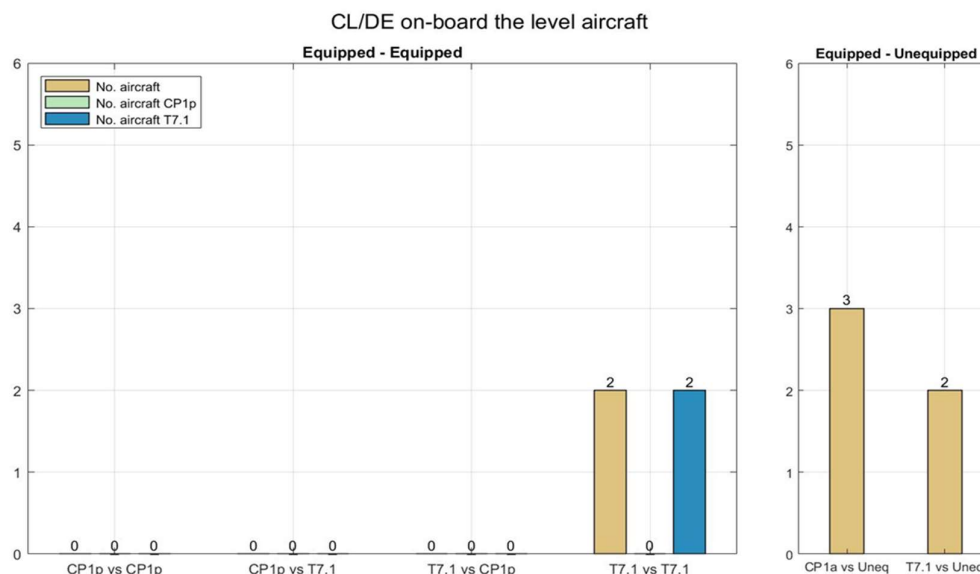
ATM model results are consistent with radar data results, i.e. showing that ACAS Xa CP1 does better than TCAS.

### 5.3.2.2.2. P1o3 Climb/descend RA alert on-board the level aircraft (aircraft perspective)

#### 5.3.2.2.2.1. Radar data

Confidence

- EE same equipage: very low
- EU: very low



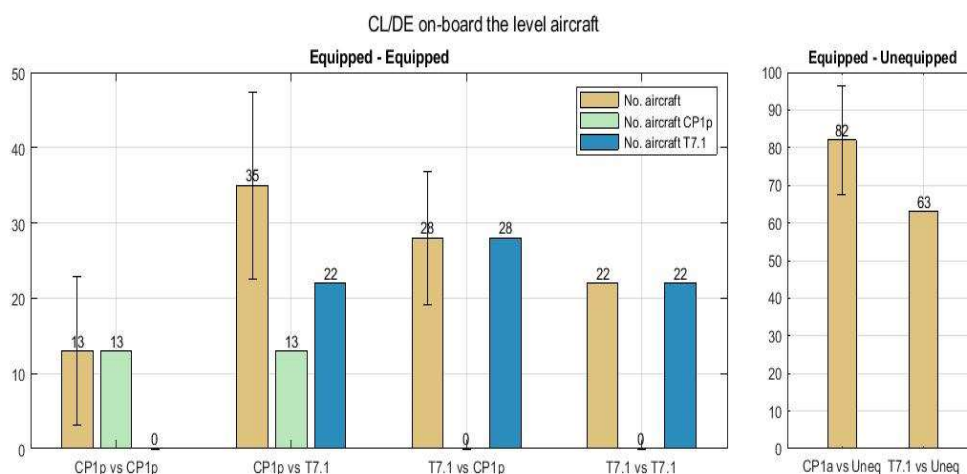
**Figure 24 Radar data Climb/Descend on-board the level aircraft**

There was too little radar data determine whether ACAS Xa CP1 had different performance from TCAS II on this metric.

#### 5.3.2.2.2.2. ATM model

Confidence

- EE same equipage: 93.5%
- EU: 98.4%



**Figure 25 ATM model climb/descend on-board the level aircraft**

The ATM model suggests that ACAS Xa CP1 issues more climb or descend RAs on the level aircraft in single level off geometries. Although the number of such events operationally is likely to be very small, it would nevertheless be prudent to monitor for such events.

## 5.4. SESAR acceptance criteria priority 2 results (to be satisfied)

### 5.4.1. Overall airspace - pilots follow the RAs

#### 5.4.1.1. P2s1 Risk ratio in multi-aircraft encounters

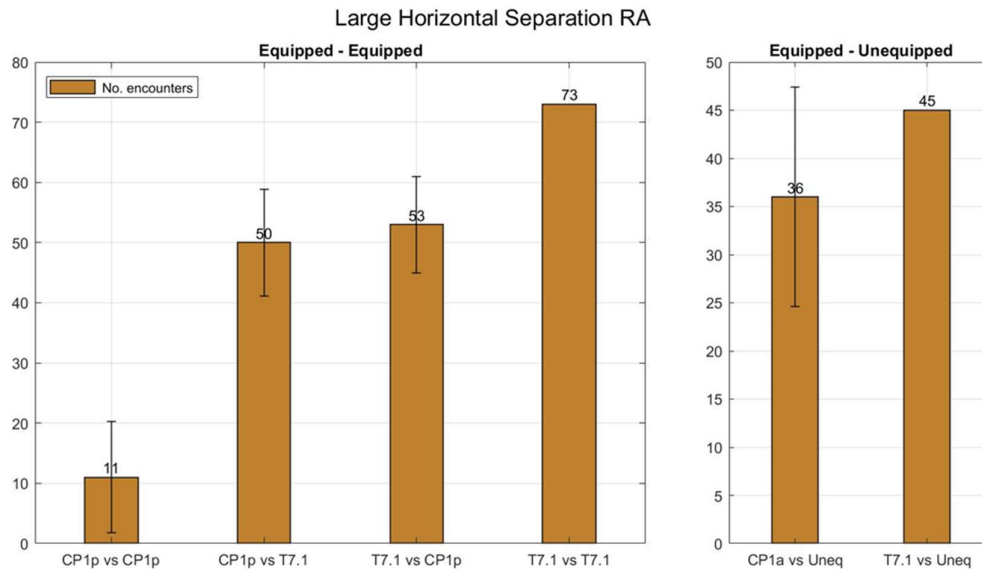
Out of scope – performed in US. Shows ACAS Xa CP1 performs better than TCAS II V7.1.

#### 5.4.1.2. P2o1 RA alert in encounters with large horizontal separation (encounter perspective)

##### 5.4.1.2.1. Radar data

Confidence

- EE encounter perspective same equipage: >99%
- EU: 91%



**Figure 26 Radar data large horizontal separation RA**

RAs with large horizontal separations are defined as RAs in which the horizontal separation at CPA between the two aircraft is above 1.2 NM in TMA airspace; or above 2 NM in En-Route airspace.

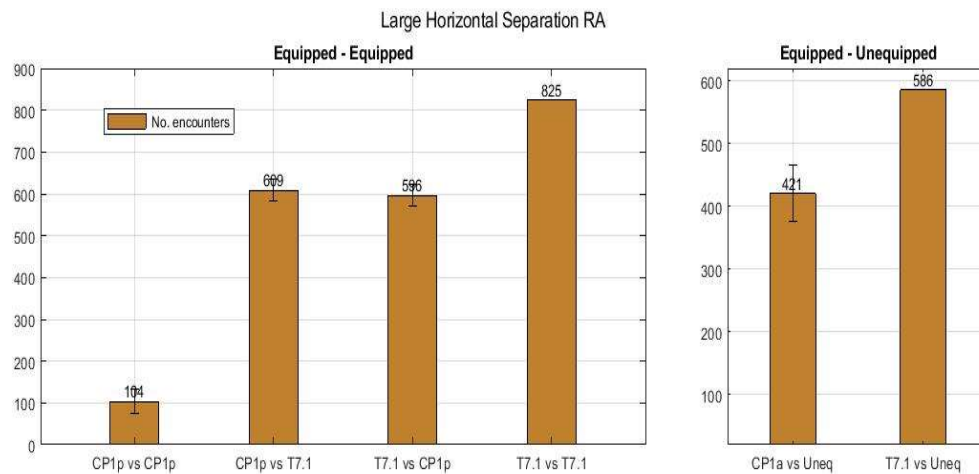
With radar data:

- Against ADS-B out intruders, ACAS Xa CP1 reduces the number of RAs with large horizontal separation by 85%.
- Against only unequipped intruders without ADS-B out, ACAS Xa CP1 did not give a statistically significant reduction in the number of RAs with large horizontal separation.
- Overall, with current equipages, ACAS Xa CP1 is expected to reduce the number of RAs with large horizontal separation by 60%.

##### 5.4.1.2.2. ATM model

Confidence

- EE encounter perspective same equipage: >99%
- EU: >99%



**Figure 27 ATM model large horizontal separation RA**

With the ATM model the same trends are shown as with the radar data:

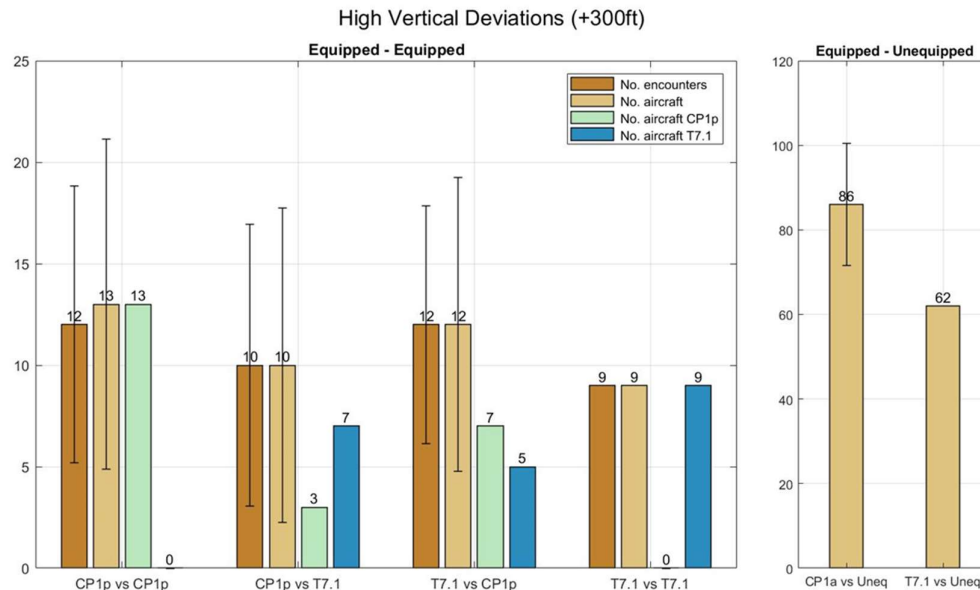
- Against ADS-B out intruders, ACAS Xa CP1 reduces the number of RAs with large horizontal separation by 87%.
- Against only unequipped intruders without ADS-B out, ACAS Xa CP1 reduced the number of RAs with large horizontal separation by 28%.
- Overall, with current equipages, ACAS Xa CP1 is expected to reduce the number of RAs with large horizontal separation by 63%.

### 5.4.1.3. P2o2 Rate of encounters with high vertical deviations

#### 5.4.1.3.1. Radar data

##### Confidence

- EE encounter perspective same equipage: 77%
- EE aircraft perspective same equipage: 80%
- EU: 99%



**Figure 28 Radar data high vertical deviation (>300 ft)**

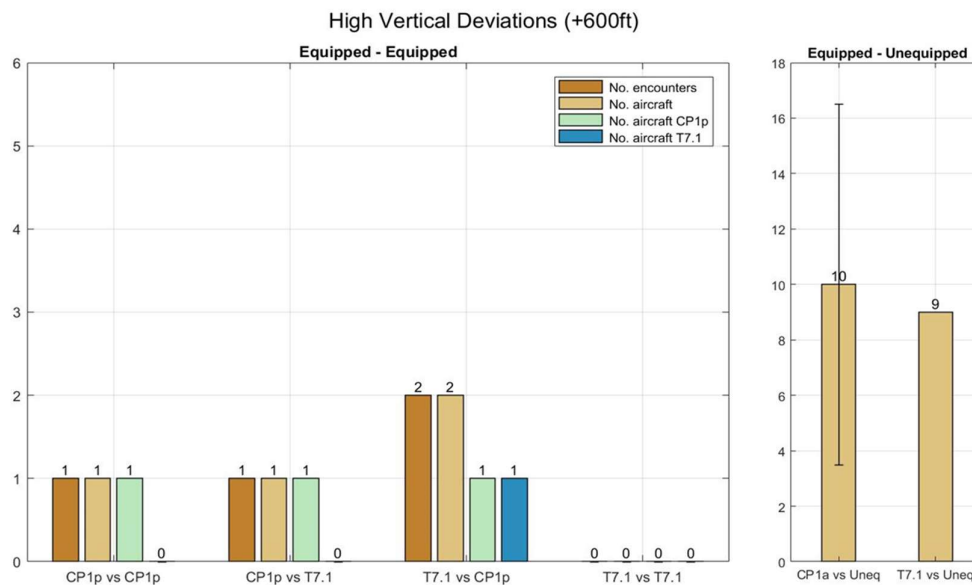
With radar data,

In EU encounters, ACAS Xa CP1 increases the number of vertical deviations >300ft by 39%

Overall encounters (EE + EU), ACAS Xa CP1 increases the number of vertical deviations >300ft by 39%

##### Confidence

- EE encounter perspective same equipage: very low
- EE aircraft perspective same equipage: very low
- EU: 60%



**Figure 29 Radar data high vertical deviations (>600 ft)**

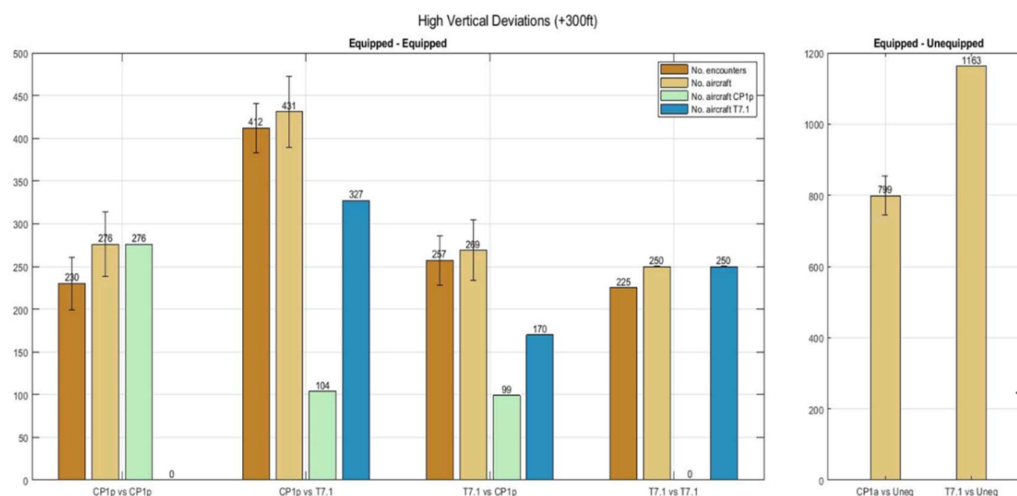
There was insufficient radar data to see any significant differences in the number of RAs leading to vertical deviations >600ft.



### 5.4.1.3.2. ATM model

#### Confidence

- EE encounter perspective same equipage: 60.5%
- EE aircraft perspective same equipage: 88.9%
- EU: >99%



**Figure 30 ATM model high vertical deviations (>300 ft)**

With the ATM model the tendencies were opposite to those with radar data:

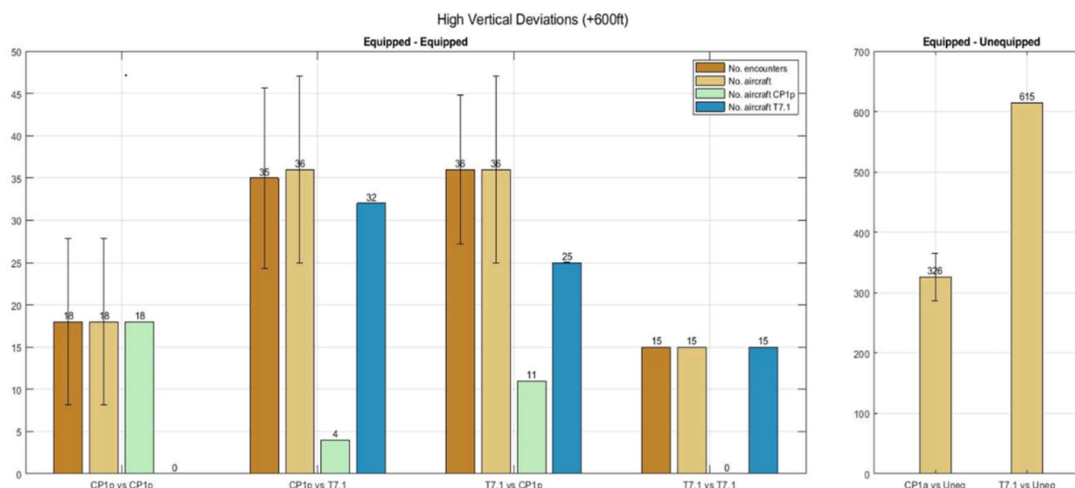
In EU encounters, ACAS Xa CP1 decreases the number of vertical deviations >300ft by 31%

Overall encounters (EE + EU), ACAS Xa CP1 decreases the number of vertical deviations >300ft by 24%

In cases where the ATM model shows tendencies opposite those of radar data, generally the radar data results should be favoured since there is less scope for introducing distortions in the encounters that are simulated.

#### Confidence

- EE encounter perspective same equipage: 69.5%
- EE aircraft perspective same equipage: 69.5%
- EU: >99%



**Figure 31 ATM model high vertical deviations (>600 ft)**

Despite the availability of statistically significant results in the ATM model, these should not be treated as trustworthy in the light of the 300ft deviation statistics.

#### 5.4.1.4. P2o3 Reverse RA alert rate (aircraft perspective)

##### 5.4.1.4.1. Radar data

Confidence

- EE encounter perspective same equipage: 77%
- EE aircraft perspective same equipage: 85%
- EU: 98%

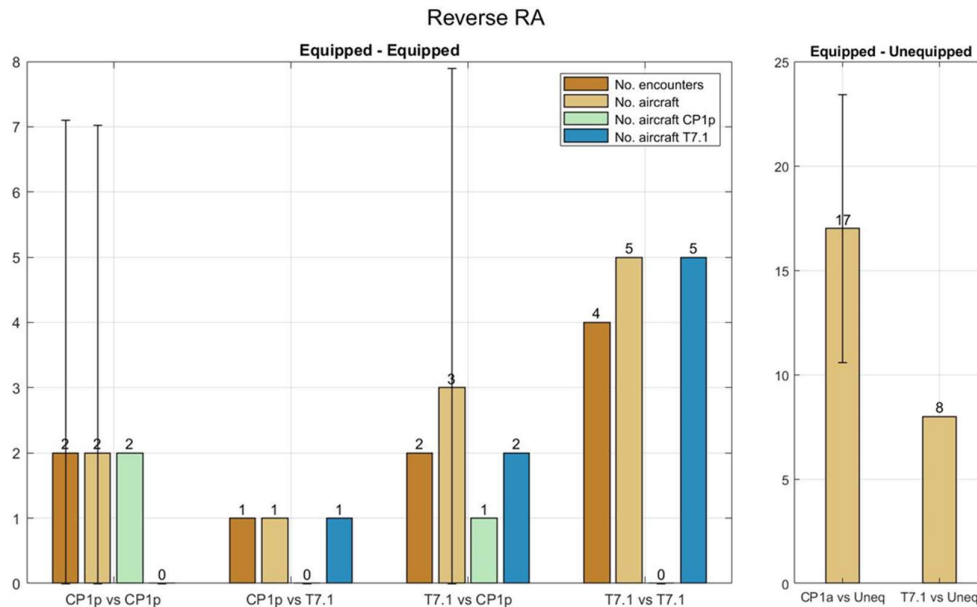


Figure 32 Radar data Reverse RA count

##### 5.4.1.4.2. ATM model

Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU: 98.3%

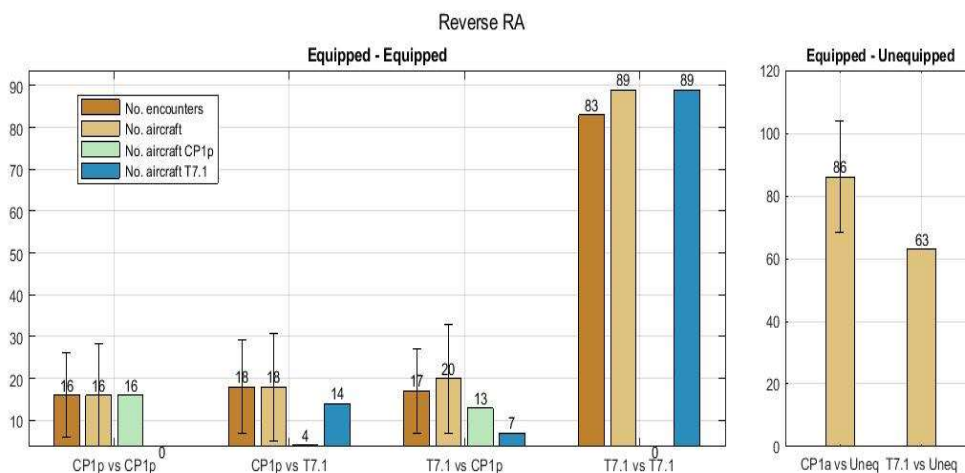


Figure 33 ATM model Reverse RA count

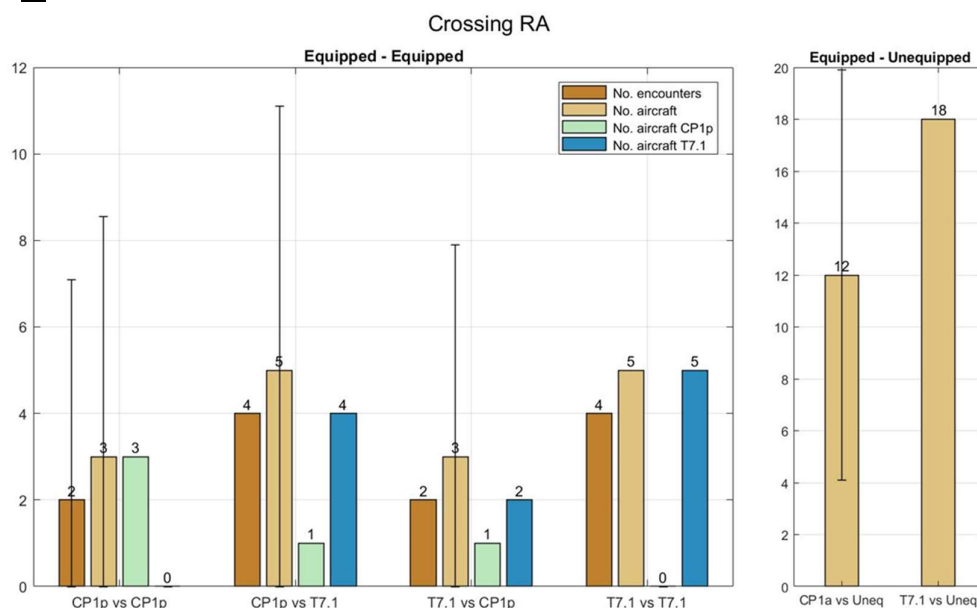
Both the radar data and the ATM model show the same trend that in EU encounters ACAS Xa CP1 issues more reversal RAs than TCAS II. For EE encounters, the ATM model suggests that ACAS Xa CP1 issues fewer reversal RAs and this is not inconsistent with the radar data. For combined counts of EE and EU encounters the radar data shows that there are more reversals with ACAS Xa CP1 but the ATM model shows the opposite. Overall there is a possibility that ACAS Xa CP1 may increase the rate of reversal RAs. This can be acceptable if associated with an increase in safety.

#### 5.4.1.5. P2o4 Crossing RA alert rate

### 5.4.1.5.1. Radar data

#### Confidence

- EE encounter perspective same equipage: 77%
- EE aircraft perspective same equipage: 75%
- EU: 90%



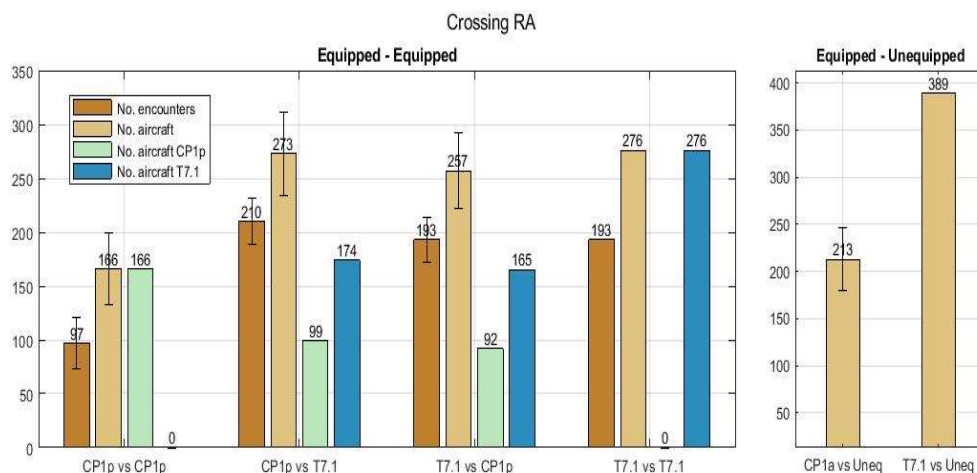
**Figure 34 Radar data crossing RA sequence**

There was insufficient radar data to determine with good statistical significance that ACAS Xa CP1 will issue fewer crossing RA alerts than TCAS II V7.1.

### 5.4.1.5.2. ATM model

#### Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU: >99%



**Figure 35 ATM model crossing RA sequence**

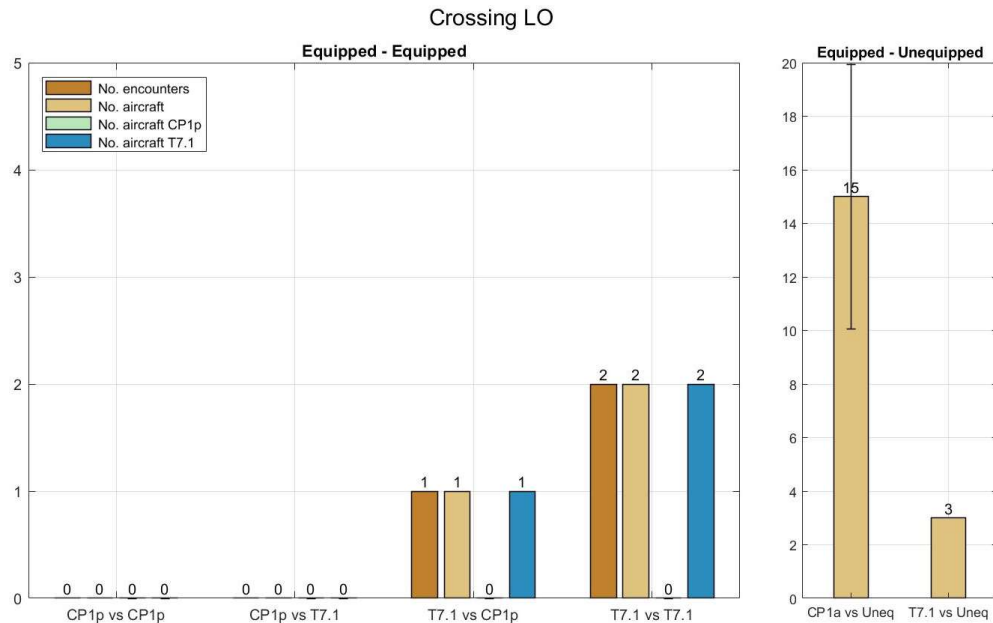
The ATM model suggests that ACAS Xa CP1 will reduce the crossing RA sequence rate by 45% for EU encounters and by 40% for EE encounters and by 43% overall (EE + EU). As some pilots are reticent to follow RAs that cross through the altitude of an intruder, this may provide a safety improvement.

### 5.4.1.6. P2o4a Crossing level off RA

#### 5.4.1.6.1. Radar data

## Confidence

- EE encounter perspective same equipage: very low
- EE aircraft perspective same equipage: very low
- EU: 99%



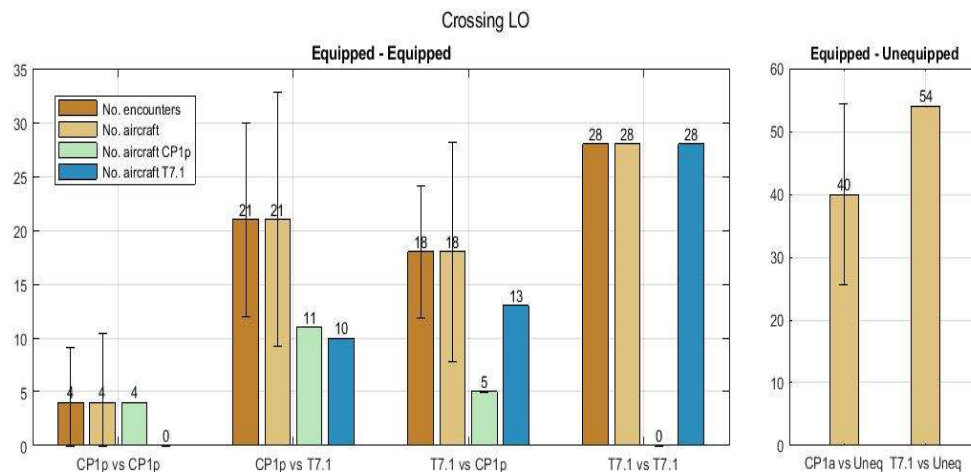
**Figure 36 Radar data crossing level off RA**

In European radar data, crossing level off RAs in EU encounters are simulated significantly more with ACAS Xa CP1 than with TCAS II V7.1.

