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Abstract

This study provides figures concerning the safety of ACAS after the introduction of RVSM and for each phase the ACAS mandate. The first part of this study is based on the use of the methodology developed during the ACASA project. The second part deals with full system risk ratios which are provided for CVSM and RVSM environments and for each phase of the ACAS mandate.

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CONTACT PERSON: John Law		TEL: 32 2 7293766	UNIT: ACAS Programme EHQ	

Authors: Stéphan Chabert, Thierry Arino

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ACAS Safety Study
Safety Benefit of ACAS II Phase 1 and 2
in the New European Airspace Environment

Drafted by: Stéphan Chabert

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1. Introduction

1.1. The ACASA study

Work package 1 of the ACASA project has investigated the safety of ACAS in Europe. This study provided information regarding the former European environment (i.e., before the continental RVSM introduction). More specifically, work package 1.2 of the ACASA project has dealt with the implication of fitting small aircraft subject to the 2005 mandate with ACAS II in the former European CVSM environment [1], [2], [3]. However, this work package did not address the implications of the introduction of RVSM in the European environment.

Work package 3 of the ACASA project has investigated the interaction between ACAS and RVSM. This study has ascertained:

- Whether there are any significant operational implications for ACAS II performance due to European RVSM implementation; and also
- Whether the benefits expected from RVSM could be compromised due to the operation of ACAS II.

This study has focused on technical issues but also on potential operational issues. It has also provided logic risk ratios to assess the implication of the switch from CVSM to RVSM in terms of safety. However, resource constraints did not allow to look at several areas of interest.

1.2. Current study

The current study provides figures concerning the safety of ACAS after the introduction of RVSM and for each phase the ACAS mandate. The purpose is to perform additional simulations on operationally realistic scenarios (i.e., with a proportion of aircraft not fitted with ACAS and in the same time a proportion of pilots not following their RAs), to address the areas not covered by the ACASA project and in particular to:

- Provide logic risk ratios for the full airspace after RVSM introduction;
- Perform a full system safety study after RVSM introduction;
- Look at the contribution of switching from phase I to phase II of the ACAS mandate after RVSM introduction; and
- Take into account aircraft classes for the RVSM layers.

The first part of this study is based on the use of the methodology developed during the ACASA project. This methodology has been applied to generate encounter models which are representative of the former CVSM environment and of the current RVSM

environment¹, for several altitude bands of interest (i.e., the altitude band going from 1000ft to FL290, the altitude band going from FL290 to FL410 and the full airspace). Logic risk ratios are provided for CVSM and for RVSM, for each of these altitude bands, for each phase of the ACAS mandate, taking into account aircraft performances classes and pilot who do not follow their RA.

The second part of this study deals with full system risk ratios, which are computed using the event tree developed for work package 1.6 of the ACASA project [4]. Unlike logic risk ratios, full system risk ratios enable to take into account factors which are not linked to the performance of the logic and which influence the safety brought by ACAS (e.g., visual acquisition, controller instructions, etc). Full system risk ratios are provided for CVSM and RVSM environments and for each phase of the ACAS mandate.

2. Background

2.1. ACAS mandate

In 1995, the ECAC (European Civil Aviation Conference) States agreed a common ACAS policy and implementation schedule for the mandatory carriage of an ACAS II in Europe. This policy was confirmed by the ECAC Transport Ministers in 1997. The approved policy requires that:

- from 1st January 2000, all civil fixed-wing turbine-engine aircraft having a maximum take-off mass exceeding 15000 kg or a maximum approved passenger seating configuration of more than 30 will be required to be equipped with ACAS II (Phase I); and
- from 1st January 2005, all civil fixed-wing turbine-engine aircraft having a maximum take-off mass exceeding 5,700 kg or a maximum approved passenger seating configuration of more than 19 will be required to be equipped with ACAS II (Phase II).

TCAS II version 7.0 is the only equipment, which complies fully with ACAS II Standards and Recommended Practices (SARPs) published by the International Civil Aviation Organisation (ICAO). Therefore TCAS II version 7.0 is required to meet the European ACAS II mandate.

2.2. RVSM environment

RVSM is an approved ICAO concept to reduce aircraft separation minimum from 2000ft to 1000ft from FL290 to FL410 inclusive. The purpose of RVSM is to increase airspace capacity and provide airspace users with more flight levels and thus optimised flight profiles.

¹ In this report, when considering the full airspace, the current RVSM environment means the new environment including RVSM layers.

On 12 July 2001 the EUROCONTROL Provisional Council confirmed the implementation of RVSM in the European airspace with effect from the 24 January 2002, between FL290 and FL410. Except where transition tasks are carried out, only aircraft, which are RVSM approved, will be authorised to operate within the EUR RVSM airspace.

In order to be RVSM approved, aircraft need to meet requirements defined in MASPS. These requirements define the altimetry system error performance, the most stringent being as follows:

- At the point in the envelope where the mean Altimetry System Error reaches its largest absolute value that value should not exceed 25m (80ft);
- At the point in the envelope where absolute mean Altimetry System Error plus three standard deviations of Altimetry System Error reaches its largest absolute value, the absolute value should not exceed 60m (200ft).

In the following of the report, the RVSM environment means the new environment including RVSM layers (full airspace). The upper layer of the RVSM environment means the altitude band going from FL290 to FL410 of the RVSM environment. The same terminology is used for CVSM.

2.3. Previous ACAS II safety studies

The benefits brought by phase II have already been presented in former studies, for the CVSM environment. This part summarises briefly the main conclusions of these studies.

Report [2] shows how phase II would bring significant safety benefits: reduction of the risk of collision by 41%, when all pilots follow their RAs. A full system safety study [12] confirms these trends showing that full system risk ratios would decrease from 29.9% to 24.2% when proceeding from phase I to phase II, this time assuming that pilots do not always follow their RAs.

Report [3] shows that on an aircraft perspective, phase II brings:

- Substantial safety benefits to small aircraft (i.e., those subject to phase II), dividing the risk of collision by 9.4 if all pilots follow their RAs and by 3.6 if 20% of the pilots do not follow their RAs²;
- Significant safety benefits to aircraft with a maximum take-off mass below 5700kg (i.e., light aircraft, not subject to any mandatory carriage);
- Small benefits to large aircraft (i.e., subject to phase I).

These studies recommended that these significant safety benefits had to be brought to the attention of the European decision makers in order to support phase II.

However these studies did not provide any figures concerning phase II and RVSM: only CVSM was considered when assessing the benefits brought by phase II. Full

² This proportion of pilots who do not follow their RAs is considered as realistic [9a].

system risk ratios were provided for phase II in [12] but this was not done for RVSM. [10] only provides logic risk ratios for CVSM and RVSM. This was done only for the upper layer of these environments and without aircraft classes being simulated. In addition, the benefits of phase II were not directly assessed even if several levels of equipage were simulated.

3. ACAS II logic safety study

3.1. *Methodology*

3.1.1. European ACAS Safety Encounter Model

This study uses the European ACAS safety encounter model [5]. This encounter model consists in a very large set of encounters that are built according to a set of probability tables. These probability tables describe the statistical distribution of parameters which define the trajectories of each aircraft and pair of aircraft (e.g., altitude, approach angle, horizontal manoeuvres, vertical miss-distance, ground speed, etc).

The probability tables are defined for several layers of altitude:

- Layer 1: between 1000ft and FL50;
- Layer 2: between FL50 and FL135;
- Layer 3: between FL135 and FL215;
- Layer 4: between FL215 and FL295; and
- Layer 5: between FL295 and FL415.

The probabilities tables were initially built analysing ground radar data recorded in UK and in France over several months. However this data did not allow to fill the probability tables for altitudes over FL290 correctly, as only 26 encounters involved aircraft flying over FL290.

Thus new tables based on real-time ATC simulation data for RVSM and for CVSM were used for this study. These tables are based on a larger number of encounters than the tables initially used for layer 5 of the European ACAS safety encounter model (i.e., 173 encounters for CVSM, 840 for RVSM instead of 26 encounters). Therefore, in this study, the layer 5 realism is improved. It enhances the European ACAS safety encounter model used in WP1 of the ACASA project.

Two different sets of probability tables were used for the current study, one for the CVSM environment and one for the RVSM environment. These sets of probability tables were used to generate 5 sets of encounters:

- A set for altitudes under FL295, corresponding to layers 1 to 4 of the European ACAS safety encounter model;
- A set for altitudes between FL295 and FL415, corresponding to layer 5 of the European ACAS safety encounter model, for CVSM;

- A set for altitudes between FL295 and FL415, corresponding to layer 5 of the European ACAS safety encounter model, for RVSM;
- A set taking into account the full airspace (i.e., layers 1 to 5) for the former CVSM environment;
- A set taking into account the full airspace (i.e., layers 1 to 5) for the new RVSM environment.

