

**Decision criteria for  
regulatory measures on TCAS II version 7.1**

**Safety Issue Rectification Extension Plus Project  
(SIRE+ Project)**

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## RECORD OF CHANGES

Issue	Date	Detail of changes
0.1	18-06-2008	Initial draft
0.2	27-06-2008	Revised version following internal review
1.0	27-06-2008	Initial version delivered to EUROCONTROL
1.1	17-07-2008	Revised version taking into account comments from EUROCONTROL
1.2	25-07-2008	EUROCONTROL editorial changes

**IMPORTANT NOTE:** ANY NEW VERSION SUPERSEDES THE PRECEDING VERSION, WHICH MUST BE DESTROYED OR CLEARLY MARKED ON THE FRONT PAGE WITH THE MENTION *OBSOLETE VERSION*

## Executive Summary

EUROCAE and RTCA have jointly developed revised Minimum Operational Performance Standards (MOPS) for Traffic alert and Collision Avoidance System (TCAS) II published in [ED-143] and [DO-185B] respectively, to be known as TCAS II version 7.1.

There were two overriding reasons for revising the TCAS II MOPS:

- The failure of TCAS to reverse some Resolution Advisories (RA) when a reversal is required to resolve the collision threat (i.e. safety issue SA01 described in [DO-298]) and
- Frequent instances of flight crews' unintentional incorrect manoeuvres in the wrong direction to "Adjust Vertical Speed" RAs (i.e., safety issue SA-AVSA described in [DO-299]).

Due to the combination of these two safety issues, aircraft equipped with TCAS II version 7.0 face a mid-air collision risk of  $2.7 \times 10^{-8}$  per flight hour, corresponding to one collision every 3 years in the European airspace. **This exceeds the tolerable rate for catastrophic events related to equipment hazards by a factor of more than 25.**

EUROCAE WG75 and RTCA SC147 have evaluated and endorsed proposals made by the EUROCONTROL SIRE team to address these issues. These proposals are referenced as CP112E for the proposed improvements in the RA sense reversal logic and CP115 (also termed "Level-off, Level-off") for the proposal to change "Adjust Vertical Speed" RAs to "Level-off" RAs. The validation of these changes has been recorded in RTCA [DO-298] and EUROCAE [ER-1] respectively.

The sole reason for revising the TCAS II MOPS and introducing TCAS II version 7.1 is to address safety issues that are occurring at an unacceptable rate while being avoidable. The Überlingen accident and the numerous severe incidents resulting from safety issues described above could have been avoided with TCAS II version 7.1.

The speed with which the reduction in the above mentioned risk is achieved depends on the policy used for introducing TCAS II version 7.1 into the European airspace. The goal of the present study is therefore to provide key elements to determine the best approach in terms of regulatory measures and associated timescales. These elements are obtained by comparing the performance of several scenarios for the entry into force of version 7.1 in the European airspace. The key metric used for this comparison is the risk of mid-air collision, derived from probabilities of collision due to issues SA01 and SA-AVSA and computations based on the EUROCONTROL safety encounter model.

Fifteen scenarios for the introduction of TCAS II version 7.1 have been investigated in the study involving a range of start and completion dates for the transition phase and various speeds of retrofits, including the "late rush" retrofit hypothesis (which assumes that the proportion of version 7.1 equipage increases slowly until close to the mandate term, and then increases very rapidly in the last months).

Conclusion:

Based on the investigated scenarios, the present study concluded:

- **Maximum benefit is achieved with aggressive installation schemes;**
  - A regulation based solely on forward fit brings no benefits on the risk of mid-air collision in the short term, and only limited benefits in the long term.
  - Progressive retrofit brings significant benefits when compared to the typical scheme (i.e., late rush).
  - A 2 year (or longer) delay in the start of the transition phase would result in a serious debasement of the safety benefits brought by TCAS.
  - Only aggressive scenarios of entry into force enable to meet SESAR initial objective of improving safety by a factor of 3 in 2020 ([SESAR]).
- **Realistic scenarios are such that a risk of mid-air collision due to SA01 and SA-AVSA continues to exist during the transition phase;**
  - In only one scenario, with the most aggressive implementation schedule, does the transition phase end before the probability calculations indicate, an SA01/SA-AVSA collision can occur.

Recommendation:

**As TCAS II version 7.1 provides further significant reduction in the risk of mid-air collisions; it is therefore strongly recommended that TCAS II version 7.1 is implemented as rapidly as possible.**

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## GLOSSARY

ACAS	<p>Airborne Collision Avoidance System – a system standardised in the ICAO SARPs that uses transponder replies from other aircraft to warn the pilot of a risk of impending collision.</p> <p>Hereafter, ACAS always refers to ACAS II – a system that generates traffic advisories (TAs) and also generates resolution advisories (RAs) in the vertical plane.</p>
ACASA project	ACAS Analysis – a study commissioned by EUROCONTROL in support of the mandate for the carriage of ACAS II in Europe, before implementation of RVSM.
ASARP project	ACAS Safety Analysis post-RVSM Project – a study commissioned by EUROCONTROL to investigate the safety of ACAS following the introduction of RVSM in Europe.
AVSA RA	An “Adjust Vertical Speed, Adjust” RA is an RA requiring the pilot to reduce his aircraft vertical rate to 2000, 1000, 500 or 0 fpm. It is a restriction of manoeuvre intended to maintain a minimum vertical separation from the intruder. The proper response to an AVSA RA is always a reduction in vertical speed.
CP112E	A change to the TCAS II MOPS addressing a safety issue labelled SA01 and related to an inappropriate reversal logic operation. This change is included in TCAS II version 7.1.
CP115	A change to the TCAS II MOPS addressing the safety issue of unintentional opposite responses to initial AVSA RAs. It consists in replacing AVSA RAs with a single “Level-off” RA. This change is included in TCAS II version 7.1.
EUROCONTROL safety encounter model	A safety encounter model developed in a series of EUROCONTROL project. It has been built out of the characteristics of recent close encounters observed in Europe. It is therefore representative of current operations in European airspace.
ICAO safety encounter model	A safety encounter model defined in the ICAO SARPs and built out of the characteristics of close encounters observed in the US and in Europe before the introduction of RVSM. It is therefore not representative of any given airspace.
Intruder	A transponder-equipped aircraft within the surveillance range of ACAS and that is tracked by ACAS.
Near Mid-Air Collision	An encounter in which the horizontal separation between two aircraft is less than 500 ft and the vertical separation is less than 100 ft. The rate of NMACs to actual collisions is 10 to 1.

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Negative RA	An RA requiring the flight crew to conform to a restriction of manoeuvre in order to maintain a minimum vertical separation from the intruders. AVSA RAs are a type of negative RAs.
Positive RA	An RA requiring the flight crew to perform a manoeuvre in order to achieve a minimum vertical separation from the intruder.
RA sense	The sense of an ACAS II RA is “upward” if it requires a climb or a limitation of the rate of descent and “downward” if it requires a descent or a limitation of the rate of climb.
Resolution Advisory	A resolution advisory (RA) is an ACAS alert instructing the pilot on how to modify or regulate his vertical speed in order to reduce the risk of collision diagnosed by the system.
Safety encounter model	<p>A mathematical model which reproduces the distributions and interdependencies of the parameters characterising risk bearing encounters likely to occur in ATM operations.</p> <p>The encounters that matters are those in which two aircraft are on a close encounter course and in which there exist a risk of mid-air collision or in which the response of pilots to ACAS RAs can result in a risk of mid-air collision.</p>
Safety issue	An issue that has the potential to debase the safety benefits brought by ACAS, possibly leading to reduced vertical separations or even NMACs.
SIRE+	<p>Safety Issue Rectification – a series of studies (SIR, SIRE, SIRE+) commissioned by EUROCONTROL in order to improve TCAS safety performance.</p> <p>SIRE+ addresses two safety issues:</p> <ul style="list-style-type: none"><li>- SA01: inappropriate reversal logic operation,</li><li>- SA-AVSA: misinterpretation of AVSA RAs leading to unintentional responses in the opposite sense.</li></ul>
TCAS	Traffic alert and Collision Avoidance System – an aircraft equipment that is an implementation of an ACAS.

## 1. Introduction

### 1.1. Context

- 1.1.1. The European Organisation for Civil Aviation Equipment (EUROCAE) and RTCA have jointly developed revised Minimum Operational Performance Standards (MOPS) for Traffic alert and Collision Avoidance System II (TCAS II) in [ED-143] and [DO-185B] respectively.
- 1.1.2. There were two overriding reasons for revising the TCAS II MOPS. The first one was the failure of TCAS to reverse some Resolution Advisories (RAs) when a reversal is required to resolve the collision threat (i.e., safety issue SA01 described in [DO-298]). The second reason was that, not infrequently, flight crews unintentionally manoeuvre in the wrong direction to “Adjust Vertical Speed, Adjust” (AVSA) RAs (i.e., safety issue SA-AVSA described in [DO-299]). Due to the combination of these two safety issues, aircraft equipped with TCAS II version 7.0 face a mid-air collision risk of  $2.7 \times 10^{-8}$  per flight hour, corresponding to one collision every 3 years in the European airspace.
- 1.1.3. EUROCAE Working Group 75 (WG75) and RTCA Special Committee 147 (SC147) have evaluated and endorsed proposals made by the EUROCONTROL Safety Issue Rectification (SIRE) team to address these issues. These proposals are referenced in the RTCA arena as Change Proposal 112E (CP112E) for the proposed improvements in the RA sense reversal logic and CP115 for the proposal to change “Adjust Vertical Speed” RAs to “Level-Off” RAs. The validation of these changes has been recorded in RTCA [DO-298] and EUROCAE [ER-1] respectively.
- 1.1.4. These revisions to TCAS II version 7.0 will be included in TCAS II version 7.1, and reduce the mid-air collision risk to one collision every 12 years in the European airspace, once the fleet is fully equipped with version 7.1 equipage.
- 1.1.5. Because the risk of mid-air collision due to issues SA01 and SA-AVSA exceeds the tolerable rate of catastrophic events related to equipment hazards by a factor of more than 25, regulatory measures are required for airlines and aircraft operators to rapidly upgrade the whole fleet with TCAS II version 7.1.

### 1.2. Scope and objectives

- 1.2.1. The speed with which the safety benefits provided by TCAS II version 7.1 are obtained depends on the policy used for upgrading from version 7.0. The goal of the present study is therefore to provide key elements to determine the best approach in terms of regulatory measures and associated timescales.
- 1.2.2. These elements are obtained by comparing the performance of several scenarios for the entry into force of TCAS II version 7.1 in the European airspace. The key metric used for this comparison is the risk of mid-air collision, derived from probabilities of collision due to issues SA01 and SA-AVSA and computations based on the EUROCONTROL safety encounter model.



### **1.3. Document overview**

- 1.3.1. Part 1 is the present introduction.
- 1.3.2. Part 2 presents some background on the safety issues addressed by TCAS II version 7.1, and on the solutions to these issues.
- 1.3.3. Part 3 presents the scenarios for the entry into force of TCAS II version 7.1 that have been assessed in this report, and the assumptions made to define these scenarios.
- 1.3.4. Part 4 presents the results of the study and an analysis of these results.
- 1.3.5. Part 5 is the conclusion of this report, also providing some recommendations based on the outcomes of several years of work towards the resolution of the TCAS II version 7.0 safety issues.

## 2. Background

### 2.1. ACAS and TCAS

#### 2.1.1. ACAS

- 2.1.1.1. ICAO (International Civil Aviation Organization) has developed, since the beginning of the eighties, standards for Airborne Collision Avoidance Systems (ACAS).
- 2.1.1.2. ACAS II provides two levels of alert to the pilot: Traffic Advisories (TAs) and vertical RAs. The TAs aim to help the pilot in the visual search for the 'intruder' aircraft, whereas the RAs are indications to the pilot of manoeuvres intended to provide separation from one or several 'threats'; or manoeuvre restrictions intended to maintain existing separation<sup>1</sup>. When the threat aircraft is also fitted with an ACAS system, both ACAS' co-ordinate their RAs through the Mode S data link, in order to select complementary resolution senses.
- 2.1.1.3. The ACAS II mandate applies worldwide to all civil fixed-wing turbine-engined aircraft having a maximum take-off mass exceeding 5,700 kg, or a maximum approved passenger seating configuration of more than 19 (Paragraph 6.18 of [ANN6], requirement 1.668 of [EUOP1]).
- 2.1.1.4. The European policy regarding ACAS II is to require the mandatory carriage and operation of an airborne collision avoidance system by defined civil aircraft in the airspace of the Member States of the European Civil Aviation Conference (ECAC). This implementation process has been managed by the Mode S Programme in EUROCONTROL on behalf of the ECAC States.

#### 2.1.2. TCAS

- 2.1.2.1. TCAS II version 7.0, as specified in [DO-185A], is the only equipment which complies fully with ACAS II standards and recommended practices, published by ICAO. Therefore version 7.0 is required to meet the ACAS II mandate in the ECAC Member States. Version 7.0 was developed to address a number of issues identified through the operational monitoring of the former version 6.04a performance.
- 2.1.2.2. In the former TCAS II version 6.04a, negative RAs<sup>2</sup> were announced as "Reduce Climb, Reduce Climb" or "Reduce Descent, Reduce Descent". The proper response to a negative RA is always a reduction in vertical speed, i.e. a manoeuvre towards level flight. However, pilots sometimes misunderstood the aural message as "Climb" or "Descend" and responded to the RA by increasing their vertical rate. Version 7.0

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<sup>1</sup> A guide to the use of ACAS and its functionality can be found in the EUROCONTROL ACAS brochure ([ACA1]).

<sup>2</sup> A negative RA is typically issued when a TCAS-equipped aircraft is climbing or descending towards another aircraft, and the TCAS logic determines that the TCAS-desired vertical miss distance between the two aircraft can best be achieved by the TCAS aircraft reducing its vertical speed, while maintaining its current vertical direction. These RAs, mainly occurring in 1000 ft level-off geometries, represent two thirds of all RAs observed in the European airspace [EMO1].

replaced the aural annunciation associated to negative RAs with “Adjust Vertical Speed, Adjust”.