### 5.4.1.6.2. ATM model

## Confidence

- EE encounter perspective same equipage: 99.99%
- EE aircraft perspective same equipage: 99.95%
- EU: 98.0%



**Figure 37 ATM model crossing level off RA**

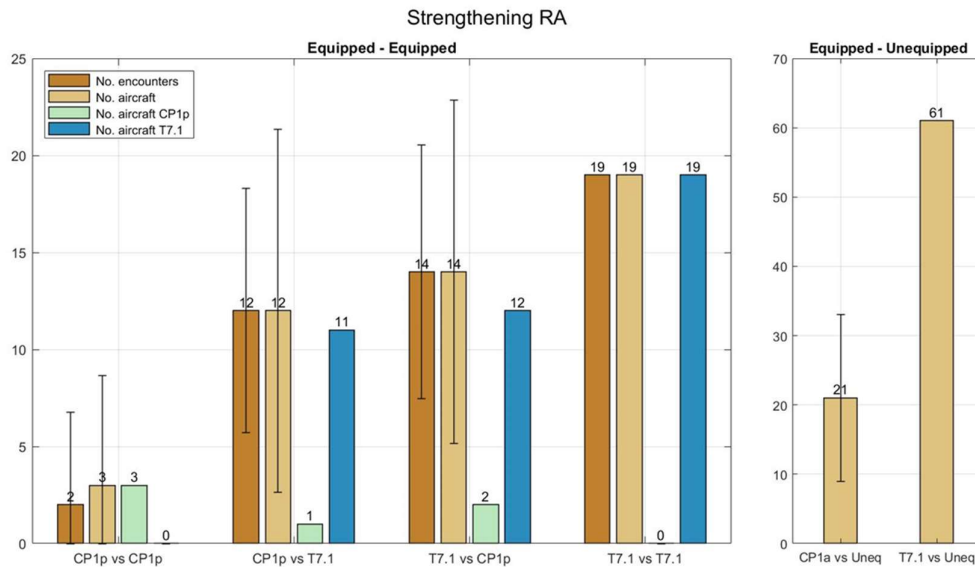
The same trend is not observed in the ATM model – ACAS Xa CP1 issues fewer crossing level off RAs both in EE and EU encounters. Nevertheless, this is not inconsistent with the possibility of ACAS Xa CP1 issuing more crossing level off RAs that increase induced risk.

### 5.4.1.7. P2o5 Strengthening RA sequence alert rate

#### 5.4.1.7.1. Radar data

##### Confidence

- EE encounter perspective same equipage: 99.9%
- EE aircraft perspective same equipage: 99.9%
- EU: >99%



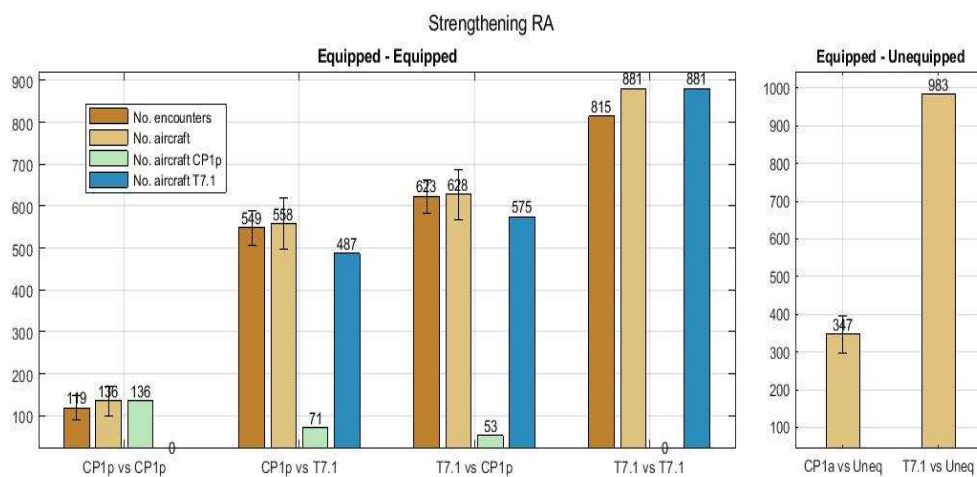
**Figure 38 Radar data strengthening RA**

Radar data analysis shows that ACAS Xa CP1 issues fewer strengthening RAs than TCAS II V7.1. This is considered beneficial as there is less probability of issuing stressful strengthening RAs that pilots may not follow.

#### 5.4.1.7.2. ATM model

##### Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU: >99%



**Figure 39 ATM model strengthening RA**

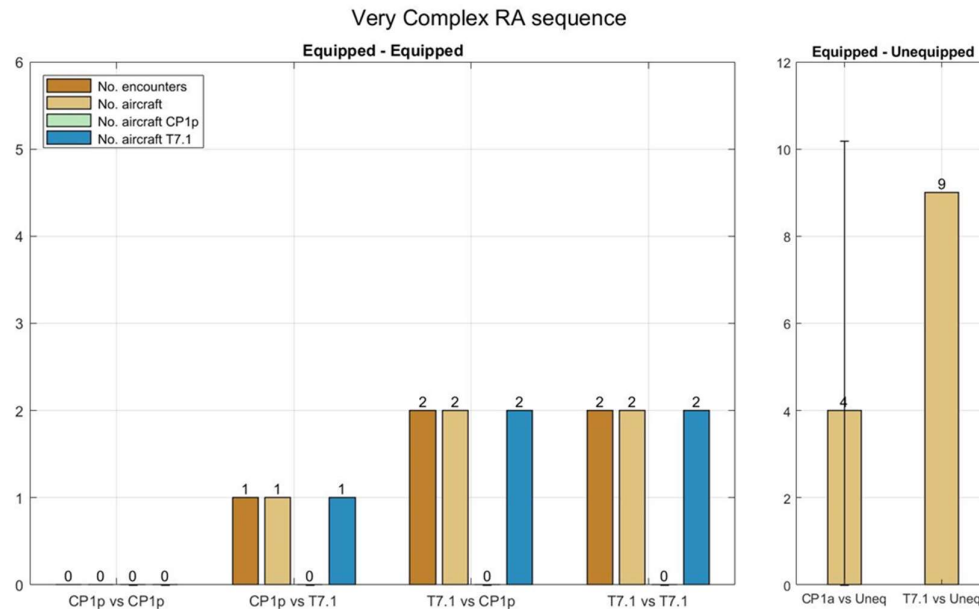
The ATM model analysis also shows that ACAS Xa CP1 issues fewer strengthening RAs than TCAS II V7.1.

### 5.4.1.8. P2o6 Very complex RA sequence alert rate

#### 5.4.1.8.1. Radar data

##### Confidence

- EE encounter perspective same equipage: very low
- EE aircraft perspective same equipage: very low
- EU: 91%



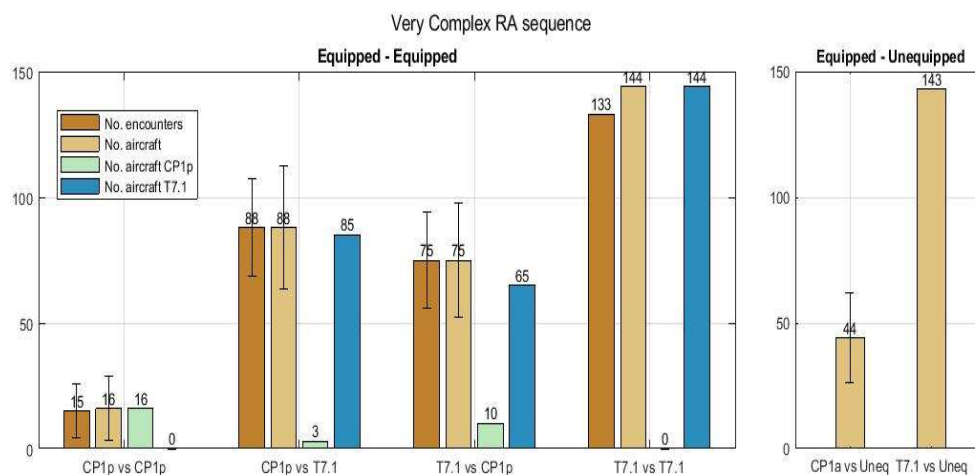
**Figure 40 Radar data very complex RA sequence**

There was too little radar data to note a statistically significant change in the frequency of complex RA sequences with ACAS Xa CP1

#### 5.4.1.8.2. ATM model

##### Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU: >99%



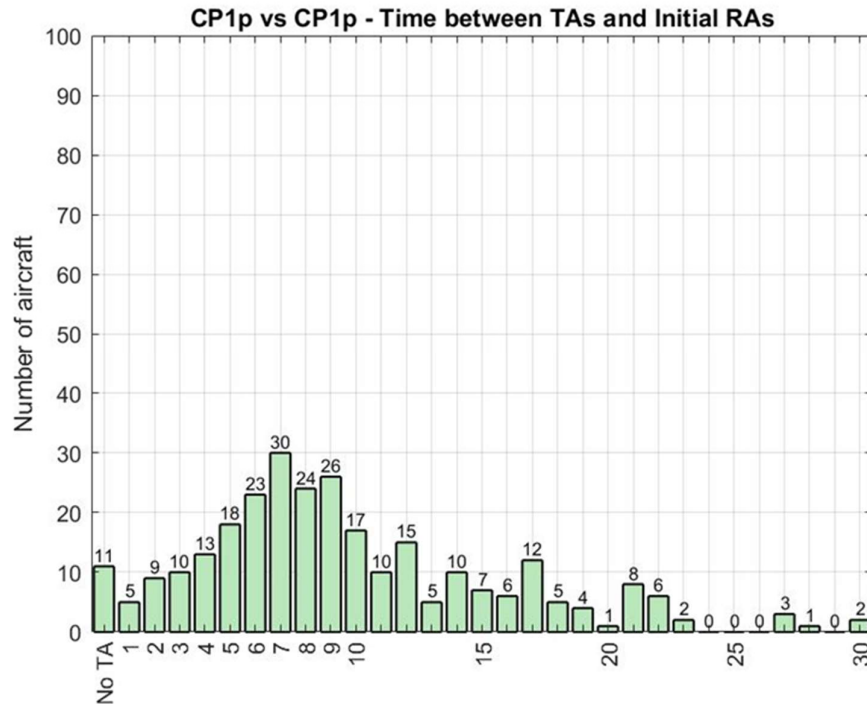
**Figure 41 ATM model very complex RA sequence**

However, with the ATM model, ACAS Xa CP1 issues fewer very complex RA sequences (more than 4 alerts). This is considered beneficial as it is thought less likely that pilots will follow long sequences of RAs correctly.

#### 5.4.1.9. P2o7 Time between TA and initial RA

##### 5.4.1.9.1. Single equipage

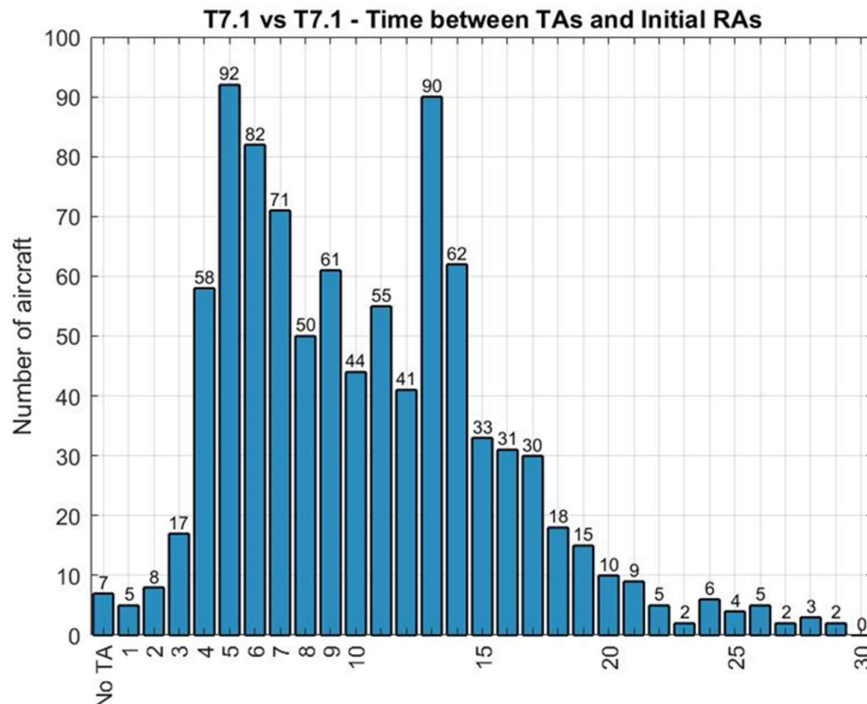
##### 5.4.1.9.1.1. Radar data



**Figure 42 Radar data time between TA and initial RA – ACAS Xa CP1**

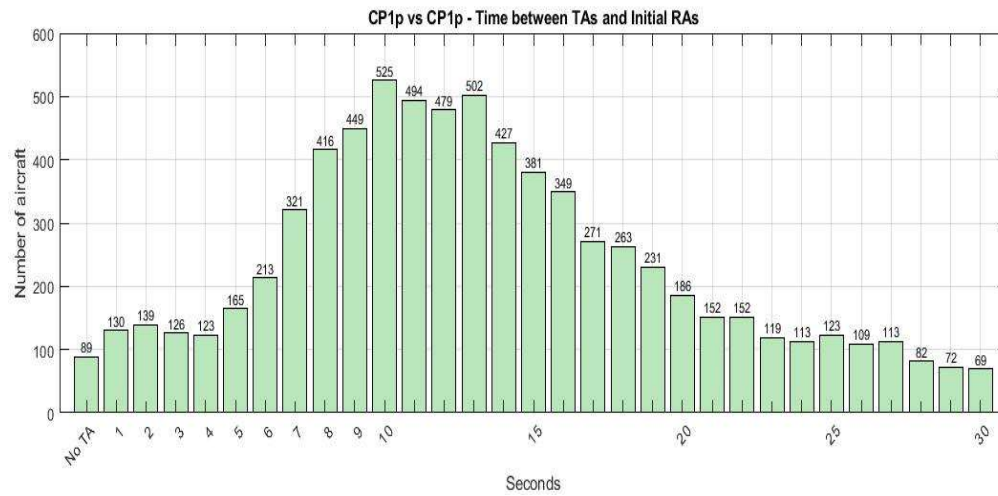
The purpose of TAs is to prepare flight crews to react to RAs, and to allow them time to identify nearby traffic. Any TA with less than 6 seconds warning (or no TA) before an RA is considered to give inadequate warning time. In the case of simulated radar encounters, for ACAS Xa CP1 there were 66 RAs where there was less than 6s TA warning time compared to 187 with TCAS II V7.1. This is a reduction of about 65%.

At the other extreme, RAs are nominally expected 15 seconds after a TA, so any RAs more than 25 seconds after a TA might be considered as being issued too early. In the case of radar encounters, a similar sized reduction is seen with 6 early RAs for ACAS Xa CP1 and 12 for TCAS II V7.1.

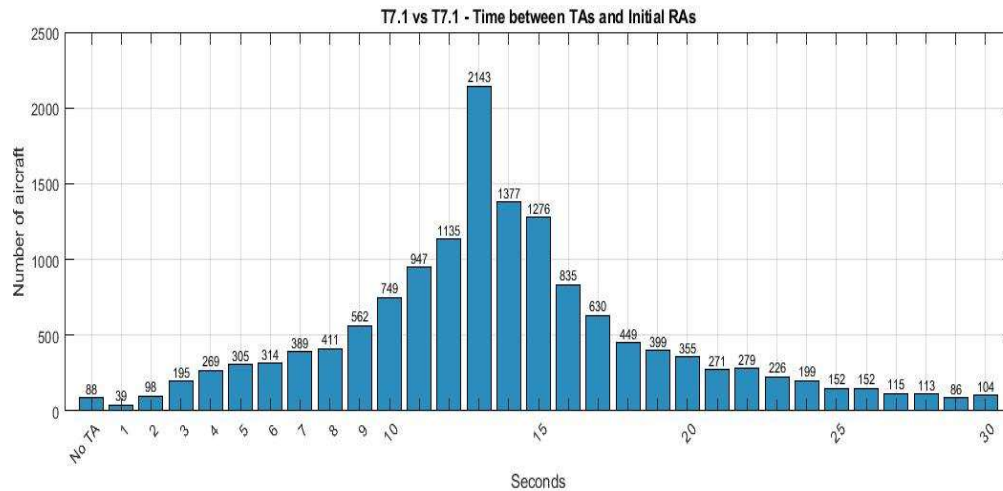


**Figure 43 Radar data time between TA and initial RA - TCAS**

#### 5.4.1.9.1.2. ATM model



**Figure 44 ATM model time between TA and initial RA – ACAS Xa CP1**



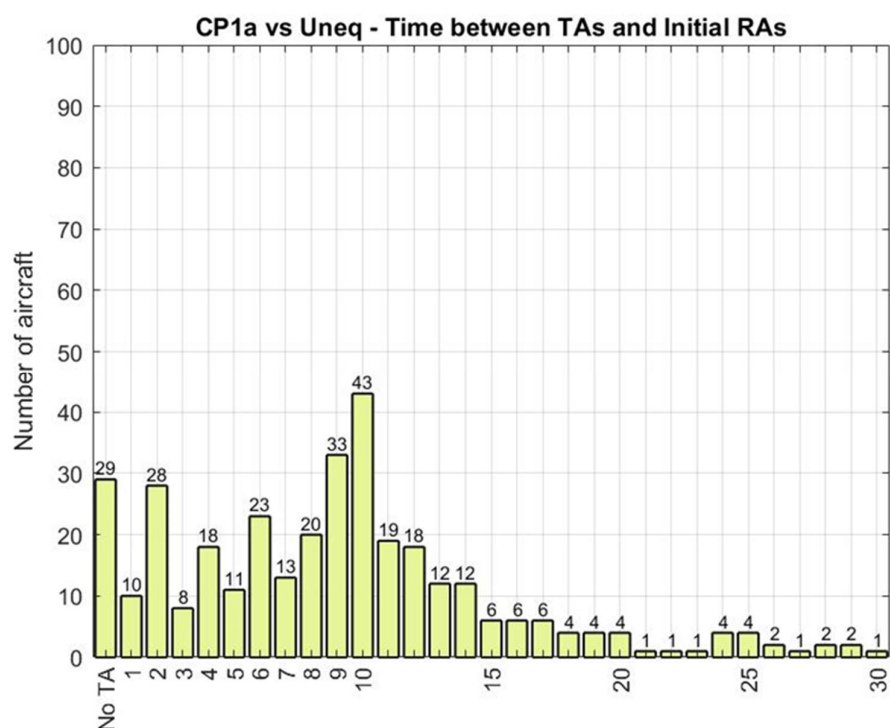
**Figure 45 ATM model time between TA and initial RA – TCAS**

The same trends are observed with the ATM model as with the radar data for the relative timings of TAs relative to RAs for ACAS Xa CP1 and TCAS II V7.1. In particular it should be noted that overall there are fewer ACAS Xa CP1 RAs leading to fewer possibilities for the logic to issue TAs too early or too late.

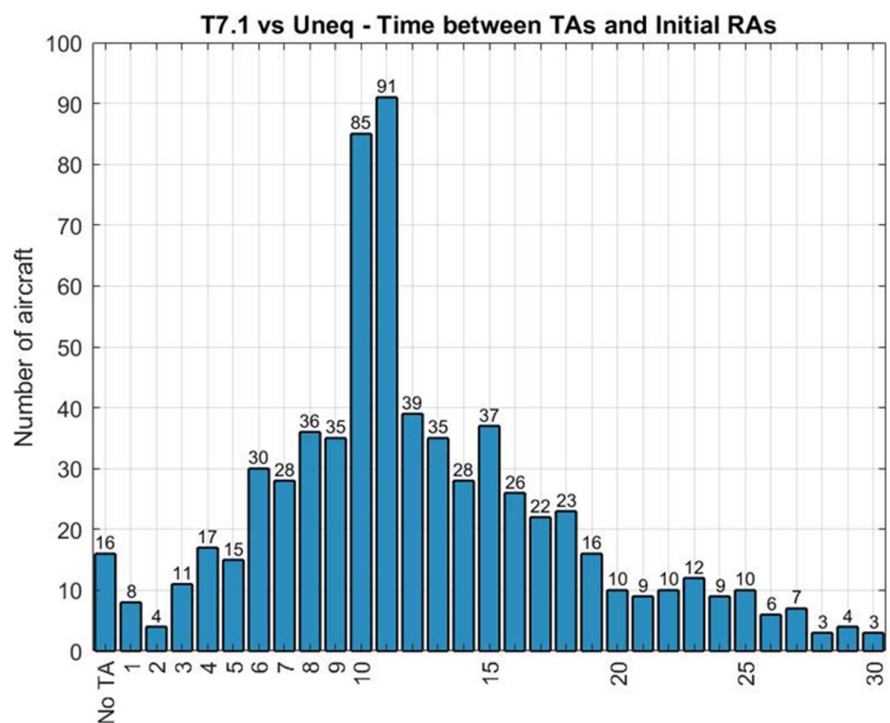


### 5.4.1.9.2. Equipped v Unequipped

#### 5.4.1.9.2.1. Radar data

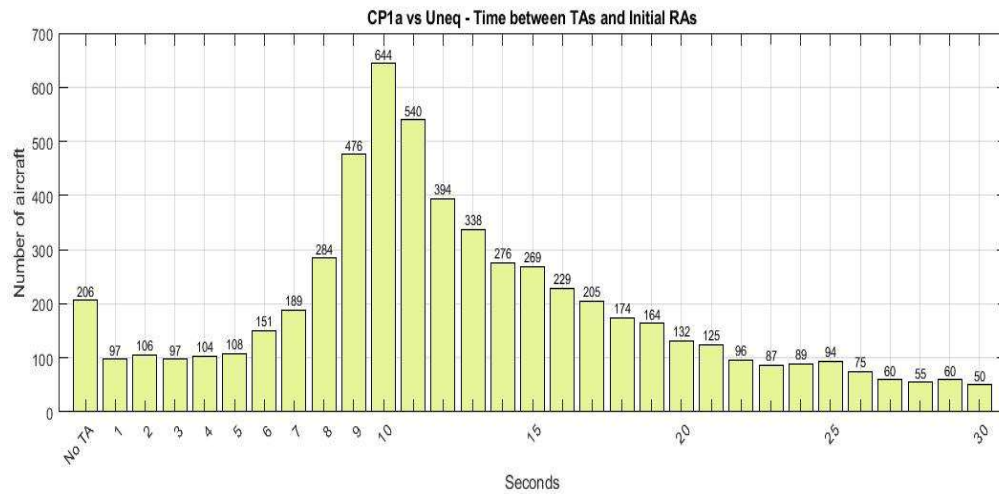


**Figure 46 Radar data time between TA and initial RA – ACAS Xa CP1 active v unequipped**

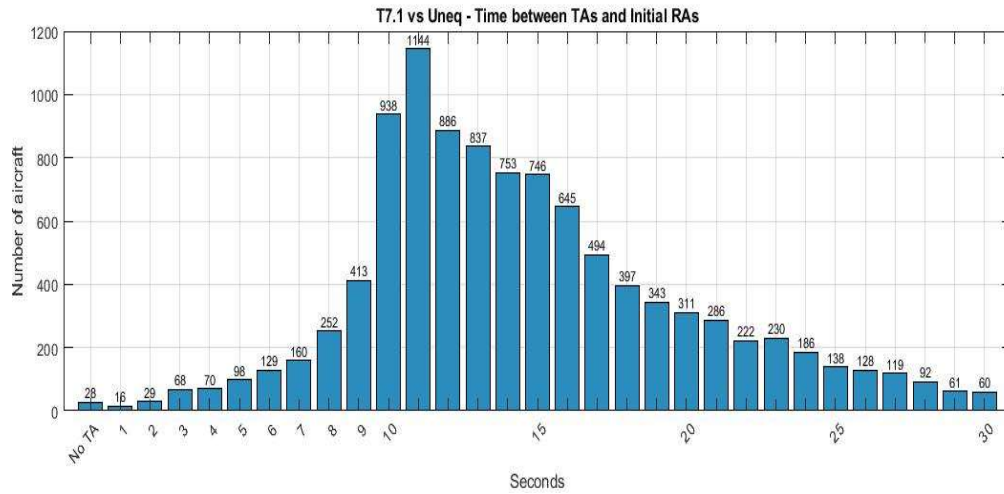


**Figure 47 Radar data time between TA and initial RA – TCAS v unequipped**

#### 5.4.1.9.2.2. ATM model



**Figure 48 ATM model time between TA and initial RA – ACAS Xa active v unequipped**

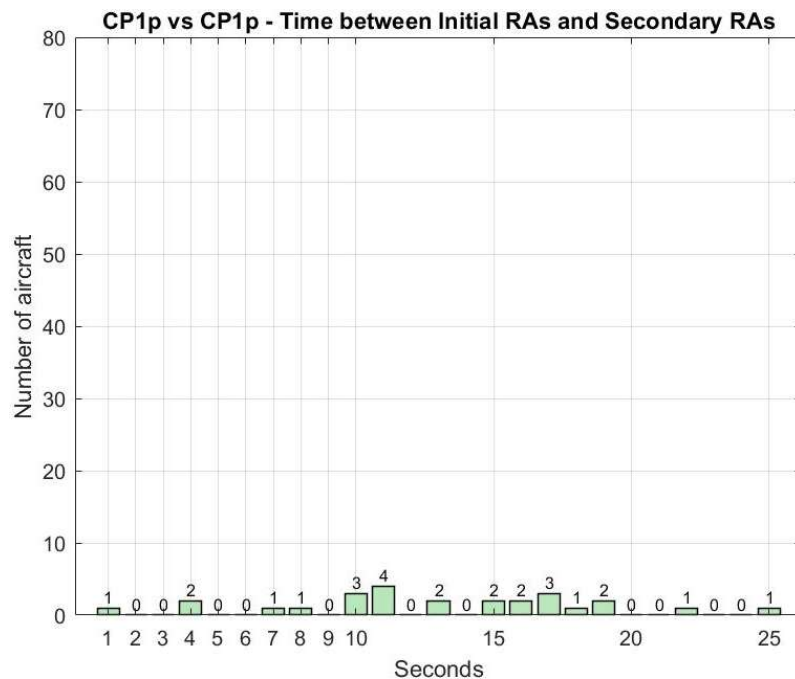


**Figure 49 ATM model time between TA and initial RA – TCAS v Unequipped**

#### 5.4.1.10. P2o8 Time between initial and secondary RA

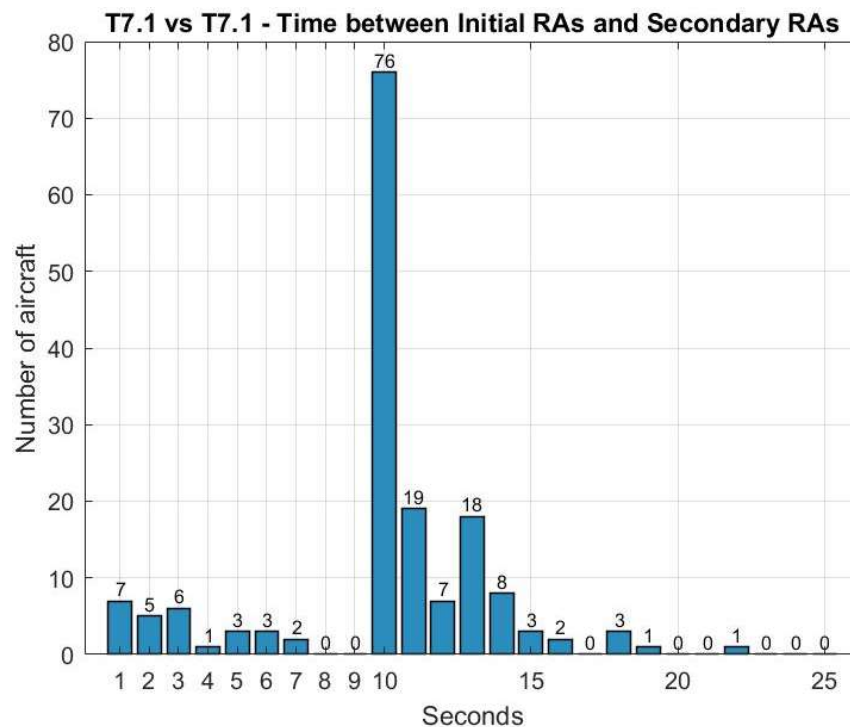
##### 5.4.1.10.1. Single equipage

##### 5.4.1.10.1.1. Radar data



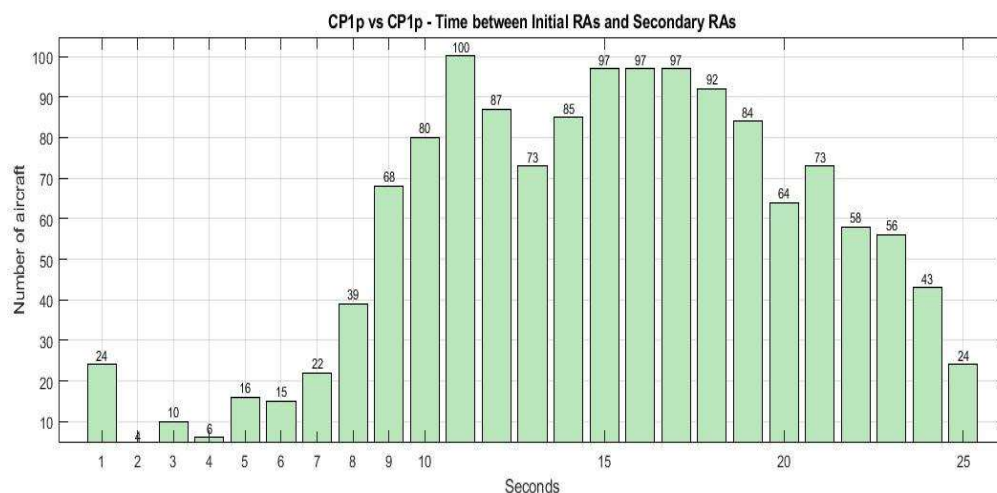
**Figure 50 Radar data time between initial RA and secondary RA – ACAS Xa CP1 passive**

The fewer occasions that a secondary RA is issued the better the initial RA was at collision avoidance. Also secondary RAs issued very shortly after an initial RA suggest that the initial RA was poorly chosen. In the case of comparing ACAS Xa with TCAS II V7.1 using radar data, there are fewer secondary RAs shortly after the initial RA and far fewer secondary RAs in general.

