VR-APFD Validation report for automatic responses to ACAS RA

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Abstract

Since TCAS II was mandated for all civil turbine-engined aircraft with more than 19 passengers or weighing more than 5,700 kg in the European airspace in 2005, it has demonstrated its effectiveness in reducing the risk of mid-air collision. However, the pilots do not very often respond to the triggered RAs exactly as expected by TCAS II and this negatively affects TCAS II safety benefits and compatibility with ATC operations.

A solution to this issue would be to link TCAS with the Auto-Pilot so that the aircraft would automatically respond to the RAs instead of the current manual response performed by pilots. Airbus has already developed, certified and implemented this solution on some aircraft.

The objective of this study was to assess the impact of implementing automatic response to RAs for all TCAS-equipped aircraft types and not only Airbus aircraft. Furthermore some particular aspects (i.e. vertical performance limitations and reduction of TCAS initial RA time threshold) were investigated. The validation was built on the model-based methodology that has been used in TCAS II studies conducted in Europe for more than 10 years. A list of key performance indicators related to safety, operational compatibility with ATC and pilot acceptability, were computed and compared to some pre-defined acceptance criteria.

The validation has shown that with a delay of response to RAs equal to or below 4 s, the automatic responses to RAs bring significant additional safety and operational benefits to TCAS II performance, whatever the assumption in terms of equipage and compliance rate to RAs.

The reduction of TCAS initial RA time threshold associated to a shortened delay of response to RAs brings additional operational benefits, increasing the compatibility with ATC and the acceptability by pilots of the triggered RAs. This solution seems therefore a promising solution.

It was also observed through the investigation of several operationally realistic situations that during high altitude encounters it is preferable to perform a manoeuvre even with a vertical rate lower than that expected by TCAS rather than using the existing RA climb inhibition feature.

Authoring & Approval

Prepared By		
[redacted] DSNA/Egis Avia	[redacted]	29/04/2011

Reviewed By		
[redacted] DSNA/Egis Avia	[redacted]	13/04/2011
[redacted] DSNA		13/04/2011
[redacted] DSNA/Egis Avia		13/04/2011
[redacted] DSNA		29/04/2011
[redacted] EUROCONTROL		27/04/2011
[redacted] NATS		28/04/2011
[redacted] NATS		27/04/2011
[redacted] AENA/INECO		26/04/2011
[redacted] AIRBUS		11/05/2011
[redacted] DSNA/Egis Avia		13/04/2011
[redacted] DSNA/Egis Avia		13/04/2011

Approved By		
[redacted] DSNA	[redacted]	03/11/2011
[redacted] NATS		04/11/2011
[redacted] EUROCONTROL		04/11/2011
[redacted] AIRBUS		10/11/2011

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Executive summary

Since 2005, all civil turbine-engined aircraft with more than 19 passengers or weighing more than 5,700 kg flying in the European airspace are required to be equipped with TCAS II. This system has been introduced in order to reduce the risk of mid-air collisions or near mid-air collisions between aircraft as a last-resort safety net and it has demonstrated its effectiveness. However, the safety benefits provided by TCAS II and its compatibility with Air Traffic Control (ATC) operations depend on the pilots' responses to the triggered RAs and operational monitoring programmes have shown that some pilots do not follow their RAs and for those responding to the RAs, the actual reactions vary from the expected ones (e.g. too slow, too aggressive, etc.).

To address this problem, Airbus has recently developed, certified and implemented a solution that links TCAS II to the Auto-Pilot for an automatic response to RAs. The objective of this activity is to investigate the impact of linking TCAS to the Auto-Pilot for an automatic response to RAs for all TCAS-equipped aircraft (not only Airbus). A list of validation objectives is defined to address the stakeholder expectations.

The validation was built on the model-based methodology that has been used in TCAS II studies conducted in Europe for more than a decade. It relies on a set of tools including several models to allow replicating the environment in which TCAS is being operated. These models consist essentially of an encounter model, a pilot response model and an altimetry error model. An Auto-Pilot model was defined for the simulations and a sensitivity analysis was carried out through slight variations of its characteristics (delay and vertical acceleration), different impact of the RA response rate (same as manual or 100% compliance) and two equipage assumptions (50% and 100% of TCAS II equipped aircraft). As a result, an exhaustive list of scenarios was defined.

To support the validation, key performance indicators with associated acceptance criteria were defined for three different areas (safety; operational compatibility with ATC; and pilot acceptability) and they were computed according to airspace and/or aircraft perspective(s).

The validation has shown that with a delay of response to RAs equal to or below 4 s, the automatic responses to RAs bring significant safety and operational benefits to TCAS II performance, whatever the assumption in terms of equipage and compliance rate.

Furthermore, an initial investigation was conducted on the possibility to enhance the TCAS logic by reducing the initial RA time thresholds thanks to the availability of the automatic response to RAs. Simulations were conducted using a modified TCAS logic including initial RA time thresholds reduced by 3 seconds and an automatic response to RAs after 2 seconds instead of the expected 5 seconds. The reduction of TCAS initial RA time threshold associated to a shortened delay of response to RAs brings additional operational benefits when compared to other automatic response scenarios, increasing the compatibility with ATC and the acceptability by pilots of the triggered RAs. This solution seems therefore a promising solution.

Finally, a case study was conducted on some encounters to evaluate the impact of providing the TCAS logic with the indication that the own aircraft is vertical performance limited and cannot achieve the nominal climb rate of 1,500 fpm for a "Climb" RA. It was observed through this investigation of several operationally realistic situations that during high altitude encounters, it is preferable to perform a manoeuvre even with a vertical rate lower than that expected by TCAS rather than using the existing RA climb inhibition feature.

1 Introduction

1.1 Purpose of the document

The purpose of this validation report is to present the validation activities on the subject of linking TCAS to the Auto-Pilot for an automatic response to RAs for all TCAS-equipped aircraft and not only Airbus aircraft, the end goal being the definition of Safety and Performance Requirements for automatic responses to RAs.

1.2 Intended readership

This document is intended for the partners involved in the project. It is also intended to provide inputs to Projects 4.2/5.2 and 4.8.3.

It may also serve to initiate coordination with standardisation bodies, in particular EUROCAE WG75, RTCA SC-147 and RTCA SC-220.

1.3 Background

Since 2005, all civil turbine-engined aircraft with more than 19 passengers or a maximum take-off mass of more than 5,700 kg flying in the European airspace are required to be equipped with TCAS II. This system has been introduced in order to reduce the risk of mid-air collisions or near mid-air collisions between aircraft as a last-resort safety net and it has demonstrated its effectiveness. However, the safety benefits provided by TCAS II and its compatibility with Air Traffic Control (ATC) operations depend on the pilots' responses to the triggered RAs.

TCAS II operational monitoring programmes have shown that pilots do not always follow their RAs thus undermining the safety enhancement brought by TCAS. Pilot non-compliance with RAs is the main factor that lowers TCAS performance. Furthermore, some studies have also shown that pilots following the RAs do not manoeuvre exactly as expected by TCAS specifications. These variations can affect TCAS II safety benefits (e.g. inefficient manoeuvre due to slow and smooth reaction) or degrade compatibility with ATC operations (e.g. unnecessary large vertical deviations due to over-reaction).

To address this problem, the proposed solution is to perform automatic responses to RAs instead of responses manually flown by pilots.

Airbus has already developed, certified and implemented a solution by linking TCAS to the Auto-Pilot (AP) for an automatic response to RAs. Airbus solution also links TCAS to the Flight Director (FD) to improve manual responses by pilots.

The main objective of this validation activity was to investigate the impact of linking TCAS to the Auto-Pilot for an automatic response to RAs for all TCAS-equipped aircraft and not just Airbus aircraft.

The proposed solution was built upon the existing Airbus solution but:

- Some variations of the parameters for the automatic responses were evaluated to assess the impact of the performances of the various TCAS-equipped aircraft; and
- The impact of providing, when appropriate, TCAS with the indication that the aircraft will not be able to comply with "Climb" or "Increase Climb" RAs due to performance limitations was investigated.

Furthermore, an initial investigation was conducted on the possibility to enhance the TCAS logic by reducing the initial RA time thresholds due to the availability of the automatic response to RAs[1].

The methodology used for the validation activities addressed in this report is based on that used for TCAS II studies conducted in Europe for more than ten years and acknowledged at ICAO and RTCA level. The tools developed during several past projects of the EUROCONTROL Mode S and ACAS Programme (ACASA, ASARP, AVAL) were reused and adapted as needed.

1.4 Acronyms and Terminology

Term	Definition
Acceptance criteria	If they are met, the change is acceptable without discussion.
ACAS	Airborne Collision Avoidance System
ACASA	ACAS Analysis – a study commissioned by EUROCONTROL in support of the mandate for the carriage of ACAS II in Europe, before implementation of RVSM.
AEM	Altimetry Error Model
ANSP	Air Navigation Service Provider
AP/FD	Auto-Pilot / Flight Director
ASARP	ACAS Safety Analysis post-RVSM Project – a study commissioned by EUROCONTROL to investigate the safety of ACAS II following the introduction of RVSM in Europe.
ATC	Air Traffic Control
ATM	Air Traffic Management
AVAL	ACAS on VLJs and LJs – a study commissioned by EUROCONTROL to assess the effect of equipping very light jet and light jets with TCAS II.
CAS	Collision Avoidance System

[1] Task 3.3 of P4.8.2.Work Area 3 will evaluate possible adaptations of ACAS to autoflight CAS (including the reduction of ACAS time thresholds) for longer term implementation. In particular, the investigated evolutions will address much more significant time reduction than that assessed in this activity.

Term	Definition
CPA	Closest Point of Approach
EASA	European Aviation Safety Agency
HMD	Horizontal Miss Distance
MOPS	Minimum Operational Performance Standard
MTOM	Maximum Take-Off Mass
NMAC	Near Mid-Air Collision
RA	Resolution Advisory
SESAR	Single European Sky ATM Research Programme
SJU	SESAR Joint Undertaking (Agency of the European Commission)
SJU Work Programme	The programme which addresses all activities of the SESAR Joint Undertaking Agency.
SESAR Programme	The programme which defines the Research and Development activities and Projects for the SJU.
TCAS	Traffic alert and Collision Avoidance System
VMD	Vertical Miss Distance

2 Summary

2.1 Introduction

The goal of this part is to provide a summary of the findings of this study, and to provide some links to the other parts of the document.

The whole set of results for all the safety performance indicators are provided in this part. More details are shown in part 3, but only for the most pertinent safety performance indicators because it is not worthwhile to show all of them.

2.2 Sensitivity analysis parameters

Pilot and auto-pilot responses are entirely defined by the following parameters: delay before start of manoeuvre, acceleration of the manoeuvre and targeted vertical speed. They are presented in detail in [3].

The sensitivity analysis was made varying the following parameters of the auto pilot response model.

- The delay to start to perform a manoeuvre; and
- The acceleration used to perform this manoeuvre.

The targeted vertical speed was not altered (200 fpm more than the prescribed TCAS vertical speed when there is one, just outside of the TCAS forbidden vertical speeds if there is no TCAS prescribed vertical speed).

The following couples of delay/accelerations were used:

		Acceleration			
Delay		0.15g	0.20g	0.25g	0.30g
	3s	X	X	X	X
	4s		X	X	X
	5s		X	X	X
	7s		X	X	X

Table 1: Delays and accelerations

Two types of pilot response were used [3]:

- A Standard response. This response assumes a perfect response to RAs. The scenarios using this type of pilots will be referred to as standard scenarios.
- A Typical response. This response assumes an operationally realistic response to RAs, with delays and acceleration varying according to a distribution established in [2]. The scenarios using this type of pilots will be referred to as typical scenarios.

Comparisons are made against two reference scenarios: one assuming standard responses to RAs, one assuming typical responses to RAs.

Three rates of equipage of the automatic response functionality were used: 0% (reference), 50% (partial equipage) and 100% (full equipage).

It was assumed that 20% of pilots having TCAS II and not the automatic response to RAs (i.e. 30% below FL50 and 10% above FL50) do not respond to the RAs. This assumption is used for the reference scenarios, and for partial equipage scenarios (for the half of aircraft with TCAS II and without the automatic response).

When introducing the automatic response to RAs, two rates of response to RAs are considered for the 'Auto-Pilot response model':

- Partial compliance: all the pilots who do not follow RAs when not equipped with the automatic response functionality still do not follow RAs when equipped with it. This scenario therefore assumes that only pilots who already follow their RAs without the automatic response feature benefit from it when equipped. As a consequence, this scenario does not modify the overall response rate to RAs, and is useful to assess the effect of the introduction of the automatic response in terms of delay and acceleration applied.