- 2.1.2.3. TCAS II version 7.0 also introduced the capability to reverse the sense of RAs (e.g., from climb to descend) to resolve deteriorating conditions during an encounter with another TCAS-equipped aircraft. A reversal may be needed after the initial RA when one pilot does not respond to TCAS RA guidance, or worse, manoeuvres in the opposite direction.

## **2.2. Safety Issue SA01**

### **2.2.1. Description**

- 2.2.1.1. The design principles of TCAS II version 7.0 allow only one sense reversal and care has been taken to ascertain the relative position of aircraft and their trajectories. Notably, reversing the on-going RA is not permitted while aircraft are manoeuvring in the vertical dimension and are at co-altitude. This can lead to delaying the decision to reverse if both aircraft are climbing or descending at similar vertical speeds. In the extreme, no sense reversal can be issued although it would be required. This problem can occur either in encounters with an unequipped aircraft<sup>3</sup> or in TCAS-TCAS encounters.
- 2.2.1.2. The SA01 issue was initially predicted early in 2000 by analyses and simulations conducted within a EUROCONTROL project named European Maintenance Of TCAS version 7 (EMOTION-7) ([EMO1]). This issue was subsequently observed during European monitoring efforts from 2001 to 2005. Analysis indicates that the SA01 issue has been a factor contributing to two major events: the Yaizu (Japan) accident in 2001 and the Überlingen mid-air collision in 2002. In 5 years, 8 other occurrences have been observed in the European airspace. Each of these events resulted in severe losses of separation where collision was only avoided by chance. These severe incidents were only identified when actual occurrences of safety issue SA01 were actively tracked.
- 2.2.1.3. Safety issue SA01 can occur when two aircraft are flying at the same Flight Level (FL) and are converging in range. A very late Air Traffic Control (ATC) instruction then induces the intruder to manoeuvre, thwarting the initial RAs. Figure 1 illustrates this issue for two aircraft at FL110, and the behaviour expected from TCAS.

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<sup>3</sup> In this situation, a TCAS unit operating in stand-by or TA-only mode is also considered unequipped

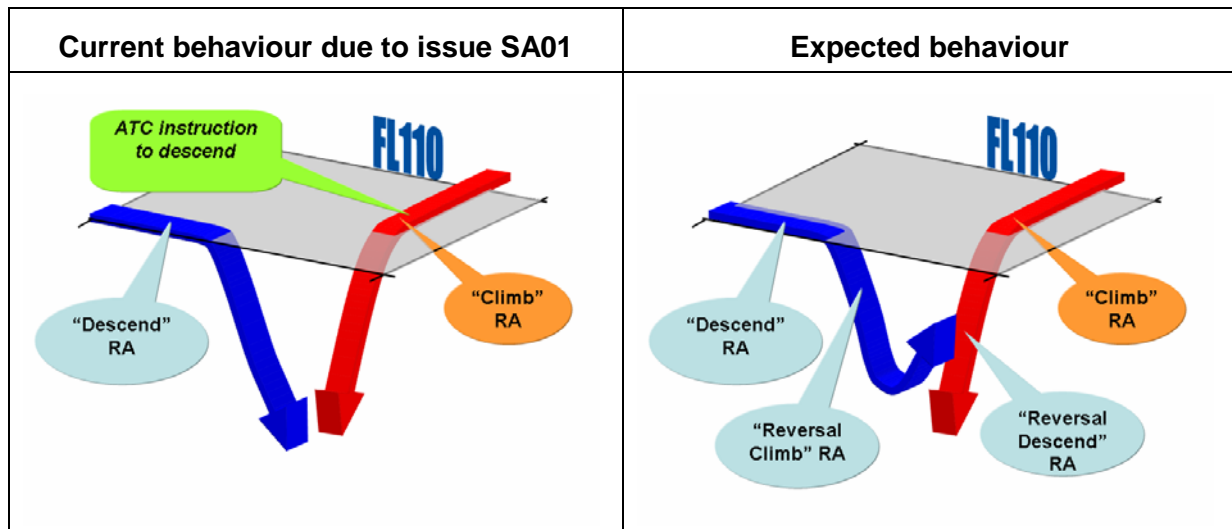


Figure 1: Issue SA01

## 2.2.2. SA01 issue illustration: Überlingen mid-air collision

- 2.2.2.1. This scenario occurred over Überlingen on 1<sup>st</sup> July 2002. As indicated in Figure 2, it involved a Boeing 757 on a northern course (in blue in Figure 2) and a Tupolev 154 on a western course (in red in Figure 2). Both aircraft were level at FL360 and on converging tracks.
- 2.2.2.2. ATC gave the Tupolev 54 a late instruction to expedite its descent to FL350. As the flight crew started to descend, a “Climb” RA was triggered by its TCAS II unit, requesting a 1500 fpm climb rate. Despite this “Climb” RA, the Tupolev 154 flight crew continued to descend according to the ATC instruction. A coordinated “Descend” RA was generated onboard the Boeing 757, requesting a 1500 fpm descend rate. The flight crew responded correctly and followed this RA
- 2.2.2.3. .As the Boeing 757 started its descent, its TCAS unit strengthened its advisory to an “Increase Descent” RA, requesting a 2500 fpm rate of descend. This RA was also correctly followed by the flight crew. Because the Tupolev 154 flight crew had not acknowledged his instruction, the controller repeated the instruction to expedite descent to FL350. This time, the flight crew acknowledged and increased the rate of descent. Despite an “Increase Climb” RA requesting a 2500 fpm rate of climb, the Tupolev 154 flight crew continued to descend and the aircraft collided at 34890 ft.
- 2.2.2.4. As indicated in 2.2.1, the sense of the initial RAs was not reverse because the aircraft remained at co-altitude until they collided. In this accident, a reversal in the sense of RAs might have prompted action to avoid the collision.
- 2.2.2.5. It is important to note that, although the Überlingen accident involves two TCAS-equipped aircraft, a similar event can occur with an aircraft not equipped with TCAS, or having its TCAS unit set on TA-only mode, manoeuvring in the same direction as the TCAS-equipped aircraft.

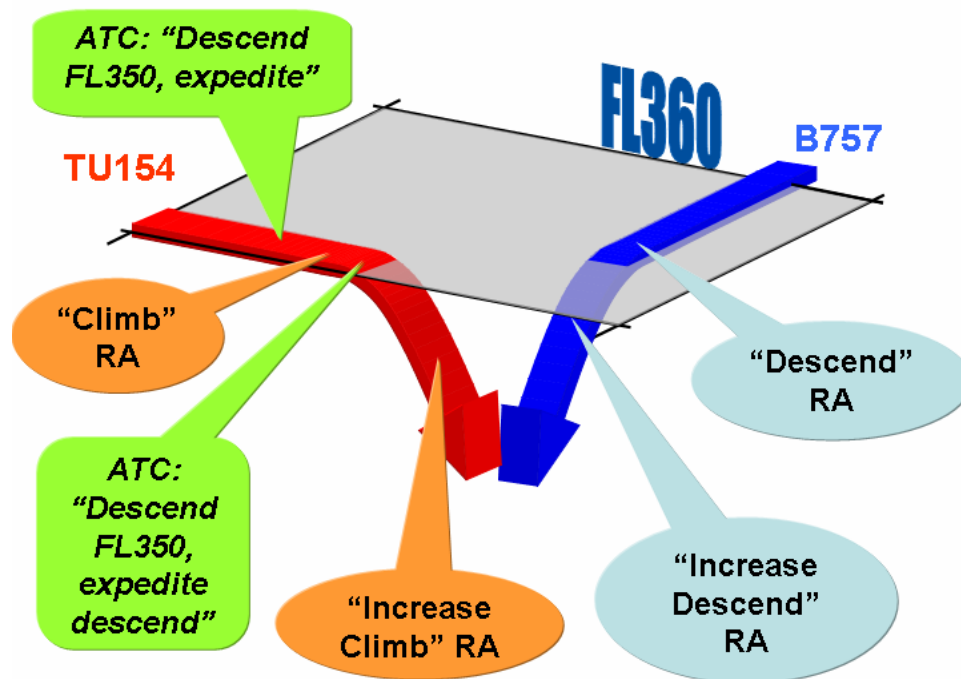


Figure 2: Überlingen collision description

### 2.2.3. Probability of collision

2.2.3.1. Using data provided by a major European airline, an assessment of the probability of occurrence of issue SA01 has been performed by the EUROCONTROL EMOTION-7 project ([EMO2]).

2.2.3.2. Analysis of the data provided allowed to find 2 actual occurrences of issue SA01. Given the number of hours flown annually by this airline, it was derived that an SA01 event could be observed at an estimated rate of once every 211,330 flight hours in the European airspace, or  $4.7 \times 10^{-6}$  per flight hour.

2.2.3.3. Using this probably, and data on SA01 events identified between 2002 and 2005, a probability of collision due to issue SA01 was derived, and was found to be  $2.2 \times 10^{-8}$ , which corresponds to one collision every 4 years in the European airspace, due to issue SA01.

2.2.3.4. Further details on this computation are provided in Appendix A and in [DO-298].

### 2.2.4. CP112E solution to issue SA01

2.2.4.1. Solving the issue with the reversal logic was done through a significant code change of TCAS II version 7.0, which has been submitted to RTCA as CP112E to amend the TCAS II MOPS.

2.2.4.2. CP112E brings two significant improvements to the reversal logic of TCAS II. First, it introduces a monitoring of the aircraft vertical rate in order to detect any non-compliance with the RA sense. Then it includes a better projection of the current aircraft trajectories to identify encounters where two co-altitude aircraft maintain similar vertical rates.

2.2.4.3. The former is designed to solve occurrences of SA01 between two TCAS-equipped aircraft while the former is intended to address occurrences of SA01 with an aircraft not equipped with TCAS. If CP112E detects either situation, it relaxes the conditions for reversing the ongoing RA so that it can occur at an earlier time than with current TCAS II version 7.0.

## 2.3. Safety Issue SA-AVSA

### 2.3.1. Description

2.3.1.1. Monitoring of TCAS performance performed separately by airlines and by EUROCONTROL has highlighted several instances where flight crews responded unintentionally in the opposite direction to that specified by TCAS when an initial AVSA RA was issued. The proper response to an AVSA RA is always a reduction in vertical speed (i.e., a manoeuvre towards level flight). When a flight crew manoeuvres in the opposite direction to an AVSA RA, it is almost always manoeuvring towards the intruder and thus increases the risk of collision

2.3.1.2. Several causes have been identified that can explain an unintentional opposite reaction to an AVSA RA, including a lack of training for this type of RAs. However, the main factor remains the design of the AVSA RAs. First, the aural annunciation associated with AVSA RAs (i.e., "Adjust Vertical Speed, Adjust") does not give explicit instructions on the required manoeuvre.

2.3.1.3. Then, some TCAS displays prove to be difficult to interpret when AVSA RAs are posted. Indeed, the position of the green arc on vertical speed displays can be misleading for some pilots who react to TCAS RAs according to the position of the green area relatively to the 0 fpm indicator. This is illustrated by Figure 3 which shows a number of RAs as they are displayed on a vertical speed tape and what the requested reaction to these RAs is. A correct behaviour when faced with positive RAs (e.g., "Climb" or "Descend" RAs) leads to opposite reactions to AVSA RAs requesting vertical rates of 500, 1000 or 2000 fpm

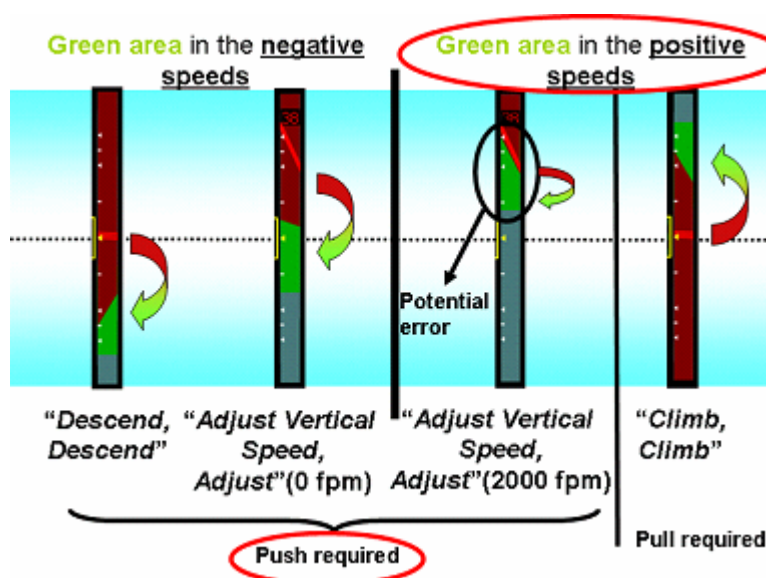


Figure 3: Requested reactions to RAs

2.3.1.4. Several European airlines have assessed the frequency of this issue through their Flight Data Management programme and have discovered that unintentional opposite responses occurred in close to 5% of initial AVSA RAs. Numerous occurrences have also been identified through accident investigation, pilot and controller reports. This highlights that issue SA-AVSA can be observed as soon as it is actively tracked, as recently confirmed by a new occurrence discovered in radar data collected in Northern Europe.

### 2.3.2. SA-AVSA illustration

2.3.2.1. This event occurred in French airspace in 2003 and is shown in Figure 4. It involves an Airbus 320 level at FL270, heading South (in blue in Figure 4), and a second Airbus 320 cleared to climb to FL260, heading North (in red in Figure 4). The second aircraft's rate of climb was about 3300 fpm.