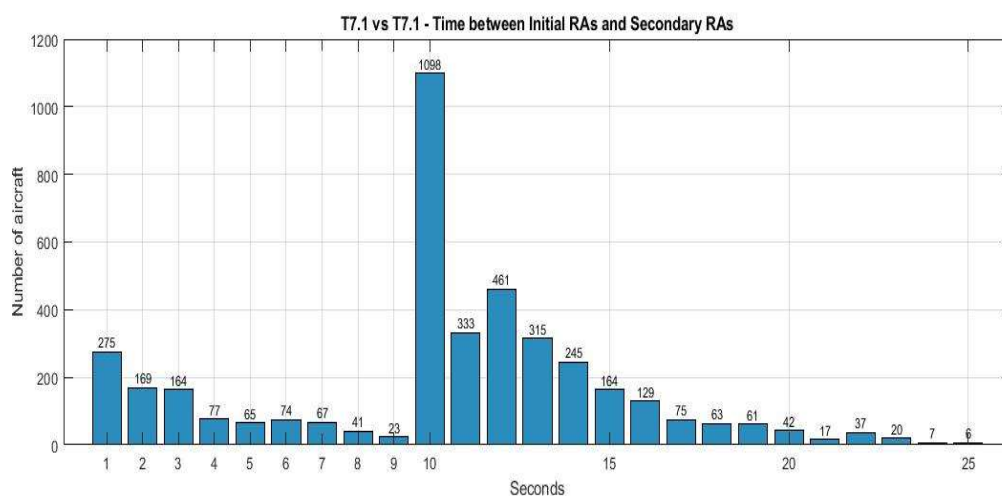


**Figure 51 Radar data time between initial RA and secondary RA – TCAS**

#### 5.4.1.10.1.2. ATM model



**Figure 52 ATM model time between initial RA and secondary RA – ACAS Xa CP1**



**Figure 53 ATM model time between initial RA and secondary RA – TCAS**

With the ATM model there are similar trends to the radar data

ACAS Xa CP1 issues fewer secondary RAs just after the initial RA than TCAS II V7.1, and issues fewer secondary RAs in general. However, ACAS Xa CP1 does issue more secondary RAs greater than 17 seconds after the initial RA when compared to TCAS II V7.1. The operational value of this observation is not clear.

## 5.4.1.10.2. Equipped v Unequipped

### 5.4.1.10.2.1. Radar data

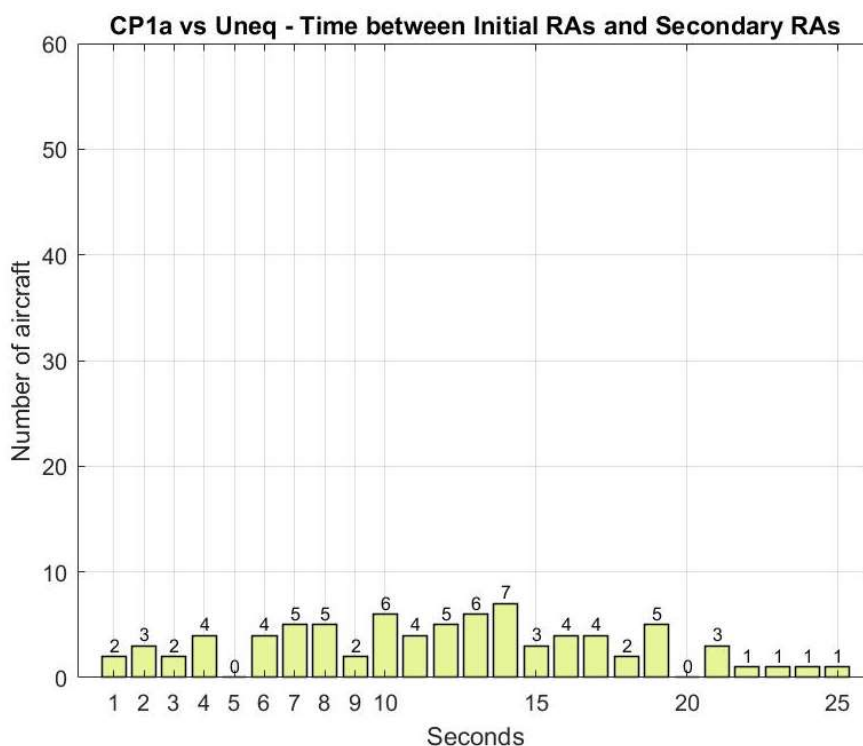


Figure 54 Radar data time between initial RA and secondary RA – ACAS Xa CP1 active v unequipped

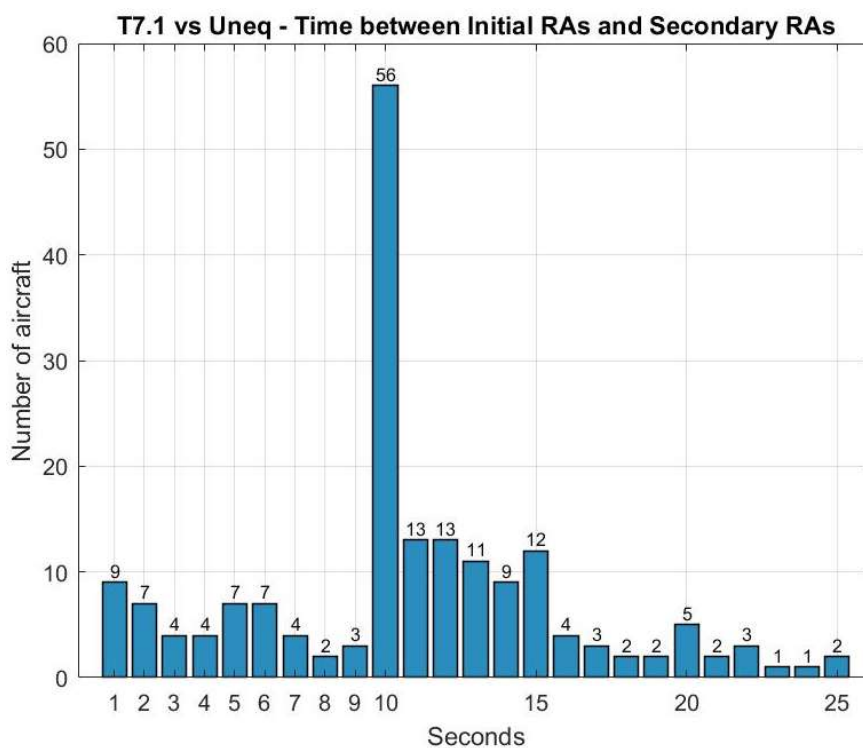
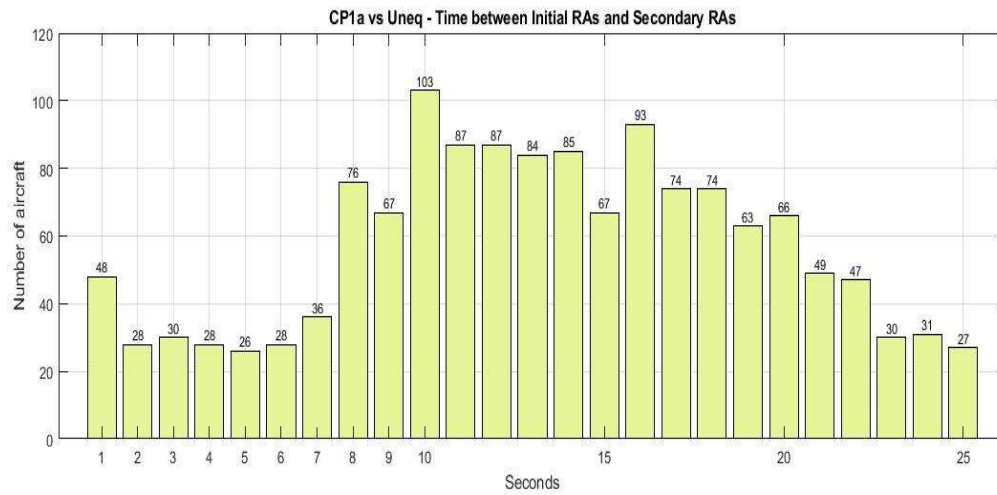
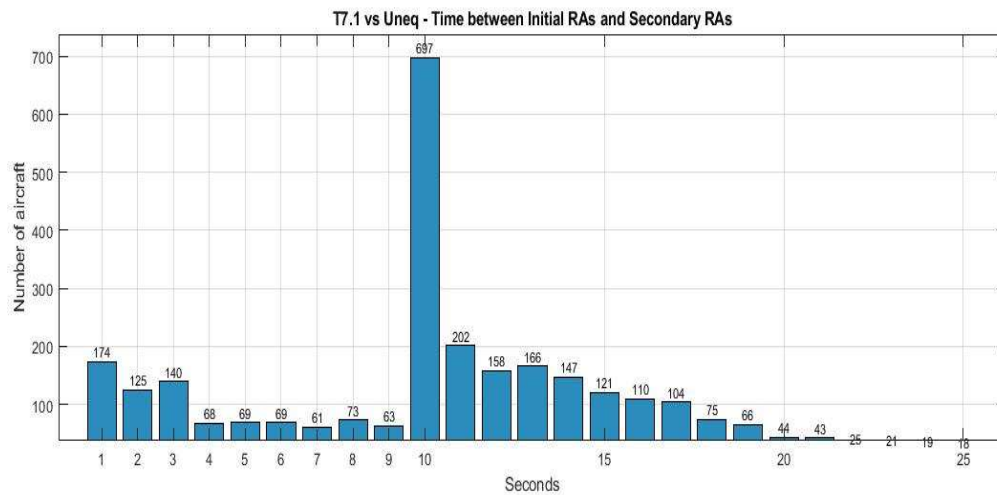


Figure 55 Radar data time between initial RA and secondary RA – TCAS v unequipped

### 5.4.1.10.2.2. ATM model



**Figure 56 ATM model time between initial RA and secondary RA – ACAS Xa active v unequipped**

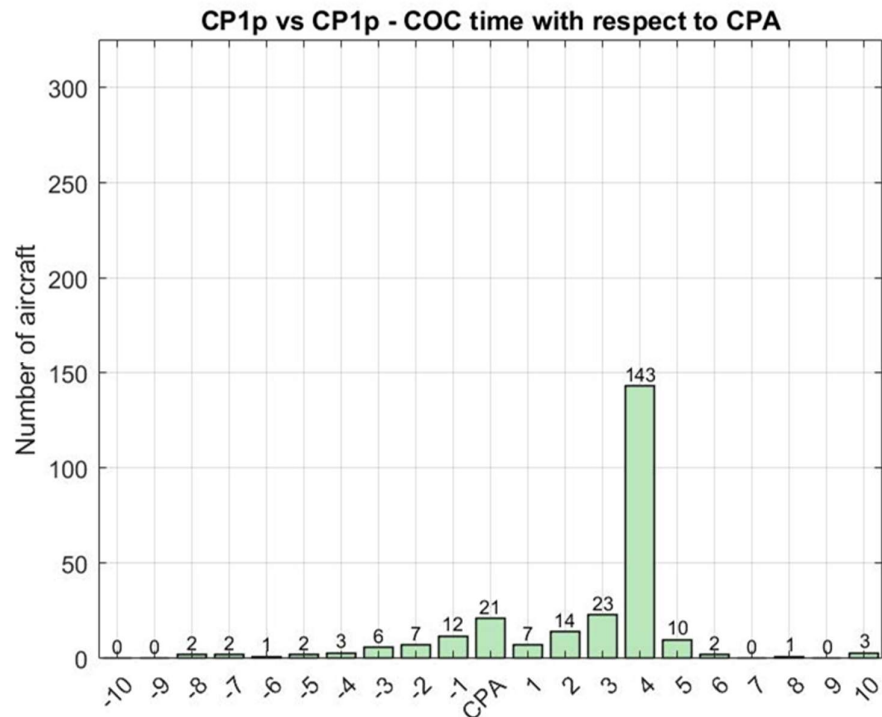


**Figure 57 ATM model time between initial RA and secondary RA – TCAS v unequipped**

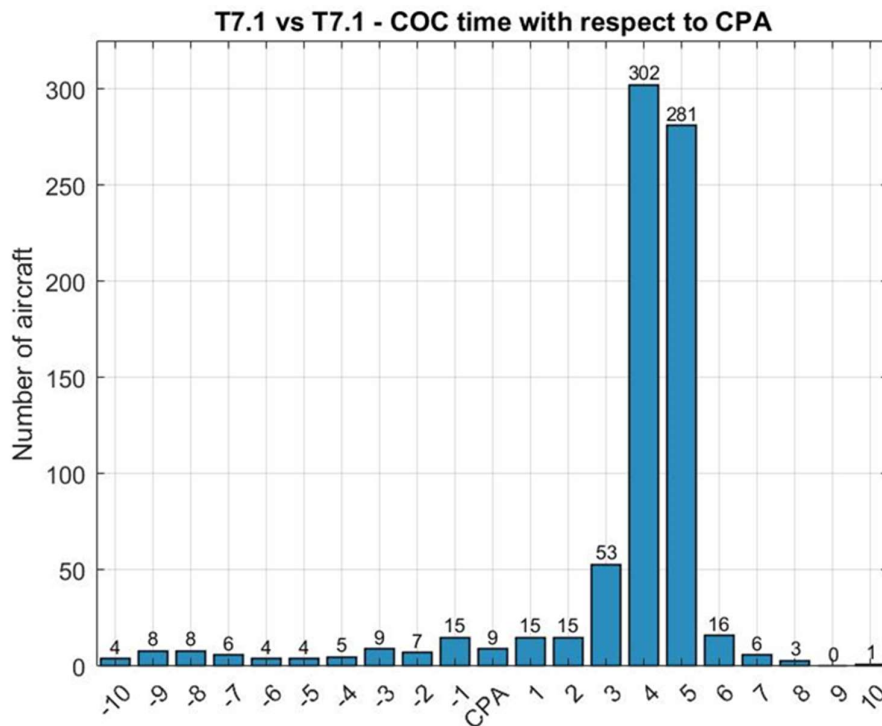
#### 5.4.1.11. P2o9 Early clear of conflict alert rate

##### 5.4.1.11.1. Single equipage

##### 5.4.1.11.1.1. Radar data



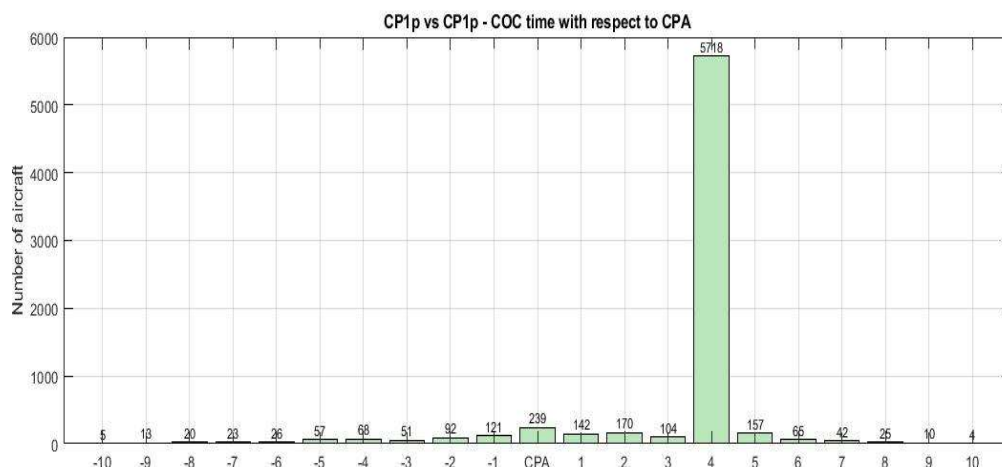
**Figure 58 Radar data clear of conflict time from CPA – ACAS Xa CP1 passive**



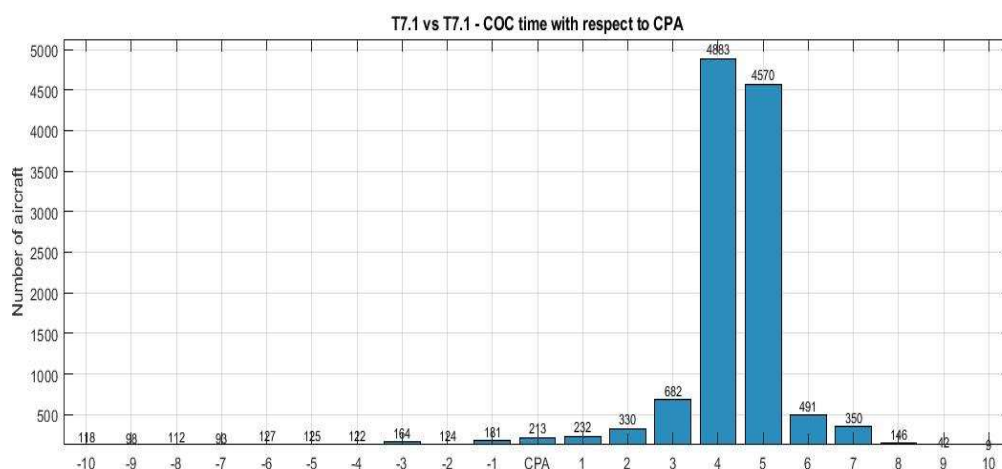
**Figure 59 Radar data clear of conflict time from CPA – TCAS**

The shape of the distribution of COC timing with radar data is qualitatively similar for ACAS Xa CP1 and TCAS II V7.1. ACAS Xa CP1 issues fewer RAs than TCAS II V7.1 and this is seen across the distribution of COC timings.

#### 5.4.1.11.1.2. ATM model



**Figure 60 ATM model clear of conflict time from CPA – ACAS Xa CP1 passive**



**Figure 61 ATM model clear of conflict time from CPA – TCAS**

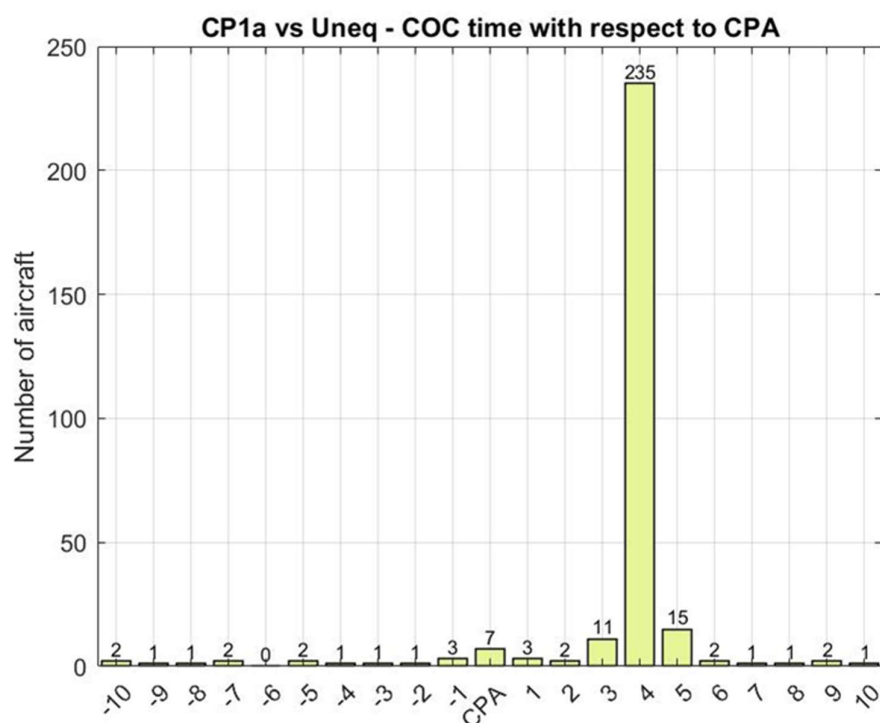
As with the radar data, the shape of the distribution for of COC timing with the ATM model is qualitatively similar for ACAS Xa CP1 and TCAS II V7.1. ACAS Xa CP1 issues fewer RAs than TCAS II V7.1 and this is seen across the distribution of COC timings.

Comparing the distributions of COC timings from the radar data and ATM model shows less spread of COC timings with the ATM model, arguably suggesting that the ATM model provides slightly more predictable trajectories.

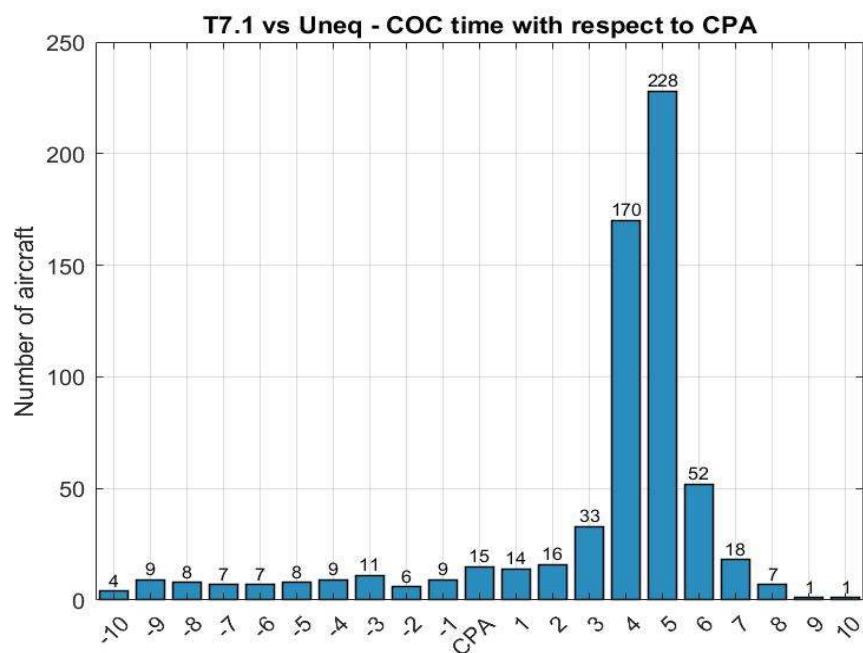


## 5.4.1.11.2. Equipped v Unequipped

### 5.4.1.11.2.1. Radar data

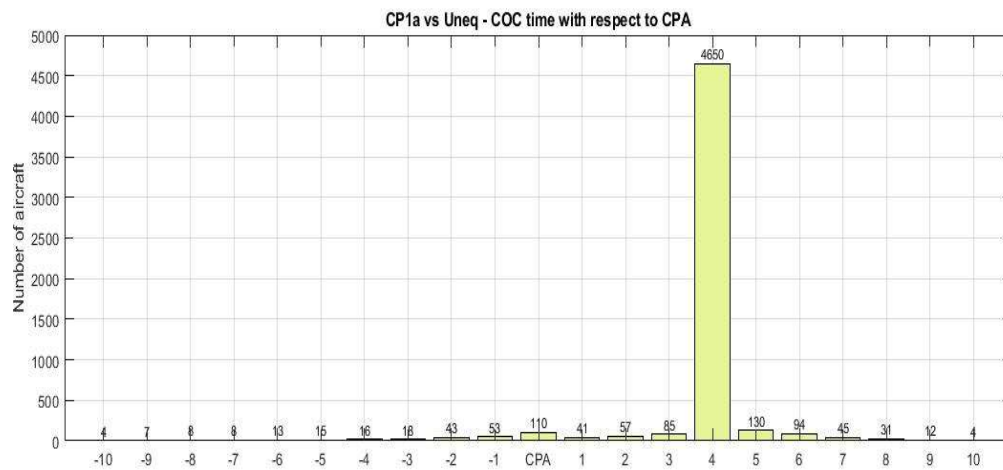


**Figure 62 Radar data clear of conflict time from CPA – ACAS XA CP1 active v unequipped**

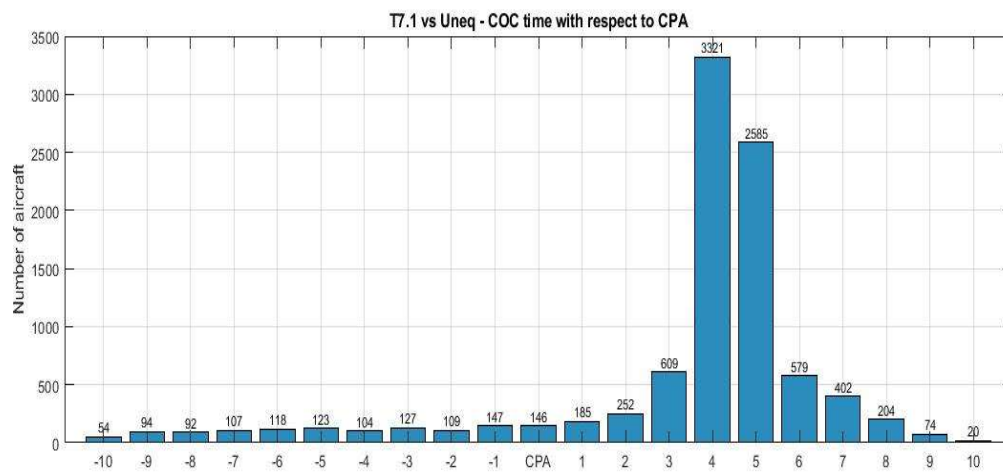


**Figure 63 Radar data clear of conflict from CPA – TCAS v unequipped**

## 5.4.1.11.2.2. ATM model



**Figure 64 clear of conflict time from CPA – ACAS XA active v unequipped**



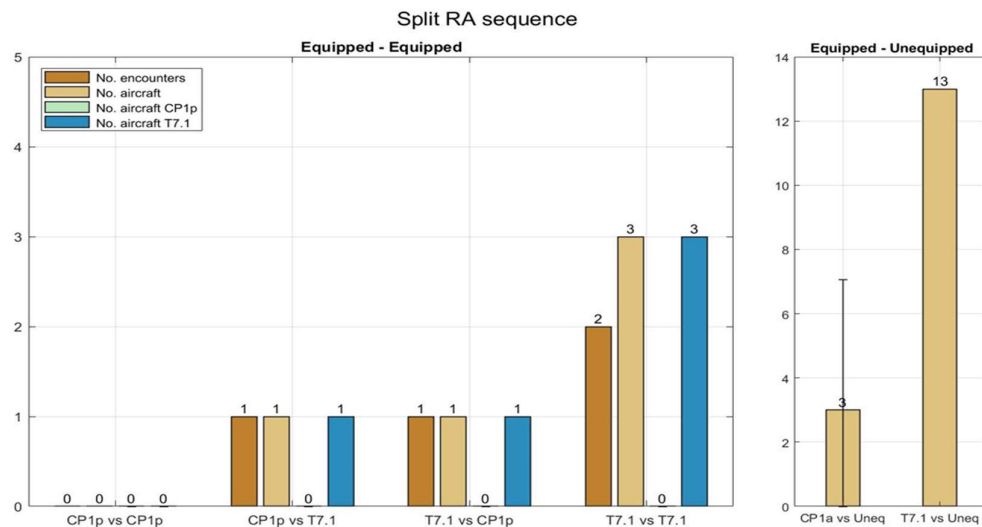
**Figure 65 ATM model clear of conflict from CPA – TCAS v unequipped**

### 5.4.1.12. P2o10 Split RA sequence

#### 5.4.1.12.1. Radar data

##### Confidence

- EE encounter perspective same equipage: very low
- EE aircraft perspective same equipage: very low
- EU: 99%



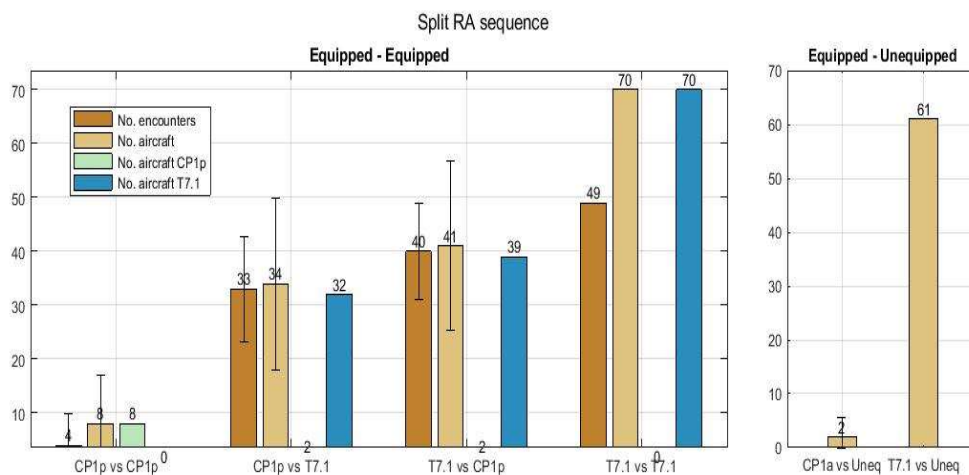
**Figure 66 Split RA sequence – equipped v equipped**

A split RA sequence is when an encounter includes a new RA against an intruder that has already had COC issued against it. This is clearly an undesirable event. Based on radar data, ACAS Xa CP1 is expected to reduce the number of split RAs by a factor of between 2 and 4 for EU encounters.

#### 5.4.1.12.2. ATM model

##### Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU: >99%



**Figure 67 Split RA sequence – equipped v equipped**

Based on the ATM model, ACAS Xa CP1 reduces the number of split RAs by a factor greater than 4 for both EU and EE encounters.