- Full compliance: all the pilots who do not follow RAs when not equipped with the automatic response functionality follow RAs when equipped with it.

An additional scenario was simulated using TCAS II logic version 7.1 and RA thresholds reduced by 3s, with a 2s delay and 0.25g acceleration pilot [3].

2.3 Performance indicators summary

The performance indicators names used in the summary tables hereafter are shown in the following table.

Key performance indicators		Airspace perspective	Aircraft perspective	Acceptance criterion
Safety				
SA1	Risk ratio	SA1S	SA1A	Decrease
SA2	Vertical Miss Distances	SA2S	SA2A	≥1
SA3	Collision rate per flight hour (unresolved and induced)	SA3S	SA3A	Decrease
SA4	Number of RAs without provision of ALIM	SA4S	SA4A	Decrease
SA5	Number of increase RAs	SA5S	SA5A	Decrease
SA6	Number of reversal RAs	SA6S	SA6A	Decrease
Operational compatibility with ATC				
CA1	Number of RAs with incompatible sense selection	CA1S	-	No increase
CA2	Number of encounters with RAs	CA2S	-	Decrease
CA3	Number of crossing RAs	CA3S	-	No increase
CA4	Vertical deviations	CA4S	-	≥1
Pilot acceptability				
PA1	Number of aircraft receiving RAs	PA1S	-	No increase
PA2	Number of crossing RAs	-	PA2A	No increase
PA3	Number of RAs opposite to the aircraft trajectory	-	PA3A	No increase
PA4	Number of initial RAs opposite to the aircraft trajectory	-	PA4A	No increase
PA5	Number of multiple RAs	-	PA5A	No increase
PA6	Number of complex RA sequences	-	PA6A	No increase

Table 2: Performance indicators

The following table present a summary of the performance indicators computed for this analysis.

Green zones are used when the acceptance criteria is met without discussion for a given indicator, orange zones are used when the acceptance criteria are not met directly but only after an analysis, and red zones are used when the acceptance criteria are not met, even after an analysis. White zones are used when a given metric has not been computed, because considered not relevant.

The values shown in the table are expressed as a gain, in percentage, when compared to the reference scenario, except for the performance indicators SA2 (VMD ratio) and CA4 (deviation ratio) which are expressed as a ratio between a value with the AP/FD and a value without the AP/FD. For these specific indicators, a gain when compared to the reference scenario is expressed by a value higher than 1.

The results are grouped by delay of response time, then by acceleration, and then by the type of scenario simulated (with the equipage and compliance rate). The higher in the table, the lower is the delay. The scenario with the reduced CAS logic threshold is shown in this table, with a 2 s delay, at the first line.

delay	acc.	Resp.	Eqp	Compl.	SA1S	SA1A	SA2S	SA2A	SA3S	SA3A	SA4S	SA4A	SA5S	SA5A	SA6S	SA6A	CA1S	CA2S	CA3S	CA4S	PA1S	PA2A	PA3A	PA4A	PA5A	PA6A
2	0.25	Standard	Full	Full	-59.7	-58.1	2.2	1.8	-70.9	-83.3	-69.8	-77.8	-40.5	-43.3	-55.6	-54.1	-7.3	-5.5	-12.5	0.4	-6.5	-8.2	-18.7	-13.9	50.0	-40.8
3	0.15	Standard	Full	Full	-55.2	-54.1	6.1	4.2	-67.3	-75.0	-66.0	-73.7	-42.5	-35.0	-39.1	-36.5	14.4	0.0	-2.6	0.2	-0.3	-2.7	-2.1	-0.5	50.0	-20.9
3	0.15	Standard	Full	Partial	-1.0	-4.2	4.8	3.4	0.0	33.3	-4.6	-19.4	-4.5	-2.6	-12.6	-14.8	4.5	0.0	-2.3	0.3	-0.2	-3.1	-0.2	-0.3	50.0	-7.2
3	0.15	Standard	Partial	Full	-27.9	-49.0	5.7	3.8	-25.5	-85.7	-33.4	-78.3	-22.7	-44.8	-19.8	-26.7	7.4	0.0	-1.0	0.2	-0.1	-2.0	-1.2	0.0	50.0	-20.5
3	0.15	Standard	Partial	Partial	-0.9	-7.0	4.5	3.0	1.8	-50.0	-3.0	-33.3	-3.6	-5.3	-7.7	-6.5	2.6	0.0	-1.0	0.3	-0.1	-2.2	0.2	0.0	50.0	-6.1
3	0.20	Standard	Full	Full	-61.2	-59.2	17.7	15.7	-72.7	-83.3	-73.1	-81.8	-49.0	-43.3	-42.0	-38.8	15.4	0.0	-2.3	0.2	-0.4	-1.8	-1.8	-0.6	50.0	-22.3
3	0.20	Standard	Full	Partial	-4.0	-12.5	15.0	14.1	-3.6	0.0	-11.1	-47.2	-13.4	-5.3	-14.5	-18.0	5.0	0.0	-2.0	0.2	-0.2	-2.0	0.2	-0.3	50.0	-7.5
3	0.20	Standard	Partial	Full	-31.5	-54.5	16.4	14.8	-30.9	-85.7	-36.7	-82.6	-25.1	-48.3	-22.7	-31.1	8.3	0.0	-0.7	0.2	-0.2	0.0	0.0	-0.2	50.0	-18.2
3	0.20	Standard	Partial	Partial	-2.4	-14.1	13.8	12.7	-1.8	-50.0	-5.7	-50.0	-7.3	-5.3	-9.7	-12.9	3.3	0.0	-0.7	0.2	-0.1	0.0	2.1	0.0	50.0	-1.5
3	0.25	Standard	Full	Full	-64.0	-62.0	24.9	20.8	-76.4	-83.3	-75.3	-85.9	-55.9	-55.0	-44.9	-41.2	15.6	0.0	-2.6	0.2	-0.4	-2.7	-2.8	-0.7	50.0	-26.0
3	0.25	Standard	Full	Partial	-6.1	-16.7	21.0	18.3	-3.6	0.0	-13.3	-58.3	-19.4	-21.1	-16.9	-19.7	5.0	0.0	-2.0	0.2	-0.3	-2.0	-1.3	-0.4	50.0	-12.9
3	0.25	Standard	Partial	Full	-33.4	-58.5	24.1	22.4	-34.5	-85.7	-38.0	-87.0	-27.9	-48.3	-23.2	-31.1	8.3	0.0	-0.7	0.2	-0.2	0.0	-0.2	-0.2	50.0	-17.6
3	0.25	Standard	Partial	Partial	-3.7	-20.3	20.1	19.0	-1.8	-50.0	-7.1	-61.1	-8.9	-10.5	-10.1	-12.9	3.3	0.0	-0.7	0.2	-0.2	0.0	1.4	0.0	50.0	-2.3
3	0.30	Standard	Full	Full	-65.5	-63.3	23.4	20.2	-80.0	-83.3	-76.6	-84.8	-59.9	-66.7	-45.4	-41.2	15.7	0.0	-3.3	0.2	-0.4	-3.6	-2.8	-0.7	100.0	-27.4
3	0.30	Standard	Full	Partial	-7.2	-19.4	19.4	17.4	-5.5	0.0	-14.7	-55.6	-22.7	-34.2	-17.4	-19.7	5.2	0.0	-2.6	0.2	-0.3	-3.1	-0.8	-0.4	100.0	-12.9
3	0.30	Standard	Partial	Full	-34.4	-60.1	21.1	18.6	-34.5	-85.7	-38.3	-87.0	-31.6	-65.5	-23.7	-31.1	8.5	0.0	-1.7	0.2	-0.2	-3.9	-0.2	-0.2	50.0	-19.9
3	0.30	Standard	Partial	Partial	-4.3	-22.9	17.6	16.0	-1.8	-50.0	-7.6	-61.1	-11.3	-26.3	-10.6	-12.9	3.5	0.0	-1.7	0.3	-0.2	-4.4	1.9	0.0	50.0	-3.1
4	0.20	Standard	Full	Full	-57.4	-56.1	13.1	10.9	-74.5	-75.0	-63.0	-68.7	-42.1	-28.3	-36.2	-31.8	13.3	0.0	-2.3	0.1	-0.2	-1.8	-2.0	-0.3	50.0	-18.2
4	0.20	Standard	Full	Partial	-2.4	-8.2	10.9	9.5	-5.5	33.3	-2.2	-11.1	-3.6	7.9	-7.7	-6.6	2.8	0.0	-2.3	0.1	-0.1	-2.0	-0.4	-0.1	50.0	-5.0
4	0.20	Standard	Partial	Full	-30.6	-53.0	11.2	9.3	-32.7	-71.4	-32.1	-71.7	-22.3	-37.9	-16.9	-22.2	6.4	0.0	-1.3	0.1	-0.1	-3.9	-1.4	0.0	50.0	-17.6
4	0.20	Standard	Partial	Partial	-1.7	-9.2	9.3	7.9	-1.8	0.0	-2.2	-27.8	-2.8	0.0	-3.9	3.2	1.4	0.0	-1.3	0.1	-0.1	-4.4	0.2	0.0	50.0	-3.1
4	0.25	Standard	Full	Full	-61.3	-59.5	27.1	26.3	-76.4	-83.3	-68.8	-76.8	-44.1	-33.3	-36.7	-31.8	13.3	0.0	-2.3	0.1	-0.2	-1.8	-2.0	-0.3	100.0	-20.1
4	0.25	Standard	Full	Partial	-4.4	-12.1	23.1	24.3	-5.5	0.0	-7.1	-33.3	-7.3	0.0	-9.7	-8.2	3.3	0.0	-2.3	0.1	-0.1	-2.0	-0.4	-0.1	100.0	-6.8
4	0.25	Standard	Partial	Full	-32.0	-55.8	24.8	26.7	-32.7	-85.7	-35.9	-82.6	-23.1	-37.9	-17.9	-22.2	6.7	0.0	-1.0	0.1	-0.1	-2.0	-0.8	0.0	50.0	-18.2
4	0.25	Standard	Partial	Partial	-2.6	-15.5	21.0	23.4	-1.8	-50.0	-4.9	-50.0	-4.0	0.0	-5.3	0.0	1.9	0.0	-1.0	0.2	-0.1	-2.2	0.5	0.0	50.0	-3.8
4	0.30	Standard	Full	Full	-62.0	-60.1	31.2	30.3	-74.5	-75.0	-70.4	-78.8	-47.4	-35.0	-37.7	-32.9	13.7	0.0	-2.0	0.1	-0.2	-0.9	-1.8	-0.3	50.0	-19.8
4	0.30	Standard	Full	Partial	-4.9	-14.1	26.6	27.6	-5.5	0.0	-8.4	-36.1	-10.5	2.6	-10.6	-9.8	3.6	0.0	-2.0	0.1	-0.2	-1.0	0.0	-0.1	50.0	-5.4
4	0.30	Standard	Partial	Full	-32.7	-56.9	30.9	33.2	-32.7	-85.7	-36.4	-84.8	-25.1	-41.4	-18.4	-22.2	6.9	0.0	-0.7	0.2	-0.1	0.0	-0.2	0.0	50.0	-16.5
4	0.30	Standard	Partial	Partial	-2.9	-17.0	26.1	29.2	-1.8	-50.0	-5.2	-50.0	-6.1	0.0	-5.8	0.0	2.1	0.0	-0.7	0.2	-0.1	0.0	1.4	0.0	50.0	-0.8
5	0.20	Standard	Full	Full	-45.7	-45.0	1.8	1.3	-54.5	-75.0	-53.3	-56.6	-25.9	-11.7	-26.6	-25.9	10.6	0.0	0.0	0.1	-0.1	0.9	-0.6	-0.2	50.0	-9.5
5	0.20	Standard	Full	Partial	6.9	14.7	1.1	0.9	7.3	33.3	6.8	27.8	10.5	34.2	2.4	0.0	0.5	0.0	1.0	0.1	0.0	1.0	1.5	0.0	50.0	4.7
5	0.20	Standard	Partial	Full	-26.5	-46.5	1.7	1.2	-27.3	-85.7	-26.6	-58.7	-15.0	-27.6	-10.6	-22.2	4.5	0.0	-0.3	0.1	0.0	-2.0	-0.8	0.0	50.0	-13.6
5	0.20	Standard	Partial	Partial	1.8	6.5	1.0	0.8	1.8	-50.0	3.8	16.7	4.5	15.8	2.4	3.2	-0.5	0.0	-0.3	0.1	0.0	-2.2	0.9	0.0	50.0	1.5
5	0.25	Standard	Full	Full	-52.0	-50.9	24.4	31.9	-69.1	-75.0	-59.8	-63.6	-33.2	-18.3	-29.0	-27.1	11.2	0.0	0.3	0.0	-0.1	0.9	-1.5	-0.2	50.0	-14.0
5	0.25	Standard	Full	Partial	2.4	4.1	17.2	25.0	0.0	33.3	0.5	2.8	3.6	23.7	-1.0	0.0	0.9	0.0	0.7	0.0	0.0	1.0	0.2	0.0	50.0	-0.7
5	0.25	Standard	Partial	Full	-30.1	-52.5	23.8	30.4	-34.5	-85.7	-30.7	-67.4	-17.8	-31.0	-13.0	-22.2	5.0	0.0	0.0	0.1	0.0	0.0	-1.4	0.0	50.0	-15.9
5	0.25	Standard	Partial	Partial	-1.0	-6.4	17.0	23.3	-3.6	-50.0	-0.5	-16.7	1.2	10.5	0.0	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	50.0	-1.5
5	0.30	Standard	Full	Full	-55.1	-53.9	37.5	52.4	-70.9	-75.0	-63.0	-67.7	-38.9	-28.3	-31.4	-28.2	11.9	0.0	-1.0	0.1	-0.1	0.0	-1.0	-0.2	50.0	-13.4
5	0.30	Standard	Full	Partial	-0.4	-2.1	31.8	49.8	-1.8	33.3	-3.0	-11.1	-1.6	10.5	-3.4	-1.6	1.6	0.0	-0.7	0.1	0.0	0.0	0.8	0.0	50.0	0.0
5	0.30	Standard	Partial	Full	-31.4	-55.2	32.9	42.7	-34.5	-85.7	-32.6	-71.7	-19.8	-37.9	-13.5	-22.2	5.2	0.0	-0.3	0.1	0.0	0.0	-0.6	0.0	50.0	-14.2
5	0.30	Standard	Partial	Partial	-2.0	-10.9	27.9	38.5	-3.6	-50.0	-2.2	-27.8	-0.4	0.0	-0.5	3.2	0.2	0.0	-0.3	0.1	0.0	0.0	1.2	0.0	50.0	0.8
7	0.20	Standard	Full	Full	-19.6	-19.6	1.0	0.9	-27.3	-16.7	-24.7	-23.2	8.5	35.0	-2.4	0.0	2.6	0.0	1.7	0.1	0.2	4.5	0.9	0.1	100.0	6.1
7	0.20	Standard	Full	Partial	28.3	68.0	0.6	0.6	29.1	233.3	29.3	94.4	36.4	86.8	28.0	37.7	-8.5	0.0	2.0	0.1	0.3	5.1	3.0	0.1	100.0	22.6
7	0.20	Standard	Partial	Full	-11.2	-20.2	0.9	0.8	-9.1	-42.9	-15.5	-34.8	4.5	17.2	1.9	0.0	0.9	0.0	0.3	0.1	0.1	2.0	1.0	0.2	50.0	2.8
7	0.20	Standard	Partial	Partial	13.4	55.6	0.5	0.5	14.5	100.0	13.9	72.2	18.2	57.9	15.9	41.9	-4.3	0.0	0.3	0.2	0.1	2.2	3.0	0.3	50.0	19.1
7	0.25	Standard	Full	Full	-29.2	-28.8	1.1	1.0	-32.7	-33.3	-33.2	-32.3	-0.8	28.3	-6.8	-4.7	4.7	0.0	2.0	0.1	0.2	6.4	0.7	0.1	100.0	3.1
7	0.25	Standard	Full	Partial	19.5	47.0	0.6	0.7	23.6	166.7	24.2	75.0	28.7	76.3	22.7	29.5	-6.6	0.0	2.3	0.1	0.3	7.1	2.8	0.1	100.0	18.3
7	0.25	Standard	Partial	Full	-16.5	-29.9	1.0	0.9	-12.7	-57.1	-17.9	-41.3	0.0	10.3	0.0	-2.2	1.6	0.0	0.7	0.1	0.1	3.9	0.6	0.2	50.0	-0.6
7	0.25	Standard	Partial	Partial	8.7	35.7	0.6	0.6	10.9	50.0	12.5	61.1	14.2	47.4	13.0	35.5	-3.8	0.0	0.7	0.1	0.1	4.4	2.6	0.3	50.0	14.5
7	0.30	Standard	Full	Full	-34.7	-33.2	1.1	1.1	-50.9	-50.0	-38.3	-40.4	-7.3	18.3	-8.7	-5.9	4.8	0.0	2.3	0.1	0.2	7.3	0.4	0.1	100.0	0.6
7	0.30	Standard	Full	Partial	15.2	37.2	0.7	0.7	9.1	100.0	18.5	61.1	23.5	60.5	19.8	27.9	-5.9	0.0	3.0	0.1	0.2	8.2	2.4	0.1	100.0	14.7
7	0.30	Standard	Partial	Full	-18.7	-33.5	1.1	1.0	-20.0	-57.1	-20.9	-45.7	-3.2	6.9	0.0	-2.2	1.4	0.0	1.0	0.1	0.1	5.9	0.8	0.2	50.0	-1.1
7	0.30	Standard	Partial	Partial	7.5	30.2	0.7	0.7	7.3	50.0	8.7	55.6	11.7	42.1	13.0	35.5	-4.0	0.0	1.0	0.1	0.1	6.7	2.8	0.3	50.0	13.7