2.3.2.2. When passing through FL253, its TCAS triggered an initial AVSA RA requiring a reduction in the rate of climb to 1000 fpm. However, the flight crew misinterpreted the RA and reacted opposite to it: the rate of climb was increased to more than 6000 fpm instead.

2.3.2.3. The closure rate increased between the two aircraft and the initial AVSA RA was strengthened to a "Descend" RA. The flight crew followed this second RA but the manoeuvre took some time to be effective.

2.3.2.4. As a result of this opposite reaction to the initial AVSA RA, the climbing Airbus 320 busted its flight level by 1200 ft and the level Airbus 320 received a "Climb" RA requesting a 1500 fpm rate of climb. Even though the flight crew correctly followed this last RA, the aircraft were only separated by 300 ft vertically and 0.8 Nautical Miles (NM) horizontally at their point of closest approach.

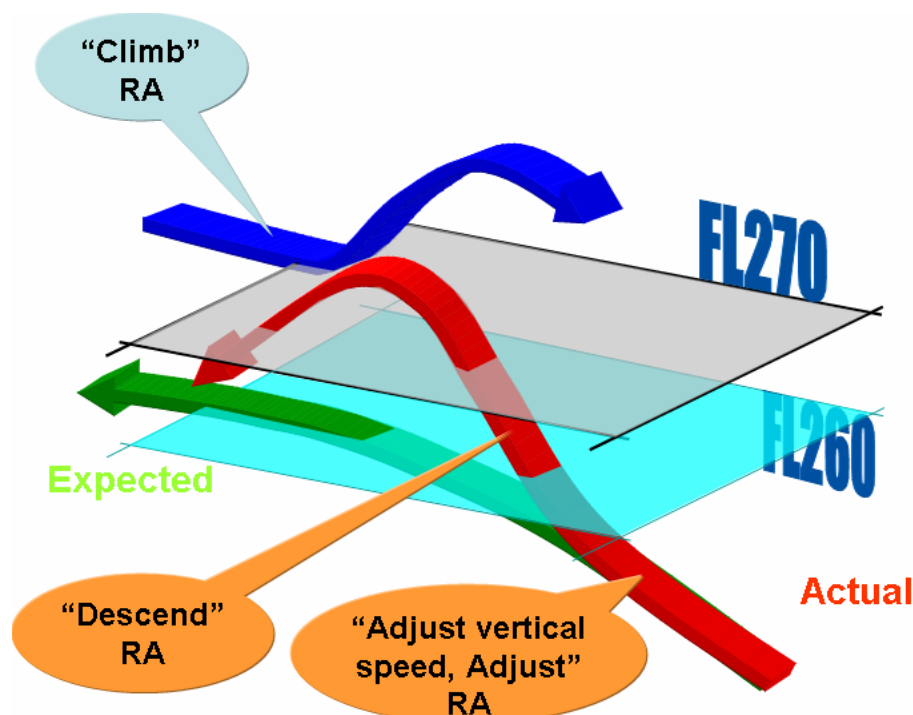


Figure 4: SA-AVSA event in French airspace in 2003

2.3.2.5. If the flight crew had correctly reduced their rate of climb as required by TCAS, simulations show that not only would the climbing Airbus 320 have levelled off correctly, but that the level Airbus 320 would not have received any RA.

### 2.3.3. Probability of collision

2.3.3.1. In 2004 and 2005, 15 opposite responses to initial AVSA RAs leading to an altitude bust have been identified in French airspace, involving operators from various States. Given the total number of  $3.93 \times 10^6$  flight hours flown during these two years, the probability of occurrence of such opposite responses can be estimated to  $3.82 \times 10^{-6}$  per flight hour.

2.3.3.2. A probability of collision resulting from an opposite response to an initial AVSA RA was derived from the miss distances in the observed events and was estimated to  $1.41 \times 10^{-3}$ .

2.3.3.3. By combining the above two figures, the resulting estimated risk of collision because of SA-AVSA amounts to 5.4 collisions per  $10^9$  flight hour. This rate is equivalent to 1 collision every 15 years when extrapolated for European airspace as a whole.

2.3.3.4. Further details on the above computation are provided in Appendix B and in [ER-1].

### 2.3.4. CP115 solution to issue SA-AVSA

2.3.4.1. It has been observed that enhancements in training alone can only improve the behaviour of a flight crew when an AVSA RA is issued, but are not sufficient to avoid all the opposite reactions. Therefore, to fully address issue SA-AVSA a complete solution had to be envisaged, including a change in the TCAS logic.

2.3.4.2. The solution adopted by RTCA SC147/EUROCAE WG75, and endorsed by major airlines participating to these groups, is to simplify the TCAS RA design and replace the different AVSA RAs with a single Level-off RA. The associated aural message, "Level-off, Level-off", is straightforward and the associated manoeuvre corresponds to the standard manoeuvre already performed in critical situations. Additionally, this replacement also simplifies the TCAS procedure and training.

2.3.4.3. This solution, referenced in the RTCA arena as CP115, is illustrated in Figure 5, in the case of climbing aircraft. The result is equivalent for descending aircraft.

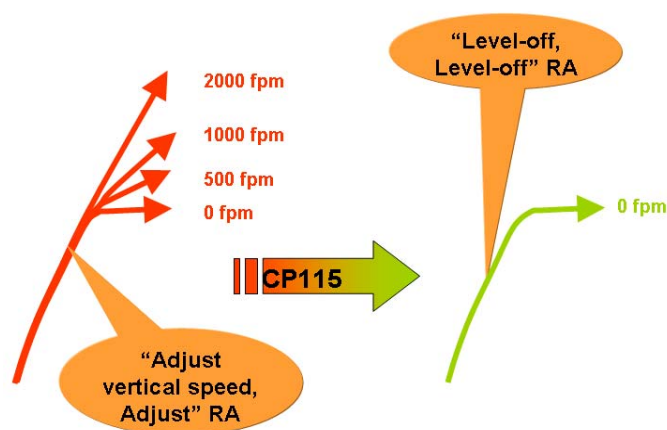


Figure 5: Solution to the SA-AVSA issue



## **2.4. DO-185B/ED-143**

- 2.4.1. Following the identification of these two safety issues, RTCA decided in 2004 to reconvene SC147 to evaluate their severity, validate the CP112E and CP115 solutions proposed by the EUROCONTROL SIRE team and draft revised TCAS II MOPS. At the end of 2006, EUROCAE initiated WG75 to update standards for TCAS jointly with RTCA through a contribution to the development of the updated TCAS II MOPS.
- 2.4.2. Within SC147/WG75, an extensive validation of CP112E has been conducted by several European (EUROCONTROL, DSN, Egis Avia) and US (FAA, MITRE, MIT Lincoln Lab, John Hopkins University) organisations. The result of this validation has been recorded in [DO-298], which concluded that the TCAS II MOPS should be revised to include the CP112E solution and recommended that international authorities initiate work towards regulation action that would expedite implementation of the new MOPS.
- 2.4.3. In the meantime, SC147 and WG75 have also conducted an in-depth analysis of the SA-AVSA issue which has been described in [DO-299]. The validation of the CP115 solution in the European airspace has been conducted along three axes: a safety performance analysis, an operational performance study and a Human Factors study. Several European and US carriers were involved in this validation work. The results have been published by EUROCAE in [ER-1], which concluded that the major European stakeholders supported CP115 as an effective solution to the SA-AVSA issue and recommended it be included in revised TCAS II MOPS.
- 2.4.4. Based on these recommendations, RTCA SC147 and EUROCAE WG75 have jointly developed revised TCAS II MOPS, referenced as [DO-185B] and [ED-143], which notably include CP112E and CP115 among other changes.

### **3. Evaluation of ACAS safety performance in Europe**

#### **3.1. Introduction**

- 3.1.1. ACAS is not designed, nor intended, to achieve any specific Target Level of Safety (TLS). Instead, the safety benefit afforded by the deployment of ACAS is usually expressed in terms of a risk ratio that compares the risk of a Near Mid-Air Collision<sup>4</sup> (NMAC) both with and without ACAS. In the ACAS II Standards And Recommended Practices (SARPs), ICAO has defined a set of target risk ratios for different scenarios of aircraft equipage in a theoretical airspace described by a safety encounter model ([ANN10]).
- 3.1.2. A safety encounter model is a mathematical model reproducing the distributions and interdependencies of the parameters characterising risk bearing encounters likely to occur in Air Traffic Management (ATM) operations. The encounters that matters are those in which two aircraft are on a close encounter course and where there is a risk of mid-air collision, or where the response of pilots to ACAS RAs can result in a risk of mid-air collision.
- 3.1.3. This framework initiated at ICAO level when defining ACAS minimum performances has been further developed through various ACAS-related projects in Europe. These projects include the full-system safety study completed in the ACAS Analysis (ACASA) project ([ACA2], [ACA3]) performed in support to the mandates for the carriage of ACAS II in Europe, and more recently the ACAS Safety Analysis post-RVSM (ASARP) Project ([ASA1]). This same methodology has been used to validate the forthcoming TCAS II version 7.1 ([ER-1, DO-298]).
- 3.1.4. These projects delivered a comprehensive framework which includes a set of models allowing the replication of the environment in which ACAS is being operated in Europe. These models consist in a safety encounter model, models of pilot responses to RAs and a model of altimetry errors applicable in European airspace.

#### **3.2. Safety encounter model**

- 3.2.1. A safety encounter model is a model of traffic situations that captures the properties of close encounters as a series of statistical distributions describing the parameters of a typical encounter and their interdependencies. The encounter model approach is a powerful technique by which a large set of risk bearing encounters (which are rare events in actual operations) can be generated stochastically to assess the safety benefits of ACAS or, indeed, any other ATM safety nets.
- 3.2.2. One limitation of the ICAO safety encounter model defined in [ANN10] lies in the fact that it is not representative of any given airspace. To address this issue, the former EUROCONTROL ACASA project developed a safety encounter model that was representative of operations in Europe at that time ([ACA3]). This model was then regularly updated in a series of projects, culminating in the ASARP project which

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<sup>4</sup>An NMAC is an encounter in which aircraft are separated by less than 500ft horizontally and less than 100ft vertically at closest approach.

updated the EUROCONTROL safety encounter model to reflect Reduced Vertical Separation Minima (RVSM) operations ([ASA1]). The present study uses this most recent safety encounter model.

- 3.2.3. The EUROCONTROL safety encounter model has been built using several years of radar data recorded in the Core Area, and extracting from this data the distributions of the various parameters characterising risk bearing encounters. The EUROCONTROL safety encounter model is thus operationally realistic and representative of current operations in Europe.

### **3.3. Pilot response model**

- 3.3.1. The ICAO ACAS SARPs ([ANN10]) define a 'standard' pilot response to RAs, which is used by the ACAS logic to project aircraft trajectories once RAs have been issued. This standard pilot response is defined by a delay between the issuance of the RA and the start of the pilot manoeuvre, a target vertical speed and a vertical acceleration used to achieve this speed. Depending on the type of the RA, these parameters can take different values (e.g., in response to a "Climb" RA, the ACAS logic expects the pilot to react after 5 seconds using an acceleration of 0.25g to achieve the required 1500 fpm vertical velocity).
- 3.3.2. However, observation of actual pilot behaviour when faced with RAs indicates that first a proportion of RAs are not followed, and then that responses show great variability. Consequently, when evaluating ACAS performance, it is required to introduce a pilot response model that replicates in a realistic manner the pilot responses observed in actual operations.
- 3.3.3. To define this realistic response model, the EUROCONTROL ASARP project has analysed on-board data recorded by some contributing European airlines during 3 years. To support a comparison with the ICAO SARPs standard pilot response, the actual pilot responses were quantified in terms of:
- Time between the issuance of the RA and the beginning of the manoeuvre,
  - Vertical acceleration taken to perform the manoeuvre,
  - Vertical speed achieved by the manoeuvre.
- 3.3.4. Figure 6 provides an overall picture of the observed pilot responses and the frequencies for each of the different response types. This distribution defines the pilot response model. In line with the figure commonly observed for the European airspace, this response model includes a 20% proportion of non-responding pilots.

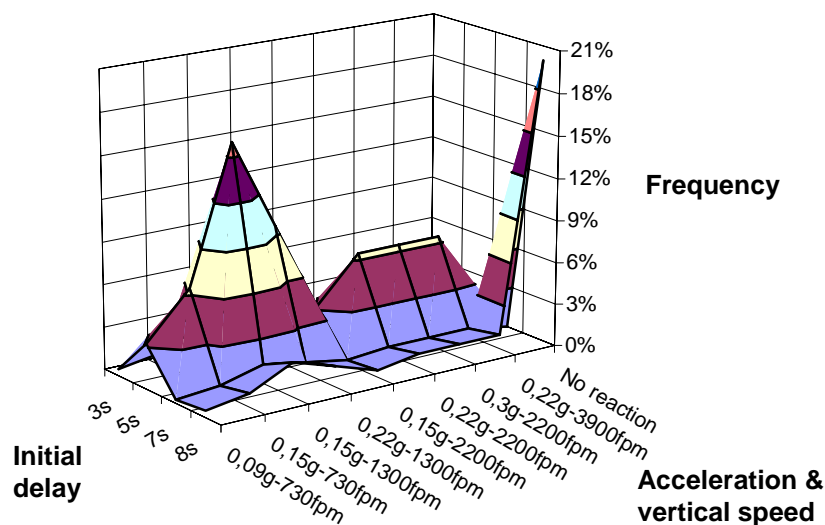


Figure 6: ASARP pilot model

3.3.5. Additionally, recent commercial airline monitoring has shown that opposite responses to RAs happened in a few percents of cases. In order to replicate occurrences of issue SA-AVSA, modelling used for the present study includes 2% of opposite responses to initial AVSA RAs.

### 3.4. Operational model assumptions

3.4.1. Using the encounter and pilot models described above, a key reference model of operations has been defined for European airspace. This reference model encompasses a full range of typical pilot responses to TCAS RAs and the 80% RA response rate observed in European airspace.