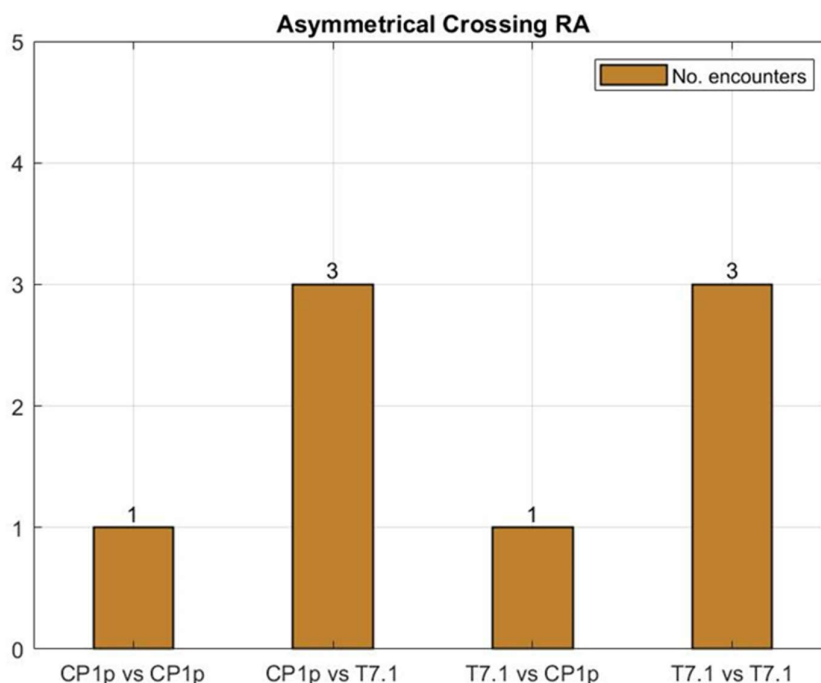
## 5.4.2. Equipped-equipped subset - pilots follow the RAs

### 5.4.2.1. P2o11 Crossing RA alert rate (encounter perspective) (Interop)

#### 5.4.2.1.1. Radar data

Confidence

- EE encounter perspective same equipage: very low



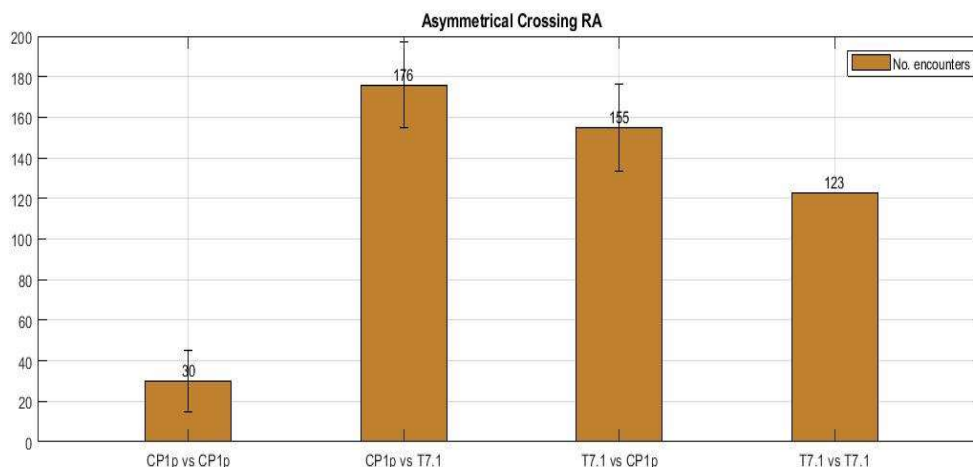
**Figure 68 Radar data crossing RA alerts – encounter perspective**

There was insufficient radar data to assess the effect of ACAS Xa CP1 on asymmetrical crossing RAs

#### 5.4.2.1.2. ATM model

Confidence

- EE encounter perspective same equipage: >99%



**Figure 69 ATM model crossing RA alerts – encounter perspective**

Using the ATM model suggests that during the transition to full ACAS Xa CP1 equipage, there will be a considerable period when there will be more crossing RAs issued in EE encounters than is currently the case. This evolution should be monitored to ensure continued compliance with RAs and operational acceptability of the system.

### 5.4.2.2. P2012 Reverse RA alert rate in EE encounters (encounter perspective)

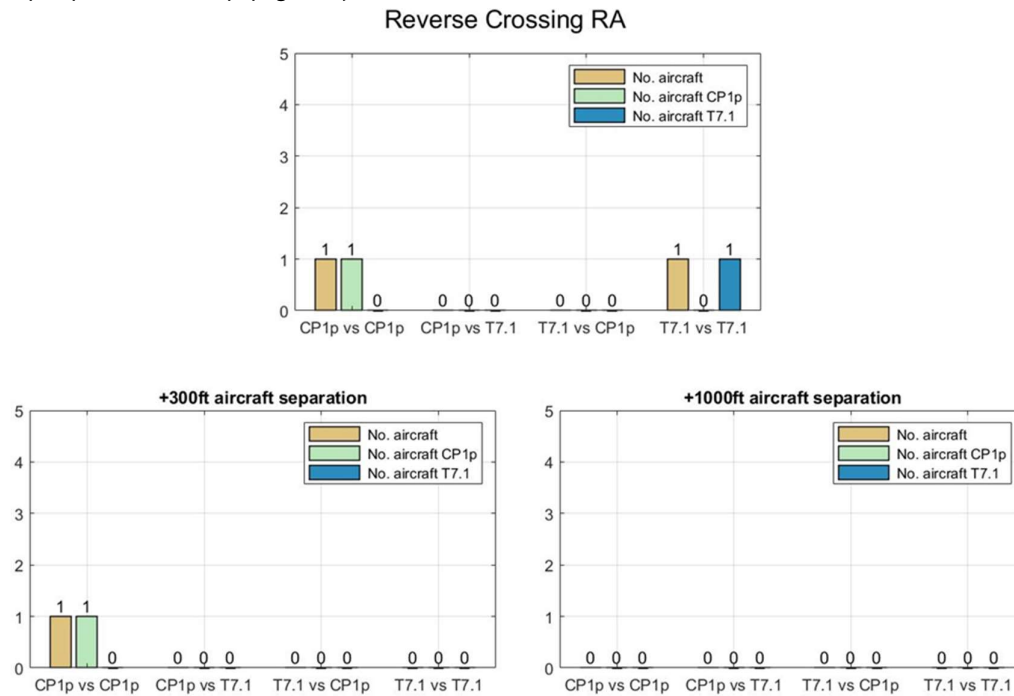
See P2o3

### 5.4.2.3. P2o13 Reverse crossing RA alert (encounter perspective) (Interop)

#### 5.4.2.3.1. Radar data

Confidence

- EE perspective same equipage: very low



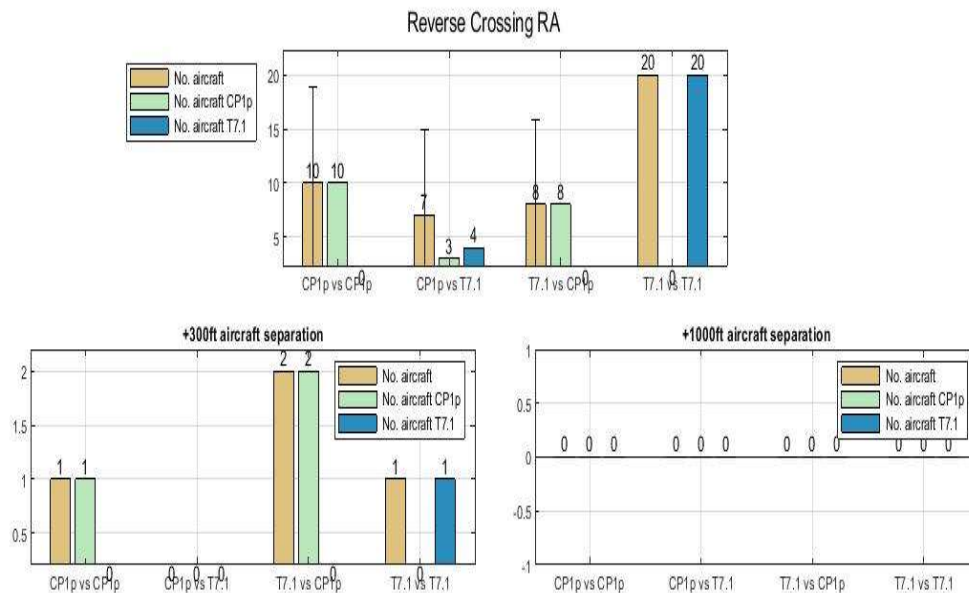
**Figure 70 Radar data reverse crossing RA**

There was insufficient radar data to compare reverse crossing RAs on ACAS Xa CP1 and TCAS II V7.1

#### 5.4.2.3.2. ATM model

Confidence

- EE same equipage: 96.7%



**Figure 71 ATM model reverse crossing RA**

Even with the ATM model, reverse crossing RAs could only be assessed on a whole airspace perspective showing that ACAS Xa CP1 is expected to reduce the number of reverse crossing RAs.

### 5.4.3. Überlingen-like subset - one pilot does not follow the RAs

#### 5.4.3.1. P2o14 Efficient reverse RA alert rate (interop)

Out of scope – performed by US

#### 5.4.3.2. P2o15 Rate of RA sequences with more than one reverse RA on-board the same aircraft (aircraft perspective) (interop)

Out of scope – performed by US

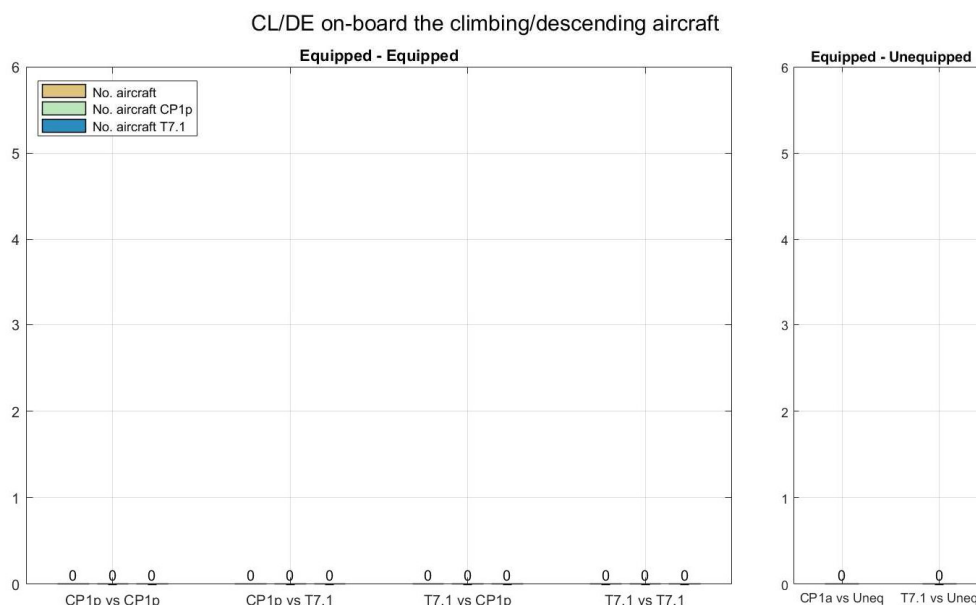
## 5.4.4. 1,000 feet level-off subset - pilots follow the RAs

### 5.4.4.1. P2o16 Climb/descend RA alert rate on-board descending/climbing aircraft (aircraft perspective)

#### 5.4.4.1.1. Radar data

Confidence

- EE same equipage: -
- EU: -



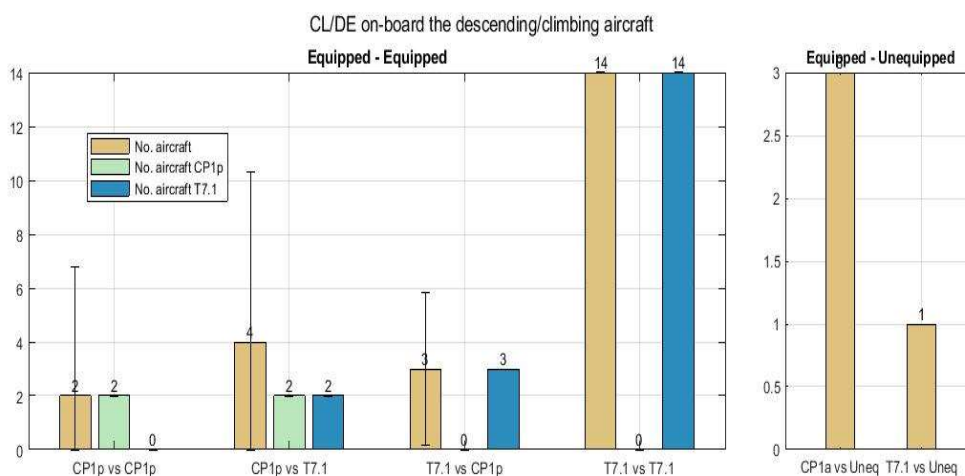
**Figure 72 Radar data climb/descend RA on-board descending/climbing aircraft**

There was insufficient radar data to assess this metric.

#### 5.4.4.1.2. ATM model

Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >95%
- EU: inadequate data (fewer than 5 cases for each system).



**Figure 73 ATM model climb/descend RA on-board descending/climbing aircraft**

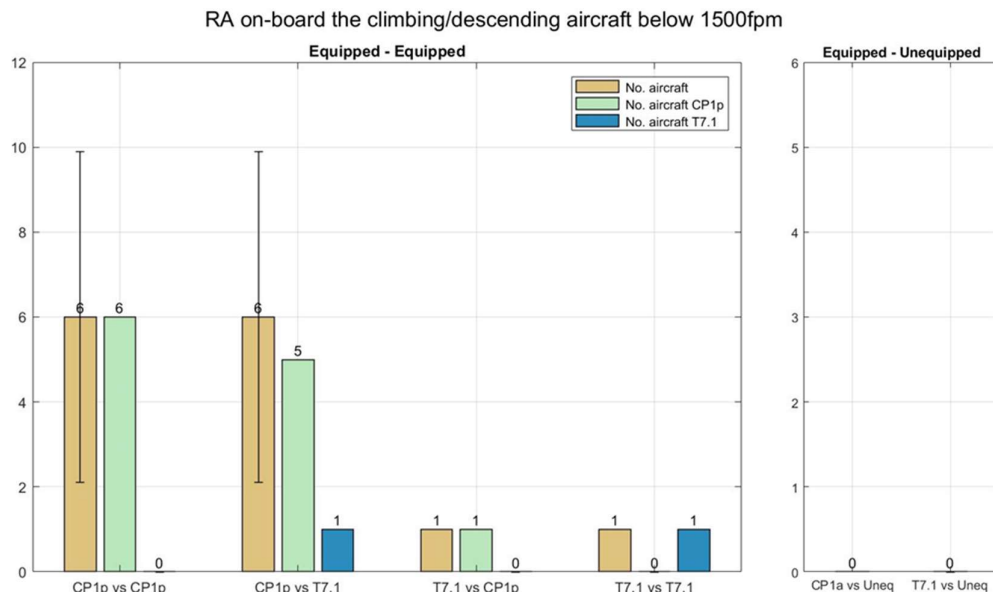
Based on the ATM model, it is expected that ACAS Xa CP1 will reduce the number of opposite sense RAs on climbing/descending aircraft during a level off encounter. The uncertainties are too large to accurately estimate this improvement.

#### 5.4.4.2. P2o17 RA alert rate on-board aircraft climbing/descending below 1,500 fpm (aircraft perspective)

##### 5.4.4.2.1. Radar data

###### Confidence

- EE same equipage: 96%
- EU: -

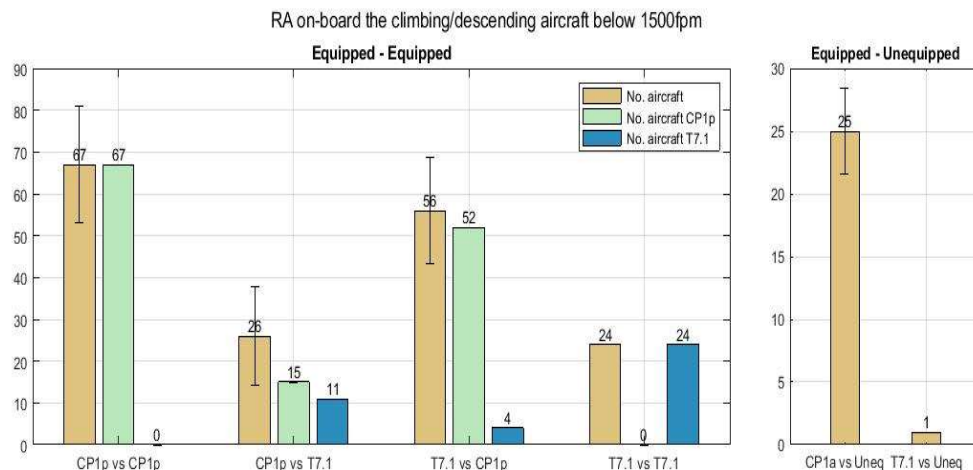


**Figure 74 Radar data RA on-board climbing or descending aircraft < 1,500 fpm**

##### 5.4.4.2.2. ATM model

###### Confidence

- EE same equipage: >99%
- EU: >99%



**Figure 75 ATM model RA on-board climbing or descending aircraft < 1,500 fpm**

Both the radar data and the ATM model suggest a statistically significant increase in the number of RAs issued on an aircraft climbing or descending <1500fpm to level off. As ICAO recommends 1500 fpm vertical rate in the last 1000' before levelling if a pilot is aware of adjacent traffic (e.g. due to a TA or traffic information) it is important to ensure that following this advice rarely allows RAs to occur. Fortunately this was indeed the case, with only 6 cases observed in 12 million flight hours of radar data. Also, overall ACAS Xa CP1 reduces the number of alerts in level off situations.



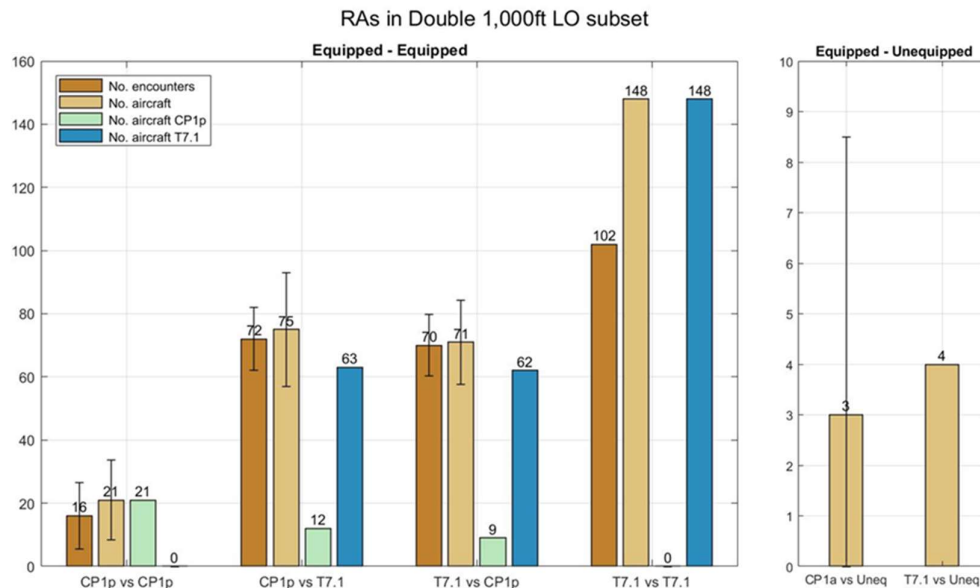
## 5.4.5. Double 1,000 feet level-off subset – pilots follow RAs

### 5.4.5.1. P2o18 RA alert rate (Interop)

#### 5.4.5.1.1. Radar data

##### Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU: 63%



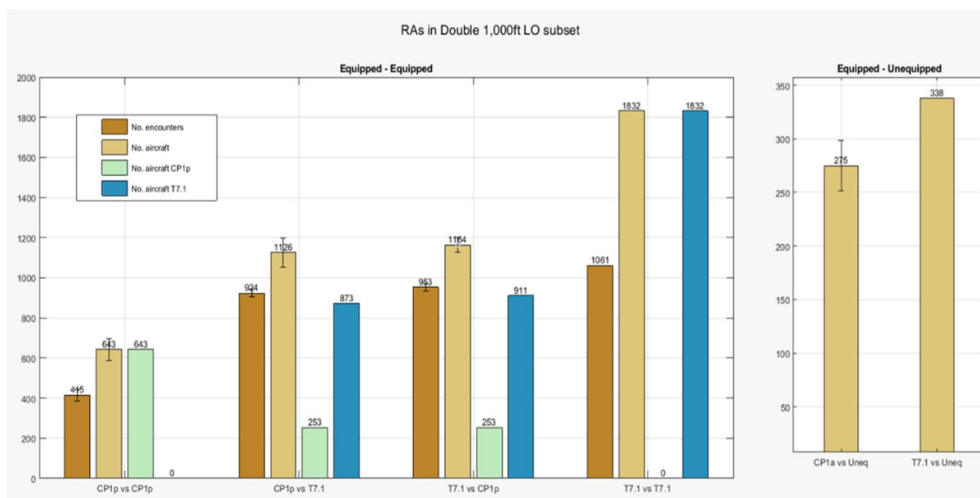
**Figure 76 Radar data RAs in double 1,000 ft level off subset**

Double 1000ft level off encounters occur when two aircraft simultaneously level off 1000ft apart and at least one receives an RA. In EE encounters (the vast majority of double level off cases) based on radar data ACAS Xa CP1 reduces the number of alerts by 86%.

#### 5.4.5.1.2. ATM model

##### Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU: >99%



**Figure 77 ATM model RAs in double 1,000 ft level off subset**

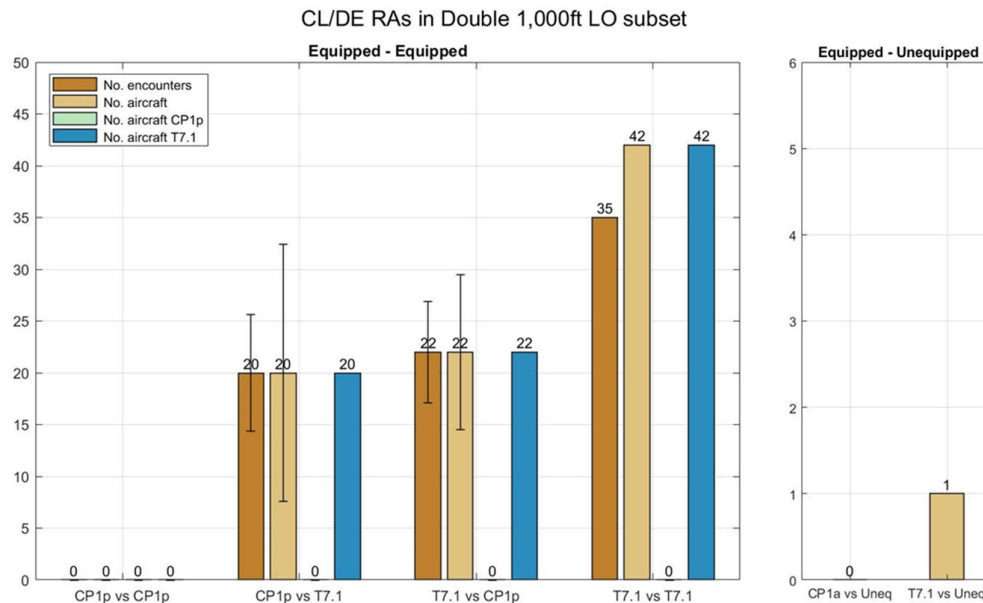
Based on the ATM model, ACAS Xa CP1 reduces the number of EE double level off RAs by 65% and the number of EU double level off RAs by 19%.

## 5.4.5.2. P2o19 Climb/Descend RA alert rate (aircraft & encounter perspective) (Interop)

### 5.4.5.2.1. Radar data

#### Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU: Insufficient data



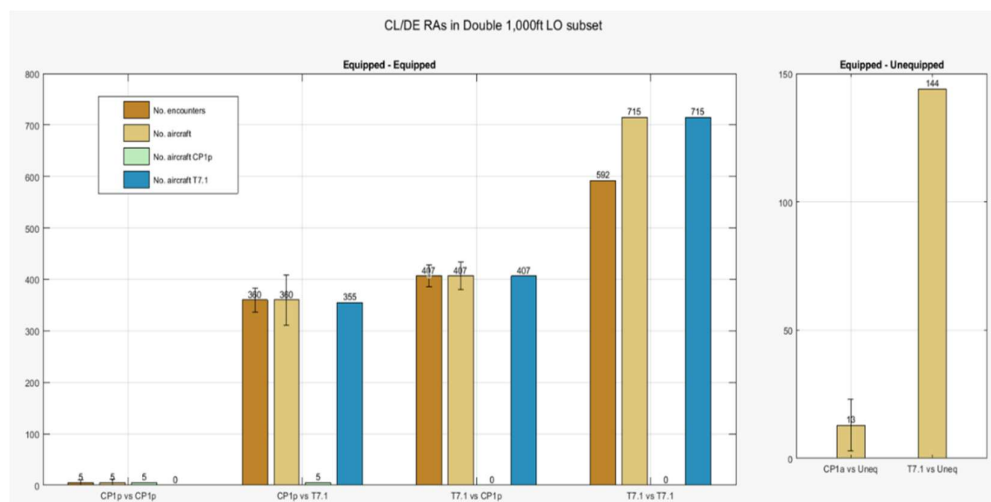
**Figure 78 Radar data climb/descend RA in double 1,000 ft level off subset**

Based on radar data, ACAS Xa CP1 reduces the number of climb/ descend RAs in EE double level off encounters by 52%.

### 5.4.5.2.2. ATM model

#### Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU: >99%



**Figure 79 ATM model climb/descend RA in double 1,000 ft level off subset**

Based on the ATM model, ACAS Xa CP1 reduces the number of climb/ descend RAs in EE double level off encounters by 99% and by 91% in EU double level off encounters. The radar data figures probably provide better estimates for these improvements because they include perturbations not included in the ATM model.

## 6. Analysis of results

### 6.1. SESAR acceptance criteria Priority 1

#### 6.1.1. Safety

Table 14 Results summary – Priority 1 safety metrics

ID	Metric	Result
<b>Pilots follow the RAs</b>		<b>Safety model</b>
<b>Overall airspace (EE+EU)</b>		
<b>P1s1</b>	Risk Ratio (ALT)	Between -16% and -24% depending upon intruder ADS-B out equipage. However in Layer 2 with intruders that do not have ADS-B out, +39% (94% confidence).
<b>P1s2</b>	Induced Risk Ratio	No statistically significant difference observed
<b>P1s3</b>	Unresolved Risk Ratio	Between 17% and 27% improvement
<b>P1s4</b>	Very close encounters	<u>85% of very close encounters trigger corrective RAs</u>
<b>EE subset</b>		
<b>P1s5</b>	Risk Ratio in EE encounters (INTEROP) (ALT)	Overall there is no significant difference in performance. However in Layer 2 degradation between 12% (intruders with ADS-B out) and 30% (without ADS-B out)
<b>One pilot does not follow the RAs<sup>(2)</sup></b>		
<b>P1s6</b>	Risk Ratio in Überlingen-like encounters (INTEROP) (ALT)	<u>Out of scope.</u> Nevertheless CAFE SA01 model is consistent with US results and shows 70% improvement.
<b>P1s7</b>	Risk Ratio in EE encounters when one pilot does not follow the RAs (INTEROP) (ALT)	Improvement better than 5% and up to 47%

Note: Metric ID has format 'P[1,2][s,o]n' where 'P' is for priority, 's' for safety, 'o' for operational acceptance, and n is the metric number.

#### 6.1.2. Operational acceptance

Table 15 Results summary - Priority 1 operational acceptance metrics

ID	Metric	Result	
	<b>Pilots follow the RAs</b>		
	<b>Overall airspace</b>	<b>Radar data</b>	<b>ATM model</b>
<b>P1o1</b>	<b>RA alert rate (aircraft and encounter perspective) (INTEROP)</b>	-68.5% EE (aircraft perspective confidence >99%) -67% EE (encounter perspective confidence >99%) -40% EU (confidence 91%)	-48.5% EE (aircraft perspective confidence >99%) -45.4% EE (encounter perspective confidence >99%) -41.3% EU (confidence >99%) -44.2% Total (aircraft perspective) -43.0% Total (encounter perspective)

	Single 1,000ft LO subset		
P1o2	<b>RA alert rate in single 1,000ft LO encounters (aircraft &amp; encounter perspective)</b> <small>(INTEROP)</small>	-88.6% EE (aircraft perspective confidence >99%) -88.4% EE (encounter perspective >99%) -40% EU (confidence <u>91%</u> )	-74% EE (aircraft perspective confidence >99%) -74.5% EE (encounter perspective >99%) -16.5% EU (confidence 99.8%) -39.9% Total (aircraft perspective) -40.1% Total (encounter perspective)
P1o3	<b>Climb / Descend RA alert rate on-board the level aircraft in single 1,000ft LO encounters (aircraft perspective)</b> <small>(INTEROP)</small>	-30.8% EE (confidence <u>very low</u> ) 0% EU (confidence <u>very low</u> )	-40.9% EE (confidence <u>93.5%</u> ) -30.2% EU (confidence 98.4%) -34.5% Total

## 6.2. SESAR acceptance criteria priority 2

### 6.2.1. Overall airspace

ID	Metric	Result	
	Pilots follow the RAs	Safety model	
P2s1	Risk Ratio in multi-aircraft encounters	Out of scope	
		Radar data	ATM model
P2o1	RA alert rate in encounters with large horizontal separation (encounter perspective)	-85% EE (confidence >99%) -20% EU (confidence <u>91%</u> )	-87.4% EE ( confidence >99%) -28.2 EU (confidence >99%) -52.2% Total
P2o2	Rate of encounters with high vertical deviations	>300 ft 44% EE (aircraft perspective confidence <u>80%</u> ) 33% EE (encounter perspective confidence <u>77%</u> ) <u>39%</u> EU (confidence 99%)	>300 ft <u>+10.4%</u> EE (aircraft perspective confidence <u>88.9%</u> ) <u>+2.22%</u> EE (encounter perspective confidence <u>60.5%</u> ) -31.3% EU (confidence >99%) -14.4% Total (aircraft perspective) -17.7% Total (encounter perspective)
		>600 ft -% EE (aircraft perspective confidence very low) -% EE (encounter perspective confidence very low) 11% EU (confidence 60%)	>600 ft <u>+20.0%</u> EE (aircraft perspective confidence <u>69.5%</u> ) <u>+20.0%</u> EE (encounter perspective confidence <u>69.5%</u> ) -47.0% EU (confidence >99%) -19.8% Total (aircraft perspective) -19.8% Total (encounter perspective)
P2o3	Reverse RA alert rate (aircraft perspective)	-60% EE (confidence 85%) +112.5% EU (confidence 98%)	-82.0% EE ( confidence >99%) <u>+36.5%</u> EU (confidence 98.3%) -11.6% Total
P2o4	Crossing RA alert rate (aircraft perspective)	-40% EE (confidence <u>75%</u> ) -33% EU (confidence <u>90%</u> )  Crossing level off RA -100% EE ( confidence <u>very low</u> ) <u>+400%</u> EU (confidence 99%)	-39.9% EE (confidence >99%) -45.2% EU (confidence >99%) -43.0% Total  Crossing level off RA -85.7% EE (confidence 99.95%) -25.9% EU (confidence 95%) -50.2% Total.