Table 3: Performance indicators - Standard scenario

delay	acc.	Resp.	Eqp	Compl.	SA1S	SA1A	SA2S	SA2A	SA3S	SA3A	SA4S	SA4A	SA5S	SA5A	SA6S	SA6A	CA1S	CA2S	CA3S	CA4S	PA1S	PA2A	PA3A	PA4A	PA5A	PA6A
3	0.15	Typical	Partial	Full	-28.3	-49.9	3.8	3.3	-26.4	-85.7	-35.6	-80.4	-26.5	-50.0	-20.8	-29.8	8.5	0.0	-2.0	0.5	-0.2	-3.8	-2.9	0.0	-40.0	-24.5
3	0.15	Typical	Partial	Partial	-2.0	-10.2	3.0	2.6	1.9	-50.0	-6.9	-40.0	-9.0	-17.4	-10.4	-14.7	3.9	0.0	-1.6	0.7	-0.1	-4.3	-1.8	0.0	-40.0	-14.1
3	0.20	Typical	Partial	Full	-31.8	-55.3	5.3	5.0	-32.1	-85.7	-38.6	-84.3	-28.7	-52.9	-23.5	-34.0	9.4	0.0	-1.6	0.6	-0.2	-1.9	-2.3	-0.2	-40.0	-24.0
3	0.20	Typical	Partial	Partial	-3.5	-17.0	4.1	4.1	-1.9	-50.0	-9.4	-55.0	-12.2	-17.4	-12.2	-20.6	4.6	0.0	-1.3	0.7	-0.2	-2.2	-0.7	0.0	-40.0	-12.1
3	0.25	Typical	Partial	Full	-33.6	-59.2	6.3	6.3	-35.8	-85.7	-39.9	-88.2	-30.8	-52.9	-24.0	-34.0	9.4	0.0	-1.6	0.6	-0.2	-1.9	-2.5	-0.2	-40.0	-23.4
3	0.25	Typical	Partial	Partial	-4.7	-22.3	5.0	5.2	-1.9	-50.0	-10.6	-65.0	-13.6	-21.7	-12.7	-20.6	4.6	0.0	-1.3	0.8	-0.2	-2.2	-1.4	0.0	-40.0	-12.8
3	0.30	Typical	Partial	Full	-34.6	-60.8	6.8	6.9	-35.8	-85.7	-40.1	-88.2	-34.4	-67.6	-24.4	-34.0	9.6	0.0	-2.6	0.6	-0.2	-5.8	-2.7	-0.2	-40.0	-26.0
3	0.30	Typical	Partial	Partial	-5.3	-24.8	5.4	5.8	-1.9	-50.0	-11.1	-65.0	-16.1	-34.8	-13.1	-20.6	4.8	0.0	-2.3	0.8	-0.2	-6.5	-1.1	0.0	-40.0	-14.1
4	0.20	Typical	Partial	Full	-30.9	-53.8	4.1	4.0	-34.0	-71.4	-33.9	-72.5	-26.2	-44.1	-18.1	-25.5	7.4	0.0	-2.0	0.5	-0.1	-3.8	-3.3	0.0	-40.0	-22.4
4	0.20	Typical	Partial	Partial	-2.8	-12.6	3.2	3.3	-1.9	0.0	-5.7	-30.0	-8.2	-13.0	-6.8	-5.9	2.7	0.0	-1.6	0.7	-0.1	-4.3	-2.1	0.0	-40.0	-12.1
4	0.25	Typical	Partial	Full	-32.2	-56.6	5.0	5.1	-34.0	-85.7	-37.9	-84.3	-26.9	-44.1	-19.0	-25.5	7.8	0.0	-2.0	0.6	-0.1	-3.8	-2.5	0.0	-40.0	-22.4
4	0.25	Typical	Partial	Partial	-3.6	-17.1	3.9	4.1	-1.9	-50.0	-8.7	-55.0	-9.3	-13.0	-8.1	-8.8	3.2	0.0	-1.6	0.7	-0.1	-4.3	-1.6	0.0	-40.0	-12.1
4	0.30	Typical	Partial	Full	-32.9	-57.7	5.4	5.5	-34.0	-85.7	-38.4	-86.3	-29.0	-47.1	-19.5	-25.5	8.0	0.0	-1.6	0.6	-0.1	-1.9	-2.1	0.0	-40.0	-21.4
4	0.30	Typical	Partial	Partial	-4.0	-18.6	4.2	4.5	-1.9	-50.0	-8.9	-55.0	-11.5	-13.0	-8.6	-8.8	3.4	0.0	-1.3	0.7	-0.1	-2.2	-0.9	0.0	-40.0	-10.1
5	0.20	Typical	Partial	Full	-26.9	-47.5	2.2	2.0	-28.3	-85.7	-29.0	-60.8	-20.1	-35.3	-12.2	-25.5	5.5	0.0	-0.7	0.5	0.0	-1.9	-2.3	0.0	-40.0	-17.7
5	0.20	Typical	Partial	Partial	0.6	3.6	1.5	1.5	1.9	-50.0	-0.2	10.0	-2.2	0.0	-0.9	-5.9	0.7	0.0	-0.3	0.6	0.0	-2.2	-0.9	0.0	-40.0	-6.7
5	0.25	Typical	Partial	Full	-30.4	-53.3	3.6	3.7	-35.8	-85.7	-32.7	-68.6	-22.6	-38.2	-14.5	-25.5	6.0	0.0	-1.0	0.5	-0.1	-1.9	-3.3	0.0	-40.0	-20.8
5	0.25	Typical	Partial	Partial	-2.1	-9.3	2.6	2.9	-3.8	-50.0	-4.2	-20.0	-5.0	-4.3	-3.2	-5.9	1.2	0.0	-0.7	0.7	0.0	-2.2	-2.1	0.0	-40.0	-10.7
5	0.30	Typical	Partial	Full	-31.7	-56.0	4.3	4.7	-35.8	-85.7	-34.4	-72.5	-24.7	-44.1	-14.9	-25.5	6.2	0.0	-1.3	0.5	-0.1	-1.9	-2.5	0.0	-40.0	-19.3
5	0.30	Typical	Partial	Partial	-3.1	-13.3	3.2	3.7	-3.8	-50.0	-5.7	-30.0	-6.8	-13.0	-3.6	-5.9	1.4	0.0	-1.0	0.6	0.0	-2.2	-1.1	0.0	-40.0	-8.7
7	0.20	Typical	Partial	Full	-12.1	-21.5	1.1	1.0	-9.4	-42.9	-18.3	-37.3	-2.9	0.0	-0.5	-4.3	1.8	0.0	0.3	0.4	0.1	3.8	-1.0	0.2	-40.0	-3.1
7	0.20	Typical	Partial	Partial	11.9	56.2	0.7	0.7	15.1	100.0	9.4	65.0	9.7	30.4	11.8	29.4	-3.2	0.0	0.7	0.5	0.1	4.3	0.7	0.3	-40.0	8.1
7	0.25	Typical	Partial	Full	-17.2	-31.1	1.2	1.2	-13.2	-57.1	-20.5	-43.1	-7.2	-5.9	-2.3	-6.4	2.5	0.0	0.7	0.4	0.1	5.8	-1.2	0.2	-40.0	-6.3
7	0.25	Typical	Partial	Partial	7.4	34.9	0.8	0.8	11.3	50.0	8.2	55.0	6.1	21.7	9.0	23.5	-2.7	0.0	1.0	0.5	0.1	6.5	0.5	0.3	-40.0	4.0
7	0.30	Typical	Partial	Full	-19.3	-34.6	1.3	1.3	-20.8	-57.1	-23.3	-47.1	-10.0	-8.8	-2.3	-6.4	2.3	0.0	1.0	0.4	0.1	7.7	-1.2	0.2	-40.0	-7.3
7	0.30	Typical	Partial	Partial	6.2	29.0	0.9	1.0	7.5	50.0	4.7	50.0	3.9	17.4	9.0	23.5	-2.8	0.0	1.3	0.5	0.1	8.7	0.5	0.3	-40.0	2.7

Table 4: Performance indicators - Typical scenario

The scenario with reduced CAS logic thresholds has, overall, the best performance as it has the highest number of performance indicators for which we observe a gain. More details are given about this scenario in part 4.