3.4.2. In addition, this reference model includes a mix of transponder and ACAS equipage that is representative of the actual equipage of the fleet operating in Europe. Consequently, the reference model defined for the present study provides a realistic representation of the current operations in the European airspace.

### 3.5. Methodology used for the present study

3.5.1. All the ACAS simulations performed for the present study has been conducted on the EUROCONTROL safety encounter model [ASA1], with the operational assumptions described above.

3.5.2. The present study also makes use of a number of scenarios for the entry into force of TCAS II version 7.1. These scenarios define, for each month over a long period of time, the proportion of version 7.1 equipage in the European airspace.

3.5.3. As the period of time considered for the study ranges from 1<sup>st</sup> January 2009 to 31<sup>st</sup> December 2020, each scenario requires the computation of a large number of collision risk values (i.e., one for each month) with varying proportions of TCAS II version 7.1 equipage. Consequently, all the simulations required were performed in order to obtain the risk of collision associated to each possible proportion of version 7.1 equipage, ranging from 0% up to 100% in 1% increments. The output of each

simulation is a probability of collision per flight hour associated to a given proportion of version 7.1 in the European airspace.

- 3.5.4. Then, for each month of a given scenario, the result of the simulation corresponding to the required proportion of TCAS II version 7.1 was associated. From this, the results detailed in the next section were derived.

## 4. Scenarios and associated results

### 4.1. Introduction

- 4.1.1. To provide key elements to determine the best approach in terms of regulatory measures, the present study compares the safety performance of several scenarios for the entry into force of TCAS II version 7.1 in the European fleet.
- 4.1.2. The metric used for this comparison is a risk of collision, derived from probabilities of collision with issues SA01 and SA-AVSA, and computations based on the EUROCONTROL safety encounter model.
- 4.1.3. In this study a scenario of entry into force, also referred to as scenario, is a function associating a proportion of the fleet equipped with TCAS II version 7.1 to a given month of a given year. Two dates are of particular importance when defining a scenario of entry into force:
- The date after which TCAS II version 7.1 begins to be introduced in the European airspace : this date will be called **start of transition phase**;
  - The date from which the proportion of TCAS II version 7.1 is equal to 100% in the European airspace: this date will be called **end of transition phase**.
- 4.1.3.1. The scenarios are defined between 1<sup>st</sup> January 2009 and 31<sup>st</sup> December 2020. This latter date was chosen because it offers a long term vision of what would occur for each scenario, before any significant modification related to the introduction of a future ACAS envisaged by SESAR.
- 4.1.3.2. This section presents the scenarios defined for this study. The assumptions made to define these scenarios are also presented. It also details the results of the simulations performed on these scenarios.

### 4.2. Assumptions

#### 4.2.1. Forward and retrofit

- 4.2.1.1. Three possible dates have been chosen as a start of the transition phase:
- 1<sup>st</sup> January 2009, considered an aggressive starting date;
  - 1<sup>st</sup> January 2010, allowing to introduce TCAS II version 7.1 quite rapidly in the European airspace while letting time for regulation to be put into place;
  - 1<sup>st</sup> January 2011, likely a late date when considering the risk of collision due to safety issues SA01 and SA-AVSA (i.e., one collision every 3 years in the European airspace).
- 4.2.1.2. As for the end of the transition phase, two hypotheses have been considered:
- 31<sup>st</sup> December 2011, which allows ample time for the introduction of TCAS II version 7.1 with the earlier start dates, but can be considered as challenging with the January 2011 start;

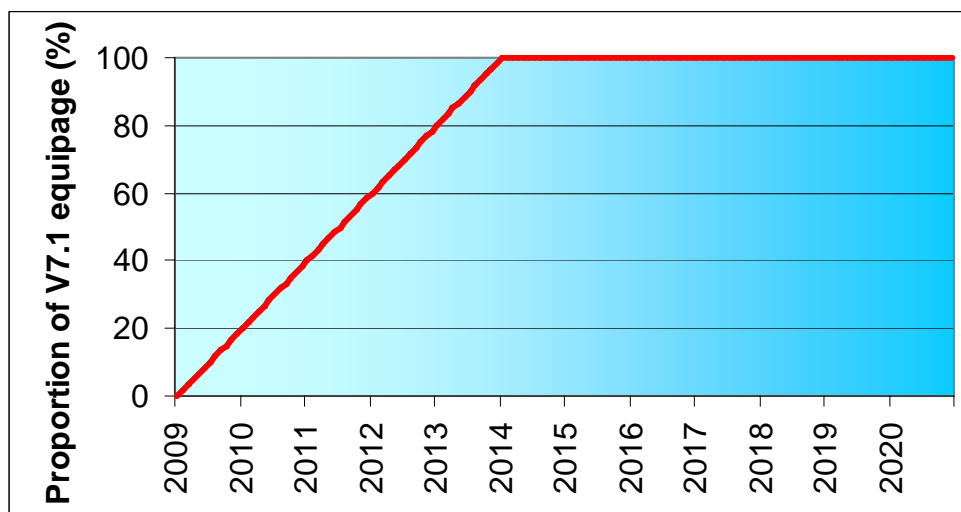
- 31<sup>st</sup> December 2013, likely a late date when considering the current existing risk of mid-air collision.

4.2.1.3. Regarding the forward fit process, it was assumed that the number of aircraft increases by 4% per year [AIR1] and that new aircraft entering the fleet after the start of the transition phase are equipped with TCAS II version 7.1.

4.2.1.4. Two retrofit hypotheses have been considered. The first one assumes a progressive retrofit of aircraft, whereas the second one assumes that airlines will wait before equipping, and then rush to retrofit their aircraft very late, close to the end of the transition phase.

4.2.1.5. Progressive retrofit assumes the proportion of TCAS II version 7.1 equipage increases linearly versus time. This scenario assumes incentive from the airlines to convert from version 7.0 to version 7.1. This scenario is proposed as some major airlines are very supportive of the changes included in version 7.1, notably the modification of AVSA RAs to “Level-off” RAs.

4.2.1.6. Figure 7 shows the evolution of the proportion of TCAS II version 7.1 equipage with a start of transition phase on 1<sup>st</sup> January 2009, and an end of transition phase on 31<sup>st</sup> December 2013, with a progressive retrofit.



**Figure 7: Progressive retrofit starting on 1-1-2009 and ending on 31-12-2013**

4.2.1.7. The “late rush” retrofit hypothesis is a typical scheme which assumes that the proportion of TCAS II version 7.1 equipage increases slowly until close to the end of the transition phase, and then increases very fast in the last months. This scenario of entry into force is closer to what has already occurred with past changes. However, it may still prove to be optimistic as in previous occurrences, a change to the fleet was eventually completed after the end of the transition phase.

4.2.1.8. Figure 8 shows the evolution of the proportion of TCAS II version 7.1 equipage with a start of transition phase on 1<sup>st</sup> January 2009, and an end of transition phase on 31<sup>st</sup> December 2013, with a late rush retrofit. The slight increase in version 7.1 equipage between 2009 and 2013 is a consequence of the forward fit occurring at this time.

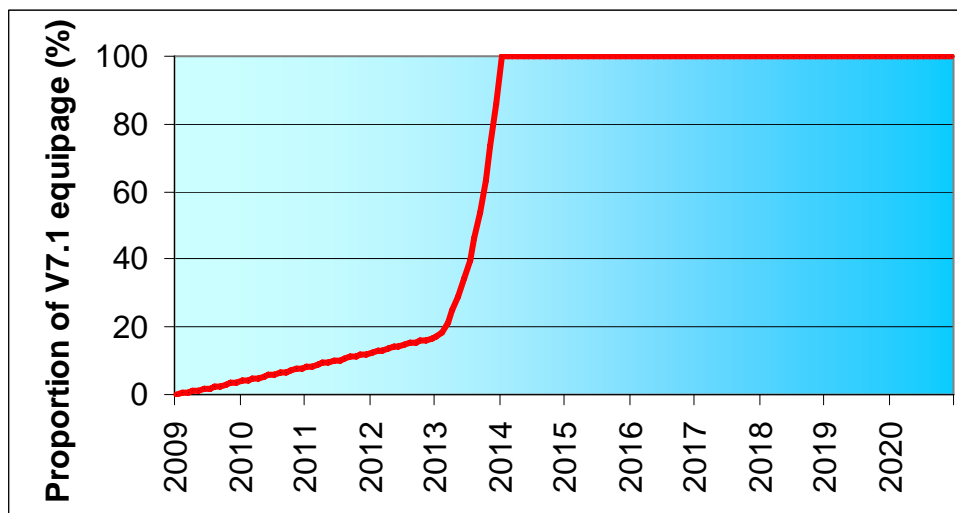


Figure 8: Late rush retrofit starting on 1-1-2009

4.2.1.9. Figure 9 shows the same hypothesis as above, but with a start of the transition phase on 1<sup>st</sup> January 2011 instead of 1<sup>st</sup> January 2009.

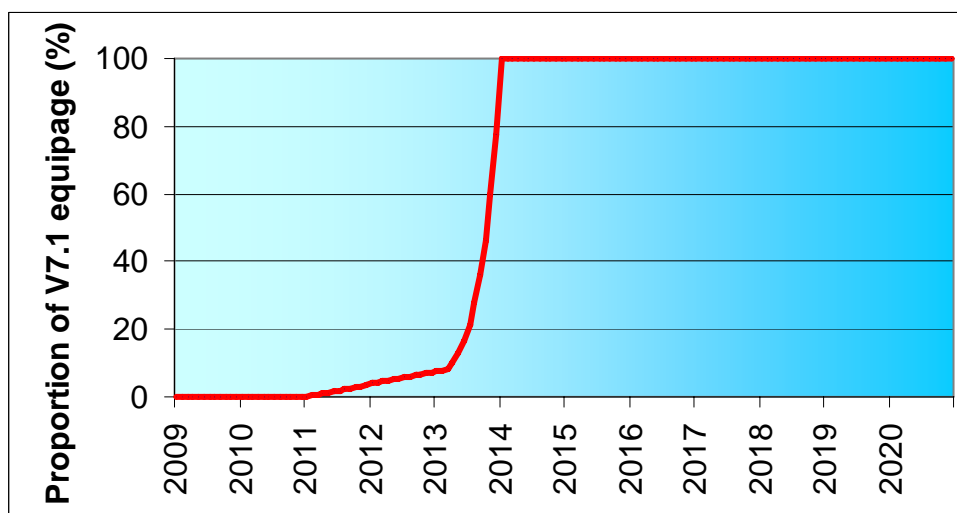


Figure 9: Late rush retrofit starting on 1-1-2011

## 4.2.2. Flight hours

4.2.2.1. The total number of flight hours per year is another key assumption for this study as the risks of collision are derived from probabilities of collision due to safety issues SA01 and SA-AVSA, given per flight hour.

4.2.2.2. The initial number of flight hours for 2009 was taken as  $12.5 \times 10^6$  as this figure was used initially for the computation of the rates of collision due to issues SA01 and SA-AVSA. Although slightly conservative, this number of flight hours allows to have a continuity between the rates of collision computed when the severity of issues SA01 and SA-AVSA has been assessed, and those computed in this report.

4.2.2.3. The traffic growth, and thus the number of flight hours, for the successive years was assumed to be equal to 5% per year [AIR1].



### **4.3. Risk of collision**

#### **4.3.1. Definition of scenarios**

4.3.1.1. Two specific scenarios have been used as a reference for assessing all the other scenarios:

- A first scenario in which the TCAS II version 7.1 equipage remains equal to 0% within the time frame considered for the study (i.e., from 1<sup>st</sup> January 2009 to 31<sup>st</sup> December 2020). This scenario is referred to as the “Do nothing scenario”;
- A second theoretical scenario in which the version 7.1 equipage reaches 100% as soon as 1<sup>st</sup> January 2009. This scenario is referred to as the “immediate full equipage scenario”.

4.3.1.2. Scenarios assuming that the regulation starts on 1<sup>st</sup> January 2009 are as follows:

- Forward fit only, with a start of transition phase on 1<sup>st</sup> January 2009;
- Late rush retrofit with a start of transition phase on 1<sup>st</sup> January 2009 and an end of transition phase on 31<sup>st</sup> December 2013;
- Late rush retrofit with a start of transition phase on 1<sup>st</sup> January 2009 and an end of transition phase on 31<sup>st</sup> December 2011;
- Progressive retrofit with a start of transition phase on 1<sup>st</sup> January 2009 and an end of transition phase on 31<sup>st</sup> December 2013;
- Progressive retrofit with a start of transition phase on 1<sup>st</sup> January 2009 and an end of transition phase on 31<sup>st</sup> December 2011;

4.3.1.3. Scenarios assuming that the regulation starts on 1<sup>st</sup> January 2010 and 1<sup>st</sup> January 2011 are as follows:

- Late rush retrofit with a start of transition phase on 1<sup>st</sup> January 2010 or 1<sup>st</sup> January 2011 and an end of transition phase on 31<sup>st</sup> December 2013;
- Late rush retrofit with a start of transition phase on 1<sup>st</sup> January 2010 or 1<sup>st</sup> January 2011 and an end of transition phase on 31<sup>st</sup> December 2011;
- Progressive retrofit with a start of transition phase on 1<sup>st</sup> January 2010 or 1<sup>st</sup> January 2011 and an end of transition phase on 31<sup>st</sup> December 2013;
- Progressive retrofit with a start of transition phase on 1<sup>st</sup> January 2010 or 1<sup>st</sup> January 2011 and an end of transition phase on 31<sup>st</sup> December 2011;

4.3.1.4. The forward fit only scenario was not assessed with a start of transition phase on 1<sup>st</sup> January 2010 and on 1<sup>st</sup> January 2011, as simulations showed that even starting as early as on 1<sup>st</sup> January 2009 with only forward fit results in limited benefits.