Each of these set was simulated for phase I and phase II of the ACAS mandate.

3.1.2. Risk ratio computation

Simulations are performed on the European ACAS safety encounter model in order to compute a risk ratio, which is a safety indicator used to assess the efficacy of ACAS II in reducing the risk of collision for a given airspace. It is computed as the ratio of the number of NMACs³ with ACAS by the number of NMACs without ACAS.

The risk ratio is computed applying an altimeter error model to the trajectories of the aircraft. The altimeter error model is defined in the ACAS SARPS [6]. However, this altimeter error model does not take into account the fact that aircraft entering the upper layer of the RVSM environment have to be MASPS compliant. For this reason, the altimeter error model was modified specifically for RVSM simulations so that the aircraft flying in the altitude band between FL290 and FL410 are MASPS compliant (cf. Appendix A).

3.1.3. Collision risk

Risk ratios are computed as the ratio between a number of NMACs with and without ACAS. Thus risk ratios computed on an encounter model are dependent on the number of NMACs in the model, when ACAS is not simulated.

For that reason, an NMAC rate was assumed for both the CVSM and the RVSM models. The NMAC rates were assumed to be the same for CVSM and for RVSM environments as it is anticipated that the switch from CVSM to RVSM will not adversely affect the safety of the on-going air traffic operations [13].

The NMAC rates were assumed to be equal to the value already used for the European ACAS safety encounter model definition, which corresponds to 3 NMACs for 10^{+7} flight hours [8]. This value was chosen on the basis of actual airmisses, and is not related to the SASP (former RGCSP) TLS of $2.5 \cdot 10^{-9}$.

³ An NMAC is an encounter in which horizontal separation is less than 500ft and vertical separation is less than 100ft simultaneously. In this study, an encounter is classified as an NMAC when, at CPA, vmd is less than 100ft and hmd is less than 500ft.

A probability of NMAC equal to 0.002666 was derived from this NMAC rate [8]. This probability of NMAC was set in the European ACAS safety encounter model using the vmd adjustment method proposed by CENA [14].

3.1.4. Aircraft performances classes

In this study, aircraft classes were simulated. They were not taken into account in the WP3 of the ACASA project, but were already simulated in some studies of WP1. Therefore, the performances limitations simulated for the current study are those which were used within WP1 of the ACASA project.

The performance limitations were simulated by constraining the following of RAs to climb. In that aim and when necessary, limited vertical speeds were used instead of the nominal values (1500fpm for climb RAs and 2500fpm for increase climb RAs).

These aircraft performance limitations vary with the type of aircraft. The mandatory carriages that were simulated (2000 and 2005) also apply on different types of aircraft. For these reasons, classes of aircraft were used:

- Class A: piston aircraft with a maximum take-off mass below 5,700 kg;
- Class B: turboprop aircraft with a maximum take-off mass below 5,700 kg;
- Class C: turboprop aircraft with a maximum take-off mass between 5,700 kg and 15,000 kg (class subject to the 2005 mandatory carriage);
- Class D: jet aircraft with a maximum take-off mass between 5,700 kg and 15,000 kg (class subject to the 2005 mandatory carriage);
- Class E: turboprop with a maximum take-off mass in excess of 15,000 kg (class subject to the 2000 mandatory carriage);
- Class F: jet aircraft with a maximum take-off mass in excess of 15,000 kg (class subject to the 2000 mandatory carriage);
- Class G: high performance jets (e.g., military fighter, small business jets).

Only classes C, D, E and F have been fitted with ACAS during the simulations, as the other classes are not subject to any mandatory carriage. Consequently, performance limitations were defined for these classes. The following table shows the vertical rate limitations that were used for the classes subject to the 2000 and 2005 mandatory carriages.

Class Layer	C Turboprop (2005 mandatory carriage)	D Jet aircraft (2005 mandatory carriage)	E Turboprop (2000 mandatory carriage)	F Jet aircraft (2000 mandatory carriage)
1: 1000ft-FL50	2046	3204	1934	2794
2: FL50-FL135	1673	3472	1555	3002
3: FL135-FL215	1301	2894	1191	2606
4: FL215-FL295	907	2117	741	1876
5: FL295-FL415	0 (276)	1140	0 (99)	1208

Table 1: Vertical rate limitations per layer and per aircraft performance class (fpm)

The vertical rates of classes C and E in layer 5 are set to zero, as turboprops usually do not go over FL295. It should also be noted that these classes of aircraft are represented in a nil or very small proportion in layer 5 (2.4% for class E, 0.0% for class C). The initial weighted mean values are indicated in parenthesis.

In addition it should be highlighted that the performance limitations do not apply when the vertical rate limitation is greater than 2500fpm (i.e., bold values in table 1).

Finally, it should also be mentioned that a climbing aircraft, which receives a “Maintain Climb” RA, does not decrease its vertical rate to comply with the appropriate value of table 1, but goes on with its current vertical rate.

3.1.5. Operational scenarios

The simulations were conducted using two different scenarios:

- Phase I: only aircraft of classes E and F were equipped with ACAS II;
- Phase II: only aircraft of classes C, D, E and F were equipped with ACAS II.

All the aircraft entering the upper layer of the RVSM environment were supposed to be MASPS compliant.

All the aircraft potentially equipped with ACAS II (i.e., classes C, D, E, and F) were simulated reporting their altitude in 25ft quanta. The proportion of aircraft reporting their altitude in 25ft quanta within classes A, B and G (i.e., non-equipped classes) was chosen to be 80%. The remaining 20% percents were reporting their altitude in 100ft quanta.

It is well known that not all pilots follow their RAs, and it was underlined in [9a] that the proportion is noticeable. Thus pilots who do not follow their RAs were simulated, and the proportion was chosen to be 20% of the whole number of pilots. This proportion is considered to be representative of the current European environment [9a]. The remaining 80% were assumed to follow their RAs (i.e., as a standard pilot [6]).

The definition of a standard pilot is as follows:

Type of RA	Time of reaction	Acceleration
Initial corrective RAs	5 s	1/4 g
Increase rate RAs	2.5 s	1/3 g
RA reversals	2.5 s	1/3 g
Weakening RAs	2.5 s	1/4 g
Strengthening RAs ⁴	2.5 s	1/4 g

Table 2: Standard pilot definition

In addition the vertical speeds adopted by the pilot in response to RAs are:

- positive RAs: +/- 1500 fpm;
- increase RAs: +/- 2500 fpm;
- VSL RAs: as appropriate (i.e., 0, 500, 1000 or 2000 fpm).

[9a] also demonstrates that among the pilots who follow their RAs, some follow their RAs slowly. These pilots were simulated within the full system safety study (cf. part 4).

⁴ *Strengthening RAs* means a subsequent RA, which revises the intensity of the preceding RA by either increasing the vertical speed limitation of a negative RA (e.g. “Reduce descent to 500 fpm” after a preliminary “Reduce descent to 1000 fpm”) or by generating a positive RA after a negative RA (e.g. “Climb” after a preliminary “Reduce descent to 1000 fpm”).

3.1.6. Aircraft class distribution

The probabilities used to ascertain the proportions of each aircraft class in the European ACAS safety encounter model are based on data collected from two volumes of CAA Airprox reports for 1997 [16][17] and DGAC Airprox reports for 1998 [18][19]. This choice was made because what we are interested in is traffic patterns with the potential to cause conflicts [5].

This section presents the proportion of each aircraft class within the European ACAS safety encounter model. As the European ACAS Safety encounter model was built using UK and French data, it shall be kept in mind that the probabilities shown in this part are only representative of a portion of the airspace which is a mix between UK and France. In addition, some of the assumptions, which were made are rather pessimistic, especially concerning the proportion of class G aircraft.

3.1.6.1. Layers 1 to 4

The figure below shows the distribution of the aircraft classes for altitude layers under FL295.