For the other scenarios, the indicator CA1S (Number of RAs with incompatible sense selection) is always debased, except for the scenario with a CAS logic threshold reduction. Indeed, this performance indicator does not take into account the fact that not all pilots follow RAs. As using the AP/FD results in more pilots following RAs in full compliance scenarios, it happens frequently that because of an RA being followed thanks to AP/FD, the sense initially chosen by ATC is not respected whereas it is respected when the RA is not followed without AP/FD (see the example hereafter). Therefore, it is not considered that debasing this performance indicator is an issue.

The following example illustrates how introducing the AP/FD can result in an encounter being counted as not compatible with the sense initially chosen by ATC. The following figure shows the encounter without TCAS contribution. Both aircraft are equipped with TCAS, and aircraft two (black aircraft) is not following RAs.

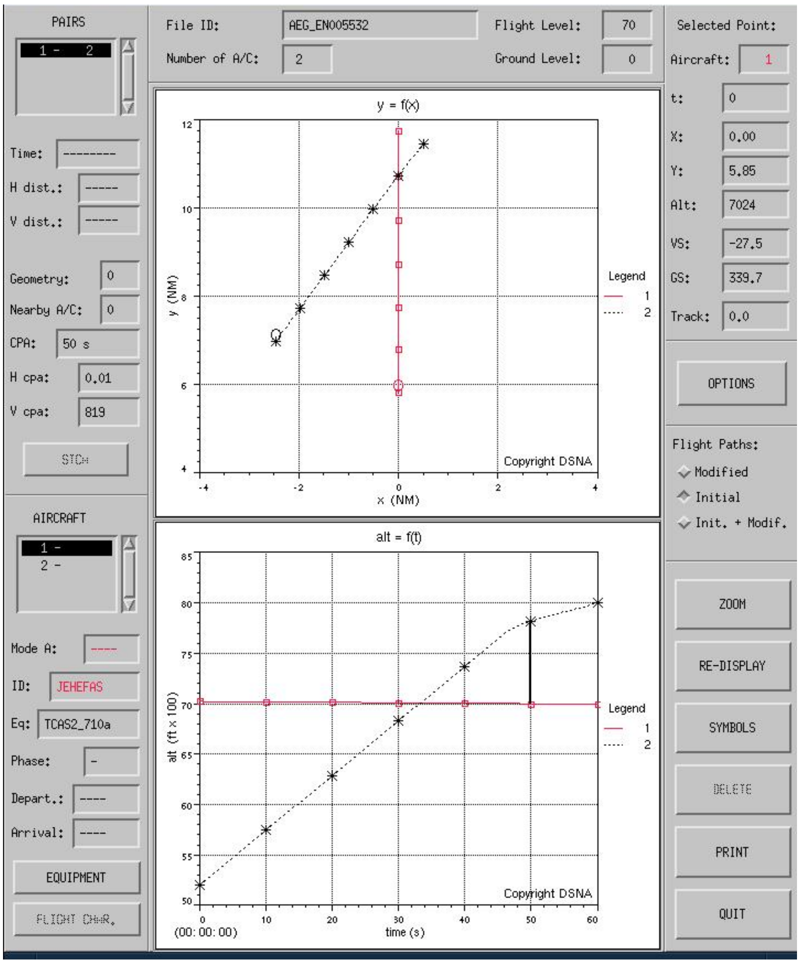
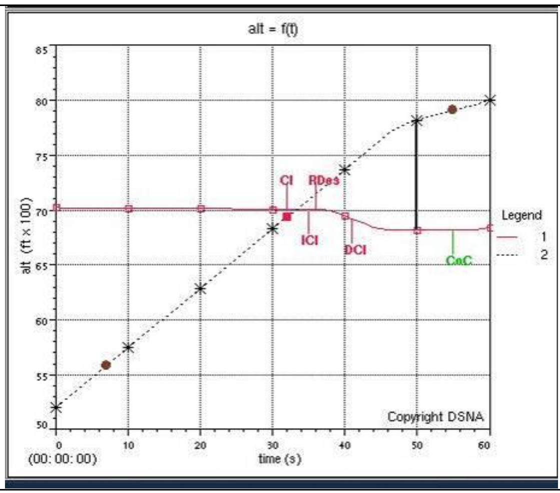
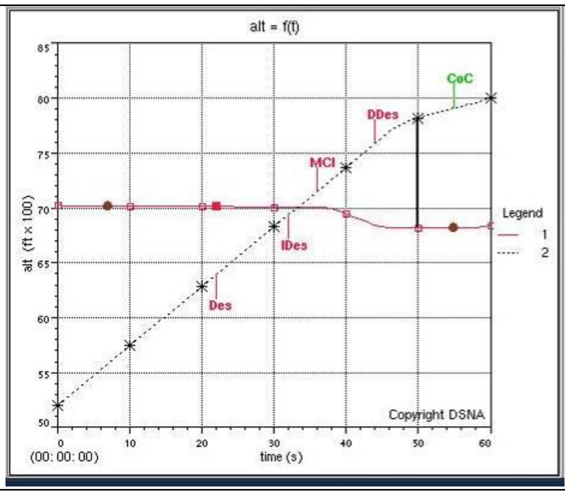


Figure 1: Encounter without TCAS contribution

The following figure shows this encounter simulated with the reference scenario.

Aircraft 1	Aircraft 2



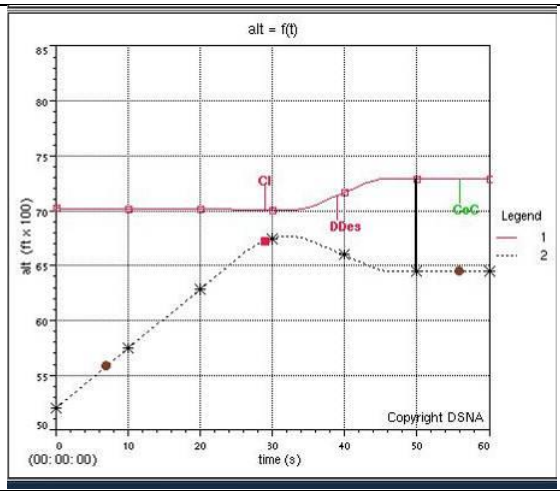


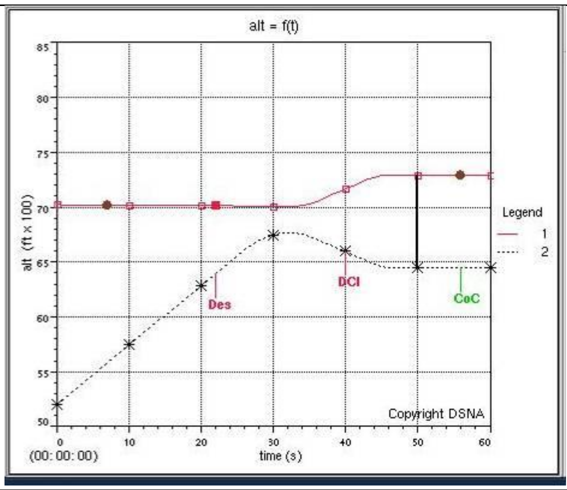
VMD=1000ft

Figure 2: Encounter with TCAS contribution – Reference scenario
Legend: Cl: Climb RA, ICl: Increase climb RA, RDes: Reversal descend RA, DCl: "Level-off' RA, Des: Descend RA, IDes: Increase descent RA, MCl: Maintain climb RA, DDes: "Level-off RA", CoC: Clear of conflict

As aircraft two is not following RAs, the encounter with RAs results in the same sense as what was chosen by ATC.

Aircraft 1	Aircraft 2





VMD=850ft

Figure 3: Encounter with TCAS contribution – AP/FD scenario
Legend: Cl: Climb RA, DDes: "Level-off RA", Des: Descend RA, DCl: "Level-off" RA, CoC: Clear of conflict

With the AP/FD functionality, the RAs are followed, and this time the trajectories are not crossing anymore in the vertical plane.

In partial compliance scenarios, the indicator CA1S can also be debased, despite the fact that the rate of response to RAs is not modified. This is explained by the 200 fpm margin used by the AP/FD response to RAs, which can change the sense of some RAs.

The indicator PA5A (number of multiple RAs) is also frequently debased by the AP/FD scenarios. In fact, the number of multiple RAs increases, but the proportion remains very small as the probability to have a multiple RA in the reference scenario is 1 every 50,000 encounters in the model. Therefore, despite the fact that important relative increases or decreases can be observed on this indicator, these changes are not considered an issue because in absolute value, they are minor.

Deviations (indicator CA4S) are increased, because the AP/FD takes a 200 fpm margin on the response to RAs (e.g., a climb RA is followed at 1700 fpm). However, even though the deviation ratio is below one, the deviations are not modified by a large amount, as detailed in the part dealing with deviations (see 3.3.1).

The AP/FD scenarios have little or nearly no effect on some safety performance indicators:

- The number of encounters with RAs (indicator CA2S) and the number of aircraft receiving RAs (PA1S). Only the CAS logic threshold reduction scenario has an effect on these indicators. Indeed, reducing the CAS logic thresholds reduces the number of aircraft with RAs and the number of encounters with RAs. In particular, it can avoid some triggering of RAs in 1000 ft level-of encounters, as shown in 4.2.2.
- The number of initial RAs opposite to the trajectory (indicator PA3A) and the number of RAs opposite to the trajectory (indicator PA4A). Here again, only the CAS logic threshold reduction scenario has a significant effect on this indicator, as shown in 4.4.2 and 4.4.3.

The scenarios with delays of 3 s and 4 s produce mainly indicators where a gain is observed, especially when the compliance rate is maximal.

Overall, the scenarios with delays of 5 s and 7 s produce a significant part of the indicators with a loss when compared to the reference scenario. Only scenarios with a 5s delay and an acceleration of 0.30 g performs closely to scenarios with delays of 4s or 3s.

From the results shown in this part, it is recommended that the AP/FD functionality is used with a response with a delay lower or equal to 4s.

2.4 Validation objectives achievement

The validation plan [3] defines a set of validation objectives. The following table presents these validation objectives, and makes an assessment of their achievement.