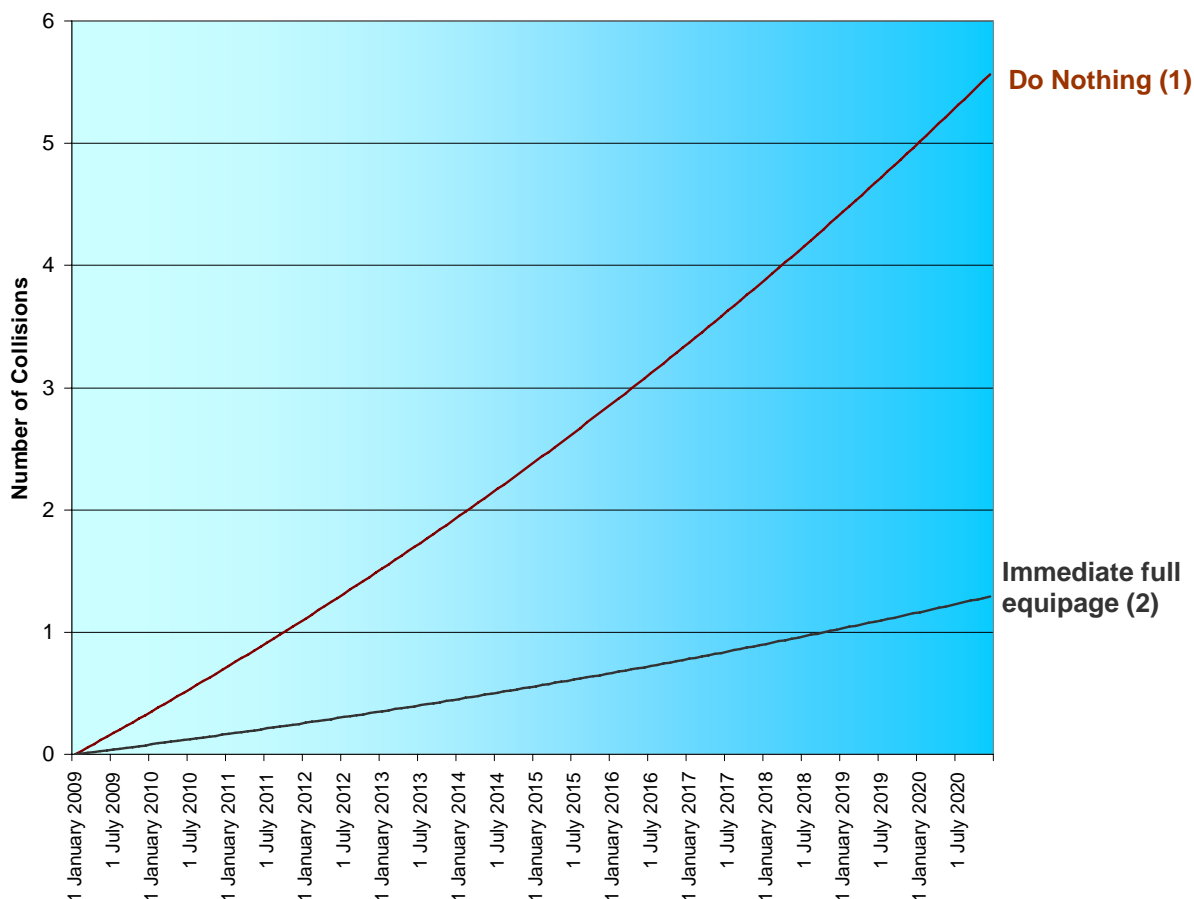
4.3.1.5. Table 1 summarises the scenarios used for this study.

Scenario number	Start of transition phase	End of transition phase	Assumption
1	1-1-2009	N/A	Do nothing
2	1-1-2009	N/A	Immediate full equipage
3	1-1-2009	N/A	Only forward fit
4	1-1-2009	31-12-2013	Late rush
5	1-1-2009	31-12-2011	Late rush
6	1-1-2009	31-12-2013	Progressive
7	1-1-2009	31-12-2011	Progressive
8	1-1-2010	31-12-2013	Late rush
9	1-1-2010	31-12-2011	Late rush
10	1-1-2010	31-12-2013	Progressive
11	1-1-2010	31-12-2011	Progressive
12	1-1-2011	31-12-2013	Late rush
13	1-1-2011	31-12-2011	Late rush
14	1-1-2011	31-12-2013	Progressive
15	1-1-2011	31-12-2011	Progressive

Table 1: List of scenarios

### 4.3.2. Risk of collision with reference scenarios

4.3.2.1. Figure 10 presents the number of collisions versus time, when the proportion of TCAS II version 7.1 aircraft remains equal to 0% (i.e., scenario 1 – “Do nothing”) and when it remains equal to 100% (i.e., scenario 2 - immediate full equipage).



**Figure 10: Risk of collision with reference scenarios**

4.3.2.2. When doing nothing, the number of collisions increases to more than 5 in 2020. The curve is not linear, because the number of flight hours flown in the European airspace is not constant and increases with time. This implies an increase in the risk of collision each year, as the probability of collision due to issues SA01 and SA-AVSA remains constant. If current TCAS II version 7.0 units are not upgraded to version 7.1, the estimates used in the present study indicate that the probability of a first collision at end of 2011 is very high.

4.3.2.3. With the assumption of an immediate full equipage, the curve is also not linear for the same reason. The estimates used in the present study indicate that the probability of a first collision at end of 2018 is very high. The number of collisions is, in January 2020, more than four times lower than if existing TCAS units are not upgraded.

4.3.2.4. These two simulations are based on theoretical scenarios, and their aim is only to set boundaries of what can be expected with operationally realistic assumptions.

### 4.3.3. Risk of collision with forward fit and retrofit starting on 1<sup>st</sup> January 2009

4.3.3.1. Figure 11 presents the risk of collision for the two reference scenarios and scenarios 4, 5, 6 and 7.

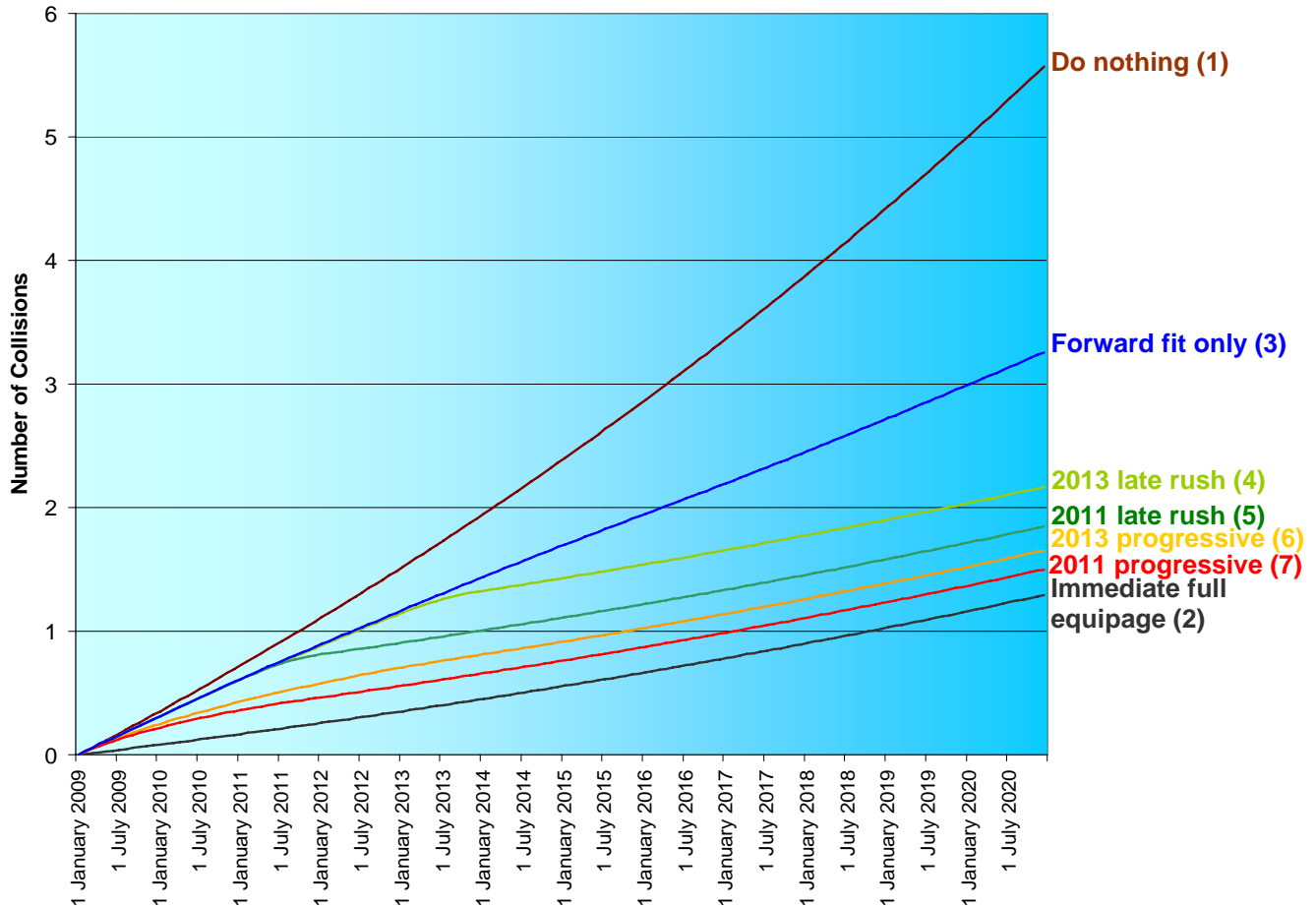
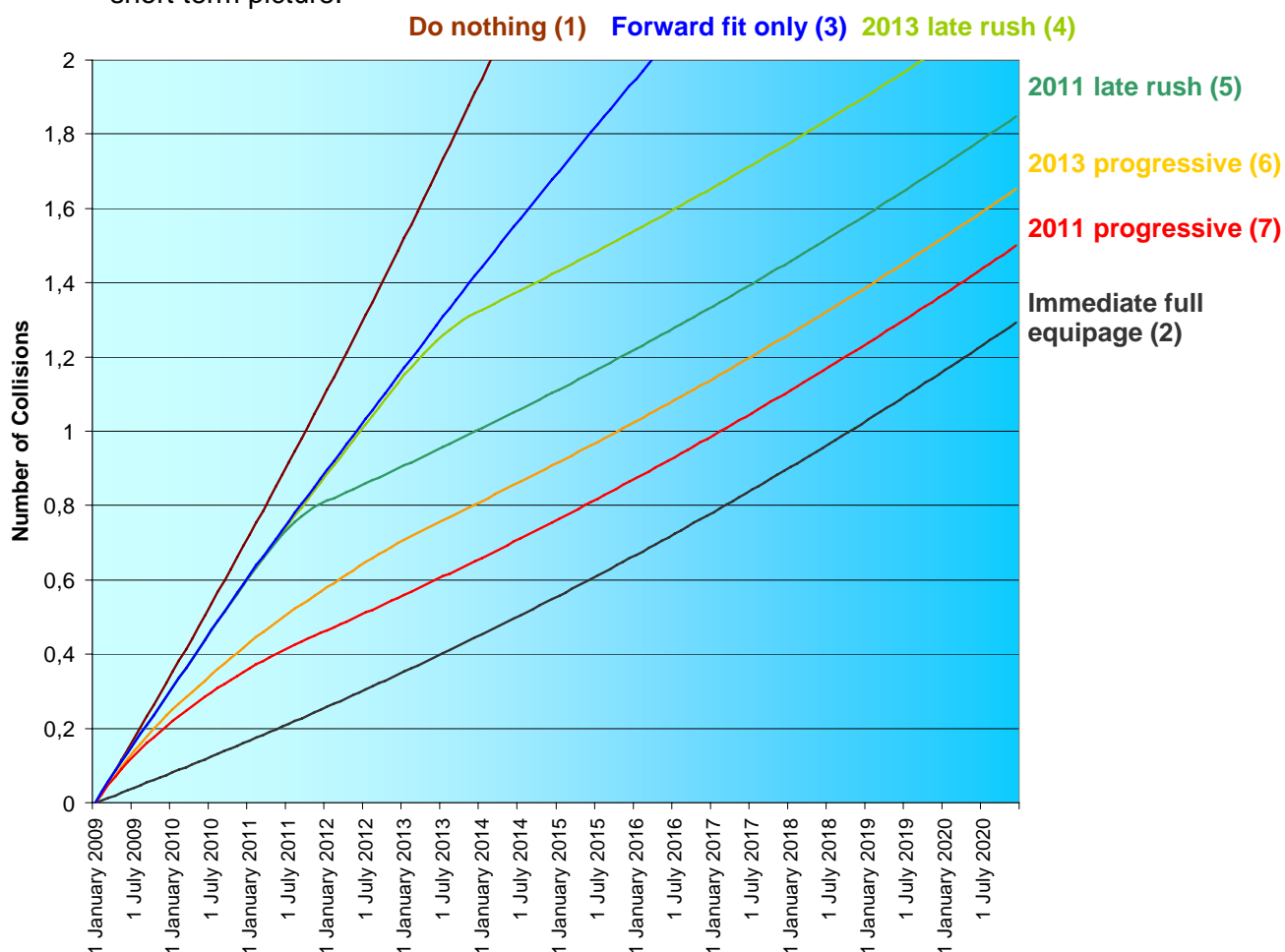


Figure 11: Collision risk for forward and retro-fit starting on 1<sup>st</sup> January 2009

4.3.3.2. Figure 12 presents the same results but with a zoomed view, so as to provide a short term picture.



**Figure 12: Collision risk for forward and retro-fit starting on 1<sup>st</sup> January 2009 (zoom)**

4.3.3.3. Table 2 provides the estimated dates at which a high probability exists for a first collision for the above scenarios.