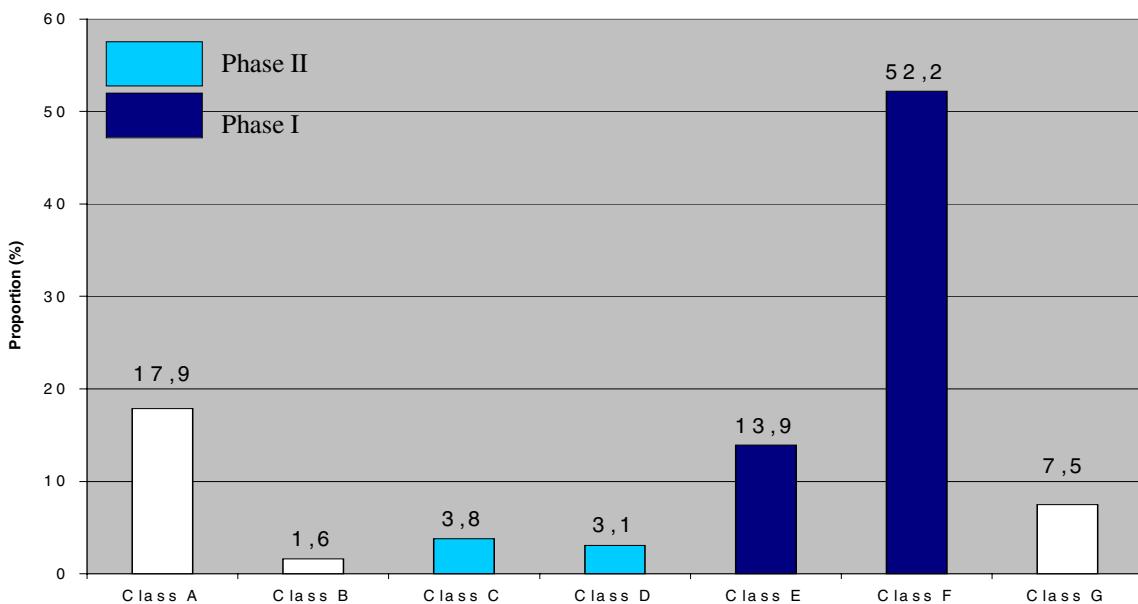


Figure 1: Aircraft class distribution –Layers 1 to 4

The aircraft subject to phase I (classes E and F) represent 66.1% of the fleet, while the aircraft subject to phase II (classes C, D, E and F) represent 73.0% of the fleet.

These figures highlight that the 2005 mandatory carriage of ACAS only concerns 6.9% of the overall fleet included in the European ACAS safety encounter model for layers 1 to 4. **This low proportion of aircraft that can be affected by phase II shall be kept in mind when considering the improvements brought by the 2005 mandate.**

3.1.6.2. Layer 5

The figure below shows the distribution of the aircraft classes for layer 5. The distribution is similar when considering CVSM and RVSM.

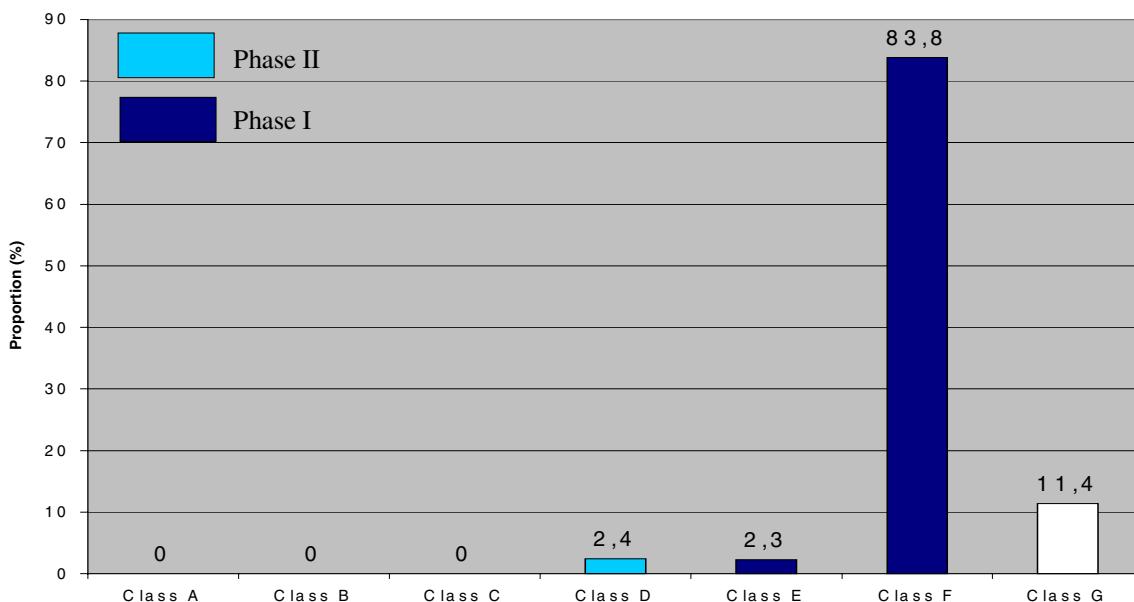


Figure 2: Aircraft class distribution – layer 5

The aircraft subject to phase I (classes E and F) represent 86.1% of the fleet, while the aircraft subject to phase II (classes C, D) represent 2.4% of the fleet.

These figures mean that 3 encounters out of 4 involve large aircraft versus large aircraft, and that 1 encounter out of 5 involve large aircraft versus high performance jets. Therefore, for the majority of encounters, which may occur in layer 5, phase II of the mandate should have slight implications. **The low proportion of aircraft that can be affected by phase II and the high proportion of aircraft already equipped with phase I enables to expect lower benefits for phase II in layer 5 than in layers 1 to 4.**

3.1.6.3.Full airspace

The figure below shows the distribution of the aircraft classes for the full airspace. The distribution is similar when considering the CVSM environment and the RVSM environment.

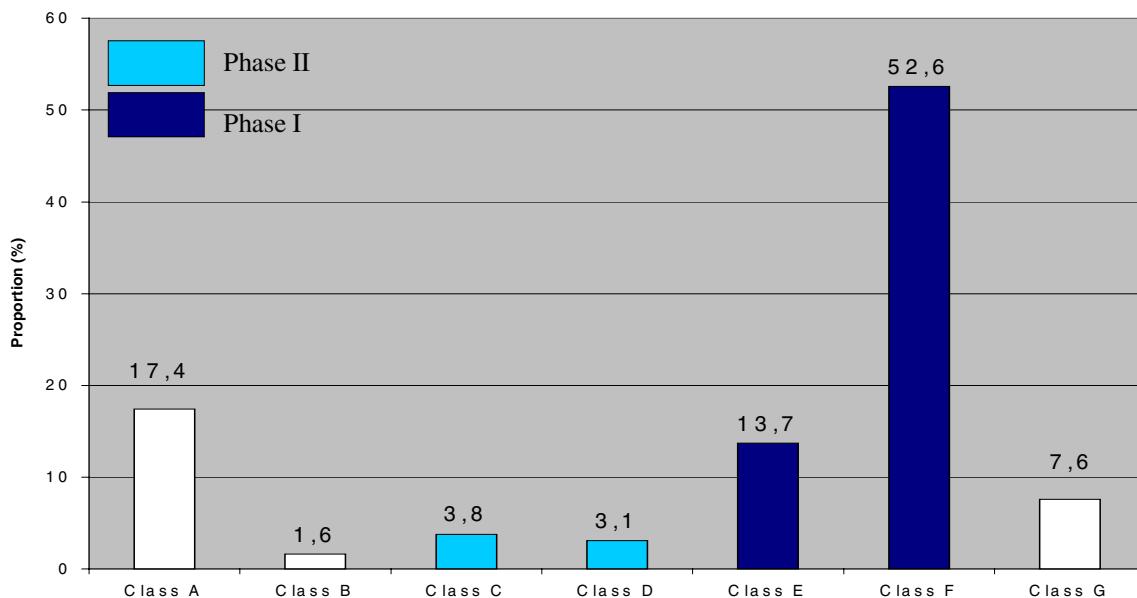


Figure 3: Aircraft class distribution – full airspace

The aircraft subject to phase I (classes E and F) represent 66.3% of the fleet, while the aircraft subject to phase II (classes C, D, E and F) represent 73.2% of the fleet.

The aircraft class distribution for the full airspace is very close to the one observed for layers 1 to 4. This is explained by the small weight of layer 5 in the definition of the European ACAS Safety encounter model.

3.2. Logic risk ratios

The goal of this part is to present the logic risk ratio figures, which were computed for the various encounters describing CVSM and RVSM.