Validation objective	Achievement	Comments
To verify that the TCAS safety performances are improved by automatic responses to RAs	Yes	Automatic response to RAs significantly improve the safety performances of TCAS when used with a delay of response to RAs of 3 or 4s (see part 3.2.1). This improvement is mainly linked to the higher rate of responses to RAs afforded by automatic responses to RAs.
To verify that TCAS operational compatibility with ATC is improved by automatic responses to RAs	Partial	The benefits of automatic responses to RA to safety are brought by a better response rate to RAs. Responding to RAs can lead to solutions chosen by ATC

		being defeated (see part 2.2). However overall, automatic responses to RAs do not debase compatibility with ATC. In addition, a CAS logic with RA thresholds reduced by 3 s with a 2 s reaction delay, when coupled with an automatic response to RAs, improves the compatibility with ATC (see parts 3.3.1, 3.3.2).
To verify that automatic responses to RAs are acceptable from a pilot perspective	Yes	Performance indicators linked to pilot acceptance are overall improved by automatic responses to RAs (see parts 3.3.2, 3.4.1, 4.4.1, 4.3.2, 4.4.2, 4.4.3, 4.4.4).
To assess and investigate the impact of the performances of the various TCAS-equipped aircraft to respond to RAs	Yes	The benefits brought by the automatic responses are noticeable when the response delay to RAs is equal to 4s or lower. In addition, the higher the acceleration, the higher the benefits. (see parts 3.2.1, 3.2.2, 3.2.3).
To assess and investigate the impact of the percentage of aircraft automatically responding to RAs	Yes	The higher the percentage of aircraft automatically responding to RAs, the higher the benefits. (see parts 3.2.1, 3.2.2, 3.2.3).
To assess and investigate the impact of taking into account vertical performance limitations	Yes	Vertical performance limitations offer a better choice than climb inhibitions (see part 5).
To assess and investigate if automatic responses to RAs allow for an enhancement of TCAS logic and its associated performances	Yes	A CAS logic with RA thresholds reduced by 3 s with a 2 s reaction delay results when coupled with an automatic response to RAs, in significant safety and operational benefits (see part 4). Other AP/FD scenarios may perform slightly better in terms of safety, however this solution improves the compatibility with ATC and the acceptance by pilots.

Table 5: Validation objectives achievement

3 Detailed validation results

3.1 Introduction

The goal of this part is to present the sensitivity analysis made using the encounter model methodology on the European safety encounter model [1]. Only some indicators are shown as not all of them are relevant and bring useful information.

The full set of results is summarized in 2.3. The goal of this part is only to detail the most noticeable results of the validation.

3.2 Indicators related to safety performance

3.2.1 Risk ratios

The following table shows the risk ratios computed on the standard scenarios. The values shown in a shaded cell are those for which the risk ratio with the AP/FD is higher than with the reference scenario.

APFD		Partial compliance				Full compliance			
	Pilot	**7s**	**5s**	**4s**	**3s**	**7s**	**5s**	**4s**	**3s**
Partial equipage	**0.15g**				32.0				23.3
	0.20g	36.6	32.9	31.8	31.5	28.7	23.8	22.4	22.3
	0.25g	35.1	32.0	31.5	31.1	27.0	22.6	22.0	21.5
	0.30g	34.8	31.7	31.4	30.9	26.3	22.2	21.8	21.2
Full equipage	**0.15g**				32.0				14.5
	0.20g	40.8	34.6	31.6	31.0	26.0	17.6	13.8	12.8
	0.25g	38.6	33.0	30.9	30.3	22.9	15.5	12.5	11.6
	0.30g	37.3	32.2	30.7	30.0	21.1	14.5	12.3	11.1
Reference	**Standard**	32.3							

Table 6: Risk ratio - Standard pilot

The following table shows the risk ratios computed on the typical scenarios.

APFD		**Partial compliance**				**Full compliance**			
	Pilot	**7s**	**5s**	**4s**	**3s**	**7s**	**5s**	**4s**	**3s**
Partial equipage	**0.15g**				32.5				23.8
	0.20g	37.2	33.4	32.3	32.0	29.2	22.7	22.9	22.6
	0.25g	35.6	32.5	32.0	31.6	27.5	23.1	22.5	22.0
	0.30g	35.3	32.2	31.9	31.4	26.8	22.7	22.3	21.7
Full equipage	**0.15g**				32.0				14.5
	0.20g	40.8	34.6	31.6	31.0	26.0	17.6	13.8	12.8
	0.25g	38.6	33.0	30.9	30.3	22.9	15.5	12.5	11.6
	0.30g	37.3	32.2	30.7	30.0	21.1	14.5	12.3	11.1
Reference	**Typical**	33.2							

Table 7: Risk ratio - Typical pilot

The scenarios with an automatic response to RAs with a delay of reaction higher than or equal to 5 s result in risk ratios which can be higher than that of the reference scenario, when partial compliance is used.

When considering full compliance to RAs, all the scenarios with an automatic response result in a gain on the risk ratio. This highlights once again that following RAs is the best way to maximise the safety benefits brought by TCAS II.

An automatic response with a delay of 4s or less ensures that safety gains can result from the use of the AP/FD functionality. Above 5s, safety gains are not observed whatever the circumstances, if the acceleration is not equal to 0.30g.

The following figure shows a diagram representing the gains on the standard scenario, expressed as a percentage of the risk ratio in the reference scenario, when using the AP/FD with different parameters. The reference is marked with a black line. All the values below this line have a negative value, which means there is a gain when compared to the reference (as an example, -50 means there is a 50% decrease of the risk ratio when compared to the reference). The results are shown for the airspace perspective and then on the aircraft perspective.

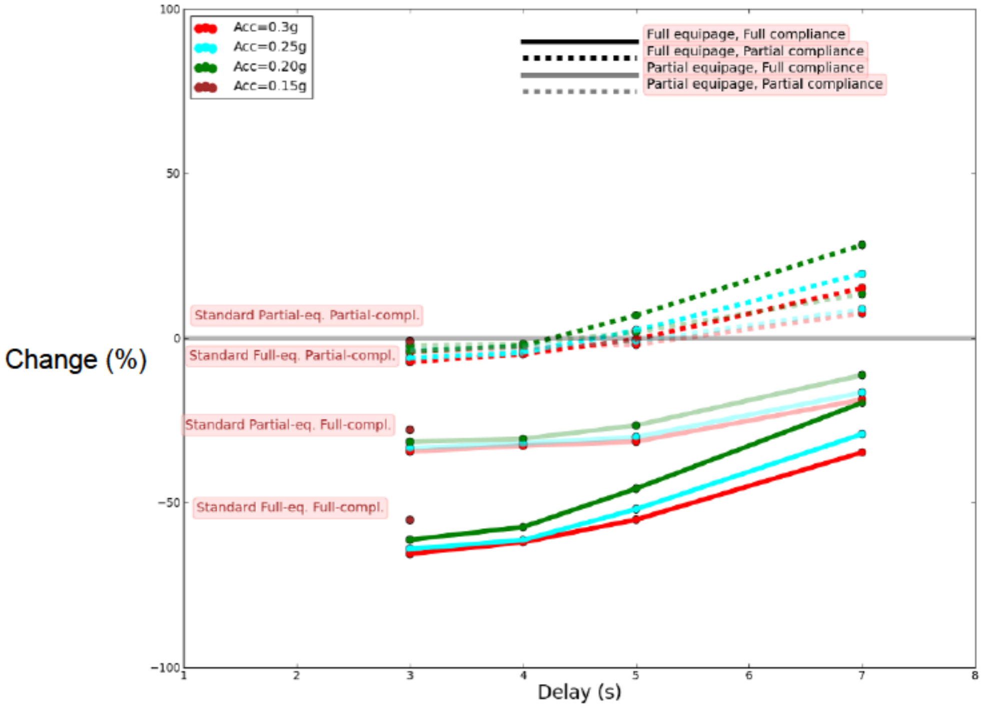


Figure 4: Risk Ratios - Gains with AP/FD – Standard scenarios – Airspace perspective

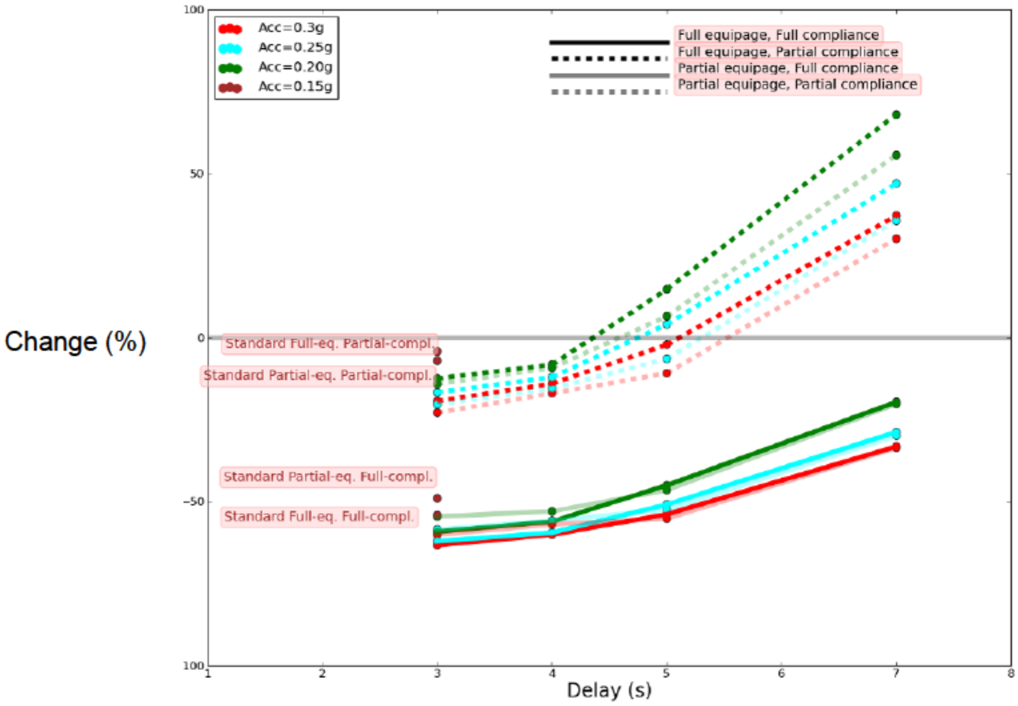


Figure 5: Risk Ratios - Gains with AP/FD – Standard scenarios – Aircraft perspective

The following figure shows the same results but this time for the typical scenarios. Full equipage scenarios are not shown again as typical scenarios and standard scenarios are identical for full equipage (as all pilots use the AP/FD functionality):

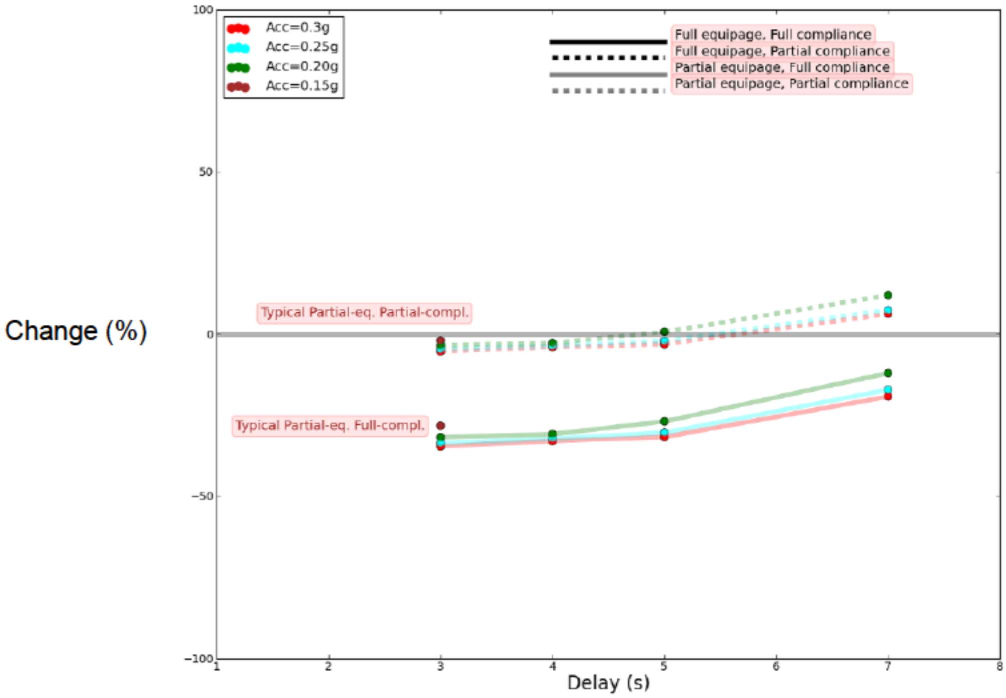


Figure 6: Risk Ratios - Gains with AP/FD – Typical scenarios – Airspace perspective