Scenario #	Scenario name	Estimated date of first collision
1	0% scenario	September 2011
2	100% scenario	October 2018
3	Forward fit only	May 2012
4	31-12-2013 late rush	July 2012
5	31-12-2011 late rush	December 2014
6	31-12-2013 progressive	October 2015
7	31-12-2011 progressive	March 2017

**Table 2: Estimated date of first collision**

- 4.3.3.4. On the short term, doing nothing and making a regulation relying only on forward fit is similar. On the long term, relying only on forward fit results in a collision risk slightly lower than when having no aircraft equipped with TCAS II version 7.1. Therefore, a regulation solely based on forward fit brings no safety benefits on the short term, and only limited safety benefits in the long term.
- 4.3.3.5. As expected, scenarios with an end of transition phase on 31<sup>st</sup> December 2011 perform better from the reduction in collision risk perspective than those with an end of transition phase on 31<sup>st</sup> December 2013.
- 4.3.3.6. The two scenarios with the late rush retrofit result in significant improvements when compared to doing nothing. For the 31-12-2013 scenario, it is noticeable that the estimated date of a first collision (i.e., July 2012) occurs nearly 2 years before the end of the transition date (i.e., 31<sup>st</sup> December 2013). For the 31-12-2011 scenario, this date occurs 2 years after the end of the transition date.
- 4.3.3.7. The two scenarios based on the progressive retrofit assumption result in even more decreased risks of collisions and have a performance close to the immediate full equipage scenario. The estimated dates for the first collision are after 2016, therefore at least 2 years after the mandate dates. Therefore one can consider that these two scenarios would nearly maximize the benefits brought by TCAS II version 7.1.

- 4.3.3.8. Consequently, investigation of these scenarios for the entry into force of TCAS II version 7.1 indicates that best benefits are achieved with aggressive installation schemes. These schemes should involve a retrofit of the European fleet, preferably on a progressive basis.**
- 4.3.3.9. However, realistic scenarios are such that a risk of mid-air collision due to SA01 and SA-AVSA continues to exist during the transition phase. In only one scenario, with the most aggressive implementation schedule, does the transition phase end before the probability calculations indicate an SA01/SA-AVSA collision can occur.**

4.3.3.10. Risk of collision with forward fit and retrofit starting on 1<sup>st</sup> January 2010

4.3.3.11. Figure 13 presents the risk of collision for the 2 reference scenarios and scenarios 8, 9, 10 and 11.

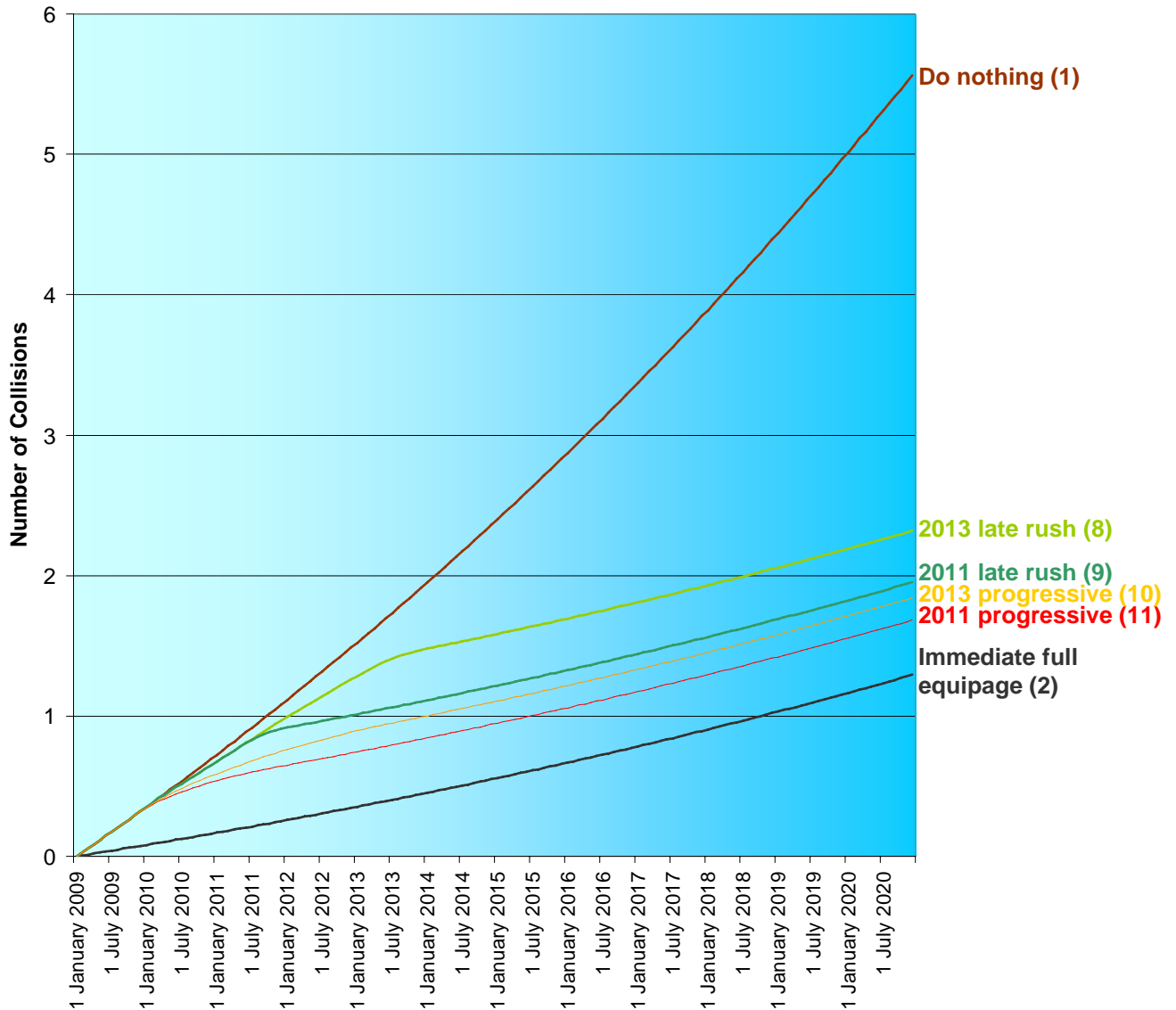


Figure 13: Collision risk for forward and retro-fit starting on 1<sup>st</sup> January 2010

4.3.3.12. Figure 14 presents the same results but with a zoomed view, so as to have a short term picture.

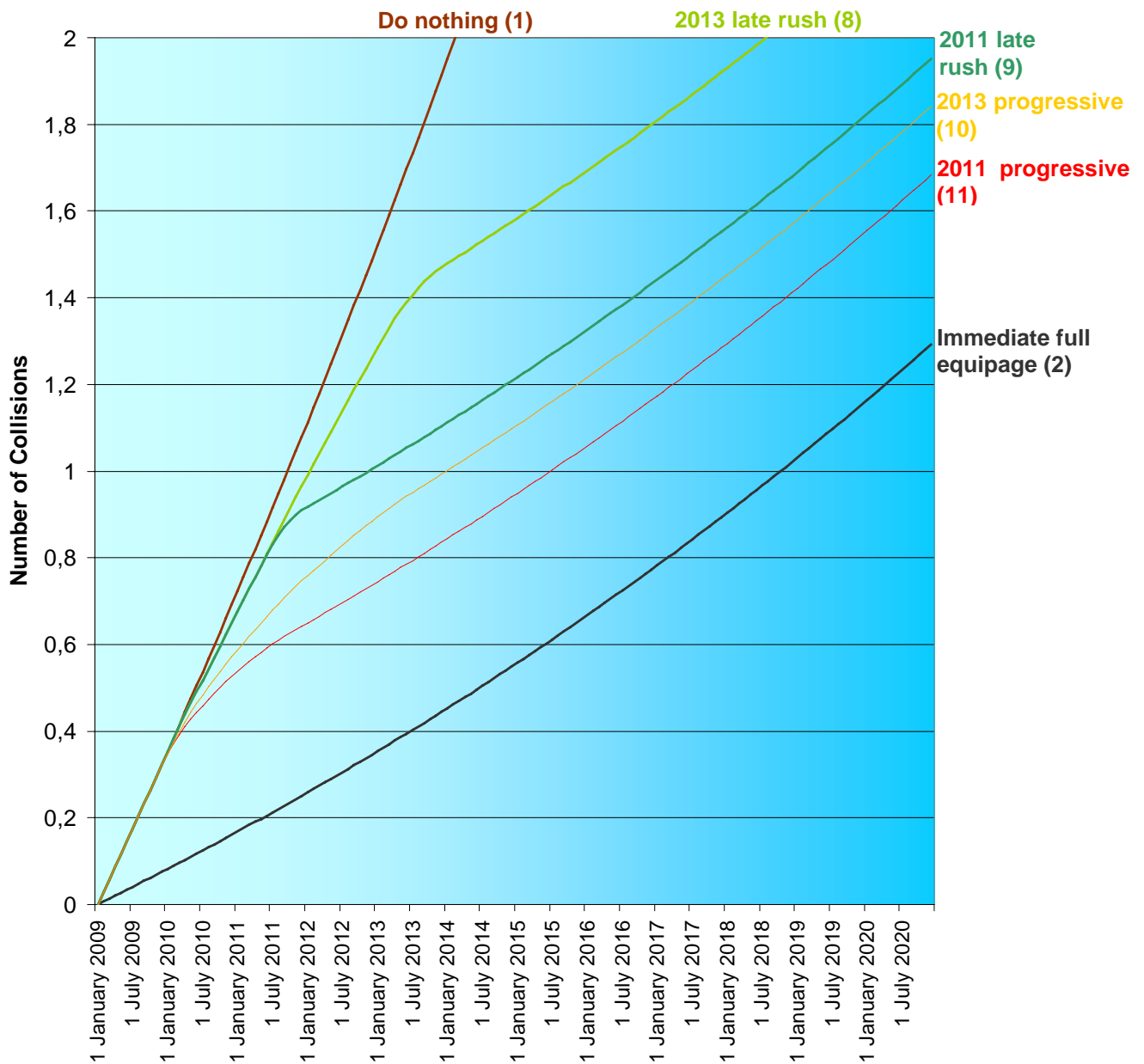


Figure 14: Collision risk for forward and retro-fit starting on 1<sup>st</sup> January 2010 (zoom)



4.3.3.13. Table 3 provides the estimated dates at which a high probability exists for a first collision for the above scenarios.

<b>Scenario #</b>	<b>Scenario</b>	<b>Estimated date of first collision</b>
1	0% scenario	September 2011
2	100% scenario	October 2018
8	31-12-2013 late rush	January 2012
9	31-12-2011 late rush	November 2012
10	31-12-2013 progressive	January 2014
11	31-12-2011 progressive	June 2015

**Table 3: Estimated date of first collision**

4.3.3.14. Delaying the start of the transition phase by one year debases the safety benefits brought by TCAS II version 7.1 when compared to a start of the transition phase on 1<sup>st</sup> January 2009. However, only scenario 8 does not enable to end the transition phase before an SA01/SA-AVSA collision is likely (probabilities) to occur, and the debasement is not significant.

#### 4.3.4. Risk of collision with forward fit and retrofit starting on 1<sup>st</sup> January 2011

4.3.4.1. Figure 15 presents the risk of collision for the 2 reference scenarios and scenarios 12, 13, 14 and 15.

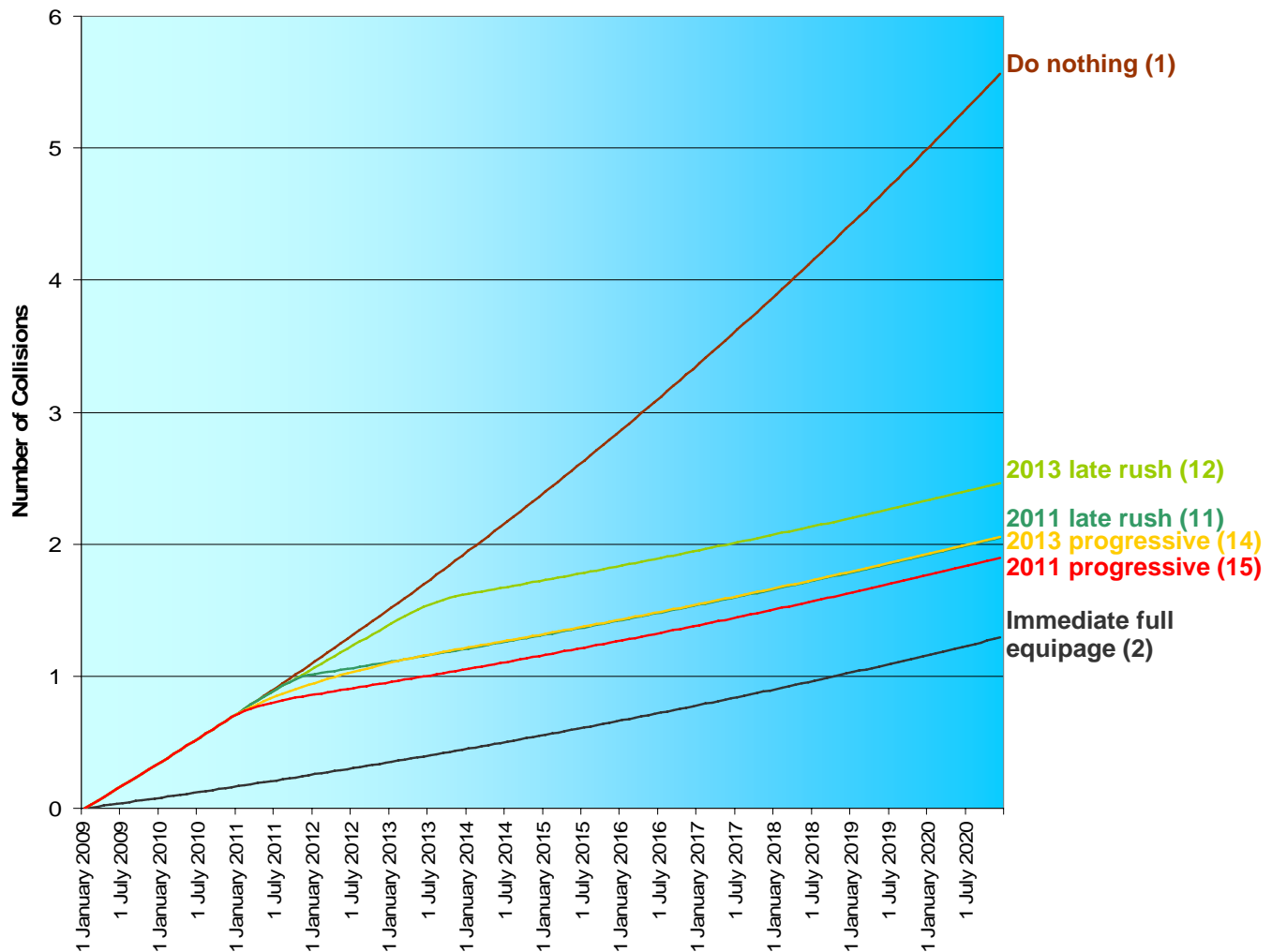


Figure 15: Collision risk for forward and retro-fit starting on 1<sup>st</sup> January 2011