<b>ID</b>	<b>Metric</b>	<b>Result</b>	
<b>P2o5</b>	<b>Strengthening RA sequence alert rate (aircraft perspective)</b>	-84% EE (confidence 99.9%) -65.5% EU (confidence >99%)	-84.6% EE (confidence >99%) -64.7% EU (confidence >99%) -72.8% Total
<b>P2o6</b>	<b>Very complex RA sequence alert rate (aircraft perspective)</b>	-100% EE (confidence <i>very low</i> ) -55.5% EU (confidence <i>91%</i> )	-88.9% EE (confidence >99%) -58.1% EU (confidence >99%) -70.6% Total
<b>P2o7</b>	<b>Time between TA and initial RA</b>	-35.3% EE fewer RAs less than 6% although 57% increase in RAs with no TA. +46% EU	-22.3% EE confidence >99% <u>+132%</u> EU confidence >99% <u>+69.3%</u> Total
<b>P2o8</b>	<b>Time between initial and secondary RA</b>	-91.7% EE confidence >99.9% -68.8% EU confidence > 99%	-93.7% EE confidence >99.9% -74.6% EU confidence 99.9% -78.1% Total
<b>P2o9</b>	<b>Early Clear of Conflict alert rate (aircraft perspective)</b>	-66.4% EE confidence >99.9% -82.5% EU confidence >99.9%	-45.1% EE confidence >99.9% -37.4% EU confidence >99.9% -40.5% Total
<b>P2o10</b>	<b>Split RA sequence alert rate</b>	-100% EE (aircraft perspective confidence <i>very low</i> ) -100% EE (encounter perspective confidence <i>very low</i> ) -77% EU (confidence 99%)	-88.6% EE (aircraft perspective confidence >99%) -91.8% EE (encounter perspective confidence >99%) -96.7% EU (confidence 99%) -93.4% Total (aircraft perspective) -94.7% Total (encounter perspective)

### 6.2.2. Equipped-Equipped subset

ID	Metric	Results	
	Pilots follow the RAs	Radar data	ATM model
P2o11	Crossing RA alert rate in EE encounters (encounter perspective) <sup>(INTEROP)</sup>	-67% EE (confidence <u>very low</u> )	-39.9% EE (confidence >99%) -75.6% EE (asymmetrical crossing confidence >99%)
P2o12	Reverse RA alert rate in EE encounters (encounter perspective) <sup>(INTEROP)</sup>	-50% EE (confidence <u>77%</u> )	-80.7% EE (confidence 98.3%)
P2o13	Reverse Crossing RA alert rate in EE encounters (encounter perspective) <sup>(INTEROP)</sup>	0% EE (aircraft perspective confidence <u>very low</u> )	-50.0% EE (aircraft perspective confidence 96.7%) Encounter perspective not available.

### 6.2.3. Überlingen-like subset

ID	Metric	Results	
	One pilot does not follow the RAs	Radar data	ATM model
P2o14	Efficient Reverse RA alert rate in Überlingen-like encounters (encounter perspective) <sup>(INTEROP)</sup>	<u>Out of scope</u>	<u>Out of scope</u>
P2o15	Rate of RA sequences with more than one Reverse RA on-board the same aircraft in Überlingen-like encounters (aircraft perspective) <sup>(INTEROP)</sup>	<u>Out of scope</u>	<u>Out of scope</u>

### 6.2.4. 1,000 feet level-off subset

ID	Metric	Results	
	Pilots follow the RAs		
	Single 1,000ft LO subset	Radar data	ATM model
P2o16	Climb / Descend RA alert rate on-board descending / climbing aircraft in single 1,000ft LO encounters (aircraft perspective)	-% EE (confidence -) -% EU	-85.7% EE (confidence 99.9%) <u>200.0% EU</u> (confidence <u>very low</u> ) +84.0% Total
P2o17	RA alert rate on-board aircraft climbing / descending below 1,500fpm in single 1,000ft LO	<u>500%</u> EE (confidence 96%)	<u>+179%</u> EE (confidence >99%) <u>+2,400%</u> EU (confidence >99%)

ID	Metric	Results	
	encounters (aircraft perspective)		<b>+1500%</b> Total
	Double 1,000ft LO subset		
<b>P2o18</b>	RA alert rate in double 1,000ft LO encounters (encounter perspective) <small>(INTEROP)</small>	-84% EE (confidence >99%) -25% EU (confidence <u>63%</u> )	-60.9% EE (confidence >99%) -18.6% EU (confidence >99%) -35.8% Total
<b>P2o19</b>	Climb / Descend RA alert rate in double 1,000ft LO encounters (aircraft & encounter perspective) <small>(INTEROP)</small>	-100% EE (aircraft perspective confidence >99%) -100% EE (encounter perspective confidence >99%) -100% EU (confidence <u>very low</u> )	-99.3% EE (aircraft perspective confidence >99%) -99.2% EE (encounter perspective confidence >99%) -91.0% EU (confidence >99%) -94.4% Total (aircraft perspective) -94.3% Total (encounter perspective)



## 7. Conclusions, Analysis and Recommendations

### 7.1. Conclusions

The safety and operational acceptance performance of ACAS Xa CP1 has been compared with TCAS V7.1 using fast-time simulation of model encounters and recorded radar data. Results with statistical confidence above 95% were used as a threshold for comparisons with SESAR acceptability criteria. Of ten Priority 1 SESAR acceptability criteria, seven were within the threshold limits at least partially, two were outside the threshold limits at least partially and one showed no significant difference between TCAS II and ACAS Xa CP1.

The main benefits of ACAS Xa CP1 are  
Priority 1

- Improvement in the overall airspace risk ratio from 4.9% for TCAS II V7.1 to between 4.2% (ACAS Xa CP1 vs intruders without ADS-B out) and 3.7% (ACAS Xa CP1 vs intruders with ADS-B out). This is a safety improvement of between 16% and 24%
- Improvement in the risk ratio for equipped-equipped encounters where one pilot does not follow their RA from 3.9% to 2.1%. This is a safety improvement of about 47%.
- Reduction in the overall number of RAs in the airspace by 60% (from 1624 to 638 in 12 million flight hours)
- In encounters where a single aircraft is levelling off 1000ft from another aircraft in level flight, ACAS Xa CP1 reduces the number of RAs by 86%.

In addition, the requirement that ACAS Xa CP1 is implemented with extended hybrid surveillance is expected long term to reduce transponder occupancy and frequency usage due to ACAS interrogations by about 90%.

The following metrics were identified, with statistical confidence above 99%, as not meeting the SESAR acceptability criteria:

Priority 1

- Risk ratio in equipped versus equipped encounters in Layer 2 between 5,000 and 13,500 feet is increased from 0.36% to 0.46% for non ADS-B out intruders and to 0.40% for intruders with ADS-B out. This is due to induced risk during vertical chase encounters. (According to the SESAR acceptability criteria 'If there is a substantial overall benefit, a marginal degradation may be tolerated in some altitude bands'.)
- 85% of very close encounters trigger corrective RAs compared to 97% with TCAS.

Priority 2

The following operationally undesirable effects were seen in 12 million flight hours of recorded radar data:

- Rate of encounters with high vertical deviations above 300 feet for equipped versus unequipped (99 encounters observed with ACAS Xa CP1 vs 71 observed with TCAS II V7.1).
- RA alert rate on board aircraft climbing/descending below 1,500 feet per minute in single 1,000 foot level-off encounters. (6 encounters observed with ACAS Xa CP1 vs 1 observed with TCAS II V7.1).
- ACAS Xa CP1 did not issue a TA at least 5 s before an RA in 104 equipped versus unequipped encounters compared with 71 for TCAS II.

### 7.2. Analysis

The lower performance values of some SESAR metrics should be put in context.

For the increase in risk ratio between FL50 and FL135 for EE encounters:

- Overall airspace there is an improvement in the absolute value of risk ratio between 0.7 and 1.2%.
- ACAS Xa CP1 is nevertheless a very effective collision avoidance system for these encounters with a risk ratio of 0.46% or better.
- The degradation of the absolute value of risk ratio is less than 0.1% in layer 2 EE encounters. If more than 1 in 18 pilots do not follow their RAs in such encounters this is mitigated by the 1.8% improvement in safety of ACAS Xa CP1 when one pilot does not follow their RAs. Operational studies suggest that the true figure is higher than this.

- ACAS Xa CP1 has better resilience to stressing encounters such as SA01 encounters (Überlingen – like) and enhanced FTEG (Fast Time Encounter Generator) encounters, and therefore is likely to be more resilient to encounters that may be under-represented in airspace encounter models such as CAFE.

For the very close encounters that do not trigger corrective RAs:

- These encounters do not have a substantial negative effect on the collision risk. RTCA SC147 and WG75 operational working groups discussed this SESAR metric and jointly agreed that the lack of alerting for some encounters with ACAS Xa CP1 is acceptable as part of a trade-off in reduced alert rate and collision risk. If appropriate, new training material could be developed to explain this design choice.

For reference, EASA requires false or misleading alerts to be less frequent than 1 in  $10^5$  flight hours in en-route airspace and less frequent than 1 in  $10^4$  flight hours in TMA. In 12 million flight hours, this corresponds to 120 or 1200 alerts respectively.

For encounters with high deviations that risk creating a new conflict with a 3<sup>rd</sup> aircraft:

- Multi-threat RAs occur in less than 1% of RA encounters. Therefore it is expected that on average there would be less than 1 occurrence of an additional unnecessary RA in 12 million flight hours. In fact, no such 3<sup>rd</sup> aircraft interaction was observed in the radar data with TCAS II V7.1.

## 7.3. Recommendations

Based on the conclusions above it is recommended:

1. That ACAS Xa CP1 is considered acceptable for European operations.

In view of:

- The improved performance of ACAS Xa CP1 against intruders with ADS-B out;
- The desirability to reduce induced risks with ACAS Xa CP1, especially in altitudes between FL50 and FL135;
- The desirability to create a single document containing all technical requirements for ACAS X;
- The different timing of RAs and the limited types of RAs that can be issued;
- The inherent limitations of any validation process.

it is also recommended that

2. There should be assessment of whether the use of ADS-B out should be encouraged on smaller aircraft to benefit from the improvement brought by ACAS Xa CP1 passive surveillance;
3. EUROCAE/RTCA should be supported to create a revision to ACAS Xa MOPS that incorporates all accepted change proposals;
4. Training material for ACAS Xa should note that some very close encounters will not result in RAs and RAs are not always preceded by a timely TA;
5. There should be focussed monitoring of ACAS Xa from its introduction into European operations.

## 8. References

1. Description of Collision Avoidance Fast-time Evaluator (CAFE) Revised Encounter Model for Europe (CREME, Single European Sky Air traffic management (SESAR) ), Deliverable D2.1.090, Edition 1.0, March 2022.
2. Minimum Operational Performance Standards for Airborne Collision Avoidance System X (ACAS Xa and ACAS Xo), RTCA DO-385, 2<sup>nd</sup> October 2018.
3. Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System II (TCAS II), Versions 7.1, Change 2, 20<sup>th</sup> March 2013.
4. SESAR vision of European acceptability criteria for ACAS Xa development, Single European Sky Air traffic management (SESAR), D101, Edition 1.02, 30<sup>th</sup> November 2015.
5. European safety encounter model, ACAS on Very Light Jets and Light Jets – Assessment of safety Level (AVAL), 13 May 2009.
6. Encounter model for safety-net related occurrences specification, Performance and safety Aspects of Short-term Conflict Alert – full Study (PASS), 9<sup>th</sup> May 2020.
7. CREME SA01 Model description, Garfield Dean, February 2022
8. Correlated Encounter Model for Cooperative Aircraft in the National Airspace System, Version 1.0, Kochenderfer, M. J., Espindle, L. P., Kuchar, J. K., Griffith, J. D., Lincoln Laboratory, Project Report ATC 344, 24<sup>th</sup> October 2008.
9. Correlated Encounter Model for Cooperative Aircraft in the National Airspace System, Version 2.0, Underhill, N. K., Harkleroad, E. P., Guendel, R. E., Weinert, A. J., Maki, D. E., Edwards, M. W. M., Lincoln Laboratory, Project Report ATC 440, 8<sup>th</sup> May 2018.
10. ACAS Xa European Verification Final Report, Egis Avia, 17<sup>th</sup> December 2022.
11. Post-Final Review And Comment (FRAC) Operational Validation Report, Traffic Alert and Collision Avoidance System (TCAS) Program Office, Federal Aviation Administration (FAA), 10<sup>th</sup> August 2018.
12. The Assessment of Pilot Compliance with TCAS RAs, TCAS Mode Selection and Serviceability using ATC Radar Data. Version 2.1 Network Manager. 9<sup>th</sup> April 2021.
13. SESAR Solution PJ.13-W2-111: Intermediate Validation Plan (VALP) for V3 - Part I. 10<sup>th</sup> March 2022.
14. Safety Study of TCAS II for Logic Version 6.04, McLaughlin, M. P., and Zeitlin, A. D., MTR 92W102, DOT/FAA/RD-92/22, July 1992.
15. Safety of TCAS II Version 7 in the UK, Hutchinson, H. J., and Carpenter, K. M., DERA/LSB1/ATCSG/ACAS/CR/PAP/11
16. ICAO Annex 10 Volume IV (Surveillance and Collision Avoidance Systems) Section 4.4.2.5 Standard Pilot Model.
17. SESAR Project 09.47 D32 Report on Improved Hybrid Surveillance Validation – Issue 2 01/02/2016
18. DO-385 Change1 CP-001 Operational Validation Report. ACAS\_RPT\_20\_004\_V1R1, DO-385 Change1 CP-001 V1R1. 7<sup>th</sup> January 2020.
19. ACAS Xa/Xo Surveillance Tracking Module Analysis. ACAS-RPT-17-006-V4R0 30<sup>th</sup> September 2017.
20. Standard Pilot Model, ICAO Annex 10 Vol. 4 section 4.4.2.5
21. Degraded Surveillance Analysis. Appendix of [2].

## 9. Appendices

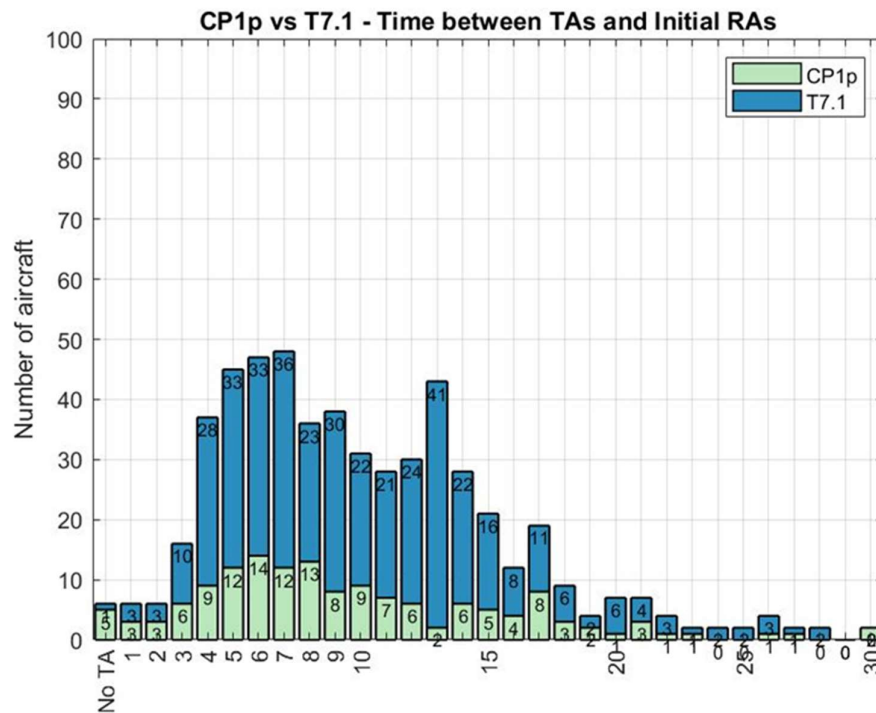
### 9.1. Additional results

#### 9.1.1. Priority 2 overall airspace – pilot follows RA

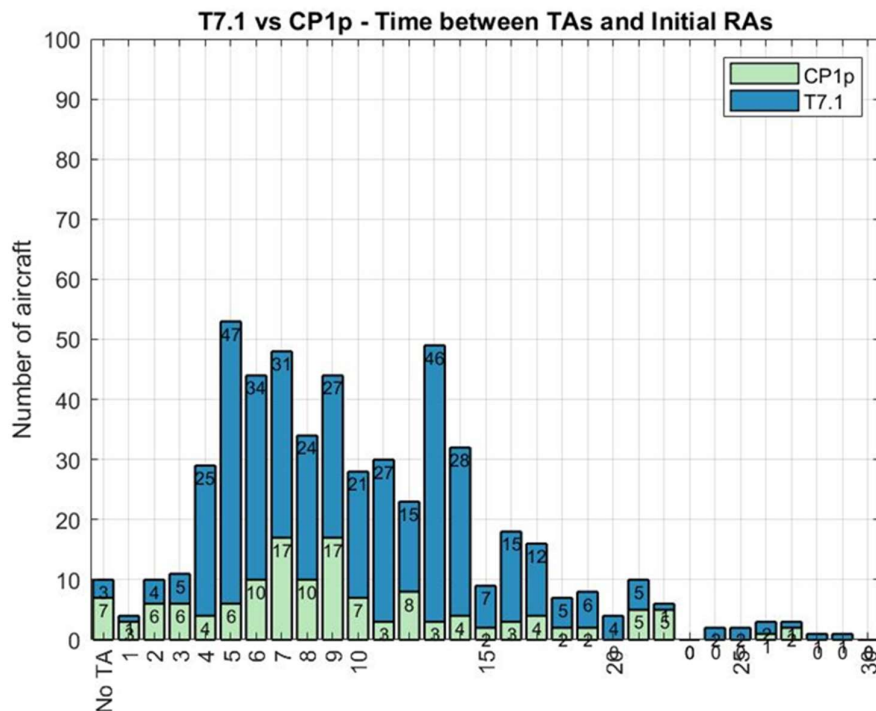
##### 9.1.1.1. Time between TA and initial RA

##### 9.1.1.1.1. Mixed equipage

##### 9.1.1.1.1.1. Radar data

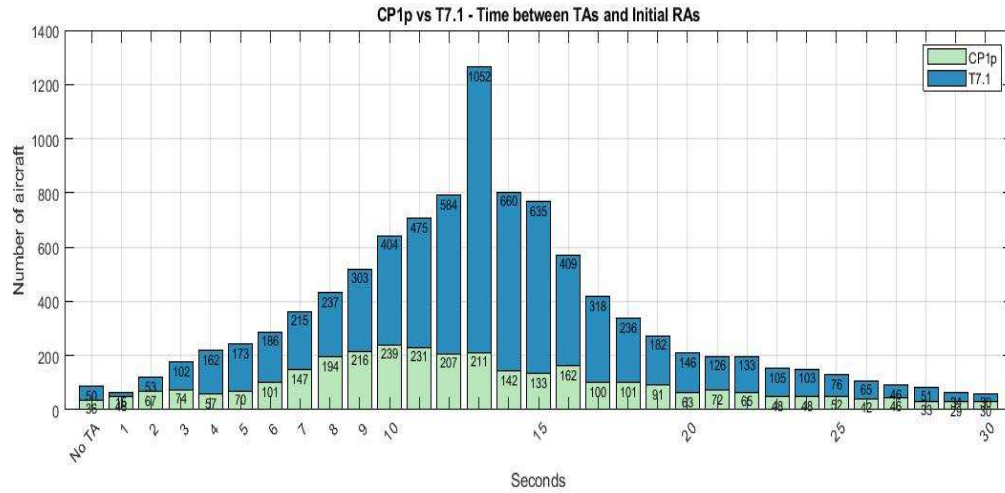


**Figure 80 Radar data time between TA and initial RA – ACAS Xa CP1 passive v TCAS**

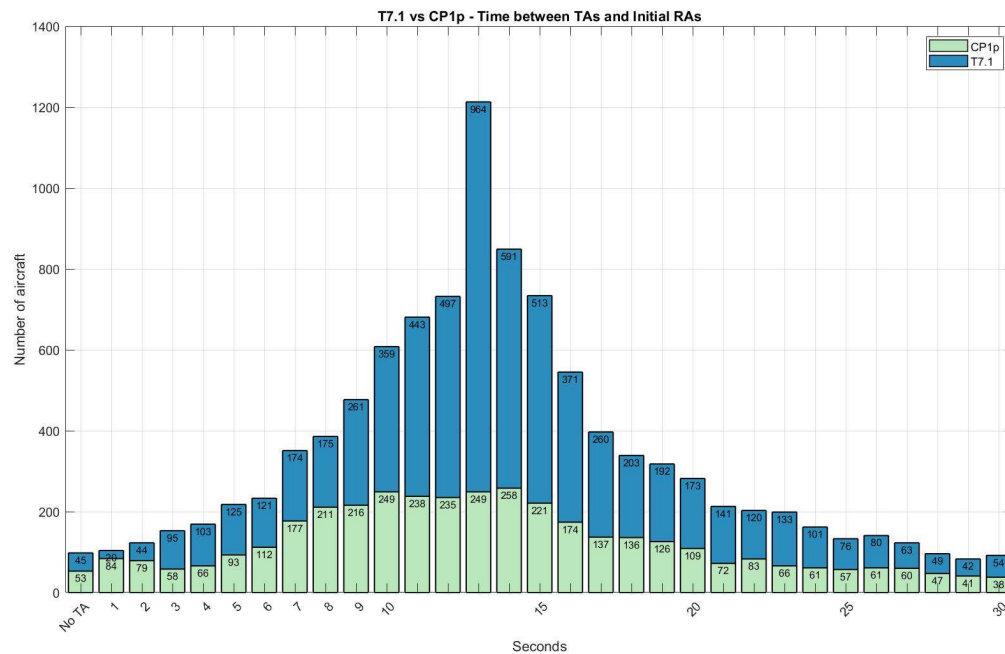


**Figure 81 Radar data time between TA and initial RA – TCAS v ACAS Xa passive**

### 9.1.1.1.2. ATM model



**Figure 82 ATM model time between TA and initial RA – ACAS Xa CP1 passive v TCAS**

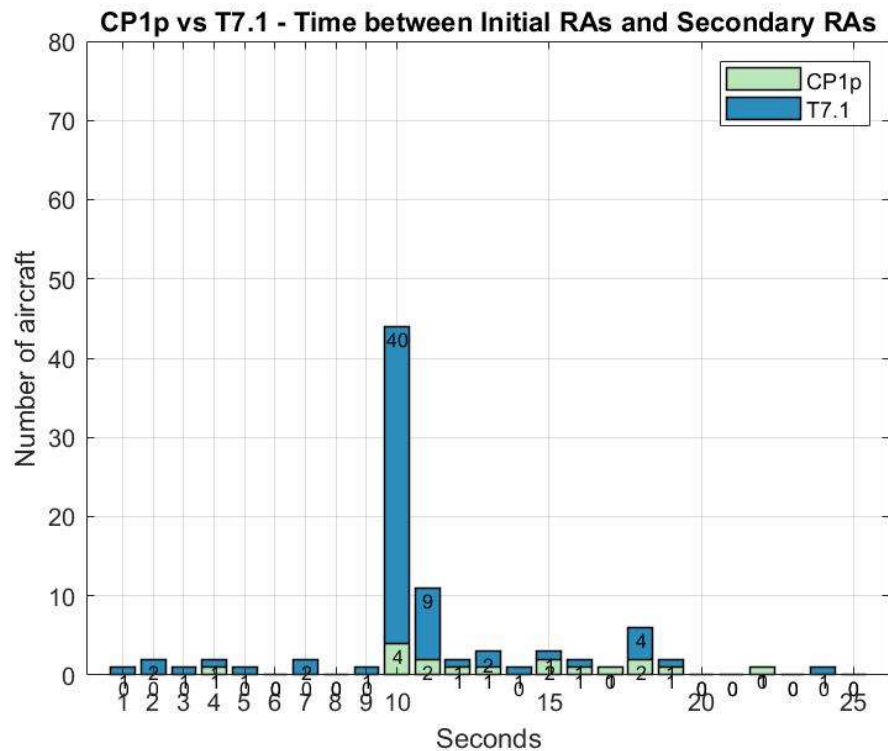


**Figure 83 ATM model time between TA and initial RA – TCAS v ACAS Xa CP1 passive**

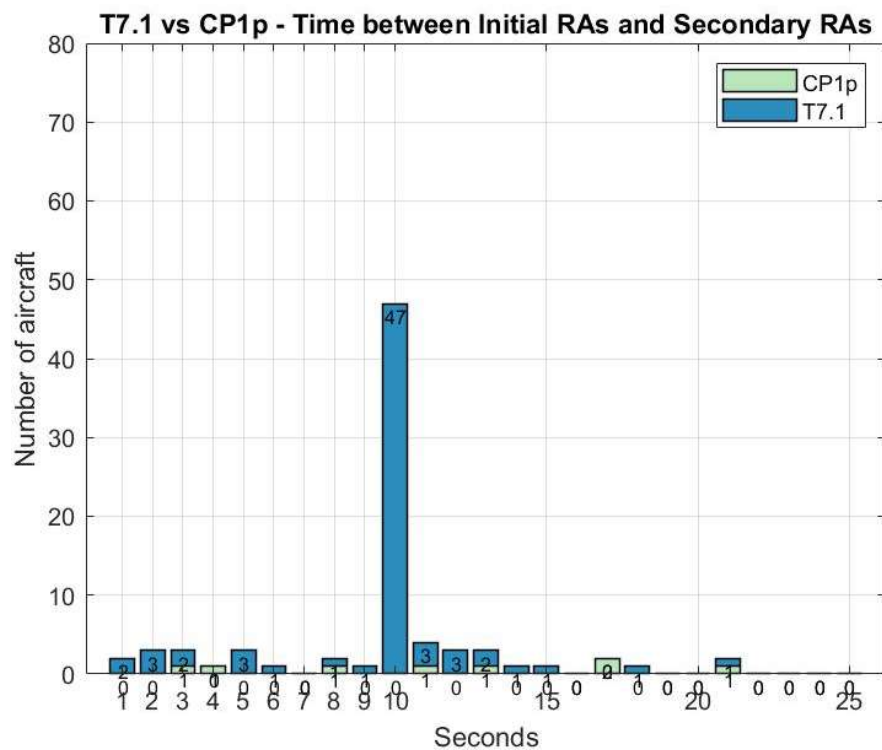
### 9.1.1.2. Time between initial and secondary RA