In this section, the risk ratios are shown as the sum of two contributions:

- “equipped and response”: this part of the risk ratios takes into account all the encounters in which ACAS II had an effect, which means at least one aircraft has manoeuvred on the basis of a resolution advisory; and
- “not equipped or no-response”: this part of the risk ratio takes into account all the encounters in which none of the aircraft has manoeuvred, either because of lack of response, or because of the aircraft equipage (i.e., no ACAS involved).

3.2.1. Layers 1 to 4

The following table shows the logic risk ratios computed on the European ACAS safety Encounter model generated for layers 1 to 4 (i.e., from 1000ft to FL295).

	Phase I	Phase II
Equipped and response	9.1%	9.4%
Not equipped or no-response	32.1%	25.2%
Logic risk ratio	41.2%	34.6%

Table 3: Logic risk ratios - layers 1 to 4 – 20% of pilots do not follow their RAs

These risk ratios show that phase II of the ACAS mandate decreases the logic risk ratio by 16% for altitude layers 1 to 4. These figures highlight the significant benefits brought by the phase II of the ACAS mandate in terms of reducing the risk of collision. **These benefits are especially remarkable when considering the low proportion of aircraft that can be affected by phase II (i.e., 6.9%).**

These figures also show that the risk ratios mainly result from encounters in which none of the aircraft has manoeuvred, either because pilots did not follow their RAs or because the aircraft were not equipped with ACAS II. It highlights once again the importance of pilot training, which was already underlined in recommendation 11.1.2 of [12]: “the consequences in terms of collision risk following failure to respond to RAs, and to do so accurately and promptly, must be emphasised to pilots by all practical means”.

The benefits brought by phase II are achieved on encounters in which no aircraft is equipped with ACAS II during phase I, because in most of them, the fact of fitting one

of the two aircraft with ACAS II resolves the NMAC. In fact, two thirds of the decrease of the logic risk ratios results from encounters that involve small aircraft versus light aircraft, as noticed in [3].

However fitting aircraft with ACAS II is not always sufficient to resolve NMACs, or can even induce NMACs. This appears in the increase from 9.1% to 9.4% of the “equipped and response” part of the risk ratio (especially because the sets of encounters considered are different, as equipping more aircraft with ACAS II implies that more encounters are counted in the “equipped and response” part of the risk ratio).

3.2.2. Layer 5

The following table shows the logic risk ratios computed on the European ACAS safety encounter model, which was generated specifically for layer 5 (i.e., FL295 to FL415).

	Phase I CVSM	Phase II CVSM	Phase I RVSM	Phase II RVSM
Equipped and response	26.2%	26.9%	78.3%	77.7%
Not equipped or no-response	9.4%	7.7%	9.2%	8.4%
Logic risk ratio	35.6%	34.6%	87.5%	86.1%

Table 4: Logic risk ratios – layer 5 - 20% of pilots do not follow their RAs

It was observed in table 3 that the logic risk ratios for layers 1 to 4 mainly result from the part “not equipped or no-response”, because of encounters involving two unequipped aircraft. Table 4 shows a different trend: the most influencing part of the risk ratio is the “equipped and response” part, as most NMACs occur during encounters involving one aircraft which manoeuvres against an aircraft which does not, either because the pilot does not follow his RAs or because the aircraft is not equipped with ACAS.

CVSM logic risk ratios

We observe that within the upper layer of the CVSM environment, ACAS II is efficient in reducing the risk of collision as the logic risk ratios are 35.6% for the phase I and 34.6% for phase II.

The 2005 mandate brings some light benefits in comparison with the 2000 mandate. These benefits are not as important as for layers 1 to 4 because the number of aircraft

on which the 2005 mandate applies and which fly in layer 5 is very small (2.4% of the aircraft flying in this layer, with 86.1% of the aircraft already equipped with phase I of the mandate).

We observe that the risk ratio is mainly influenced by encounters in which at least one aircraft manoeuvres (i.e., equipped and response part of the risk ratio). This is explained by an important contribution of encounters in which one pilot does not follow his RAs and the other does (cf. 3.2.2.4), and also of encounters in which one aircraft is not equipped with ACAS II while the other aircraft is and the pilot follows his RAs (cf. Appendix B).

RVSM logic risk ratios

The logic risk ratios computed with the upper layer of the RVSM environment are dramatically high. It means that the safety brought by ACAS is debased under certain circumstances.

These high risk ratios are the result of the very low number of NMACs without ACAS contribution within layer 5 of the European ACAS safety encounter model. However, even if risk ratios are increased, it should be noted that ACAS still continues to provide a safety benefit.

The 2005 mandate brings some slight benefits in comparison with the 2000 mandate. As for CVSM, these benefits are not as important as for layers 1 to 4. This was expected due to the low proportion of aircraft that can be affected by phase II and the high proportion of aircraft already equipped with phase I, in layer 5 (cf. 3.1.6.2).

Actually an important part of the NMACs (when ACAS contribution is considered) occur during encounters in which one pilot follows his RAs while the other does not manoeuvre because the pilot does not follow his RAs or because the aircraft is not fitted with ACAS II (cf. Appendix B).

The following section demonstrates that these high risk ratios are the result of the proportion of pilots who do not follow their RAs, and therefore highlights the need for pilots to follow their RAs.

Scenarios with improved compliance to RAs

The following table shows the logic risk ratios computed on the Encounter ACAS safety encounter model, which was generated specifically for layer 5, but with all the pilots following their RAs perfectly. This was done in order to highlight the implication of pilots who do not follow their RAs in the high logic risk ratios of table 4.

	Phase I CVSM	Phase II CVSM	Phase I RVSM	Phase II RVSM
Equipped and response	11.7%	11.4%	33.2%	30.0%
Not equipped or no-response	0.8%	0.0%	0.3%	0.4%
Logic risk ratio	12.5%	11.4%	33.5%	30.4%

Table 5: Logic risk ratios – layer 5 – all pilots follow their RAs

The risk ratios computed when all the pilots follow their RAs are roughly 3 times lower than those computed when 20% of the pilots do not follow their RAs. It shows the significant implication of pilot who do not follow their RAs in the risk ratios shown in table 4. These results emphasize once again the necessity for pilots to follow their RAs. **A proportion of 20% of pilots who do not follow their RAs debases the benefits brought by ACAS II** in the upper layer of the RVSM environment by a significant factor. This point was already underlined in [9b] and [10].

This table clearly shows that:

- The introduction of RVSM could adversely affect the safety benefit brought by ACAS (by a factor of around 3) in layer 5, as the risk ratios are multiplied by around 3 from CVSM to RVSM;
- ACAS II will still continue to provide a significant safety benefit (if all the pilots follow correctly their RAs) by reducing the risk of collision by more than 3.

These figures are close to those shown in WP3 of the ACASA project [20] [10]. In the Work Package 3 of the ACASA project, simulations were performed for layer 5 only, assuming that 90% of the aircraft were equipped and that all the pilots followed their RAs, without taking into account aircraft performances classes. The risk ratios were 17.5% for CVSM and 35.7% with RVSM.

These figures also show the very low contribution of encounters in which both aircraft are not equipped with ACAS II during phase I, as their contribution is under 1.0%

whatever the scenario. This is not surprising as the proportion of aircraft subjected to phase II is low in layer 5.

3.2.3. Full airspace

The following table shows the logic risk ratios computed on the ACAS safety encounter model generated for the full airspace.

	Phase I CVSM	Phase II CVSM	Phase I RVSM	Phase II RVSM
Equipped and response	8.7%	9.3%	9.3%	9.5%
Not equipped or no-response	32.1%	26.7%	32.4%	25.9%
Logic risk ratio	40.8%	36.0%	41.7%	35.4%

Table 6: Logic risk ratios – full airspace – 20% of pilots do not follow their RAs

These logic risk ratios are very close to those computed for layers 1 to 4. It shows that **layer 5 has a very small weight in the logic risk ratios computed for the full airspace**. This does not appear to be abnormal, as according to the definition of the European ACAS safety encounter model, the probability that an encounter occurs in layer 5 is less than 1.0%.

The phase I figures are very comparable, as well as the phase II figures. The tiny differences between the CVSM and RVSM environments only result from the variability of the process of building the encounters: the sets of encounters which were built are different.

These figures also highlight the significant benefit brought by phase II of the ACAS mandate in terms of collision risk reduction.

In addition, and as noticed for layers 1 to 4, these figures show that the risk ratios are mainly influenced by encounters in which none of the aircraft has manoeuvred, either because pilots did not follow their RAs or because the aircraft were not equipped. Moreover the benefits brought by phase II appear thanks to encounters in which none of the aircraft is equipped with ACAS II according to phase I, and especially encounters involving small aircraft versus light aircraft.