4.3.4.2. Figure 16 presents the same results but with a zoomed view, so as to have a short term picture.

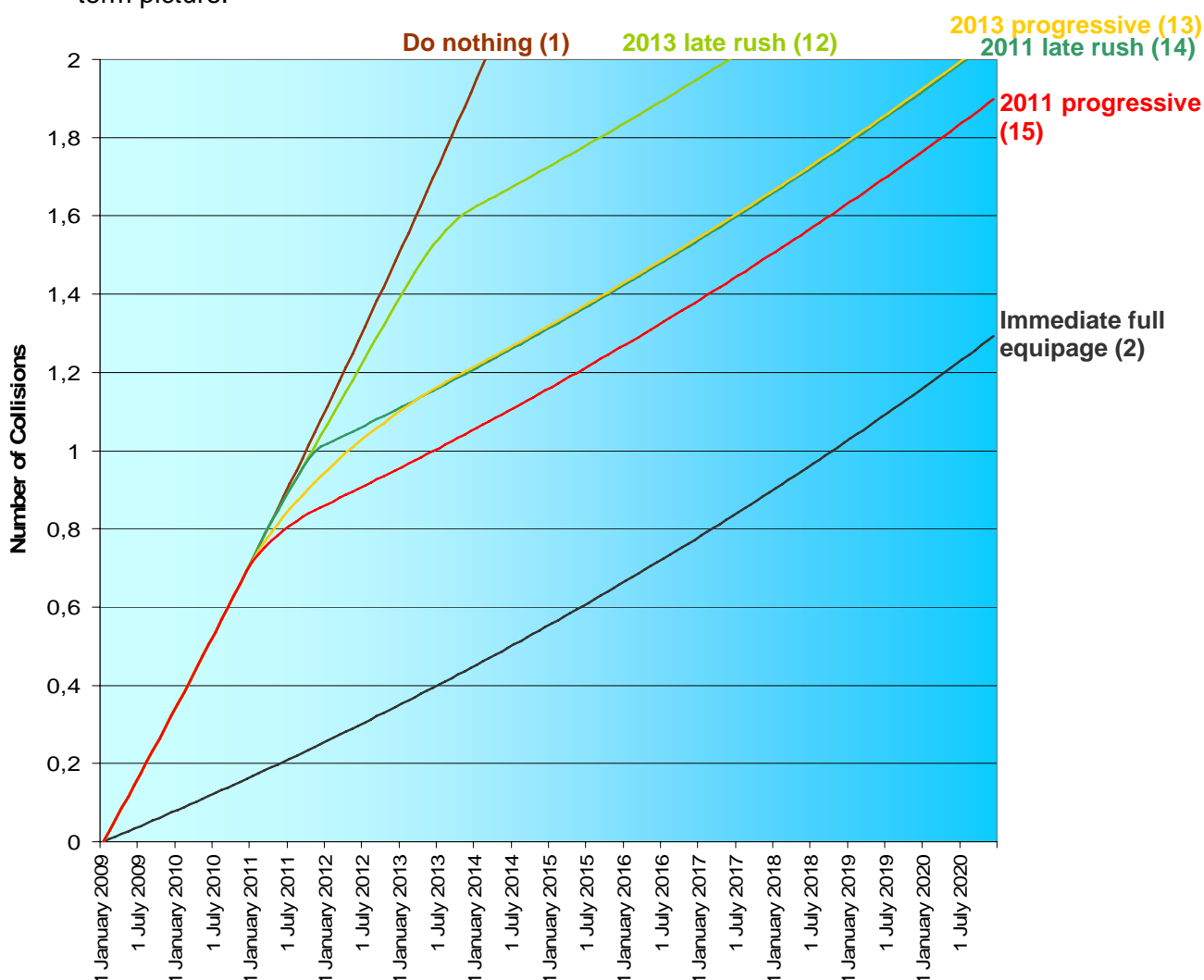


Figure 16: Collision risk for forward and retro-fit starting on 1<sup>st</sup> January 2011 (zoom)

4.3.4.3. Table 4 provides the estimated dates at which a high probability exists for a first collision for the above scenarios.

Scenario #	Scenario	Estimated date of first collision
1	0% scenario	September 2011
2	100% scenario	October 2018
12	31-12-2013 late rush	November 2011
13	31-12-2011 late rush	January 2012
14	31-12-2013 progressive	May 2012
15	31-12-2011 progressive	July 2013

Table 4: Estimated date of first collision

- 4.3.4.4. Having the start of the transition phase on 1<sup>st</sup> January 2011 rather than on 1<sup>st</sup> January 2009 delays the onset of the reduction in the risk of an SA01/SA-AVSA collision whatever the scenario.
- 4.3.4.5. Estimated dates for the first collision all occur between 2011 and 2013, which is a significantly deteriorated result when comparing to the same scenarios starting on 1<sup>st</sup> January 2009 and even on 1<sup>st</sup> January 2010, as shown in the previous paragraphs. In addition, 3 scenarios out of 4 have their date of first collision before the end of the transition phase.

**4.3.4.6. A 2 year (or more) delay in the start of transition phase in the European airspace would result in a serious debasement of the safety benefits brought by TCAS II version 7.1, both on the long term and the short term when compared to a start of transition phase on 1<sup>st</sup> January 2009, or even on 1<sup>st</sup> January 2010.**

**4.3.4.7. As TCAS II version 7.1 provides further significant reduction in the risk of mid-air collisions; it is therefore strongly recommended that TCAS II version 7.1 is implemented as rapidly as possible.**

#### 4.4. Safety gain compared to SESAR objective

##### 4.4.1. Evolution of safety gains for forward and retro-fit starting on 1<sup>st</sup> January 2009

4.4.1.1. Figure 17 shows the safety gain brought by each scenario compared to doing nothing (i.e., with a proportion of aircraft equipped with TCAS II version 7.1 remaining nil).

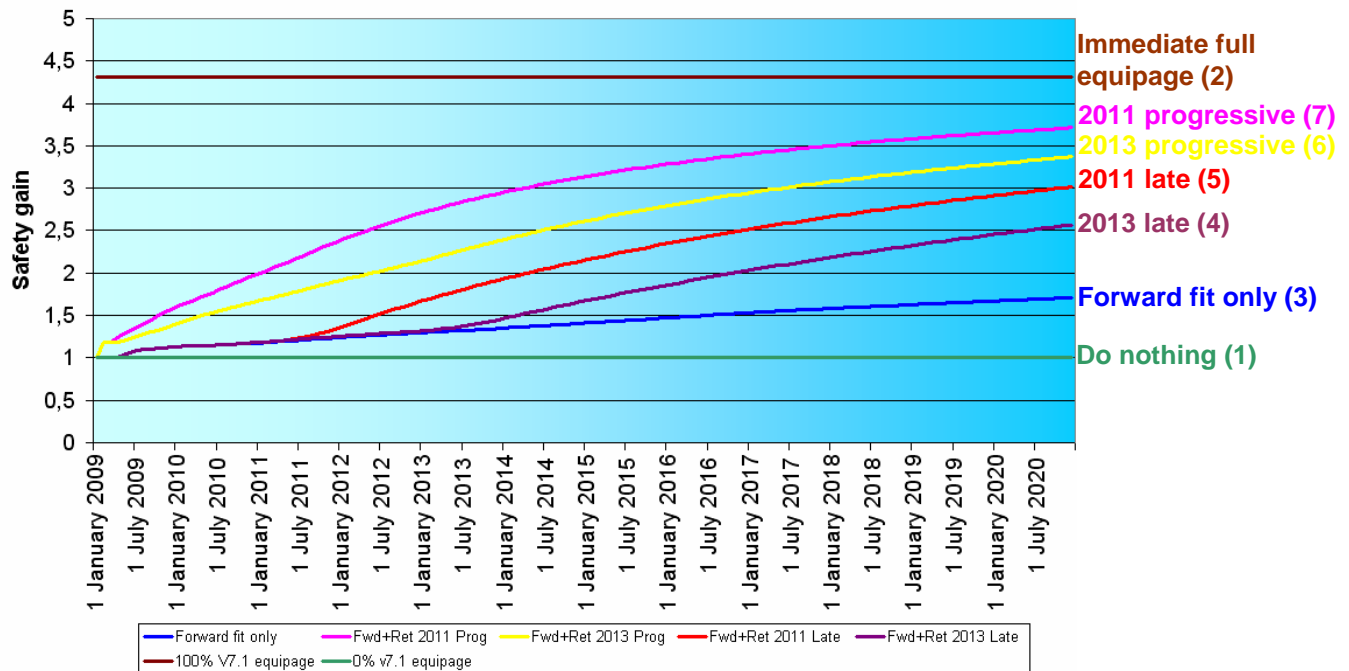


Figure 17: Safety gain – 1-1-2009 regulation

4.4.1.2. Only the two scenarios assuming a progressive retrofit are compliant with the safety objective of SESAR [SESAR], i.e. the improvement of safety by a factor of 3 in 2020. This safety objective is satisfied in 2014 with the hypothesis of a mandate ending on 31<sup>st</sup> December 2011, and 2017 for a mandate ending on 31<sup>st</sup> December 2013.

4.4.1.3. The scenario assuming a late rush retrofit with a transition phase ending on 31<sup>st</sup> December 2011 also meets this objective, but only in July 2020, while the scenario assuming a late rush retrofit with a transition phase ending on 31<sup>st</sup> December 2013 does not meet it.

#### 4.4.2. Evolution of safety gains for forward and retro-fit starting on 1<sup>st</sup> January 2010

4.4.2.1. Figure 18 shows the safety gain brought by each scenario compared to doing nothing (i.e., with a proportion of aircraft equipped with TCAS II version 7.1 remaining nil).

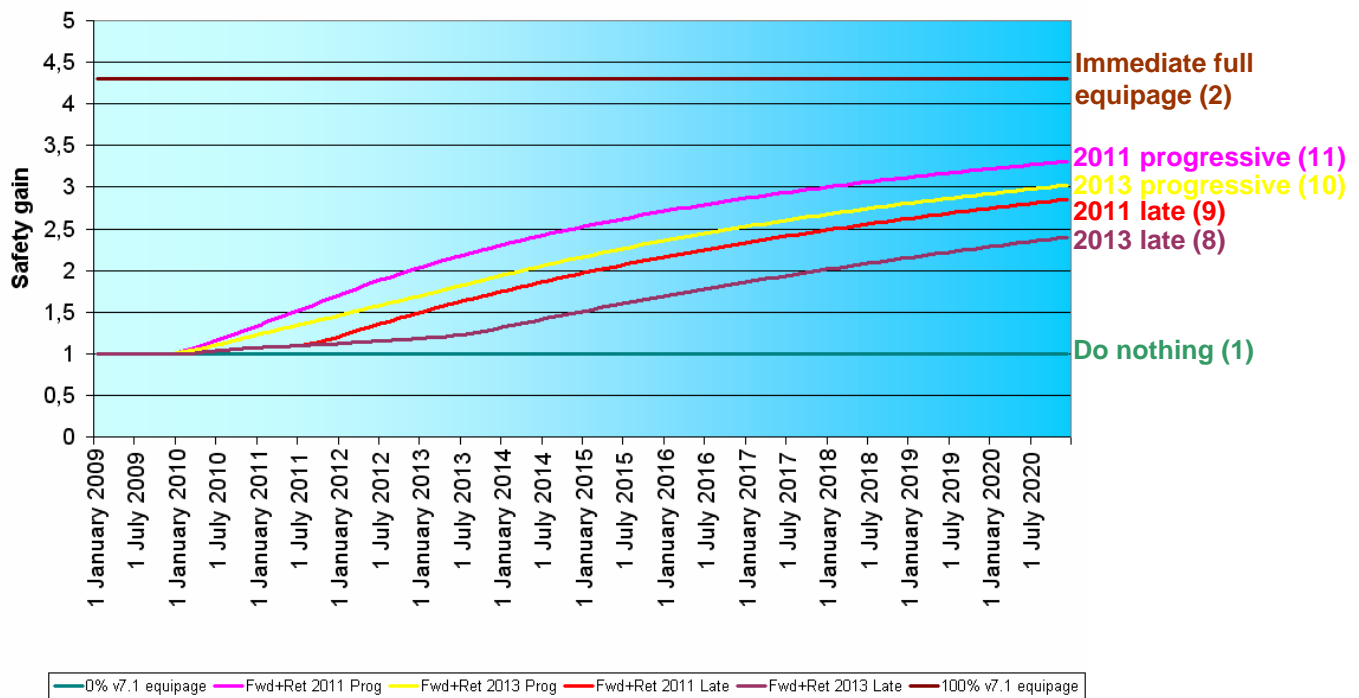


Figure 18: Safety gain – 1-1-2010 regulation

4.4.2.2. Only the two scenarios assuming a progressive retrofit perform are compliant with the safety objective of SESAR [SESAR], i.e. the improvement of safety by a factor of 3 in 2020.