#### 9.1.1.2.1. Mixed equipage

##### 9.1.1.2.1.1. Radar data

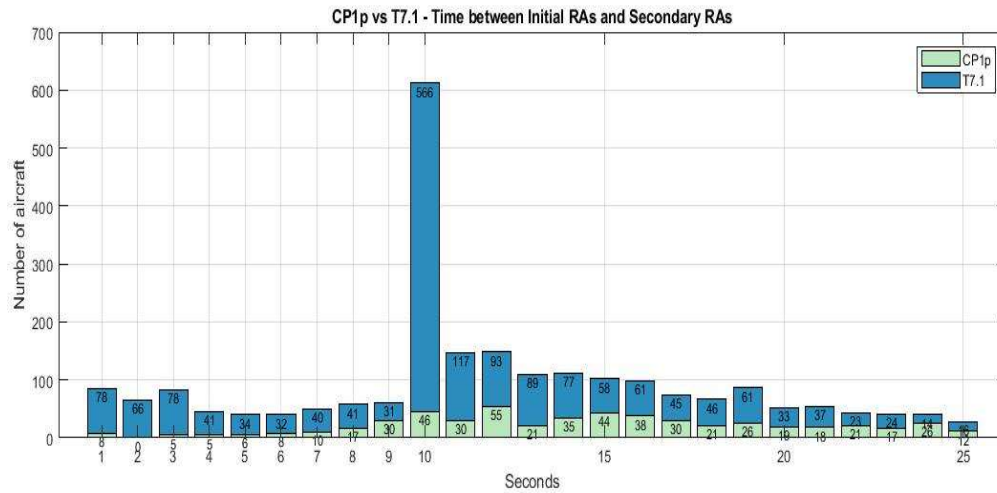


**Figure 84 Radar data time between initial RA and secondary RA – ACAS Xa passive v TCAS**

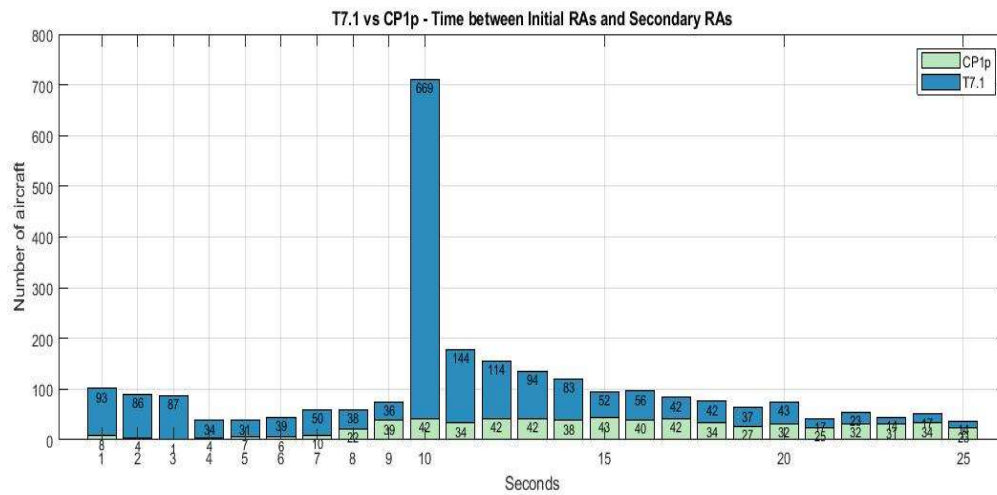


**Figure 85 Radar data time between initial RA and secondary RA – TCAS v ACAS Xa CP1 passive**

### 9.1.1.2.1.2. ATM model



**Figure 86 ATM model time between initial RA and secondary RA – ACAS Xa passive v TCAS**

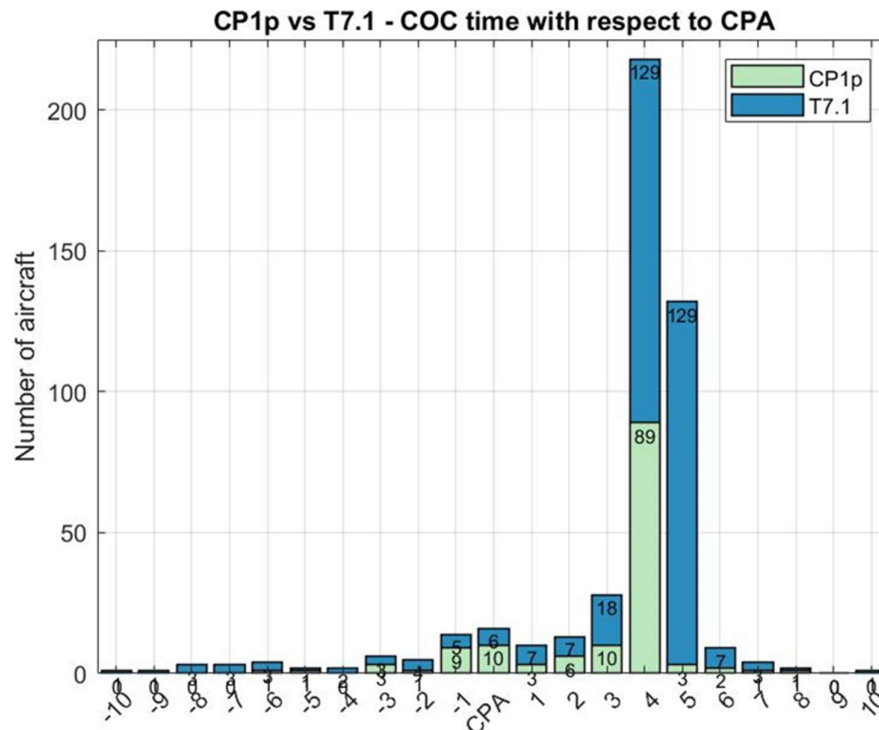


**Figure 87 ATM model time between initial RA and secondary RA – TCAS v ACAS Xa CP1 passive**

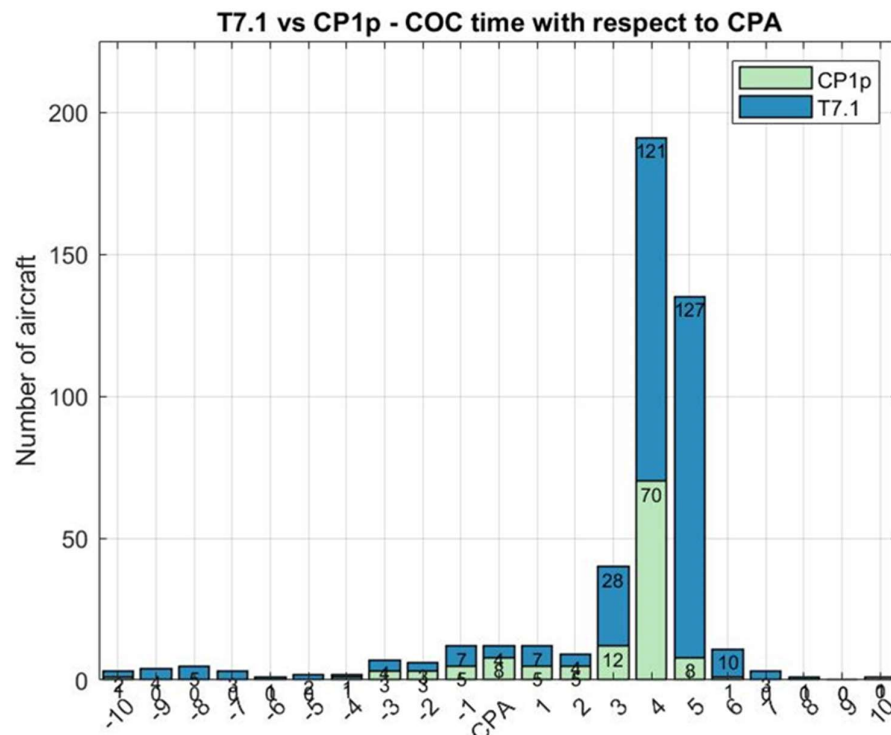
### 9.1.1.3. Early clear of conflict alert rate

#### 9.1.1.3.1. Mixed equipage

##### 9.1.1.3.1.1. Radar data



**Figure 88 Radar data clear of conflict time from CPA – ACAS Xa CP1 passive v TCAS**



**Figure 89 Radar data clear of conflict time from CPA – TCAS v ACAS Xa CP1 passive**



### 9.1.1.3.1.2. ATM model

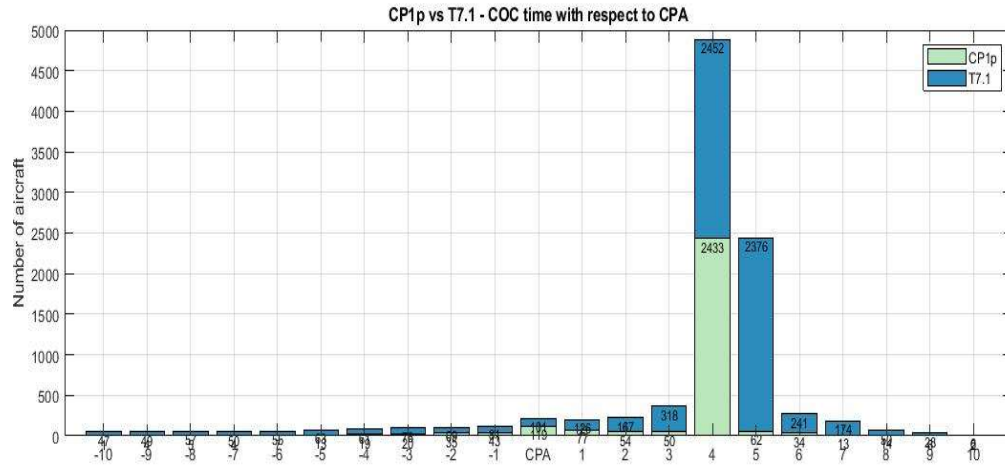


Figure 90 ATM model clear of conflict time from CPA – ACAS Xa CP1 passive v TCAS

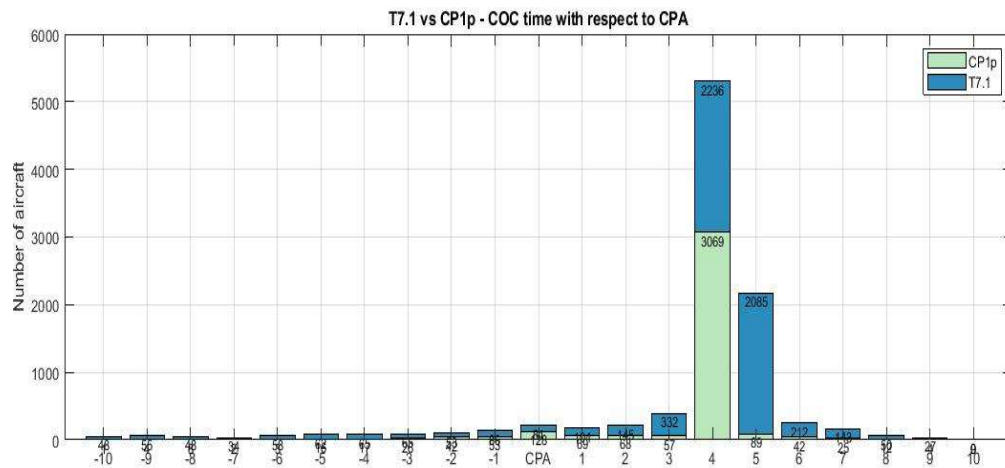


Figure 91 ATM model clear of conflict time from CPA – TCAS v ACAS Xa CP1 passive

## 9.2. Additional metrics

### 9.2.1. Increasing RA

#### 9.2.1.1. Radar data

##### Confidence

- EE encounter perspective same equipage: very low
- EE aircraft perspective same equipage: very low
- EU: 50%

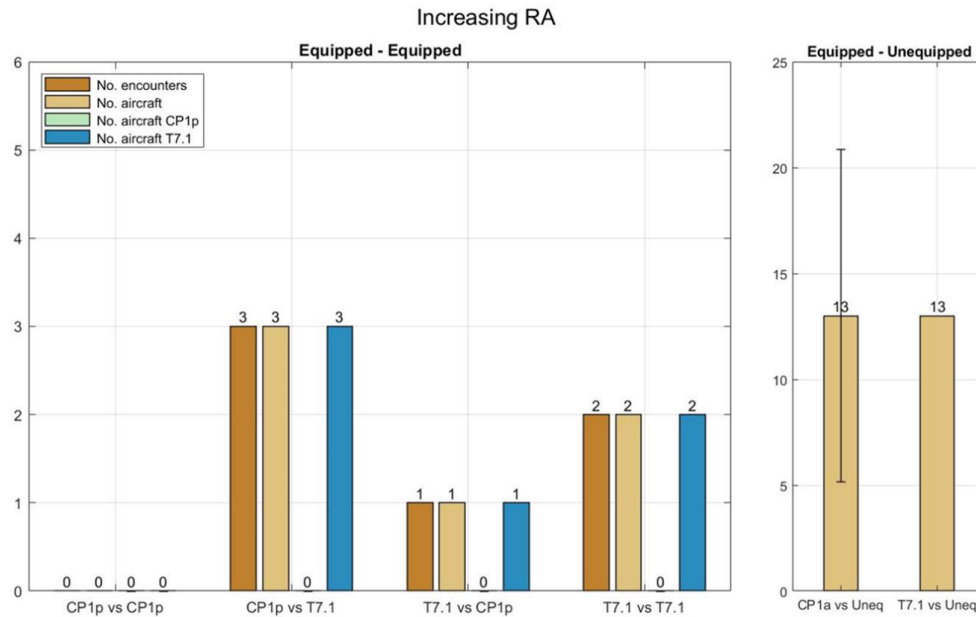


Figure 92 Radar data increasing RA

#### 9.2.1.2. ATM model

##### Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU: 91.5%

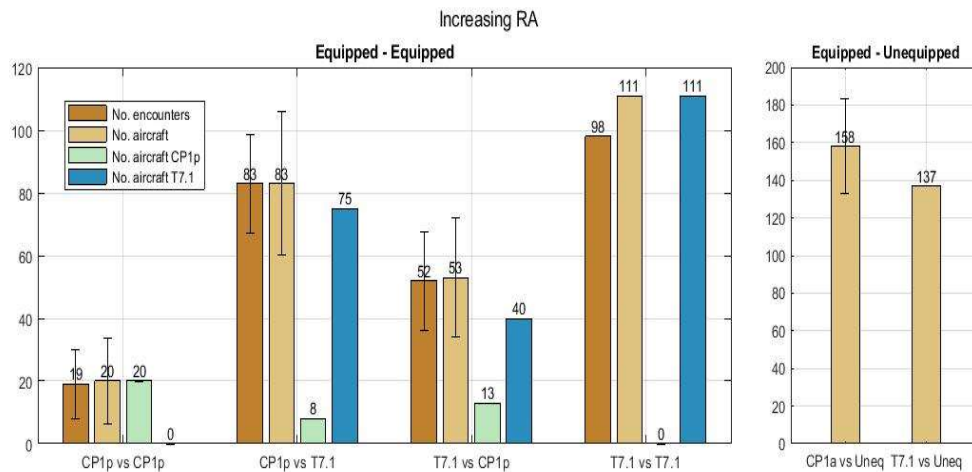


Figure 93 ATM model increasing RA

## 9.2.2. Stressful RAs (crossing, crossing level off, increasing and reversal)

### 9.2.2.1. Radar data

#### Confidence

- EE encounter perspective same equipage: 93%
- EE aircraft perspective same equipage: 93%
- EU: 91%

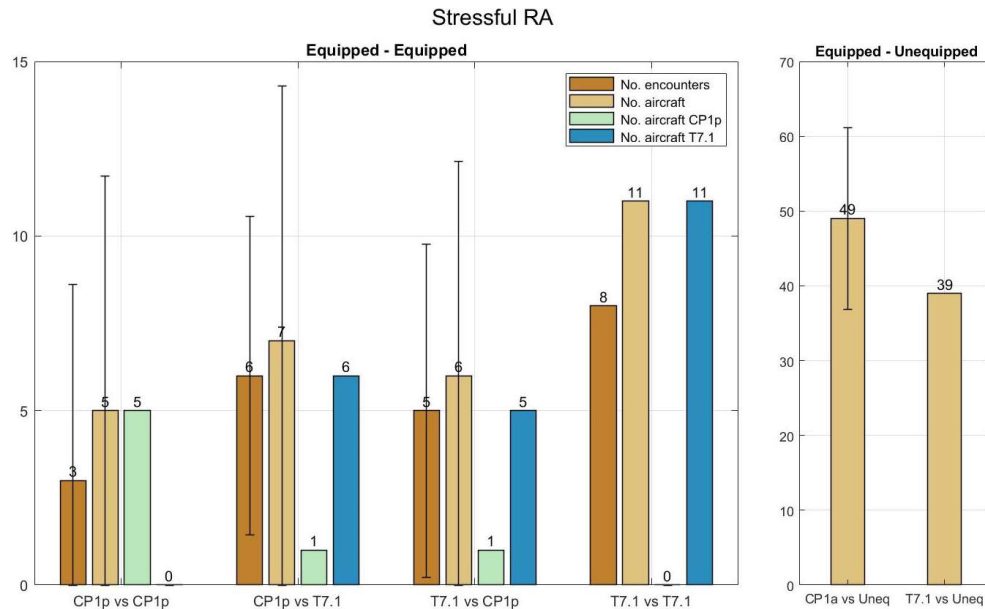


Figure 94 Radar data stressful RA

### 9.2.2.2. ATM model

#### Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU: 99.5%

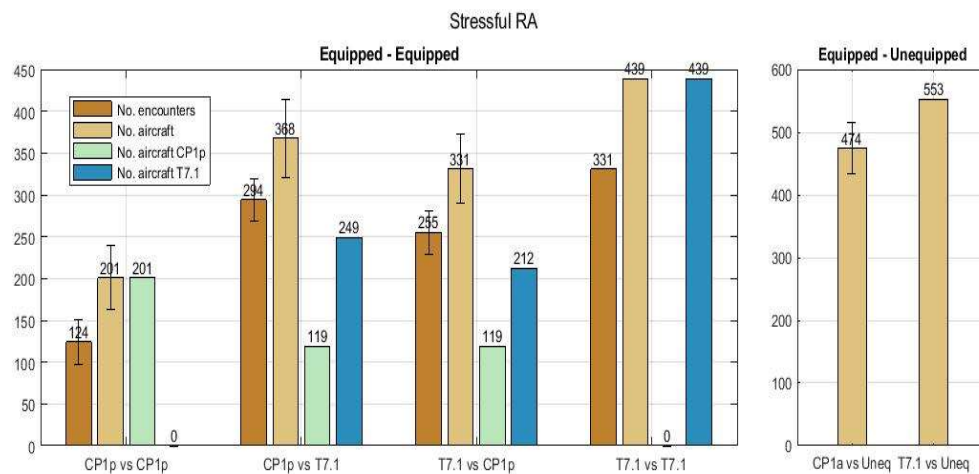


Figure 95 ATM model stressful RA

## 9.2.3. Climb/Descend RAs (Overall Airspace)

### 9.2.3.1. Radar data

#### Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU: >99%

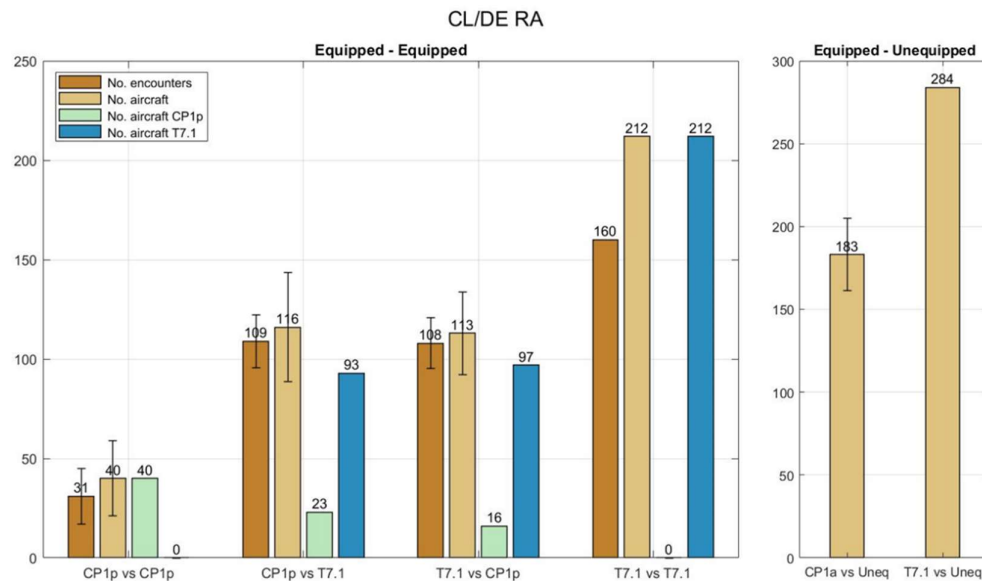


Figure 96 Radar data climb/descend RA

### 9.2.3.2. ATM model

#### Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU: >99%

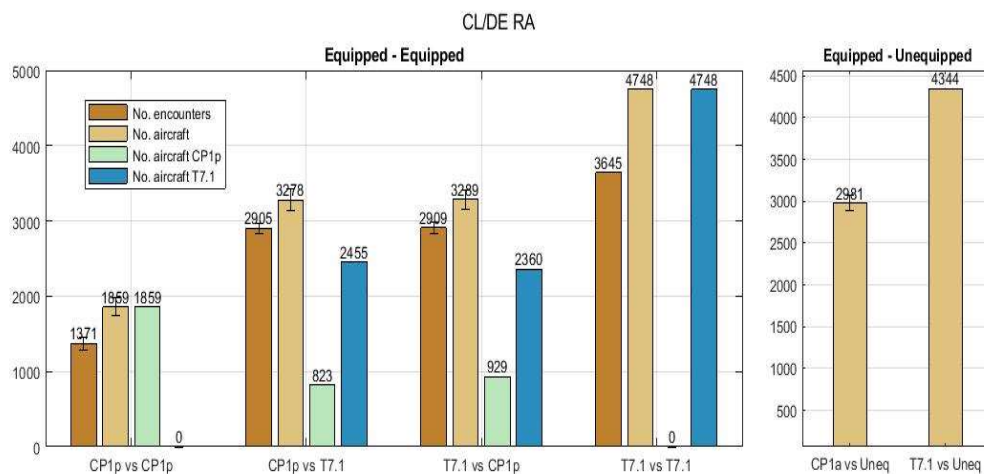


Figure 97 ATM model climb/descend RA

## 9.2.4. Jump geometries (horizontally converging and vertically diverging)

### 9.2.4.1. Radar data

#### Confidence

- EE encounter perspective same equipage: very low
- EE aircraft perspective same equipage: 99%
- EU: very low

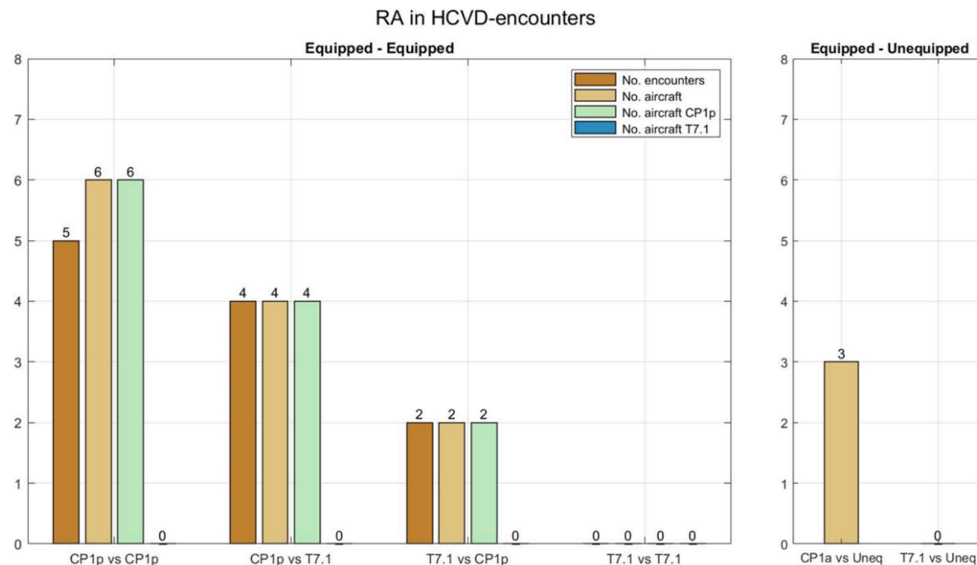


Figure 98 Radar data horizontally converging and vertically diverging

### 9.2.4.2. ATM model

#### Confidence

- EE encounter perspective same equipage: >99%
- EE aircraft perspective same equipage: >99%
- EU: >99%

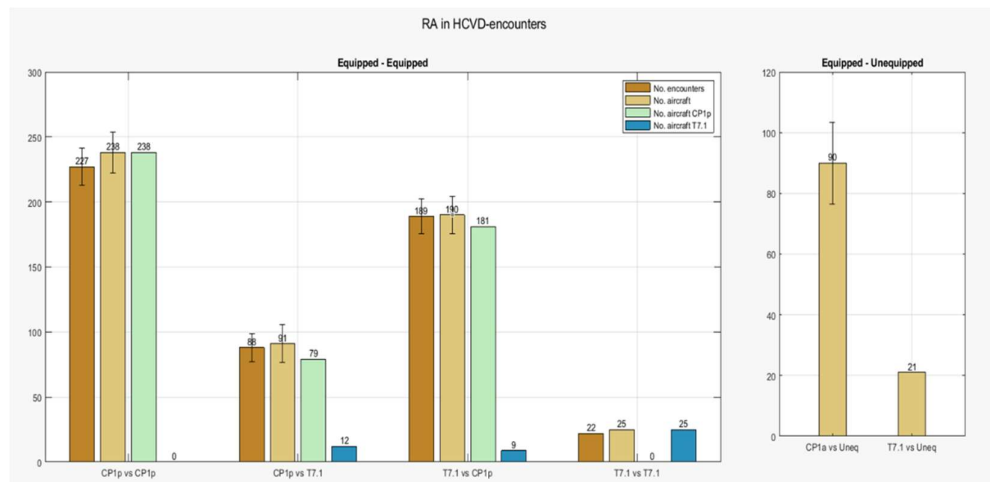
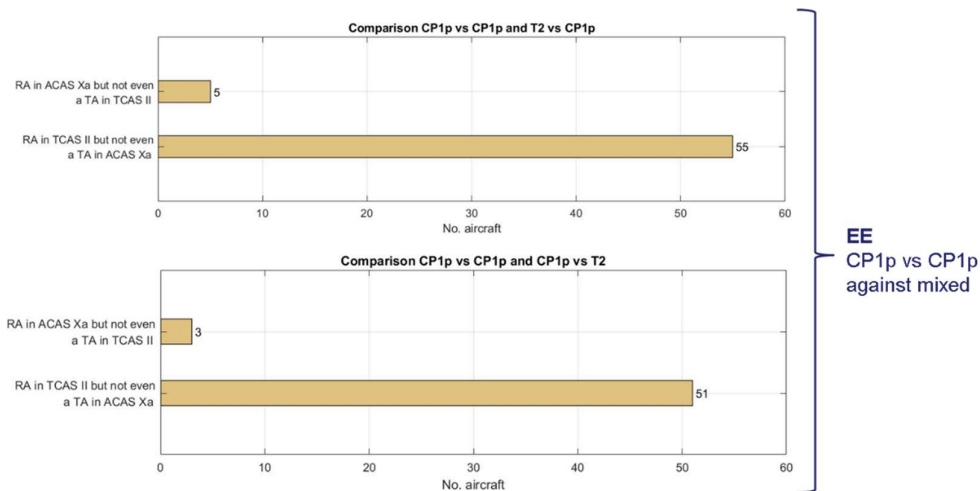


Figure 99 ATM model horizontally converging and vertically diverging

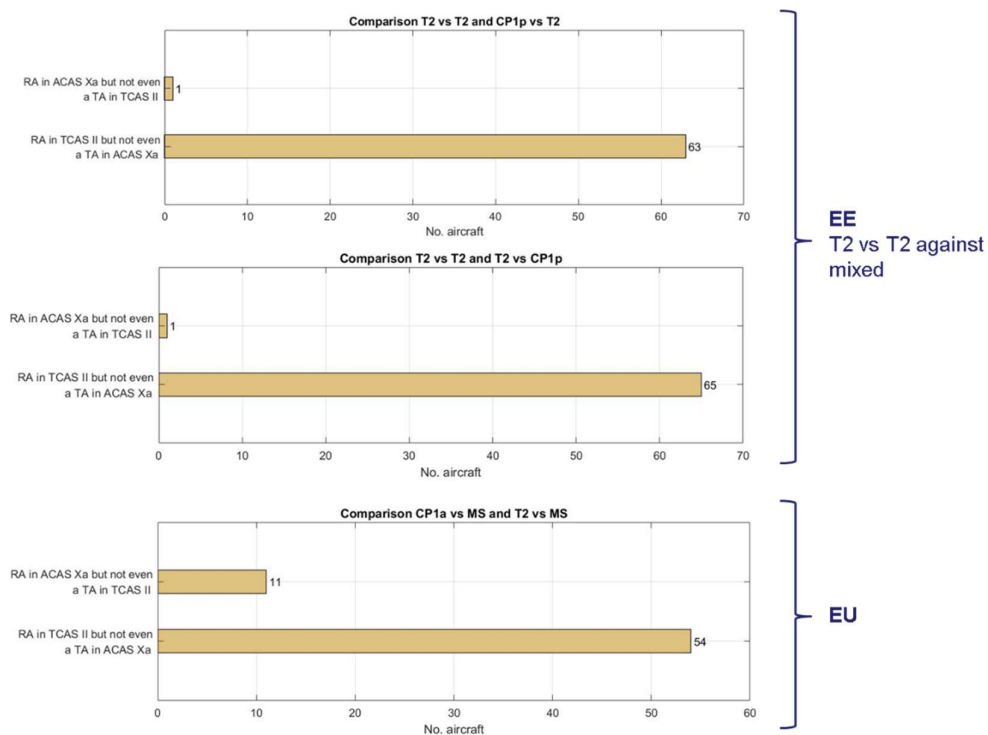
## 9.2.5. RA in one CAS but not even a TA in the other

### 9.2.5.1. Radar data

Most of the cases in which there is an RA in TCAS II but not even a TA in ACAS Xa CP1 is because of a 1,000ft Single Level Off /Double Level Off encounter.