3.3. Conclusion

Two main points have been highlighted:

- Phase II of the ACAS mandate brings significant benefits in terms of collision risk reduction, even when assuming that 20% of pilots do not follow their RAs, with a reduction of the risk of collision of up to 16%. However these benefits are limited in layer 5 as the number of aircraft subject to phase II in this layer is very low in comparison with the proportion of aircraft already subject to phase I.
- These results once again show the need for pilots to follow their RAs as even a proportion of 20% of non-followed RAs debases seriously the safety benefits brought by ACAS, especially in the upper layer of the RVSM environment (logic risk ratios multiplied by roughly 3). Thus adequate training of pilots is required.

4. Full system safety study

4.1. *Methodology*

4.1.1. Principle

This part uses the event tree developed in the scope of the ACASA project, within Work Package 1.6 [4]. This tool enables to take into account factors which have implications on the safety brought by ACAS II but which are not linked to the logic itself, such as the fact that a pilot may act on visual.

This event tree was already used in WP1 of the ACASA project to compute full system risk ratios for phase I and II with the CVSM environment. The current study adds full system risk ratios for phase I and II with the RVSM environment.

The event tree is an excel spreadsheet which uses a set of probabilities to compute a risk ratio. Some of these probabilities are related to geometry, equipment, ATC or human factors, and have fixed values which were obtained using operational analysis [11]. These probabilities do not need computations and were used as provided in the event tree. However some of these probabilities were modified slightly in order to perform a sensitivity analysis, especially the RA compliance rate and the ACAS II equipage, which are among the most influencing factors.

Other probabilities are linked to the ACAS II logic and need to be computed. They concern the interaction of the RAs generated by the collision avoidance logic and the response of the pilot to those RAs. As mentioned in [12] these values are the probabilities that the RA will fail. These probabilities are computed by analysing simulations of the performance of ACAS in encounters of the European ACAS safety encounter model.

4.1.2. Probabilities

The event tree only considers the encounters in which the horizontal miss distance is small and in which the aircraft are on RA course.

The probabilities needed for the computation of the risk ratio can be gathered in several groups, which are related to geometry, equipment, ATC, human factors and logic.

This section presents the probabilities related to the CAS logic. The probabilities related to geometry, equipment, ATC, human factors are detailed in Appendix C. The way these probabilities were obtained is detailed in [11].

4.1.2.1. Logic events

The event tree includes the probabilities that ACAS II resolves a collision and that ACAS II induces a collision for several scenarios involving different types of pilots and of equipage. The pilots can follow their RAs either as standard pilots, as slow pilots, with the wrong sense or the pilots can decide to follow no RAs. An intruder

which is not ACAS equipped can be equipped with a Mode C transponder or with a Mode S transponder.

A complete full system risk ratio computation would require the computation of 39 risk ratios. Therefore, as full system risk ratios have to be computed for the former CVSM environment and for the current RVSM environment, 78 risk ratios would be required to get all the required probabilities.

Due to time constraints and because some scenarios have a small weight in the final result, the total number of risk ratios actually computed was reduced to 36.

All the scenarios involving two aircraft reporting their altitude in 25ft quanta, or two aircraft reporting their altitude in 100ft quanta were simulated to get the required probabilities. Scenarios involving one aircraft reporting its altitude in 25 quanta and the other reporting its altitude in 100ft quanta were not simulated and the probabilities were chosen using intermediate probabilities.

In addition, it was assumed that scenarios involving wrong pilots on board aircraft reporting their altitudes in 25ft quanta and scenarios involving wrong pilots on board aircraft reporting their altitude in 100ft quanta would result in the same probabilities.

4.1.3. Pilot models

Four pilot models had to be simulated to obtain the full system risk ratio:

- The prompt pilot;
- The non-response pilot;
- The slow pilot;
- The wrong pilot.

The pilot of an ACAS II equipped aircraft has a probability of 0.1786 to follow none of the RAs (i.e., non-response pilots). The simulated non-response pilot never follows any RAs and remain on his initial flight path.

A pilot who follows his RAs has a probability of:

- 0.4546 to follow his RAs promptly, as defined in [6] (i.e., prompt pilot);
- 0.5444 to follow his RAs slowly, as defined in [9a] (i.e., slow pilot);
- 0.001 to be a wrong pilot who goes against all the RAs (i.e., wrong pilot).

The prompt pilots and the slow pilots were simulated with the parameters defined in [9a]:

	Slow	Prompt
Initial corrective RA delay	9 s	5 s
Other RA delay ⁵	2.5 s	2.5 s
Standard RA acceleration ⁶	0.10 g	0.25 g
Increase/Reversal RA acceleration	0.10 g	0.35 g
Positive RA rate	500 fpm	1500 fpm
Increase RA rate	500 fpm	2500 fpm
VSL rate	as requested by RAs	

Table 7: Slow and standard pilot models

[9a] also shows that pilots who follow their RAs can be “aggressive” pilots (i.e., after a strong acceleration, the target vertical speed achieved is very high and the reaction time is very small). These pilots are not taken into account in the event tree, as their influence on the risk ratio is rather small.

The wrong pilot had to be implemented for this study, using [21].

The following figures illustrate, for a very simple encounter, the differences of behaviour of these pilots. In this encounter, both aircraft are level at FL200, and are converging towards the same point. Both aircraft are equipped with ACAS II. The pilot of aircraft one is a prompt pilot, whereas the pilot of aircraft two is successively a prompt pilot, a slow pilot, a non-response pilot, and a wrong pilot. The left views show the RAs and reactions of pilot of aircraft one, whereas the right views show the RAs and reactions of the pilot of aircraft two. All the views show, for this encounter, altitude versus time.