### 4.4.3. Evolution of safety gains for forward and retro-fit starting on 1<sup>st</sup> January 2011

4.4.3.1. Figure 19 shows the safety gain brought by each scenario compared to doing nothing (i.e., with a proportion of aircraft equipped with TCAS II version 7.1 remaining nil).

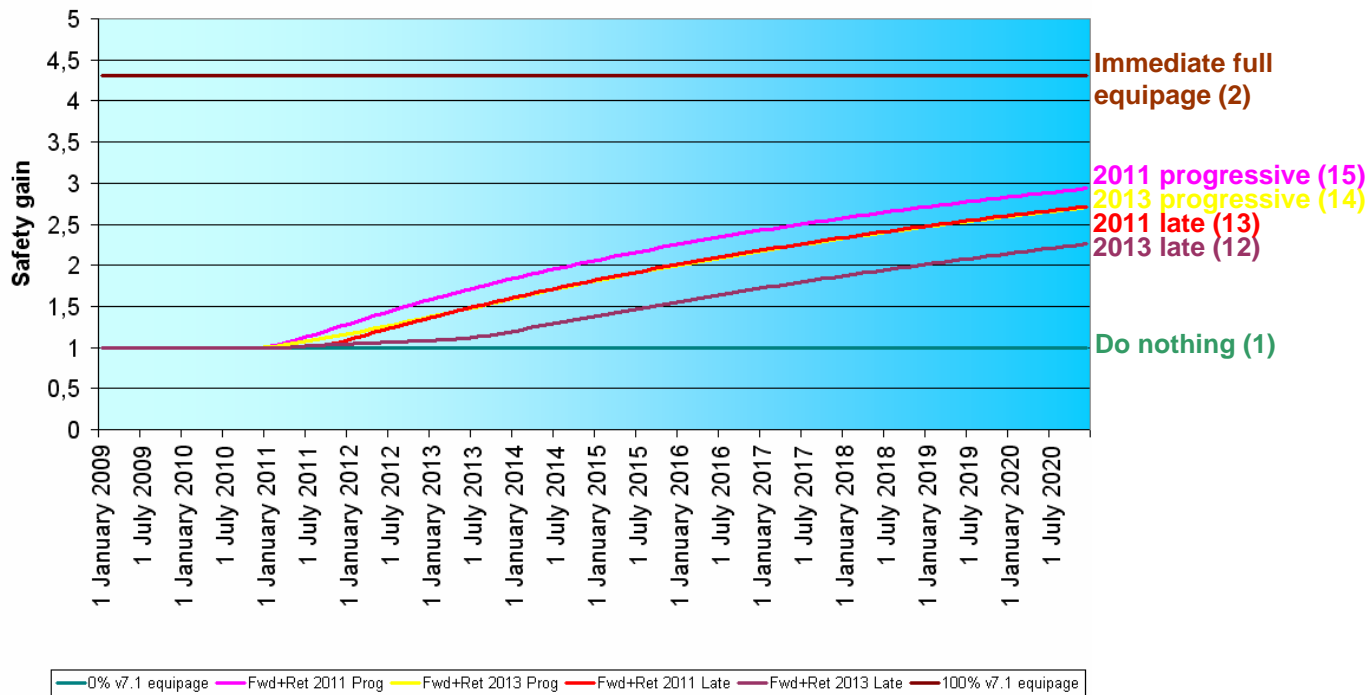


Figure 19: Safety gain – 1-1-2011 regulation

4.4.3.2. None of the scenarios meet the safety objective of SESAR [SESAR], i.e. the improvement of safety by a factor of 3 in 2020.

#### 4.4.4. Scenario comparison: Number of collisions between 1-1-2009 and 31-12-2020

4.4.4.1. Figure 20 presents all the scenarios assessed in this study, ordered according to the safety benefit they bring in 2020 when compared to having no aircraft equipped with TCAS II version 7.1.

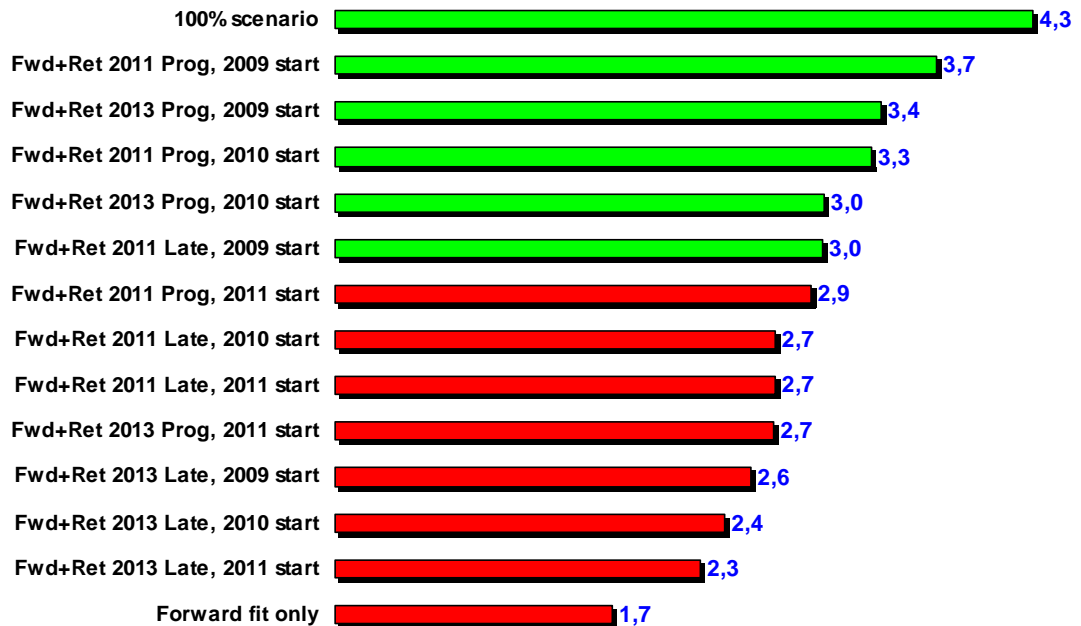


Figure 20: Safety benefits in 2020

4.4.4.2. Scenarios with a start of the transition phase on 1<sup>st</sup> January 2011 have significantly lower results than those with a start on 1<sup>st</sup> January 2009 or 1<sup>st</sup> January 2010.

4.4.4.3. The scenarios with a progressive retrofit perform significantly better than those with a late rush retrofit.

**4.4.4.4. This comparison thus indicates that only aggressive scenarios of entry into force enable to meet SESAR initial objective of improving safety by a factor of 3 in 2020 ([SESAR]).**



## 5. Conclusion and recommendations

- 5.1. The investigation of several possible scenarios for the implementation of TCAS II version 7.1 in Europe indicates that the requirement for the entry into force of this safety revision of the TCAS II equipment must be associated to an aggressive scheme in order to maximise the benefits it provides. This should notably include retrofitting the current European fleet, preferably on a progressive basis. A regulation solely based on forward fit brings only very limited benefits.
- 5.2. The transition phase from TCAS II version 7.0 to version 7.1 should be initiated as rapidly as possible. As an example, a 2 year delay in the start of the transition phase would result in a serious debasement of the safety benefits brought by version 7.1, both on the long and the short term.
- 5.3. It is noticeable that realistic scenarios of entry into force are such that a risk of mid-air collision due to SA01 and SA-AVSA continues to exist during the transition phase. Indeed, among such possible scenarios that have been investigated in the study, only the hypothesis of a transition phase spanning from 1<sup>st</sup> January 2010 to 31<sup>st</sup> December 2011, and involving a progressive retrofit, achieves a full equipage of the fleet earlier than a probable mid-air collision.

**5.4. The Überlingen accident and recurring severe incidents resulting from safety issues SA01 and SA-AVSA could have been avoided with TCAS II version 7.1. It is therefore strongly recommended that entry into force of this new version be achieved as rapidly as possible.**

## 6. References

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## 7. Acronyms

ACAS	Airborne Collision Avoidance System
ACASA	ACAS Analysis
ASARP	ACAS Safety Analysis post-RVSM Project
ATC	Air Traffic Control
ATM	Air Traffic Management
AVSA	Adjust Vertical Speed, Adjust
CP	Change Proposal
DSNA	Direction des Services de la Navigation Aérienne
ECAC	European Civil Aviation Conference
EMOTION-7	European Maintenance Of TCAS Version 7
EUROCAE	European Organisation for Civil Aviation Equipment
EUROCONTROL	European Organisation for the Safety of Air Navigation
FAA	Federal Aviation Administration
FL	Flight Level
fpm	feet per minute
ICAO	International Civil Aviation Organization
MIT	Massachusetts Institute of Technology
MOPS	Minimum Operational Performance Standards
NM	Nautical Mile
NMAC	Near Mid-Air Collision
PMC	Program Management Committee
RA	Resolution Advisory
RVSM	Reduced Vertical Separation Minima
SA01	SAfety issue 01
SA-AVSA	SAfety issue AVSA
SARPs	Standards And Recommended Practices
SC147	Special Committee 147

SIR	Safety Issue Rectification
SIRE	Safety Issue Rectification Extension
TA	Traffic Advisory
TCAS	Traffic alert and Collision Avoidance System
TLS	Target Level of Safety
WP	Work Package
WG75	Working Group 75

## Appendix A : Probability of collision due to issue SA01

The purpose of this section is to propose an estimate of the probability of collision as a consequence of the SA01 issue. This probability will be noted as  $P(\text{SA01 and collision})$  and can be expressed as the probability of occurrence of SA01 events times the probability of a collision during an SA01 event, or:

$$P(\text{SA01 and collision}) = P(\text{SA01}) \times P(\text{collision} | \text{SA01})$$

In 2001 and 2002, 2 SA01 events were found trough analysing the Air Safety Reports of a major European airline. Given the number of flight hours for this airline over these two years, this corresponds to a probability of occurrence of:

$$P(\text{SA01}) = \frac{2}{422661} = 4.7 \times 10^{-6} \text{ per flight hour}$$

After 2002 and before 2005, other SA01 events were identified. In these known SA01 events, the average horizontal miss distance is 0.8 NM (i.e., average value of 0.07 NM, 2.0 NM, 1.0 NM, 0.9 NM, 0.0 NM, 0.9 NM, 0.3 NM and 1.6 NM [SIRE1]) and the average vertical miss distance is 223 ft (average value of 130 ft, 100 ft, 100 ft, 450 ft, 0 ft, 600 ft, 400 ft and 0 ft [SIRE1]).

From [ACA4], the ratio between the rates of collisions and Near Mid-Air Collisions (NMACs) is estimated to be  $P(\text{collision}|NMAC) = 0.1$ .

Consequently:

$$P(\text{Collision} | \text{SA01}) = \frac{\text{Vertical NMAC box}}{\text{Vert.SA01 miss distance}} \times \frac{\text{Horiz. NMAC box}}{\text{Horiz.SA01 miss distance}} \times P(\text{Collision} | \text{NMAC})$$

$$P(\text{Collision} | \text{SA01}) = \frac{100}{223} \times \frac{500}{0.8 \times 6076} \times 0.1 = 4.6 \times 10^{-3}$$

Therefore, with TCAS II version 7.0, the probability of a mid-air collision as a consequence of an SA01 geometry is equal to  $4.6 \times 10^{-3}$  times  $4.7 \times 10^{-6}$ , or  $2.2 \times 10^{-8}$  per flight hour in the European airspace or 1 mid-air collision every 4 years in Europe, given the total of 12.5 million flight hours per year.

## Appendix B : Probability of collision due to issue SA-AVSA

The purpose of this section is to propose an estimate of the probability of collision as a consequence of the SA-AVSA issue. This probability will be noted as  $P(\text{SAAVSA and collision})$  and can be expressed as the probability of occurrence of SA-AVSA events times the probability of a collision during an SA-AVSA event, or:

$$P(\text{SAAVSA and collision}) = P(\text{SAAVSA}) \times P(\text{collision} | \text{SAAVSA})$$

In 2004 and 2005, 15 opposite responses to initial AVSA RAs leading to altitude busts have been identified through TCAS incident reports in France. Given the number of flight hours over these two years, this corresponds to a probability of occurrence of:

$$P(\text{SAAVSA}) = \frac{15}{3.93 \times 10^6} = 3.8 \times 10^{-6} \text{ per flight hour}$$

Based on the average vertical and horizontal separation at closest approach in these events and the dimensions of an NMAC box (*i.e.* 100ft vertically and 500ft horizontally), a probability of NMAC due to an SA-AVSA event can be derived. As the ratio of NMACs to collisions is estimated to be 10 to 1 ([ACA4]), this probability of NMAC can be converted to a probability of collision.

The observed average miss distances in the 15 SA-AVSA events mentioned above are 550ft vertically and 1.06NM horizontally. This results in a probability of collision of:

$$P(\text{Collision} | \text{SAAVSA}) = \frac{\text{Vertical NMAC box}}{\text{Vert.SAAVSA miss distance}} \times \frac{\text{Horiz. NMAC box}}{\text{Horiz.SAAVSA miss distance}} \times P(\text{Collision} | \text{NMAC})$$

$$P(\text{Collision} | \text{SAAVSA}) = \frac{100}{550} \times \frac{500}{1.06 \times 6076} \times 0.1 = 1.41 \times 10^{-3}$$

Therefore, with TCAS II version 7.0, the probability of a mid-air collision as a consequence of an SA-AVSA event is equal to  $1.4 \times 10^{-3}$  times  $3.8 \times 10^{-6}$ , or  $5.4 \times 10^{-9}$  per flight hour in the European airspace or 1 mid-air collision every 15 years in Europe, given the total of 12.5 million flight hours per year.