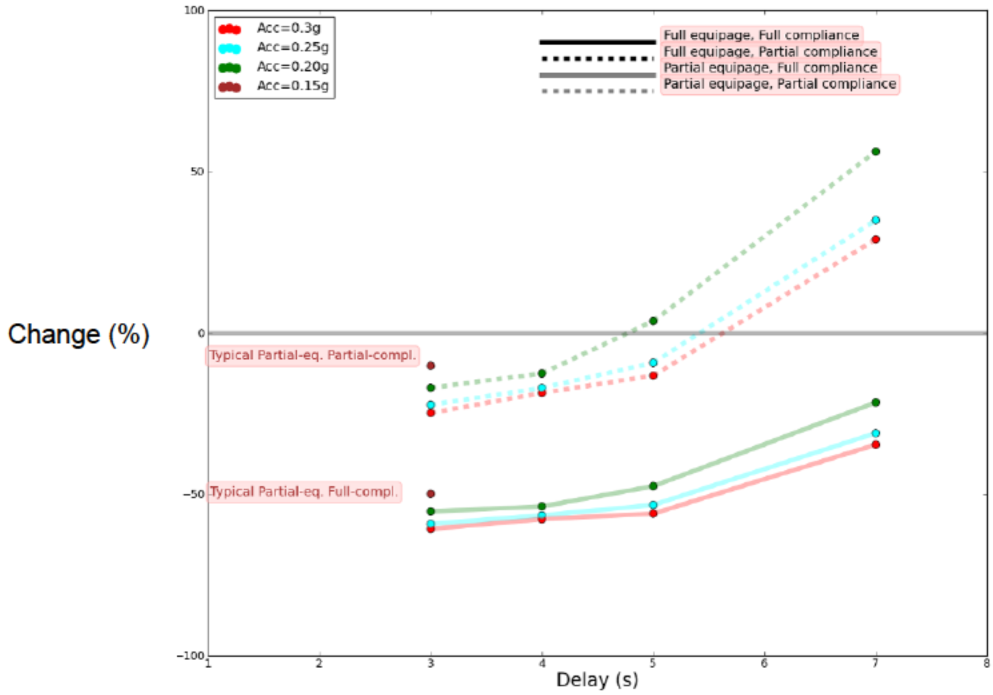


Figure 7: Risk Ratios – Gains with AP/FD – Typical scenarios – Aircraft perspective

Overall, standard and typical scenarios show the same trends, so do airspace and aircraft perspective. Therefore, results with typical pilots or with aircraft perspective may not be shown systematically farther in this report.

The shorter the delay and the higher the acceleration, the better the results. The most influencing parameter is the delay. Acceleration has a more limited effect on the performance of the AP/FD.

The best gain is obtained with full compliance scenarios, and especially with the full equipage scenario. The partial compliance scenarios obtain the worse results.

As expected, the gain afforded by the AP/FD mainly results from a better rate of compliance to RAs rather than more accurate responses to RAs.

For delays equal to or above 5s, partial compliance and partial equipage perform better than partial compliance and full equipage, because with the AP/FD the 5 s or 7 s delay also applies to the responses to increase and reversal RAs. Indeed, having more aircraft responding to increase and reversal RAs with a longer delay than with the standard pilot reduces the safety brought by TCAS II.

On the contrary, for shorter delays, partial compliance and full equipage performs better than partial compliance and partial equipage, because the delay of response to increase and reversal RAs is less of an issue.

3.2.2 Collision rate by flight hours

The following figure shows a diagram representing the gains on the standard scenario, expressed as a percentage of the collision rate in the reference scenario, when using the AP/FD with different parameters:

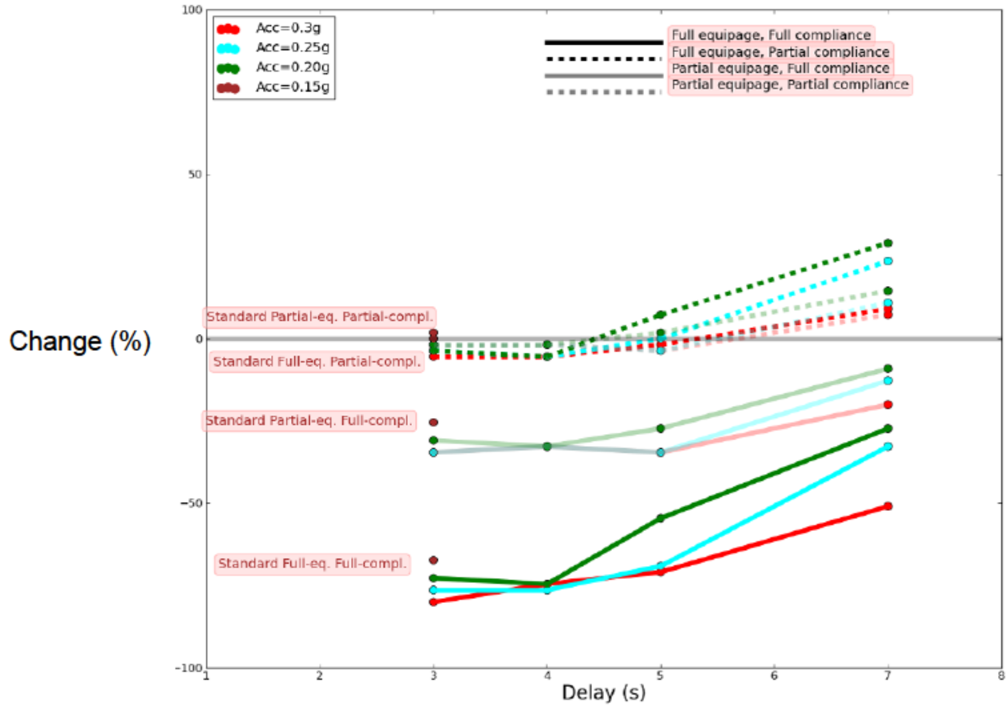


Figure 8: Collision rates - Gains with AP/FD – Standard scenarios – Airspace perspective

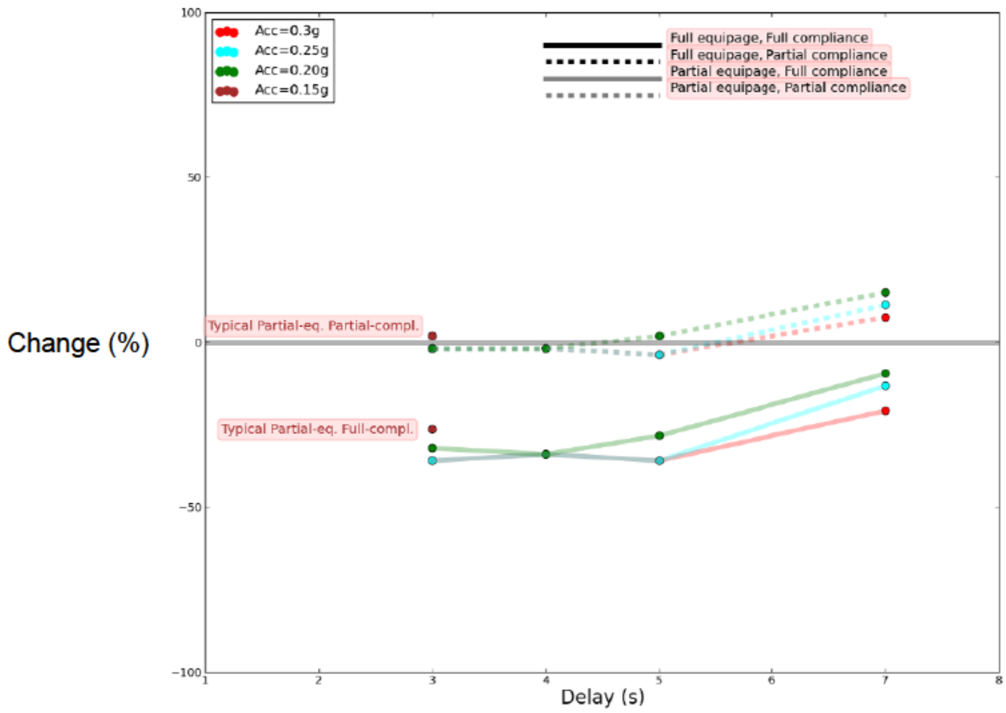


Figure 9: Collision rates - Gains with AP/FD – Typical scenarios – Airspace perspective

As expected, the trends observed for the collision rate are identical to those observed for the risk ratio.

3.2.3 Vertical miss distances

The following figure shows VMD diagrams with AP/FD scenario, with a 4s delay and 0.25g acceleration[2], with full equipage.

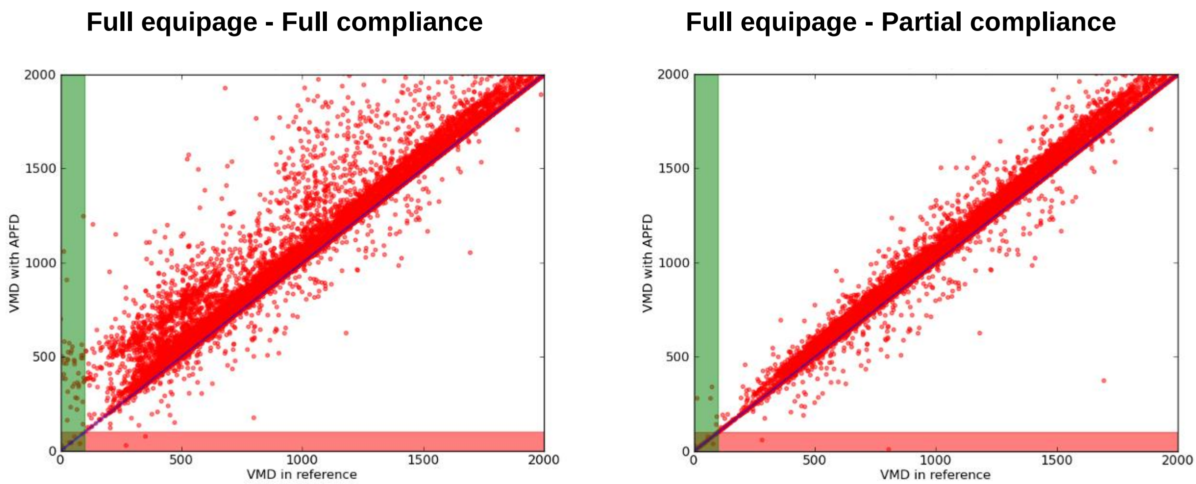


Figure 10: VMD diagrams - AP/FD with 4s delay and 0.25g acceleration - Standard scenario

Very often, the VMD is increased, but only by a small amount. This is explained by the fact that with the AP/FD, the response to RAs is made with a 200 ft margin (e.g., climb RA followed at 1700 fpm rather than 1500 fpm with the standard pilot).

The main difference between the two diagrams is for VMDs with a large gain with the AP/FD scenario. Indeed, this difference results from the better response rate in the full compliance scenario.

Small reductions of VMDs, shown by the red plots below the diagonal on the VMD diagrams, can be explained by situations in which in the reference scenario a lack of response or a response with the standard 5s delay results in increase or reversal RAs being triggered. With the AP/FD response, these RAs are no longer triggered which results in a slightly lower VMD. This is illustrated in the example below. In this example, only aircraft 2 is TCAS equipped.

[2] This scenario will be used thereafter as it offers a good compromise between performance and ease of implementation of the automatic response.