⁵ Other RAs include weakening, strengthening, increase and reverse RAs

⁶ Standard RAs include initial, strengthening and weakening RAs

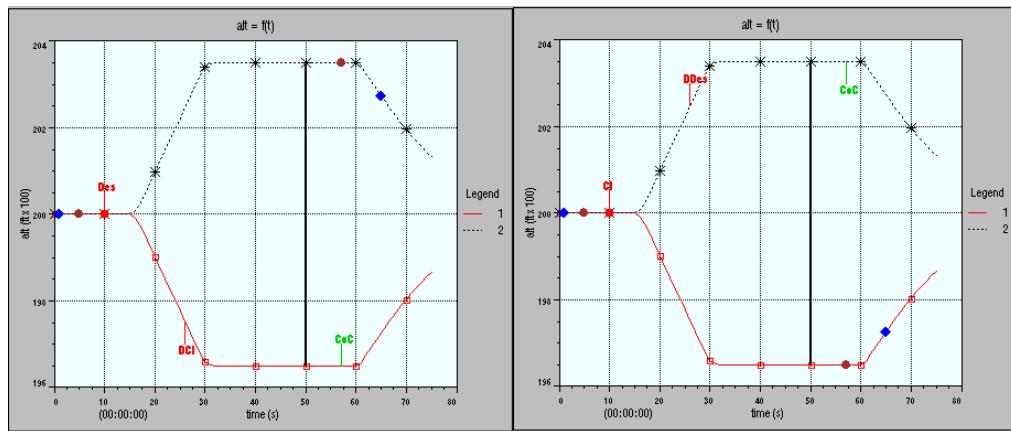


Figure 4: prompt pilot/prompt pilot

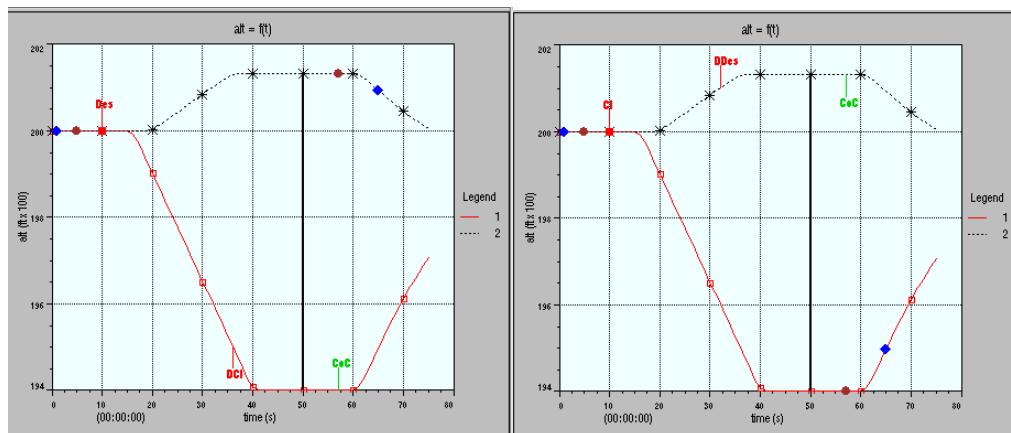


Figure 5: prompt pilot/slow pilot

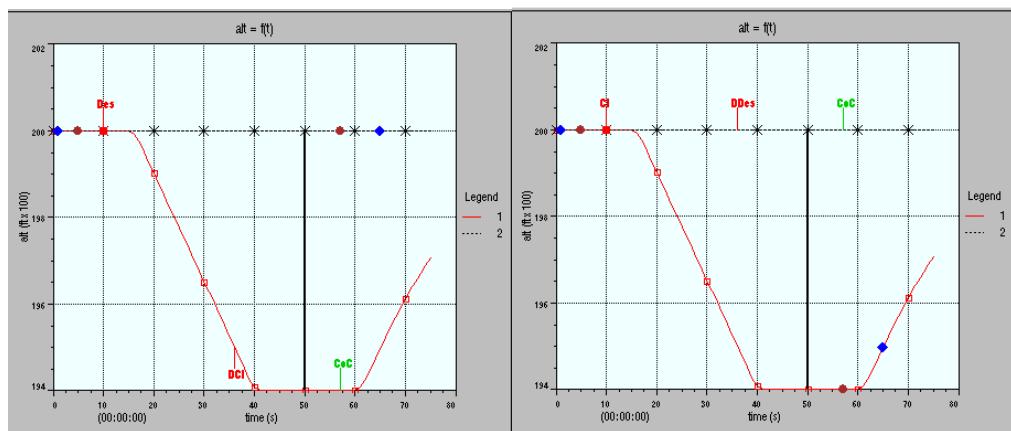


Figure 6: prompt pilot/non-response pilot

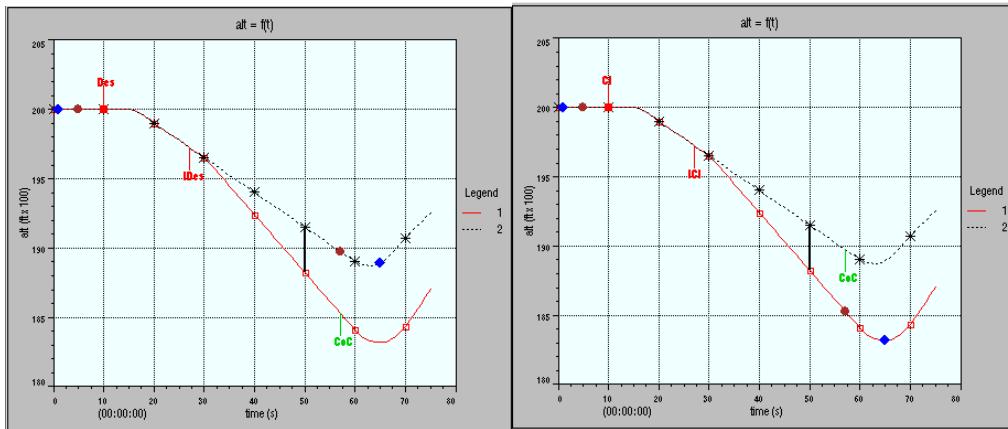


Figure 7: prompt pilot/wrong pilot

4.2. Full system risk ratios

The goal of this part is to present the full system risk ratio figures, which were computed for the various encounters describing CVSM and RVSM environments (i.e., for the full airspace).

In some cases, a sensitivity analysis is performed. An ideal scenario is always shown. This ideal scenario includes all the parameters of interest set to their best possible value (e.g., all pilots following their RAs, etc).

The scenario including the nominal values is also shown as a reference scenario, and underlined with a grey colour in the tables. This scenario includes the following proportions:

- 82.14% of pilots follow their RAs;
- 45.46% of them do it promptly;
- With phase I, 62.90% of the aircraft are equipped with ACAS II; and
- With phase II, 70.15% of the aircraft are equipped with ACAS II.

4.2.1. Nominal values

The following table shows the full system risk ratios, which were computed using the event tree, for both the CVSM and the RVSM environments.

	Phase I CVSM	Phase II CVSM	Phase I RVSM	Phase II RVSM
Full system risk ratio	27.5%	21.7%	27.3%	21.5%

Table 8: Full system risk ratios – nominal values

The full system risk ratios computed for the CVSM and RVSM environments are very close, which is in line with the observations made on logic risk ratios. It results from the fact that these full system risk ratios were computed for the full airspace, in which layer 5 has a small influence.

The full system risk ratio computed for the current RVSM environment with phase II is 22% lower than the one computed with the former CVSM environment and phase I. **Thus phase II brings significant improvements in terms of collision risk reduction.**

The full system risk ratios shown in table 8 will be referred as reference risk ratios in the following tables.

It can be surprising that the full system risk ratios shown in table 8 are lower than the logic risk ratios shown in part 3. This is explained by the fact that when computing logic risk ratios, the possibility of visual acquisition is not taken into account. The full system risk ratios computed assuming the possibility of visual acquisition is removed are as follows:

	Phase I CVSM	Phase II CVSM	Phase I RVSM	Phase II RVSM
Full system risk ratio	55.8%	50.5%	55.2%	50.0%

**Table 9: Full system risk ratios – nominal values
possibility of visual acquisition not taken into account**

The fact that ACAS II helps in the visual acquisition nearly halves the full system risk ratios. This trend had already been observed in [12].

This function of ACAS has a significant implication in terms of safety, and this study shows that only full system risk ratios enable to take them into account.

4.2.2. Sensitivity to the RA compliance rate

The following table shows the full systems risk ratios computed with several RA compliance rates, for the CVSM and RVSM environments and for both phases.

RA compliance rate	Phase I CVSM	Phase II CVSM	Phase I RVSM	Phase II RVSM
60.0%	30.1%	24.5%	30.0%	24.3%
82.14% (ref.)	27.5%	21.7%	27.3%	21.5%
100.0%	25.5%	19.5%	25.2%	19.3%

Table 10: Full system risk ratios - sensitivity to the RA compliance rate

Increasing the proportion of pilots who follow RAs from 60.0% to 82.14% decreases the risk ratios by between 2.6ppt and 2.8ppt. **It emphasizes once again the need for pilots to follow their RAs.**

According to the event tree:

- 45.46% of the pilots who follow their RAs do it promptly;
- 54.44% of the pilots who follow their RAs do it slowly.

The following table shows the full system risk ratios with several combinations of RA compliance rates, and with less or more pilots following RAs promptly.

RA compliance rate	Prompt pilots	Phase I CVSM	Phase II CVSM	Phase I RVSM	Phase II RVSM
82.14%	30.0%	28.8%	23.1%	28.6%	22.9%
82.14% (ref.)	45.46% (ref.)	27.5%	21.7%	27.3%	21.5%
90.0%	60.0%	25.3%	19.4%	25.1%	19.2%
100.0%	100.0%	20.7%	14.7%	20.5%	14.6%

Table 11: Full system risk ratios - sensitivity to the RA compliance rate and to the proportion of prompt pilots

These results clearly show that it is very important that pilots follow their RAs, but it is also very important they do it with the appropriate vertical rates and delays, as increasing the proportion of prompt pilots from 30.0% to 45.46% decreases the full system risk ratios by between 1.3ppt and 1.4ppt.

Increasing the proportion of prompt pilots from 45.46% to 60.0% and increasing the proportion of pilots who follow their RAs from 82.14% to 90.0% decreases the risk ratios further by between 2.2ppt and 2.3ppt.

4.2.3. Sensitivity to the level of equipage

The event tree assumes that 62.9% of aircraft will be fitted with ACAS with phase I, and that 70.15% of aircraft will be fitted with ACAS with phase II. The following table shows how the full system risk ratios would evolve assuming more aircraft are equipped in the future.

Proportion of aircraft equipped	CVSM	RVSM
70.15% (ref.)	21.7%	21.5%
75.0%	18.5%	18.3%
100.0%	6.4%	6.4%

Table 12: Full system risk ratios - sensitivity to the proportion of ACAS II equipped aircraft

The results confirm that the computations of the safety brought by ACAS are very sensitive to the level of equipage. A **small proportion of additional equipped aircraft increases significantly the benefits brought by ACAS on safety** and highlights the benefits to the airspace of having a higher level of equipage: increasing the equipage from 70.15% to 75.0% decreases the full system risk ratio by 3.2ppt.