**Figure 100 RA in one CAS but not even a TA in the other- ACAS Xa CP1 passive v Xa passive against mixed**

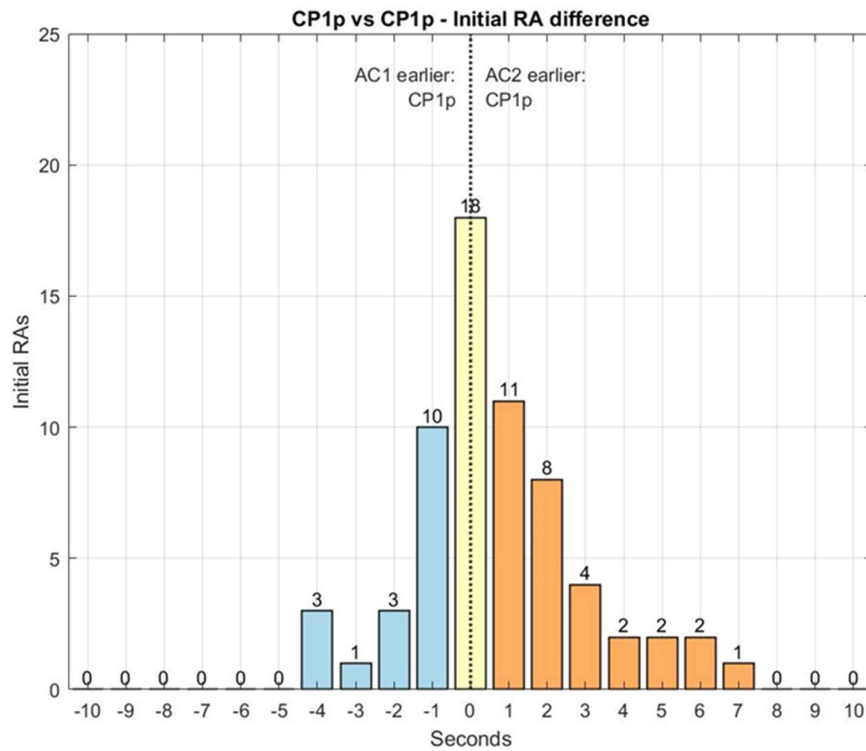


**Figure 101 Radar data RA in one CAS but not even a TA in the other- TCAS v TCAS against mixed and EU**

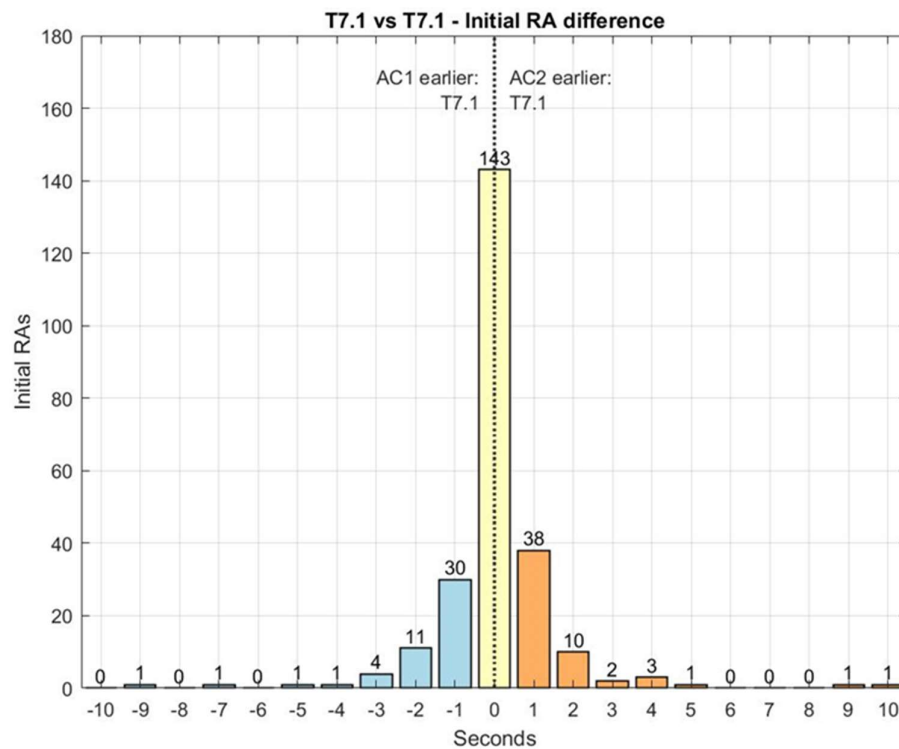
## 9.2.6. Initial RA difference between aircraft from same simulation

### 9.2.6.1. Single equipage

#### 9.2.6.1.1. Radar data



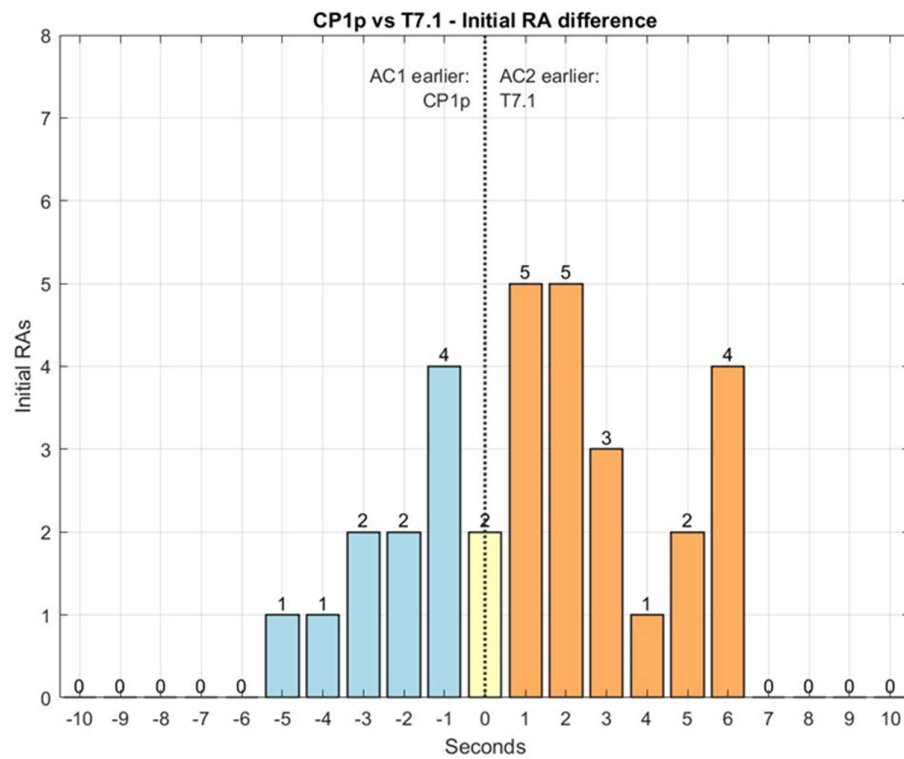
**Figure 102 Radar data initial RA difference – ACAS Xa CP1 v ACAS Xa CP1**



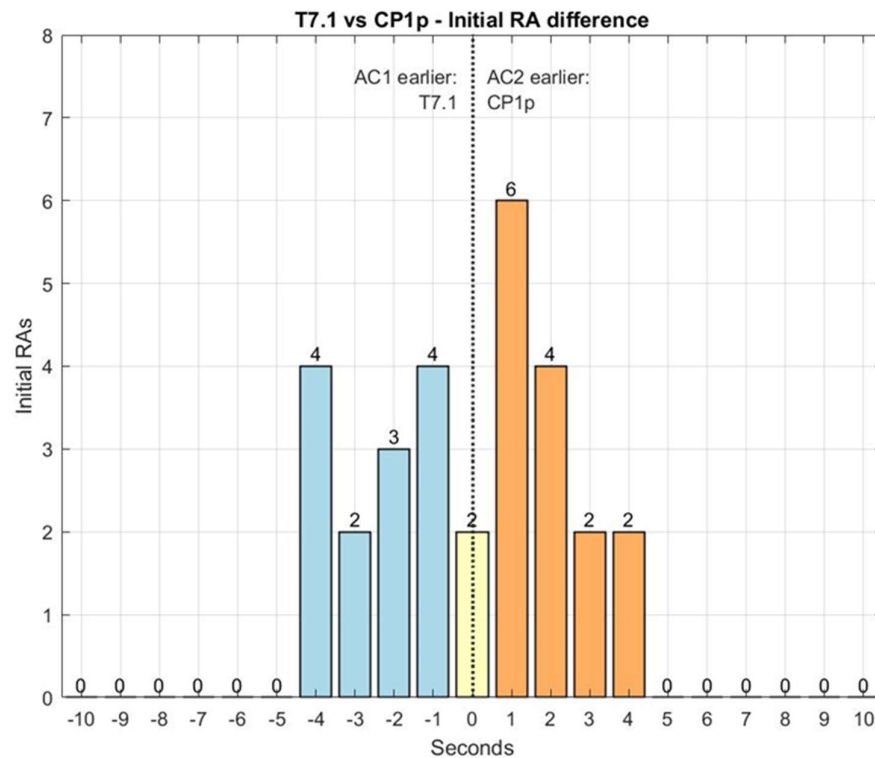
**Figure 103 Radar data initial RA difference – TCAS v TCAS**

## 9.2.6.2. Mixed equipage

### 9.2.6.2.1. Radar data



**Figure 104 Radar data initial RA difference ACAS Xa CP1 v TCAS**



**Figure 105 Radar data initial RA difference TCAS v ACAS Xa CP1**



## 9.2.7. Initial RA difference between aircraft from different simulations

### 9.2.7.1. Single equipage

#### 9.2.7.1.1. Radar data

Comparison between Initial RAs between AC1-AC1 and AC2-AC2 from different simulations. The aim is to know which CAS triggers the initial RAs earlier.

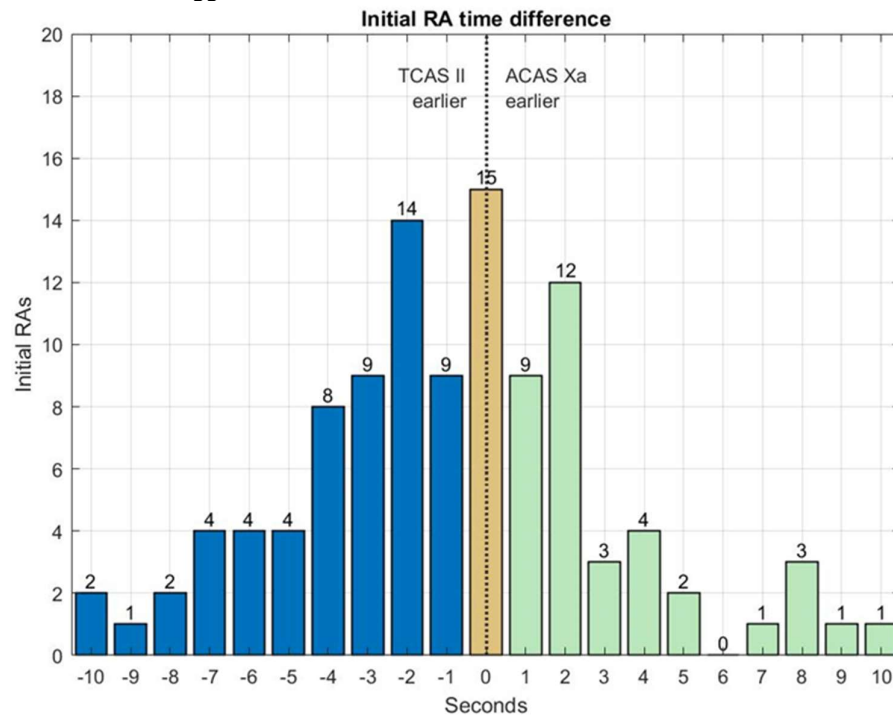


Figure 106 Radar data initial RA time difference – ACAS Xa CP1 v ACAS Xa CP1 against TCAS v TCAS

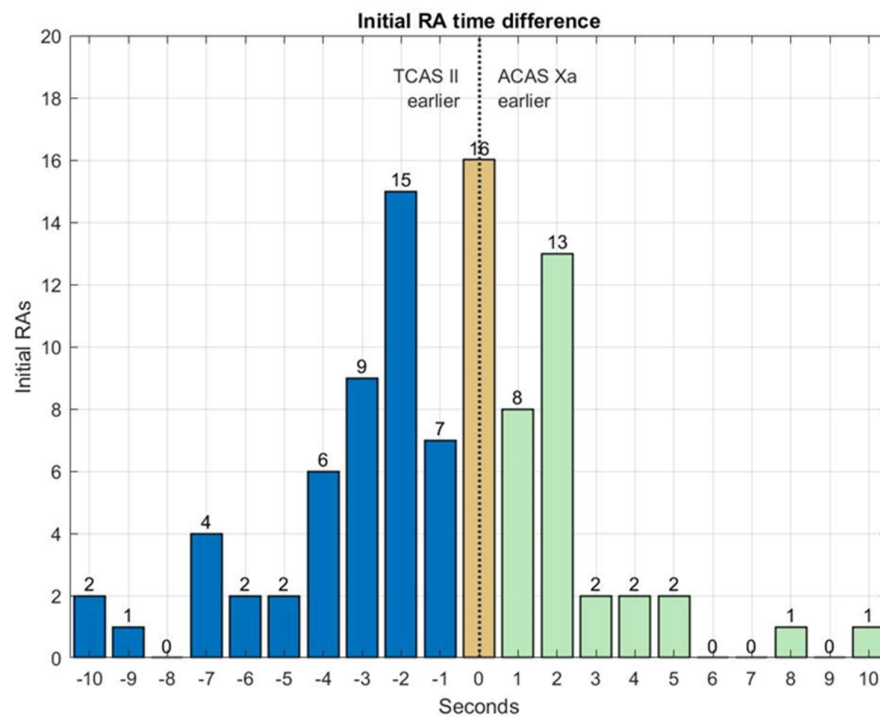


Figure 107 Radar data initial RA time difference – ACAS Xa CP1 v TCAS against TCAS v ACAS Xa CP1

### 9.2.7.2. Equipped v Unequipped

#### 9.2.7.2.1. Radar data

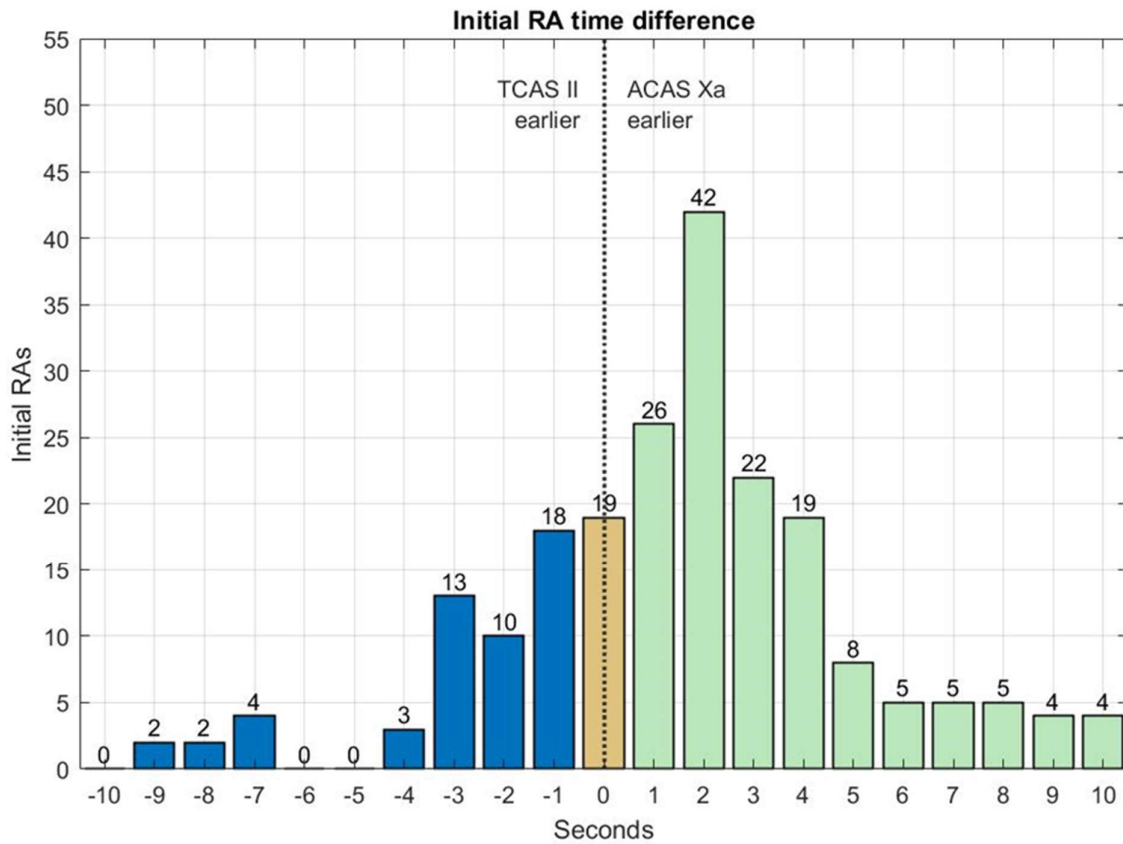


Figure 108 Radar data initial RA time difference - equipped v unequipped

## 9.3. How many encounters need to be simulated?

An obvious question to ask of encounter models is, "How many encounters should be simulated?"

The answer to this depends upon the answers to at least two other questions:

- How many encounters should be simulated to determine statistically significant differences for all metrics of interest between two collision avoidance systems?
- What is an operationally significant difference for each metric? When the difference in a metric for two collision avoidance systems is very small, an unfeasibly large number of simulations might be needed to obtain statistically significant results. In such cases, an assessment of the impact of these differences should be made.

### 9.3.1. How to determine statistical significance in ACAS Metrics?

#### 9.3.1.1. Theory of calculating statistical significance in encounter modelling

To test the performance of different collision avoidance systems, typically, two systems are simulated on the same set of encounters and for each system measurements are made of several variables (such as the presence or absence of an NMAC).

A presentation that was given to RTCA SC147 in 2016 stated: observations from encounter models can be considered as coming from binomial distributions.

In the case of encounter model simulations, we can define:

$N$  is the number of simulated encounters

$O_1$  and  $O_2$  are observations of a variable with systems 1 and 2

$\mu_1$  and  $\mu_2$  are the probabilities of the variable being observed with systems 1 and 2

$\sigma_1$  and  $\sigma_2$  are the standard deviations of the probabilities of the variable being observed with systems 1 and 2

For a binomial distribution,

$$\mu_1 = \frac{O_1}{N} \text{ and } \mu_2 = \frac{O_2}{N}$$

$$\sigma_1 = \sqrt{\mu_1(1 - \mu_1)} \text{ and } \sigma_2 = \sqrt{\mu_2(1 - \mu_2)}$$

In many conditions (especially with large number of simulations) results may be approximated by a Z (normal) distribution. The difference between systems 1 and 2 can be converted onto the equivalent normalised Gaussian distribution  $Z(0,1)$

$$Z = \frac{\mu_1 - \mu_2}{\sqrt{(\sigma_1^2 + \sigma_2^2)/N}}$$

In Excel the statistical significance is found with the function Norm.S(Z,true).

Typically, experiments with  $N = 100,000$  encounters can be rapidly and conveniently simulated on a single desktop computer. If there is a requirement to achieve a different (stricter) significance level, additional encounters can be simulated until a total of  $N'$  simulations have been undertaken.  $N'$  can be calculated as follows:

$N'$  is the number of simulated encounters required

$$Z' = \text{Norm.S.Inv(Required_Significance)}$$

$$N' = N \cdot \frac{Z'^2(\sigma_1^2 + \sigma_2^2)}{(\mu_1 - \mu_2)^2}$$

##### 9.3.1.1.1. Typical example

When calculating operational RA metrics (counts of different RA alert types) simulating 4188 radar encounters with both TCAS II V7.1 and ACAS Xa (without CP1) showed differences that were >99% significant for most metrics. The metric with the least significant difference had 47 and 49 observations when simulating with TCAS II and ACAS Xa respectively. Using the methodology shown above, it was expected that statistical significance at 99% for this metric (and all others) would be achieved if 276,613 encounters could be simulated.

##### 9.3.1.1.2. Extreme cases

The metrics that require the most simulations to obtain statistical significance have low probabilities of observing the metric and values that are very similar for the two systems being compared. In the case of AVAL encounters simulated with TCAS II and ACAS X, measurements of NMACs when both aircraft are CAS equipped, were observed to have these conditions

Simulating 308,458 encounters 2 NMACS remained with TCAS II. Typically, ACAS Xa gave 40% safety improvement over TCAS II and risks above FL300 are approximately only 1% of the total risk. Therefore, the equivalent NMAC rate for above FL300 is about 0.02 NMACS for TCAS II and 0.012 NMACS for ACAS Xa with 308,458 encounters.

In order to obtain statistical significance in this case, metrics from approximately 420 million encounters would be needed. Using importance sampling to only generate encounters in the relevant layer may reduce the number of simulations required, but the effect is likely to be less than an order of magnitude.

When very large numbers of simulations are required, it is natural to ask whether it is worthwhile to perform them.

### 9.3.1.2. Comparing systems - hypothesis testing

#### 9.3.1.2.1. Approach

We are interested to know whether the performance of one system is greater or less than another system.

We define a null hypothesis that there is no difference in performance and an alternative hypothesis that there is a difference.

We conduct an experiment with a sample of input data.

In general, the result will appear to support the alternative hypothesis that there is a difference in performance. In particular, the sign of the difference will appear to indicate a positive or negative difference.

However, since the experiment is conducted with a sample of limited size, the result is to some extent due to chance.

If we were to reject the null hypothesis and accept the alternative hypothesis, what would be the probability  $p$  that we would be making a mistake?

We will say that we have confidence  $(1 - p)$  in the alternative hypothesis.

#### 9.3.1.2.2. Examples of performance measures

For the systems under test we have a measure of performance. For example, when simulating a collision avoidance system with an encounter, some possible performance measures are:

**Table 16 Examples of performance measures**

Performance measure	Range of values
NMAC occurs	Binary, 0 or 1
Probability of NMAC occurring, for example, taking account of altimetry error	Real (0, 1)
Conduct 100 mini-simulations over a range of altimetry errors, how many result in NMAC?	Integer (0, 100)

When considering a set of encounters, a performance measure can be seen as a random variable with a distribution.

### 9.3.1.2.3. Matched pairs

When two systems are simulated with the same set of encounters, the simulations for each encounter form 'matched pairs'. When comparing two systems 1 and 2 we are interested in the difference in performance. We can define the difference in performance when simulating an encounter:

$$D \equiv P_1 - P_2$$

Since  $P_1$  and  $P_2$  are random variables, so too is their difference  $D$ . In general, we expect the performance measures  $P_1$  and  $P_2$  to be correlated. This would certainly be the case when comparing related versions of the same system. In the matched pairs approach, by directly obtaining the value of  $D$  for each encounter, the distribution of  $D$ , in particular its variance, takes account of the correlation between  $P_1$  and  $P_2$ .

[Note: in section 9.3.1.1, the error variance (the square of the standard error) of the difference was calculated by adding the (estimated) error variances of the two systems i.e.  $\sigma_1^2/N + \sigma_2^2/N$ . This addition assumes that the performance measures  $P_1$  and  $P_2$  are independent. If there is a positive correlation between the measures this will result in an over-estimate of the variance and an under-estimate of the confidence in the difference.]

For a given sample (encounter set) we can calculate the mean difference  $\mu_d$  and the variance  $\sigma_d^2$  of the sample.

If many encounter sets (from the same population) were to be simulated, the mean differences  $\mu_d$  for these encounter sets would also have a distribution – the sampling distribution of the mean. The standard deviation of this (sampling distribution of the mean) is termed the standard error of the mean and is given by

$$\text{standard error of the mean} = \frac{\text{standard deviation (of the population)}}{\sqrt{\text{number of samples}}}$$

See [https://en.wikipedia.org/wiki/Standard\\_error](https://en.wikipedia.org/wiki/Standard_error)

We can use the standard deviation of the sample as an estimate of the standard deviation of the population, so that we can estimate the standard error of the mean:

$$\widehat{\text{standard error of the mean}} = \frac{\sigma_d}{\sqrt{N}}$$

Assuming the null hypothesis, the normalised z-value of the observed value of the mean is given by

$$z = \frac{\mu_d - 0}{\sqrt{\sigma_d^2/N}}$$

If the null hypothesis (that there is zero mean difference in the performance of the systems) were true, the probability  $p$  of observing a sample mean that lies at or further away from zero than  $\mu_d$  can be found from the cumulative normal distribution, using, for example, the Excel function =NORM.S.DIST( $z$ ;TRUE).

From this  $p$  value, we can estimate the confidence  $(1 - p)$  that the performance of one system differs from the other, in the direction given by the sign of  $\mu_d$ .

The matched pairs method is described in e.g.

<http://facweb.cs.depaul.edu/sjost/csc423/documents/test-descriptions/paired-z.pdf>

### 9.3.2. Estimating the number of encounters to simulate to obtain a given level of confidence

Suppose we simulate an initial batch of  $n_1$  encounters and obtain a z value

$$z_1 = \frac{\mu_d}{\sqrt{\sigma_d^2/n_1}}$$

We can relate the z value to confidence. For example, if we are using a one-sided test, we can use the Excel function =NORM.S.DIST(z;TRUE) to give the cumulative normal distribution value corresponding to a given z value.

**Table 17 One-sided test z-value confidence**

Z-value	Confidence
1.282	0.90
1.645	0.95
2.326	0.99

Suppose we wish to conduct further simulations in order to obtain a given z value,  $z_2$ , corresponding to a required level of confidence.

For the purpose of estimating the number of encounters to simulate, let's suppose that in these further simulations, the mean  $\mu_d$  and variance  $\sigma_d^2$  of the differences do not change, so that

$$z_2 = \frac{\mu_d}{\sqrt{\sigma_d^2/n_2}}$$

Dividing the expression for  $z_2$  by that for  $z_1$  (above)

$$\frac{z_2}{z_1} = \sqrt{\frac{n_2}{n_1}}$$

or

$$n_2 = \left(\frac{z_2}{z_1}\right)^2 n_1$$

For example, when simulating a batch of 50 000 encounters, a z-score of 1.2 is obtained, which corresponds (=NORM.S.DIST(1.2;TRUE) ) to a confidence of 88.5%.

However, we wish to obtain a confidence of 99%. The z-value corresponding to a cumulative normal value of 0.99 is 2.326 (see table above). Provided there is no movement in the mean and variance in the simulation of the new set of encounters, the estimated number of encounters needed is at least

$$n_2 = \left(\frac{z_2}{z_1}\right)^2 n_1 = \left(\frac{2.326}{1.2}\right)^2 \times 50000 = 188\,000$$

### 9.3.3. When is it worthwhile performing further simulations?

There are at least 3 assumptions made while performing encounter modelling

- The cost of encounter modelling is less than the benefit it provides
- The differences being examined are greater than the uncertainties present within the model.
- The benefit sought is a substantial part of the potentially available improvements to the system.

If any of these 3 assumptions does not hold true, then encounter modelling is unlikely to be worthwhile.

#### **The cost benefit of encounter modelling**

Extrapolating from the frequency of observed NMACs, the number of flight hours flown in Europe and previous studies into the effectiveness of TCAS II V7.1 suggests that without TCAS II, collisions would occur on average approximately every 3 years in Europe rather than every 10 years. Assuming that collision avoidance systems get updated approximately every 10 years (as has been the case historically) this means that the fleet of installed ACAS prevent about 2 collisions in Europe during their operational lifetime, but nevertheless one collision is still expected to occur. With each collision potentially costing hundreds of millions of dollars, even a 1% improvement of risk ratio is expected to save many millions of dollars.

The evaluation of ACAS X suggests that up to 30% of residual risk may be removed, saving tens of millions of dollars. Encounter modelling, with countless billions of simulations in the USA, has cost a small fraction of this.

#### **Uncertainties within the encounter model**

Despite best efforts to create an accurate model of close encounters, several sources of error or uncertainty will remain:

- The low sampling rate of radars combined with measurement errors results in a need for trajectory tracking and has the consequence that there can be considerable difference from the true trajectories of encounters,
- The model does not capture all close encounters that have occurred in Europe, nor all types of encounters that reasonably might occur. When risk ratios are very low, it is quite possible for a single encounter that leads to an NMAC to dominate risk calculations. It is also quite possible that such types of encounter have not been observed or modelled. Colloquially these events can be described as “black swans”.
- Every Monte-Carlo model has simulation limits. When running millions of Monte-Carlo simulations, there is the possibility of recreating essentially the same type of encounter again and again. So far, the analysis of rare encounter types has shown benefits from analysing as many as 6 million encounters in a single SESAR layer. The reasonable upper limit has not yet been found.

Safety simulations have been conducted with encounters containing more than 2000 NMACs (corresponding to the equivalent of more than 1000 years of operation). These allow a description of risk ratio with an accuracy of about 0.1%. Risk figures that differ by this or less cannot be reasonably differentiated. A single black swan event could change the perception of a system. The consequence of this is that monitoring of new systems will be required.

#### **Magnitude of improvements being evaluated by encounter modelling**

The Pareto principle suggests that the large majority of benefits in a new system are achieved with a small proportion of the effort. The effort to create a new standard or implement a new system should be considered against other possibilities for improving safety.

In the case of CAS, as long as pilots do not accurately follow their RAs, improving CAS safety performance provides a secondary degree of improvement compared to better following of RAs. Possible improvements in CAS logic performance might be assessed against possible improvements in the following of RAs.

With this in mind, a judgement call was made that evaluations with about 2000 NMACs were commensurate with the overall degree of improvement available.

## 9.4. Calculating risk ratio<sup>14</sup>

### 9.4.1. Definition of risk ratio

The risk ratio,  $R$ , is the ratio of the risk of collision with ACAS to that without ACAS. This is interpreted as

$$R = \frac{\sum_{\text{all encounters}} \text{probability of a collision with ACAS}}{\sum_{\text{all encounters}} \text{probability of a collision without ACAS}}$$

In order to calculate  $R$  we need to calculate the probability of a collision in any given encounter and we need to develop a practical model for 'all encounters'. The probability of collision inherently depends on the distribution of altimeter error as discussed in section 9.5.

We need consider only encounters with very small HMD, but the fact that an ACAS II causes movement in only the vertical plane means that we do not need to be precise about what this means: in this study we take this to mean encounters with HMD effectively zero. However, the vertical separation threshold,  $h$ , below which a collision is considered to occur does need to be stated. So we have

$$R = \frac{\sum_{\substack{\text{encounters with} \\ \text{zero HMD}}} \text{prob}(|d_1| < h)}{\sum_{\substack{\text{encounters with} \\ \text{zero HMD}}} \text{prob}(|d_0| < h)}$$

where  $d$  is the vertical separation and the subscripts '0' and '1' indicate the situations without ACAS and with ACAS respectively.

Now introduce  $\varepsilon$ , the joint altimetry error and  $v$ , the apparent vertical separation (either with or without ACAS) such that  $v = d + \varepsilon$ , i.e.  $v$  is the altitude separation as measured by altimeters.<sup>15</sup> It is not necessary to consider discretisation errors because the modelled altimeter readings are known with arbitrary precision in the computer simulations. They are discretised before they are provided to ACAS as modelled altitude reports, which ACAS tracks. Encoding errors (specifically one bit errors) are not covered by this analysis.

Now the condition  $|d| < h$  becomes  $|v - \varepsilon| < h$ , or equivalently a collision is considered to occur if

$$v - h < \varepsilon < v + h$$

Using the subscript convention introduced above, risk ratio is calculated as

$$R = \frac{\sum \text{prob}(v_1 - h < \varepsilon < v_1 + h)}{\sum \text{prob}(v_0 - h < \varepsilon < v_0 + h)}$$

The probabilities that the combined altimetry error lies between the relevant bounds are then calculated as described in Section 9.5.2.

### 9.4.2. Unresolved and induced risk

The risk with ACAS is unresolved when

$$|d_1| < h \text{ and } |d_0| < h$$

Unresolved risk exists when  $|v_1 - v_0| < 2h$  and

$$v_1 - h < \varepsilon < v_0 + h : v_1 \geq v_0$$

$$v_0 - h < \varepsilon < v_1 + h : v_1 < v_0$$

The first case is illustrated in Figure C1 and the second case is illustrated in Figure C2.

<sup>14</sup> This section was originally presented as an appendix in [15].

<sup>15</sup> Note that the variables  $d$  and  $v$  can take either positive or negative values depending upon whether one aircraft is above or below the other. Although the altimetry error functions are symmetrical about zero it is important to preserve the relative signs of the separations with and without ACAS when calculating the unresolved and induced risk as described below. The choice of which case is considered to be a positive separation and which a negative separation is arbitrary (since the situation is clearly reversed if one interchanges the labels of the two aircraft) but serves to indicate those encounters in which the relative altitudes of the two aircraft at CPA are inverted by ACAS (in which case the separations with and without ACAS will have opposite signs). For convenience we often use a positive value to indicate a non-crossing encounter and a negative sign to indicate a crossing encounter so that when  $v_0$  and  $v_1$  are plotted on a scatter diagram the effect of ACAS on encounter geometries is readily apparent.



The risk with ACAS is induced when

$$|d_1| < h \text{ but } |d_0| > h$$

Induced risk exists when  $v_1 \neq v_0$  and

$$v_1 - h < \varepsilon < v_1 + h : |v_0 - v_1| \geq 2h$$

$$v_0 + h < \varepsilon < v_1 + h : |v_0 - v_1| < 2h \text{ and } v_1 \geq v_0$$

$$v_1 - h < \varepsilon < v_0 - h : |v_0 - v_1| < 2h \text{ and } v_1 < v_0$$

Note that in the first case all of the risk with ACAS is strictly induced risk, as illustrated in Figure C3. The second case is illustrated in Figure C1 and the third case is illustrated in Figure C2.