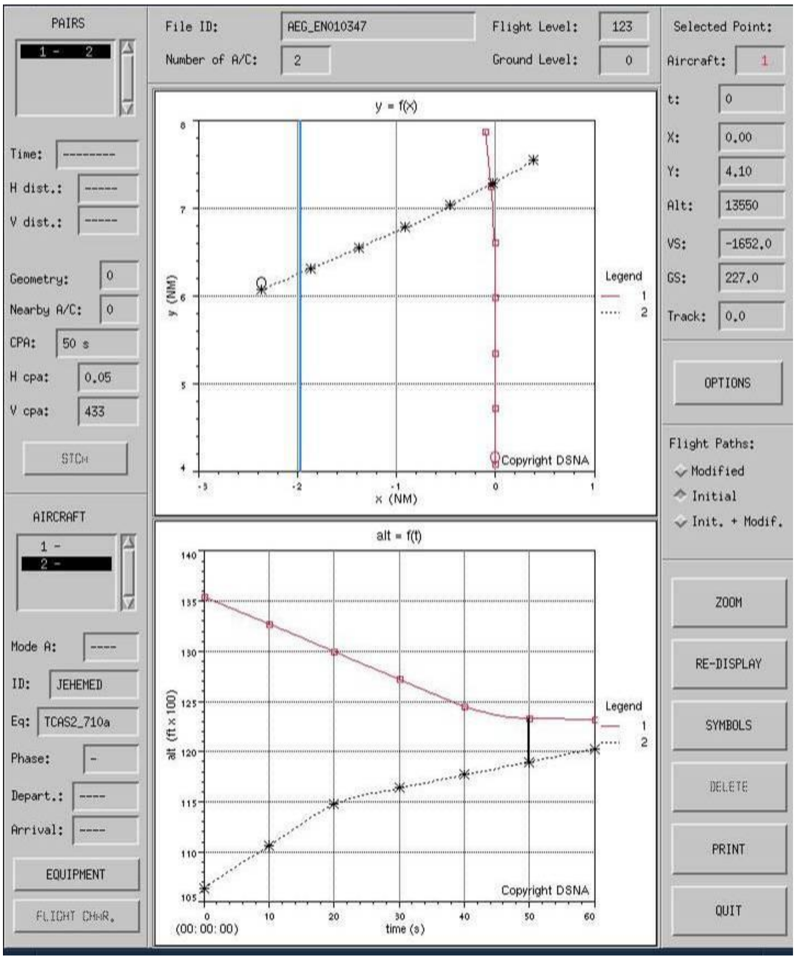


Figure 11: Encounter without TCAS contribution

The following figures show the encounter simulated with TCAS II logic version 7.1, with the reference scenario and with the AP/FD scenario.

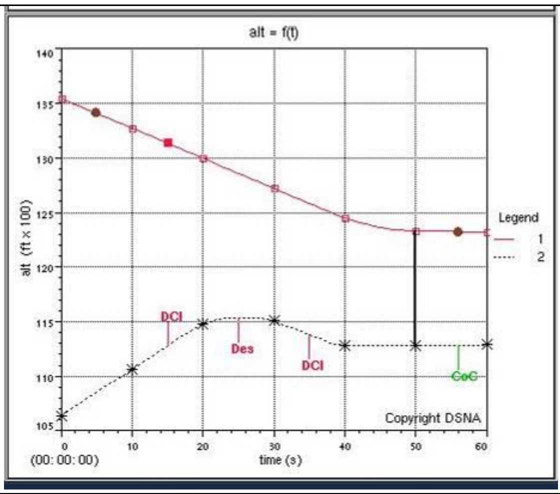
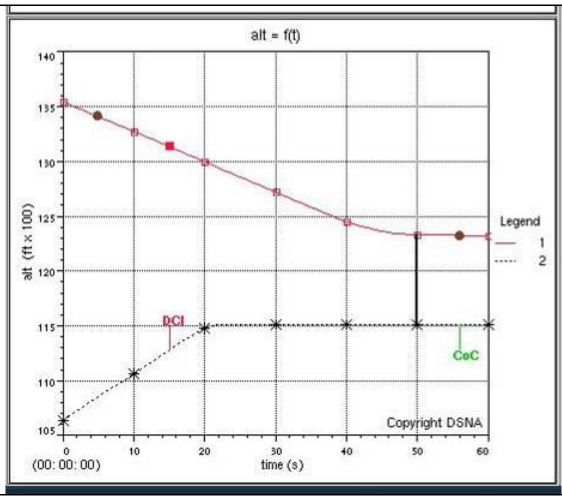
<table>
<tr><th>Reference scenario</th><th>AP/FD scenario</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>VMD=1050ft</td><td>VMD=800ft</td></tr>
</table>

Figure 12: Encounter without TCAS contribution
Legend: DCL: "Level-off" RA, Des: Descend RA, CoC: Clear of conflict

In the reference scenario, aircraft 2 receives a "level-off" RA, which turns into a descend RA a few seconds later. With the AP/FD scenario, because the delay of response to the RA is 1 s shorter than in the reference scenario, the aircraft, following the "level-off" RA, levels-off at a lower altitude than in the reference scenario, and does not receive the subsequent descend RA. Resulting from this, the vertical separation at CPA is reduced in the AP/FD scenario.

For comparison, the following figure shows a VMD diagram with the AP/FD scenario, with a 7s delay and 0.25g acceleration, with full equipage and full compliance.

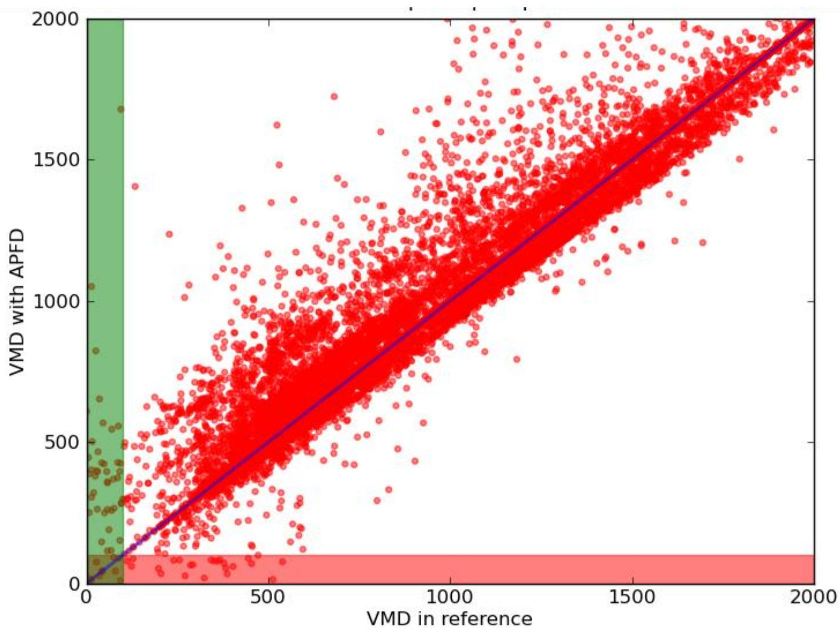


Figure 13: VMD diagram - AP/FD with 7s delay and 0.25g acceleration - Full equipage - Full compliance – Standard scenario

Here again, reductions of VMDs, shown the red plots below the diagonal on the VMD diagram, can be observed. In this situation, the explanation is the longer delay of reaction in some encounters, which can result in reduced VMDs, as shown in the following example. In this example, only aircraft 2 is TCAS equipped.

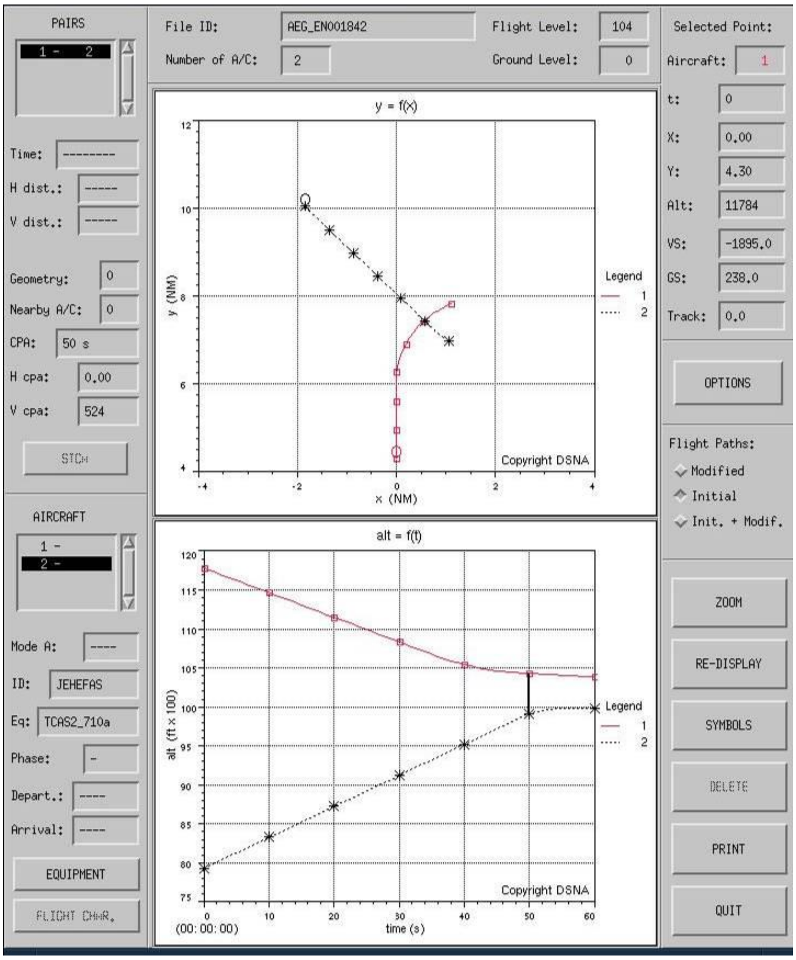


Figure 14: Encounter without TCAS contribution

The following figures show the encounter simulated with TCAS II logic version 7.1, with the reference scenario and with the AP/FD scenario.

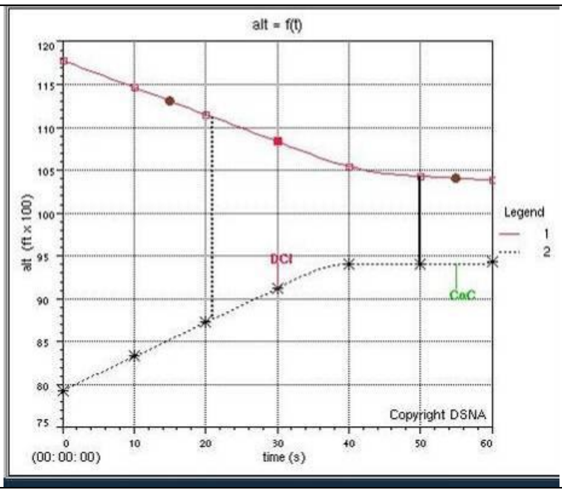
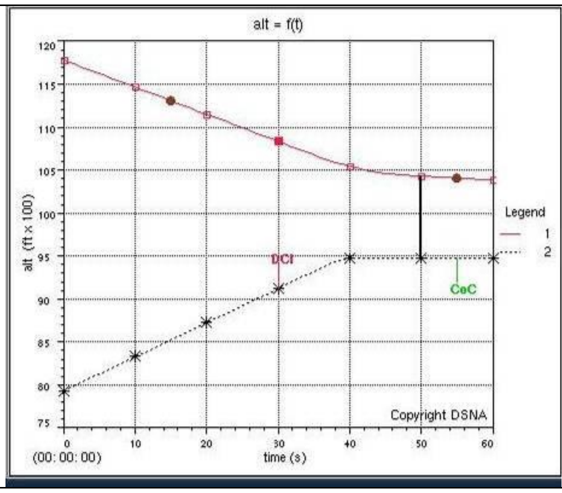
<table>
<tr><th>Reference scenario</th><th>AP/FD scenario</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>VMD=1030 ft</td><td>VMD=950 ft</td></tr>
</table>

Figure 15: Encounter with TCAS contribution
Legend: DCL: “Level-off” RA, CoC: Clear of conflict

With the AP/FD scenario and a delay of response to RAs equal to 7s, aircraft 2 levels-off slightly higher than in the reference scenario, because of the additional 2 s of delay of response to the RA.

As a result, the vertical separation at CPA is reduced in the AP/FD scenario.

3.2.4 Increase RAs

The following figure shows a diagram representing the gains on the standard scenario, expressed as a percentage of the number of increase RAs in the reference scenario, when using the AP/FD with different parameters. The results are not shown for the aircraft perspective, as the trends are identical.