4.2.4. Mixed scenarios

The following table shows full system risk ratios for several scenarios which assume a higher proportion of equipped aircraft, a higher rate of RA compliance and a higher proportion of prompt pilots.

RA compliance rate	Prompt pilots	Equipage	CVSM	RVSM
82.14% (ref.)	45.46% (ref.)	70.15% (ref.)	21.7%	21.5%
90.0%	60.0%	75.0%	16.2%	16.0%
95.0%	80.0%	80.0%	10.9%	10.7%
100.0%	100.0%	100.0%	1.3%	1.3%

Table 13: Full system risk ratios – mixed scenarios

This table mainly shows **that important gains in terms of risk of collision reduction are possible through an increased proportion of equipped aircraft together with an increased RA compliance rate and an increase in the number of prompt pilots.**

These parameters contribute highly in improving the benefits brought by ACAS II and are among the most influencing factors on the safety brought by ACAS (with visual acquisition).

5. Conclusion

5.1. Overall

This report clearly indicates that ACAS II brings significant benefits to safety in the European Airspace (cf. 3.2.1, 3.2.3 and 4.2.1).

5.2. CVSM versus RVSM

It was observed that the switch from the former CVSM environment to the RVSM environment does not decrease the safety benefits brought by ACAS II when considering the full airspace (cf. 3.2.1, 3.2.3 and 4.2.1).

When considering the upper layer of the RVSM environment only, it is expected that ACAS II still brings benefits in terms of risk of collision reduction, but this safety benefit is lower in RVSM than in CVSM. **However, ACAS II still decreases the risk of collision in this layer, especially if pilots follow their RAs (cf. 3.2.2).**

5.3. Phase II

This study highlights the significant benefits brought by phase II of the mandate. These benefits will be mainly observed in the altitude layers going from 1000ft to FL290. **The full system study showed that the risk of collision will be decreased by 22% with phase II (i.e., risk ratio decreased by 6ppt) (cf. 4.2.1).** The study also indicates that equipage requirements beyond those of phase II of the European ACAS mandate would further improve the safety gains provided by ACAS II.

5.4. Pilot response

The study also highlights the importance of pilot reaction, as even a proportion of 20% of the pilots not following their RAs debases the safety benefits brought by ACAS II, especially in the upper layer of the RVSM environment. Moreover, pilots must follow their RAs with the required vertical rates and with the expected reaction time. **Therefore pilot training will continue to be a very important matter when proceeding with phase II (cf. 3.2.2, 4.2.2, 4.2.3).**

6. Recommendations

It is proposed that:

- **the interest of fitting ACAS to smaller aircraft is brought to the attention of European decision makers to support phase II of the ACAS implementation;**
- **the need to follow correctly the RAs must be emphasized as this study shows that not following RAs debases the safety benefits brought by ACAS.**

7. Acronyms

ACAS	Airborne Collision Avoidance System
ACASA	ACAS Analysis
ATC	Air Traffic Control
CENA	Centre d'Études de la Navigation Aerienne
ECAC	European Civil Aviation Conference
FL	Flight Level
FLnnn	The Flight Level at $nnn00$ ft
fpm	feet per minute: a unit of vertical speed
hmd	horizontal miss distance
ICAO	International Civil Aviation Organization
MASPS	Minimum Aviation System Performance Standards
NM	International Nautical Mile
NMAC	Near Mid-Air Collision
RA	Resolution Advisory
RVSM	Reduced Vertical Separation Minimum
SARPs	Standards and Recommended Practices – an ICAO document
Sofréavia	Société Française d'Études et Réalisations d'Équipements Aéronautiques
TA	Traffic Advisory
TCAS	Traffic alert and Collision Avoidance System, an ACAS
vmd	vertical miss distance

8. Definitions

ACAS II

An ACAS that generates vertical, but not horizontal, avoidance manoeuvre advice.

encounter

Usually a pair of aircraft trajectories that are, in some sense that is defined by the context, close.

Flight Level

Barometric altitude, measured in units of 100ft, referenced to a standard pressure of 1013.25hPa.

horizontal miss distance

The horizontal separation at the time of closest approach between the two aircraft in an encounter.

large aircraft

In this report, a ‘large aircraft’ is an aircraft covered by Phase 1 of the European ACAS II mandate, *i.e.* one having a maximum take-off mass exceeding 15,000kg or a maximum approved seating configuration of more than 30.

light aircraft

In this report, all aircraft except ‘large aircraft’, ‘small aircraft’ and military fighters.

logic risk ratio

The proportional reduction in the risk of collision calculated for stated assumptions concerning the performance of ACAS. Typical assumptions are that certain aircraft are equipped, that all aircraft report altitude and a certain proportion do so in 25ft increments (as opposed to 100ft increments), that ACAS surveillance is perfect and that pilots respond exactly as intended. Logic risk ratio is a measure of the performance of the collision avoidance logic.

Mode C

A mode of secondary surveillance radar replies that reports altitude in whole units of 100ft.

Mode S

A mode of secondary surveillance radar that enables interrogators to address individual aircraft using their unique aircraft addresses. The replies contain aircraft address, altitude and other information. Aircraft fitted with ACAS II must be fitted with a Mode S transponder. Mode S transponders can report altitude either in whole units of 25ft or in whole units of 100ft.

percentage points

The numerical difference between two percentages. In this report, the abbreviation ppt is sometimes preferred to % when discussing a statistic that is already expressed as a percentage. The purpose is to make it clear that the quantity is an absolute change in the value of the statistic, rather than a proportional change. Thus, if the statistic has a value of $X\%$, a reduction of Y ppt results in a value of $(X - Y)\%$

Resolution Advisory

An alert issued by ACAS II advising the pilot to take avoiding action in the vertical plane. RAs may be ‘corrective’ (requiring the pilot to manoeuvre vertically) or ‘preventive’ (requiring no immediate manoeuvre but proscribing a range of vertical speeds).

Reduced Vertical Separation Minimum

The regime in which the standard cruising levels are separated by 1000ft between FL290 to FL410 inclusive.

risk ratio

The ratio of the risk of collision with ACAS to the risk of collision without ACAS.

small aircraft

In this report, a ‘small aircraft’ is an aircraft that is not large, but is covered by Phase 2 of the European ACAS II mandate, *i.e.* having a maximum take-off mass exceeding 5700kg or a maximum approved seating configuration of more than 19.

system risk ratio

A calculation of risk ratio for the ACAS system as a whole, with estimates made for the probable performance of all parts of ACAS, pilots and equipment on other aircraft.

Traffic Advisory

A preliminary alert issued by ACAS II in order to cue a visual search for the potential threat, and to prepare the pilot for a possible Resolution Advisory.

version 7

The current release of the TCAS collision avoidance logic. A requirement to fit ACAS II (conforming to the ICAO SARPs) implies a requirement to fit version 7 as opposed to version 6.04A.

vertical miss distance

The vertical separation at the time of closest approach between the two aircraft in an encounter.

9. Appendix A : altimeter error model

The risk ratio is computed applying an altimeter error model to the trajectories of the aircraft. This altimeter error model is defined in the ACAS SARPS [6]. This error is distributed as a Laplacian distribution with zero mean having probability density:

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

where $p(e)$ is the probability density function of altimetry error of value e . The probability that the altimetry error is greater than a value x is as follows:

$$p(|e| > x) = \exp\left(-\frac{|x|}{\lambda}\right)$$

The parameter λ required for the definition of statistical distribution of altimeter error for each aircraft can take two values, λ_1 and λ_2 , which depend on the altitude layer. For an aircraft equipped with ACAS, the value of λ is λ_1 . For aircraft not equipped with ACAS, the value of λ is selected randomly between λ_1 and λ_2 . The values of λ_1 and λ_2 for the altitudes corresponding to the upper layer of the RVSM environment are 72ft and 101ft according to SARPS. These values do not comply with MASPS in case of RVSM.

For this reason, the altimeter error model was modified specifically for RVSM simulations so that the aircraft flying in the altitude band between FL290 and FL410 are MASPS compliant. Thus λ was set to 35ft for the altitude band between FL290 and FL410, when simulating RVSM. This value was chosen on the basis of [7] which demonstrates that choosing $\lambda=35$ ft is consistent with the requirement of the MASPS. This assumes that all the aircraft flying in the RVSM altitude band are MASPS compliant.

10. Appendix B: problem encounters

The analysis of the sets NMAC (cf. 3.2.2) showed that a specific geometry is majority. The following figure presents such an encounter.