The sum of the unresolved and the induced risks can therefore be calculated and the overall risk ratio partitioned into two partial risk ratios: unresolved risk ratio and induced risk ratio. However, for reasons discussed in Section 9.4.4, we choose to consider the induced risk in certain encounters as 'unresolved risk' so the induced component of the risk ratios presented in this (and previous) reports will tend to be smaller than the values resulting from the strict approach adopted in this section.

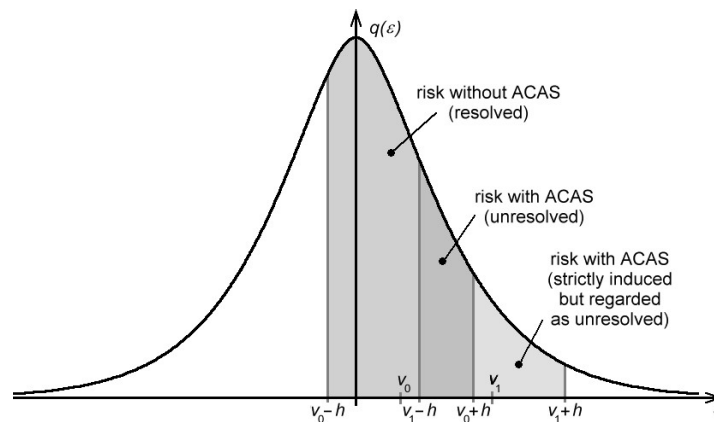


Figure C1

Non-crossing encounter with separation increased by less than 2h

The figure is drawn to scale with equal parameters of  $\lambda = 72\text{ft}$ , with  $v_0 = 60\text{ft}$  and  $v_1 = 187\text{ft}$

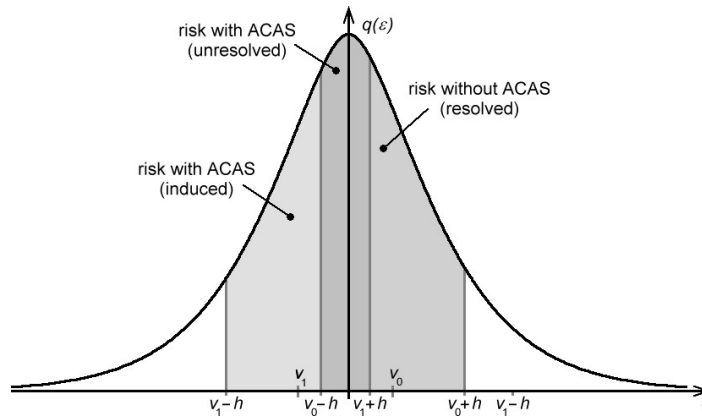


Figure C2

Non-crossing encounter with separation increased, but by a crossing advisory

The figure is drawn to scale with equal parameters of  $\lambda = 72\text{ft}$ , with  $v_0 = 60\text{ft}$  and  $v_1 = -67\text{ft}$

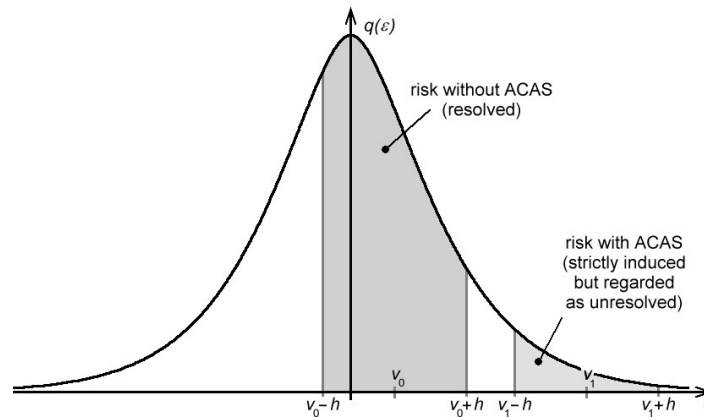


Figure C3

Non-crossing encounter with separation increased by more than  $2h$

The figure is drawn to scale with equal parameters of  $\lambda = 72\text{ft}$ , with  $v_0 = 60\text{ft}$  and  $v_1 = 330\text{ft}$

### 9.4.3. Collision model

From the discussion above and the two illustrative diagrams it is apparent that the risk of collision we estimate in any encounter depends on  $h$ , the vertical separation threshold below which a collision is considered to occur. However since the ratio of the sum of the risks is taken the dependence of the overall risk ratio is not as strong as the dependence of the individual sums.

However the partition of the risk ratio into an unresolved and an induced risk ratio is much more strongly dependent upon the value of  $h$ . In the limit of  $h \rightarrow 0$  the risk with ACAS in each individual encounter becomes either wholly unresolved (when  $v_1 = v_0$ ) or wholly induced (when  $v_1 \neq v_0$ ).

In practice a non-zero value of  $h$  is used to reflect the physical dimensions of aircraft (e.g. a Boeing 747 is 63 ft high). In this study, in common with other workers and as specified in the SARPs standard encounter model, the NMAC value of  $h = 100\text{ ft}$  has been used.

### 9.4.4. Risk due to the logic and risk due to altimetry

From the discussion in the proceeding section it is apparent that the effect of the ACAS logic (which determines the value of  $v_1$  in any encounter) and the effect of altimetry (which determines the value of  $\varepsilon$ ) on the risk of collision with ACAS are intimately linked.

Nevertheless an attempt to further divide the risk with ACAS (particularly the induced risk) into 'risk due to the ACAS logic' and 'risk due to altimetry error' can be made. There is no generally agreed basis for these distinctions and they become more complicated when non-standard pilot responses are considered.

However, the term 'induced risk' has acquired unfortunate pejorative overtones; the unwarranted assumption being that when induced risk exists ACAS is necessarily at fault. The difficulties in interpretation arise when, in straightforward encounters, the correct pilot response to ACAS significantly increases the separation of the two aircraft: a desirable result and, based on the available information (*i.e.* reported altitudes), the best that any collision avoidance system or a controller could hope to achieve. The risk that exists in these cases will be small but induced – ACAS will have 'deliberately' swapped a significant (potentially unresolved) risk in the original encounter for a smaller (but induced) risk when the pilot responds to the RA. The extreme example is given in the second paragraph of section 9.4.3 where the only way to avoid induced risk is to do nothing!

At the risk of perpetuating any misconceptions, we have chosen (in this and the earlier studies reported to consider the risk induced by ACAS when it increases the absolute value of the separation as 'unresolved' unless that increase was achieved by turning an encounter in which the two aircraft did not cross in altitude into a 'crossing encounter'.

### 9.4.5. Contributions to risk ratio

The vast majority of real encounters have a significant HMD and therefore make no contribution to the risk either without or with ACAS. Consequently such encounters have not been simulated.

A majority of the modified encounters (in which HMD is set to zero) have a large separation both without and with ACAS and so have only a small effect on risk ratio (*i.e.* removal or inclusion of such encounters from the sample makes a negligible difference to the final result).

Conversely a small number of encounters dominate the risk ratio. These are the encounters that have a small separation without ACAS and/or with ACAS. It is therefore necessary to examine only these encounters in detail in order to validate the risk ratio measurement.

In order to identify these encounters it is possible to calculate a positive quantity which we call the 'magnitude' of each encounter. The greater the magnitude of an encounter the greater its significance in the calculation of risk ratio. Recall that

$$R = \frac{\sum_{i=1}^n a_i}{\sum_{i=1}^n w_i}$$

where  $R$  is the risk ratio calculated from  $n$  encounters,  $a_i$  is the risk with ACAS for the  $i^{\text{th}}$  encounter and  $w_i$  is the corresponding risk without ACAS. The magnitude of each encounter is then calculated as

$$m_i = w_i + \frac{a_i}{R}$$

A convenient cut-off below which individual encounters need not be examined is found to be the mean magnitude. The interested reader may care to show that this is given by the expression

$$\bar{m} = \frac{2}{n} \sum_{i=1}^n w_i$$

The approach used in this analysis was slightly different: encounters were put in decreasing order of residual risk and then up to 100 encounters with risk  $>0.001$  NMAC were examined.

## 9.5. Altimeter error<sup>16</sup>

### 9.5.1. Introduction

In this study a Laplacian (also known as a Double Exponential) distribution has been used as specified in the SARPs standard encounter model. The probability density function (PDF) for the altimeter error in any single aircraft,  $p(e)$ , is described by a single parameter  $\lambda$  thus:

$$p(e) = \frac{1}{2\lambda} \exp\left(-\frac{|e|}{\lambda}\right) \quad (1)$$

The parameter  $\lambda$  is a function of altitude and aircraft equipage as described in the SARPs.

If at the closest point of approach (CPA) the reported vertical separation is  $S$ , for a 'direct hit' to occur the combined altimetry error of the two aircraft must be exactly  $S$ . However, as aircraft are not point particles, a threshold,  $h$  (comparable to the physical dimensions of real aircraft, and normally taken as 100ft), is introduced. A collision is said to occur if the combined altimetry error lies between  $S - h$  and  $S + h$ .

### 9.5.2. Analytical Approach

The form of the combined altimetry error PDF,  $q(\varepsilon)$ , is given by the convolution of the two individual altimetry error PDFs, and takes one of two forms according to whether the parameters,  $\lambda$ , (one for each aircraft) are equal or not.

When the parameters,  $\lambda$ , have the same value,  $\mu$ , the form of the PDF is given by

$$q(\varepsilon) = \frac{|\varepsilon| + \mu}{4\mu^2} \exp\left(-\frac{|\varepsilon|}{\mu}\right) \quad (2)$$

When the parameters,  $\lambda$ , have different values,  $\mu_1$  and  $\mu_2$ , the form of the PDF is given by

$$q(\varepsilon) = \frac{1}{2(\mu_1^2 - \mu_2^2)} \left( \mu_1 \exp\left(-\frac{|\varepsilon|}{\mu_1}\right) - \mu_2 \exp\left(-\frac{|\varepsilon|}{\mu_2}\right) \right) \quad (3)$$

The probability of a collision is then given by the integral of  $q(\varepsilon)$  between  $S - h$  and  $S + h$ . Equation (2) gives the following probability of collision when the PDF for altimeter error is the same in the two aircraft:

prob(collision) =

$$\begin{cases} 1 - \frac{1}{4\mu} \exp\left(-\frac{(|S|+h)}{\mu}\right) \left( (2\mu - (|S|-h)) \exp\left(\frac{2|S|}{\mu}\right) + (2\mu + (|S|+h)) \right) : |S| \leq h \\ \frac{1}{4\mu} \exp\left(-\frac{(|S|+h)}{\mu}\right) \left( (2\mu + (|S|-h)) \exp\left(\frac{2h}{\mu}\right) - (2\mu + (|S|+h)) \right) : |S| > h \end{cases} \quad (4)$$

When the PDF for altimeter error is different in the two aircraft equation (3) gives the probability of collision as:

prob(collision) =

$$\begin{cases} 1 - \frac{1}{\mu_1^2 - \mu_2^2} \left( \mu_1^2 \exp\left(-\frac{h}{\mu_1}\right) \cosh\left(\frac{S}{\mu_1}\right) - \mu_2^2 \exp\left(-\frac{h}{\mu_2}\right) \cosh\left(\frac{S}{\mu_2}\right) \right) : |S| \leq h \\ \frac{1}{\mu_1^2 - \mu_2^2} \left( \mu_1^2 \exp\left(-\frac{|S|}{\mu_1}\right) \sinh\left(\frac{h}{\mu_1}\right) - \mu_2^2 \exp\left(-\frac{|S|}{\mu_2}\right) \sinh\left(\frac{h}{\mu_2}\right) \right) : |S| > h \end{cases} \quad (5)$$

For a given encounter (either with or without TCAS) the altitudes of the two aircraft at closest approach,  $z_1$  and  $z_2$ , are noted.

The altitude of the encounter is defined as  $\frac{1}{2}(z_1 + z_2)$  and is used to determine the appropriate altitude band of the encounter which in turn will determine the values of the altimetry error parameters. If both aircraft are TCAS equipped these parameters will be equal. If one aircraft is unequipped then there is a probability (again determined by the altitude of the encounter) that the parameters will be different.

The separation is given by  $S = z_1 - z_2$ , the altimetry error parameters are known and  $h$  is predetermined so the risk of collision can be evaluated from either equation (4) or (5) as appropriate.

<sup>16</sup> The analysis in this section was derived in [14] and verified in [15].

## 9.6. CAVEAT input-output formats

### 9.6.1. Input

The Flight Track Data (FTD) format contains an initial header, indicated by a line containing "HEADER". The content of the header is:

Encounter information stored in the first line of the header: category, number\_AC.

**Table 18 FTD Header general information format**

Name	Description
category	Category of the encounter file, which can be one of the following values: <ul style="list-style-type: none"><li>• "synthetic": encounter data generated by a model (e.g. CAFE)</li><li>• "raw": radar tracking data</li><li>• "radar": radar tracking data</li><li>• "reconstructed": reconstructed encounter based on radar tracking data</li></ul>
number_AC	Number of aircraft in an encounter, being an integer larger than zero

- Aircraft info:

**Table 19 FTD Header aircraft information format**

Name	Description
AC_tracknumber	Positive integer used to uniquely identify every aircraft in the encounter
mode_S_address	Mode S address (or ICAO 24-bit address) of the aircraft, being a 6-digit hexadecimal number
mode_A_code	Mode A code of the aircraft, being a 4-digit octal number
AC_callsign	Aircraft callsign, being a string
ACAS_version	ACAS version, which is a string with the following options currently supported: <ul style="list-style-type: none"><li>• "Unknown"</li><li>• "Unequipped"</li><li>• "TCAS II 7.0"</li><li>• "TCAS II 7.1"</li><li>• "TCAS II 7.2"</li><li>• "ACAS Xa 15.2"</li><li>• "ACAS Xa 15.4"</li><li>• "ACAS Xa CP1"</li></ul>
manual_SL	Manual setting of the ACAS sensitivity level (SL). The following settings are supported: <ul style="list-style-type: none"><li>• 0: Automatic, implying that both TAs and RAs are provided;</li><li>• 1: Standby, implying that no TAs or RAs are provided;</li><li>• 2: TA only, implying that only TAs are provided.</li></ul>

After the header, the body (indicated by a line with "BODY") contains the encounter info:

**Table 20 FTD Record format**

Name	Description
time	Time stamp in hh:mm:ss.cc format
AC_tracknumber	Aircraft track number, integer larger than zero
X-position	X-position of the aircraft in ENU (East North Up) coordinate system, floating point value in nautical miles
Y-position	Y-position of the aircraft in ENU coordinate system, floating point value in nautical miles
altitude	Altitude of the aircraft, floating point value in feet.
BDS-30	RA information as a subset of BDS-30 downlinked data.

Call-sign (alpha-numeric string) is used to record aircraft number, Performance Class, and Controlled status:

- aircraft 1 non-controlled:
  - performance classes not in use:
    - call-sign = 'ABCDE';
  - performance classes in use:
    - call-sign = 'ABCCZ' for not-constrained, 'ABCCA' for class 1, 'ABCCB' for class 2, *etc.*
- aircraft 1 controlled:
  - performance classes not in use:
    - call-sign = 'ABC123';
  - performance classes in use:
    - call-sign = 'ABC000' for not-constrained, 'ABC001' for class 1, 'ABC002' for class 2 *etc.*
- aircraft 2 non-controlled:
  - performance classes not in use:
    - call-sign = 'VWXYZ';
  - performance classes in use:
    - call-sign = 'VWXCZ' for not-constrained, 'VWXCA' for class 1, 'VWXC B' for class 2, *etc.*
- aircraft 2 controlled:
  - performance classes not in use:
    - call-sign = 'XYZ123';
  - performance classes in use:
    - call-sign = 'XYZ000' for not-constrained, 'XYZ001' for class 1, 'XYZ002' for class 2 *etc.*

## 9.6.2. Output

### 9.6.2.1. Modified trajectories in Comma Separated Values (CSV) File

#### 9.6.2.1.1. Purpose

The purpose of this file is to provide the modified trajectories and ACAS events of all aircraft in an encounter scenario, for a subset of its realisations.

#### 9.6.2.1.2. Destination

The destination of the information produced is a CSV file, formatted following the specification of EUROCONTROL. This file format has been chosen because it can be easily parsed with external tools, as well as because it can store simulated data in a relatively compact way (which is advantageous for large simulations, where a big amount of data is produced).

#### 9.6.2.1.3. File structure

This file format is designed to store multiple realisations of a single encounter-scenario. These are a subset of the simulated realisations. If the number of realisations is 100 or below, all realisations are stored. For greater numbers of realisations, only the first hundred are stored in the file.

The file is comprised of two main blocks. The first block (Header) contains information that is applicable to all realisations, and which is necessary to parse the remainder of the file. The second block (Body) contains simulation results for all stored realisations.

The structure of the file is presented next, where UML multiplicity notation has been added to indicate the number of instances that each specific component is present in the file.

- Header [1]
  - Header indicator line [1]
  - Header data line [1]
  - Aircraft data lines [1..\*]
- Body [1]
  - Body indicator line [1]
  - Realisation [\*]

- Realisation indicator line [1]
- Realisation data lines [\*]

### 9.6.2.1.3.1. Header block

The header block has the following sub-blocks:

- Header indicator line
- Header data line
- Aircraft data lines

The header indicator line merely contains the string “HEADER”.

The header data line has the following fields:

**Table 21 Fields in the header data line**

Name	Description	Units	Comments
encName	Name of the encounter	-	
sceName	Name of the scenario	-	
encSceName	Name of the encounter-scenario	-	
windMag	Magnitude of wind speed vector.	kt	Wind speed vector is necessary to compute aircraft attitude from its position and velocity following the models presented in [5]. Valid values are positive.
windDir	Direction of wind speed vector. 0° degrees is north. 90° points to the east.	deg	Wind speed vector is necessary to compute aircraft attitude from its position and velocity following the models presented in [5]
numAC	Number of aircraft in the encounter-scenario	-	

After the header data line, per-aircraft data is provided in the aircraft data lines. There are numAC such lines, whose contents are presented in the following table:

**Table 22 Fields in an aircraft data line**

Name	Description	Units	Comments
trkNum	Aircraft track number	-	Different aircraft have different track numbers
callsign	Aircraft callsign	-	Different aircraft have different callsigns
acasEq	ACAS version, which is a string with the following options currently supported: <ul style="list-style-type: none"> <li>• “Unknown”</li> <li>• “Unequipped”</li> <li>• “TCAS II 7.0”</li> <li>• “TCAS II 7.1”</li> <li>• “TCAS II 7.2”</li> <li>• “ACAS Xa 15.2”</li> <li>• “ACAS Xa 15.4”</li> <li>• “ACAS Xa 15.4 CP1”</li> <li>• “ACAS Xa 15.4-CP1-CPP”</li> <li>• “ACAS Xu”</li> </ul>		The list of possible ACAS versions will be extended when other versions are supported by CAVEAT.  ACAS version is needed to decode label270 alerts.
AoA	Aircraft angle of attack.	deg	Aircraft angle of attack is necessary to compute aircraft attitude from its position and velocity following the models presented in [5]. Valid values lie in interval [-90,90]
acasDelay	ACAS Time shift + ACAS Processing time $T^{shift} + \tau_{ACAS}^{proc}$	s	The ACAS output which every aircraft provides at the end of each processing cycle has an offset with the simulation timestamps. This field stores such offset. Valid values are positive.

### 9.6.2.1.3.2. Body block

The header block has the following sub-blocks:

- Body indicator line
- Realisation blocks

The body indicator line merely contains the string "BODY"

Each realisation block has the following sub-blocks:

- Realisation indicator line
- Realisation data lines

The realisation indicator line contains the following two fields:

**Table 23 Realisation indicator line**

Name	Description	Units	Comments
realString	"REALISATION"	-	String
realID	Number of the realisation	-	Ordinal number (natural) that represents the order in which the simulation was executed.(e.g. The file may contain a single realisation with realID=4. In this case, of all the realisations that were simulated, only the one that was simulated in the fourth place has been stored in the file).

Realisation data lines store position and ACAS output associated to every simulation cycle. These lines contain the following fields:

**Table 24 Realisation data line**

Name	Description	Units	Comments
time	Time stamp in format: hh:mm:ss.cc	-	
trkNum	Track number of the aircraft to which this this line corresponds	-	
Xpos	Aircraft X position in ENU reference frame	NM	
Ypos	Aircraft Y position in ENU reference frame	NM	
Zpos	Aircraft altitude in ENU reference frame	ft	
response	Boolean if associated alert is responded by the pilot	bool	1 = response; 0 = no response
delay	Delay of the pilot to respond associated alert	s	No sense in case of no pilot response
Vert_acc	Vertical acceleration the pilot responds to the associated alert	g	No sense in case of no pilot response
label270	String from which the fields of label 270 can be derived	-	<p>This field is defined by concatenation of the following symbols:</p> <ul style="list-style-type: none"> <li>• Combined control (octal)</li> <li>• Vertical control (octal)</li> <li>• Up Advisory (octal)</li> <li>• Down Advisory (octal)</li> <li>• "_"</li> <li>• Crossing bit (binary)</li> <li>• MTE bit (binary)</li> </ul> <p>For example: 4010-00 has cc=4,vc=0,ua=1,da=0,cb=0,mte=0 and corresponds to a climb advisory.</p> <p>If aircraft cannot provide these fields (for example, because it is unequipped), they will be all set to zero (0000-00).</p>
tarVR	Target vertical rate	fpm	Target vertical rate as provided by the ACAS system.



			If aircraft cannot provide this field (for example, because it is unequipped), it will be set to zero.
hcc	Horizontal combined control	-	Combined control field of horizontal ARINC label 271 If aircraft cannot provide this field, it will be set to zero.
tarHDG	Heading to target advisory (deg from north)	deg	Target heading as provided by the ACAS system. If aircraft cannot provide this field, it will be set to zero.
alarm	Boolean alarm which indicates if the current advisory has an RA annunciation or not.	-	True: the current advisory has an RA annunciation False: the current advisory has not an RA annunciation
numInt	Number of intruders	-	Number of intruders.
Intruder data	Data for each intruder	-	

Entries must be such that:

- The same time stamps are provided for all aircraft.
- The time stamps have a time difference of one second.

The intruder data section is obtained through concatenation (in the realisation data line) of intruder data entries. These entries are separated with one another by commas. The number of such entries is equal to numInt provided in the realisation data line. The fields of each intruder entry is shown in the following table:

**Table 25 Intruder entry section**

Name	Description	Units	Comments
trafCode	Intruder traffic code. The following traffic codes are allowed: <ul style="list-style-type: none"> <li>• 0: Other Traffic</li> <li>• 1: Proximate Traffic</li> <li>• 2: TA Degraded</li> <li>• 3: TA Nominal</li> <li>• 4: RA</li> </ul>	-	
trndArrow	Intruder vertical trend arrow: <ul style="list-style-type: none"> <li>• -1: Downwards arrow</li> <li>• 0: No arrow</li> <li>• 1: Upwards arrow</li> </ul>	-	
Altitude	Altitude string used under aircraft symbol in navigation display	-	This field is directly transferred to the navigation display. The reason for storing this field as a string rather than as an altitude is that it is expected that the string representation be more compact, as the altitude tag under an intruder symbol is expected to be three characters long.
Range	Intruder range	NM	
Bearing	Intruder bearing (North 0°, east 90°)	deg	
intBooleans	Intruder Booleans, obtained by concatenation of the following fields: <ul style="list-style-type: none"> <li>• Intruder is altitude reporting</li> <li>• Bearing measurement is valid</li> <li>• Intruder is mode-S equipped</li> </ul>	-	For example: "100": Intruder is altitude reporting, but bearing measurement is invalid and intruder is not mode-S equipped. "010": Intruder is not mode altitude reporting, nor is mode-S equipped, but bearing measurement is valid. "001": Intruder does not report altitude nor is bearing measurement valid, but it is mode-S equipped.

Intruder entries are provided with increasing representation order: the first in the list will have the lowest ACAS score. This is done to ease implementation, in such a way that plotting intruders in the same order as they appear in the file will ensure that intruders with the highest priority will be shown on top of the others.

## 9.7. Illustration of Crossing LOLO RA

The following figure provides a typical illustration of an encounter where a Crossing LOLO RA can be triggered (in blue). In this type of encounter, it is preferable to trigger a Positive Descend RA followed by a weakening LOLO RA (in red) rather than only a LOLO RA in order to secure the crossing.

Indeed, it is preferable to cross in altitude largely before the trajectories cross in the horizontal plane in order to secure the prevention of an NMAC in case of:

- Non-standard pilot response to RAs (e.g. slow pilot reaction) of the blue aircraft;
- Uncertainty in the vertical tracker; or
- Late level-off manoeuvre of the black intruder aircraft (if the intruder is not ACAS equipped or does not follow the RAs).

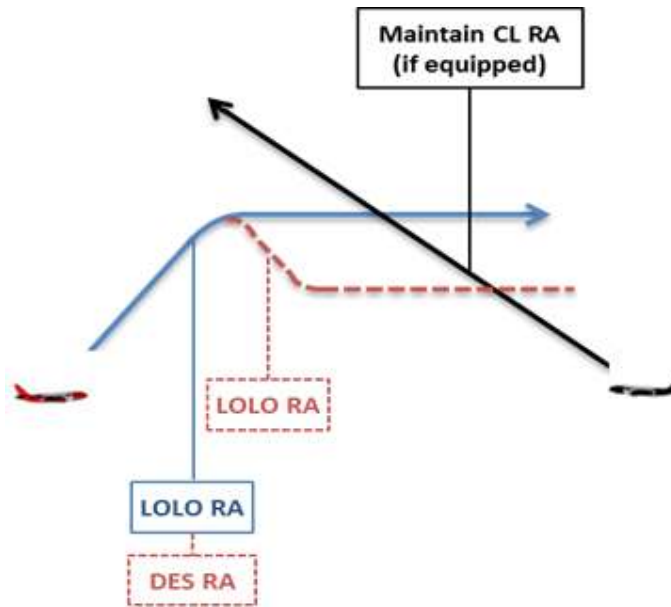


Figure 109 Crossing level off level off

## 9.8. Illustration of asymmetrical Crossing RA

The following figure provides an illustration of an encounter with an asymmetrical Crossing RA. In this type of encounter, it is preferable to trigger Crossing RAs simultaneously on-board both aircraft (i.e. to force a simultaneous Maintain Climb RA on-board the red aircraft) in order to secure the crossing.

Indeed, it is preferable to secure the crossing in order to avoid an NMAC in case of:

- Pilot non-response to RAs of the black aircraft;
- Uncertainty in the vertical tracker; or
- Late level-off manoeuvre of the blue intruder aircraft (if an RA is triggered too late or no RA is triggered).

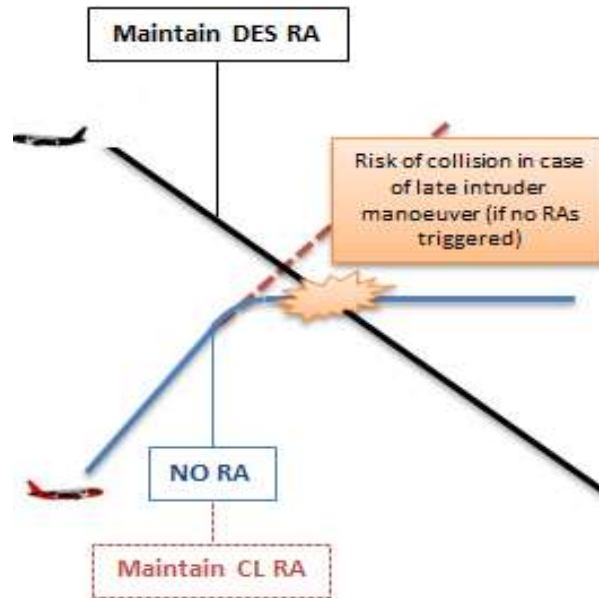


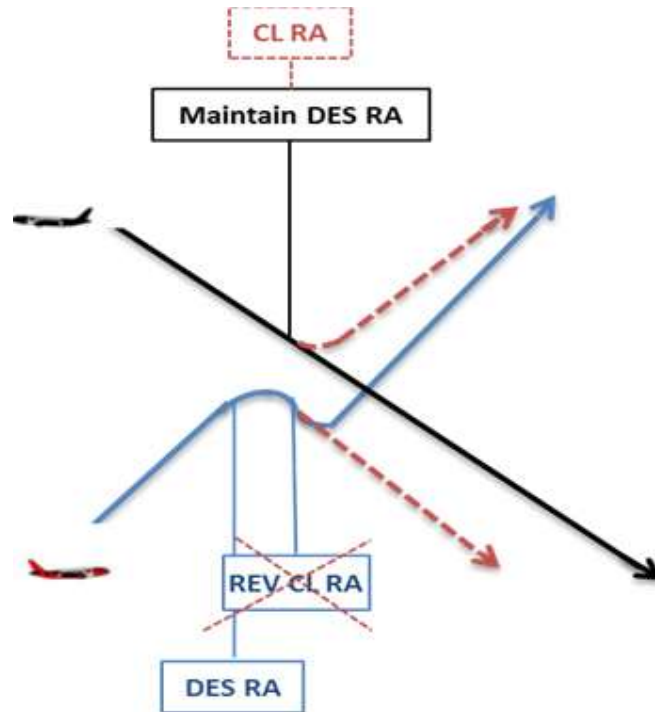
Figure 110 Asymmetrical crossing RA

## 9.9. Illustration of unnecessary Reverse RA

The following figure provides an illustration of an encounter where an unnecessary Reverse RA can be triggered (in blue). In this situation, it is preferable to avoid the Reverse Climb RA (in blue) by triggering a Climb RA (in red) rather than a Maintain Descend RA on the black aircraft. Indeed, by avoiding the Reverse RA (in red) the situation is at least as safe<sup>17</sup> (or even safer) than when triggering the Reverse RA (in black and blue).

In this case the Reverse RA is considered unnecessary and must be avoided in order to:

- Avoid the triggering of an unnecessary stressful secondary Reverse RA for pilot acceptance; and
- Avoid creating any Überlingen-like encounter in case of uncertainty of pilot response to the Reverse RA.



**Figure 111 Unnecessary reverse RA**

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<sup>17</sup> Safe = ALIM is achieved

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