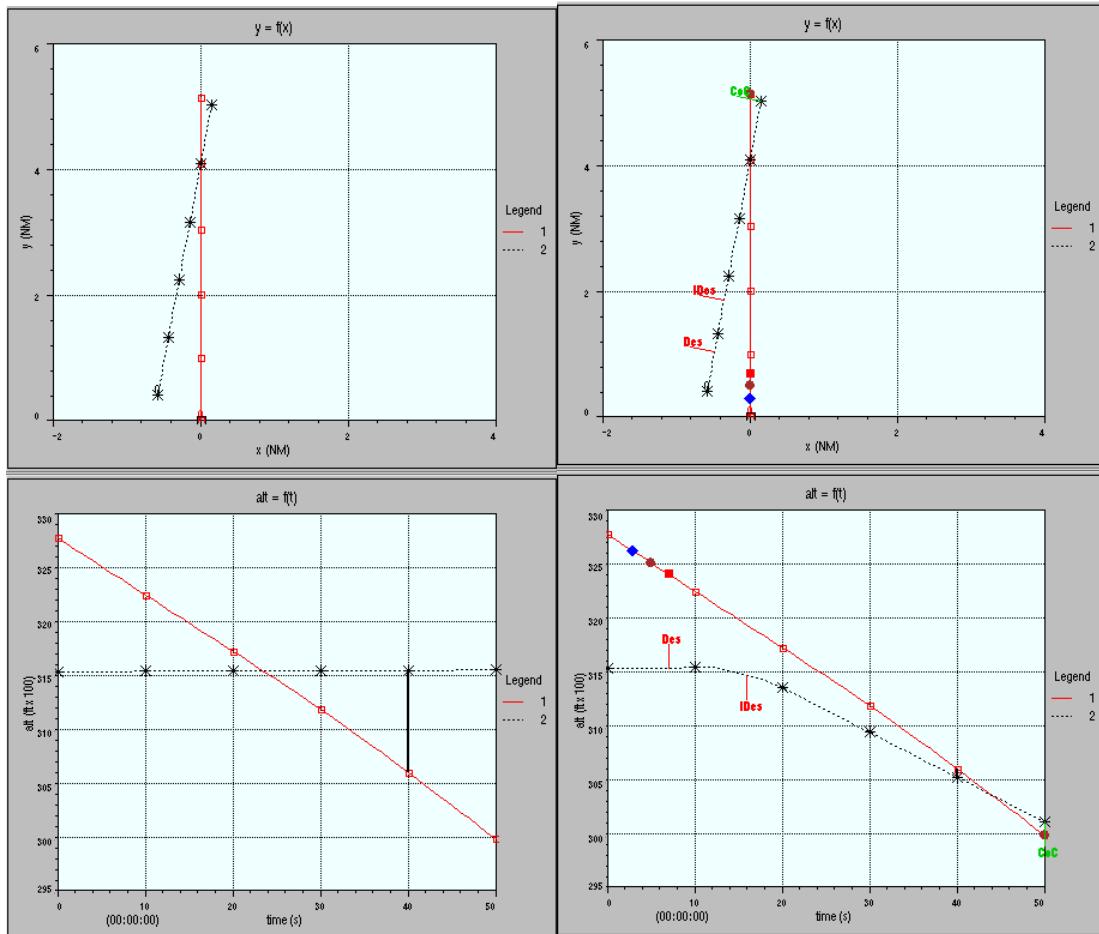


Figure 8: Induced NMAC – layer 5 – Phase I
The pilot of the descending aircraft does not follow his Ras

The left view shows the encounter without ACAS contribution. The right view shows the encounter with ACAS contribution. On both views, the upper figure shows the encounter in the horizontal plane, whereas the lower view shows the altitude of the aircraft versus time.

In this encounter, an ACAS II equipped aircraft (i.e., a small jet aircraft) is descending towards another ACAS II equipped aircraft. The vertical separation at CPA without ACAS contribution is 950ft.

We observe that the level aircraft is given a “Descend” RA. Then, an “increase descent” RA is triggered. The pilot of the descending aircraft does not follow his “Climb” RA. This encounter results in an almost nil vertical separation at CPA.

The simulations with both aircraft pilots following their RAs result in a vertical separation at CPA of 1000ft. The following figure shows the result of the simulation for this encounter, with both aircraft equipped with ACAS II.

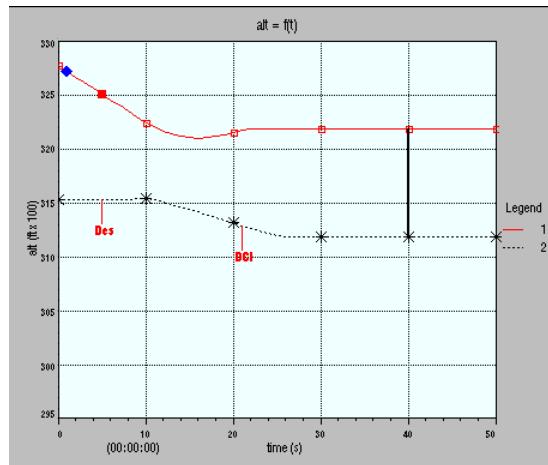


Figure 9: Same encounter – layer 5 – Phase II – both pilots follow their RAs

The level aircraft still has a “Descend” RA, but this time the descending aircraft follows the “Climb” RA, which ensures a vertical separation at CPA of 1000ft. This encounter highlights once again the need for pilots to follow their RAs.

In addition, similar encounters also occur with the descending aircraft not equipped with ACAS II, and also result in NMACs. These encounters represent a significant proportion of the NMACs.

11. Appendix C: probabilities required for the event tree

11.1. Geometry events

The event tree takes into account the probabilities:

- That visibility will make it impossible to visually acquire the intruder, independently of the relative position of the aircraft (0.2);
- That the aircraft are on collision course. These values depend on the encounter model which is simulated and on the altimeter error model which is used;
- That an intruder is not in the field of view of the cockpit window, given that aircraft are on collision course (0.196).

11.2. Equipment events

The event tree takes into account the probabilities:

- That an aircraft is ACAS II equipped, which depends on the phase of mandate simulated (0.629 for phase I and 0.7015 for phase II).
- That a non ACAS II equipped aircraft is Mode C equipped, Mode S equipped or not equipped by any transponder. These values depend on the phase of the mandate which is simulated (respectively equal to 0.9030, 0.0870 and 0.01 for phase I and 0.5940, 0.3960 and 0.01 for phase II);
- That ACAS II surveillance will enable a Mode C intruder to be tracked (0.97);
- That ACAS II surveillance will enable a Modes S intruder to be tracked (0.9950);
- That the display is operational. This value is used to determine if visual acquisition of the intruder is possible (0.9990);
- That the bearing data is available (0.95);
- That Mode C aircraft report their altitudes and that Modes S aircraft report their altitude (0.92 and 0.992).

11.3. ATC events

The event tree takes into account the probabilities:

- That an ACAS II equipped aircraft, which receives an alert, is operating with an air traffic controller (0.99);
- That, when there is a controller, he is already involved in the encounter (0.2), which means the controller is part of the problem, as the encounter results in an RA.

11.4. Human factors events

The event tree takes into account the probabilities:

- That, given there is a controller instruction when the aircraft are on a collision course, the instruction will be counter to the RA (0.0932);
- That, given there is a controller instruction when the aircraft are not on a collision course, the instruction will be counter to the RA (0.0725);
- That the pilot will contact the controller in response to an RA (0.75);
- That the pilot does not make a visual search in response to an alert (0.05);
- That the pilot, having visually acquired the intruder, fails to act on the basis on his visual information (0.01);
- That the pilot will follow an RA in the absence of a clearance (0.8214);
- That the pilot will follow the clearance in the absence of an RA (0.8446);
- That the pilot prefers the clearance (0.0883);
- That a pilot with display fails to acquire intruder (0.0194);
- That a pilot without display fails to acquire intruder (0.3719);
- That the intruder has already been visually acquired, before the RA (0.5105);
- That the visual information is wrong, because of a bad perception of the situation or because the wrong aircraft has been visually acquired (0.0094);
- That the pilot will respond promptly, slowly or with the wrong sense. Section 4.1.3 gives details about these pilot models.

11.5. Auxiliary events

The event tree takes into account the probabilities:

- That the aircraft report altitude in 25ft (0.9333 if ACAS equipped, 0.8033 if not);
- That the aircraft are in TA/RA mode (1.0) or TA only mode (0.0).

12. References

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