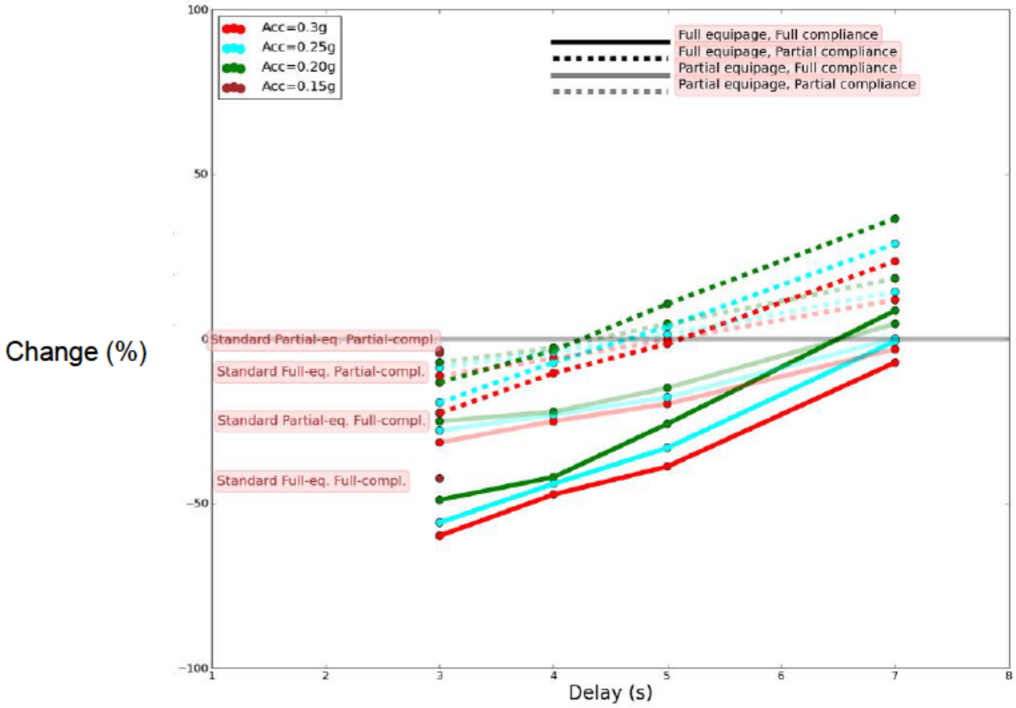


Figure 16: Increase RAs - Gains with AP/FD - Standard scenario - Airspace perspective

The following figure shows the same results but this time for the typical scenarios.

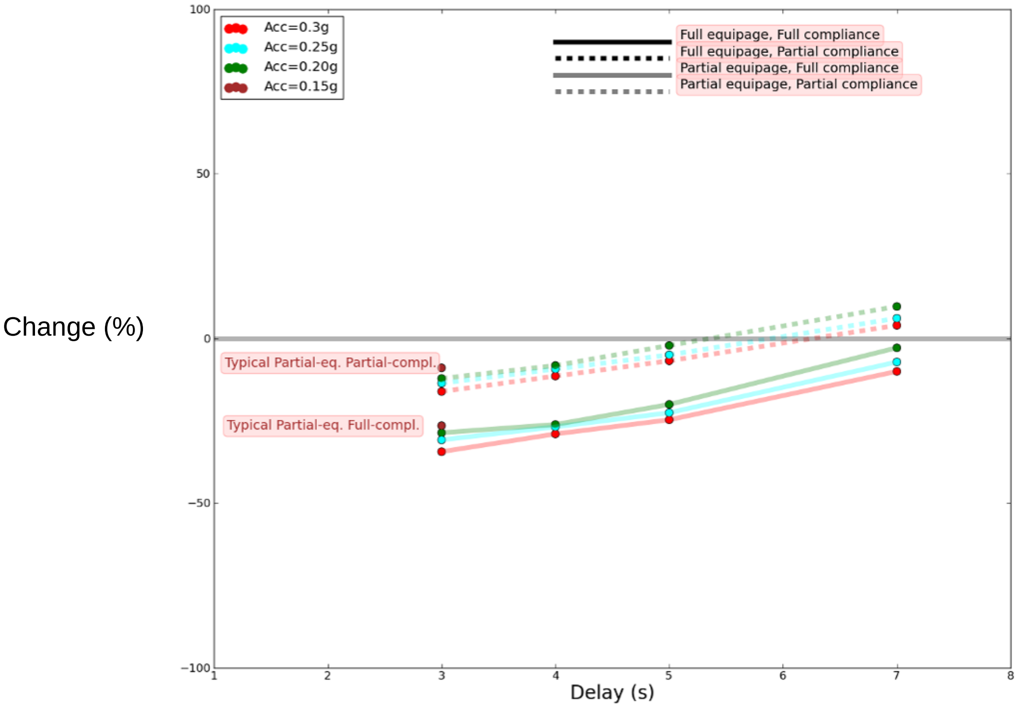


Figure 17: Increase RAs – Gains with AP/FD - Typical scenario - Airspace perspective

The number of increase RAs is significantly decreased with the shorter delays, and especially with full compliance and full equipage. This is an expected result, as this type of RA is usually triggered when the initial RA triggered by TCAS are detected as not being sufficient to ensure the expected vertical separation at CPA. Having less of these RAs is a sign that safety is increased.

On the contrary and especially with partial compliance, the 7 s delay and 5 s delay associated to slow accelerations can result in an increase of the number of increase RAs, showing that such delays should be avoided.

3.2.5 Reversal RAs

The following figure shows a diagram representing the gains on the standard scenario, expressed as a percentage of the number of reversal RAs in the reference scenario, when using the AP/FD with different parameters. The results are not shown for the aircraft perspective, as the trends are identical.

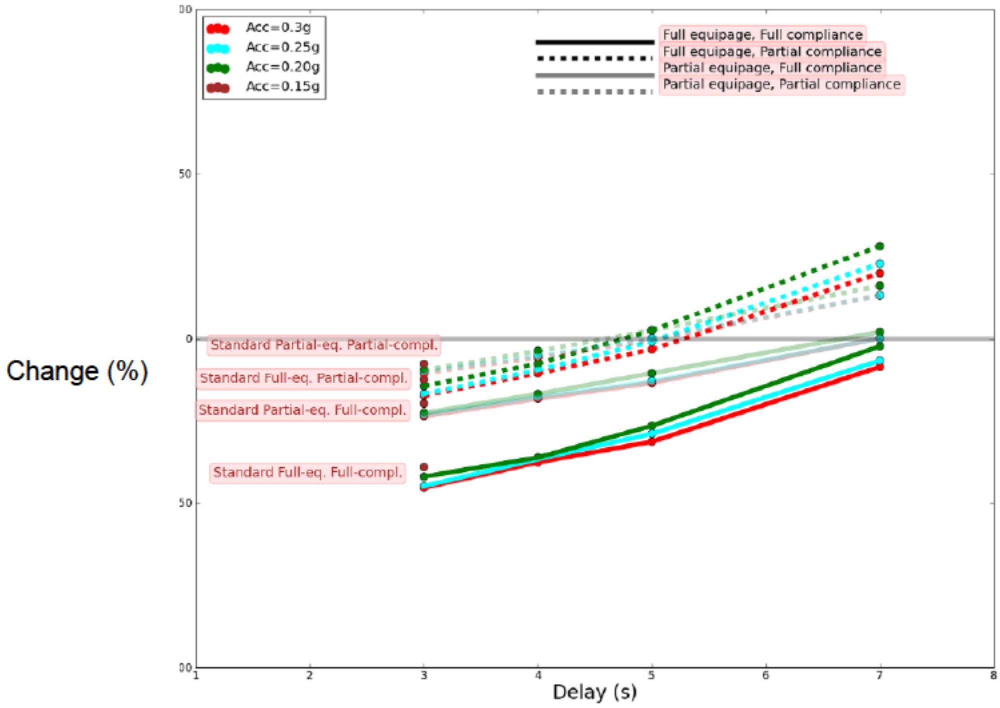


Figure 18: Reversal RAs - Gains with AP/FD - Standard scenario - Airspace perspective

The following figure shows the same results but this time for the typical scenarios.

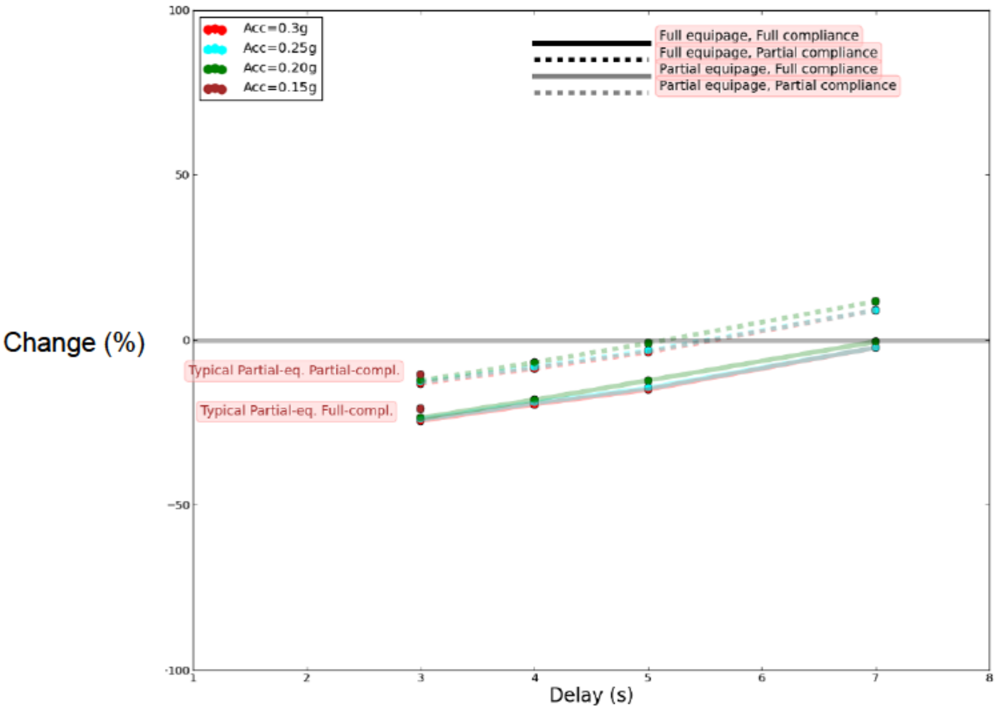


Figure 19: Reversal RAs - Gains with AP/FD - Typical scenario - Airspace perspective

As for increase RAs, the number of reversal RAs is significantly decreased with the shorter delays, and especially with full compliance and full equipage, and can be increased with the 7 s delay and with the 5 s delay associated to slow accelerations, especially with partial compliance.

3.3 Indicators related to operational compatibility with ATC

3.3.1 Deviations

The following figure shows a deviation diagram with the AP/FD scenario, with a 4s delay and 0.25g acceleration, with full equipage and full compliance. In this scenario, the deviation ratio is 0.1.

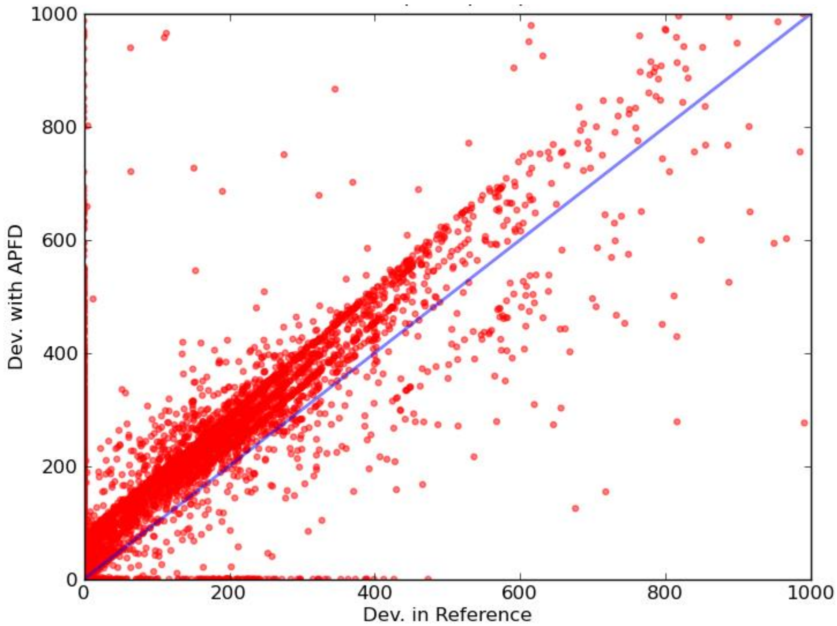


Figure 20: Deviation diagram - AP/FD with 4s delay and 0.25g acceleration - Full equipage - Full compliance – Standard scenario

Deviations are often increased (i.e., deviation ratio equal to 0.1), because the AP/FD takes a 200 fpm margin on the response to RAs (e.g., a climb RA is followed at 1700 fpm rather than 1500 fpm). However, the deviations are not modified by a large amount, as shown below.

The following figure shows the distributions of deviations with the reference scenario (shown in red) and with the AP/FD scenario (shown in green). The bins shown are 100 ft wide, ranging from the displayed value to the displayed value plus 100 ft (e.g., 100 stands for [100; 200[). Where the two distributions are super imposed, the color is dark green (or brown when printing).

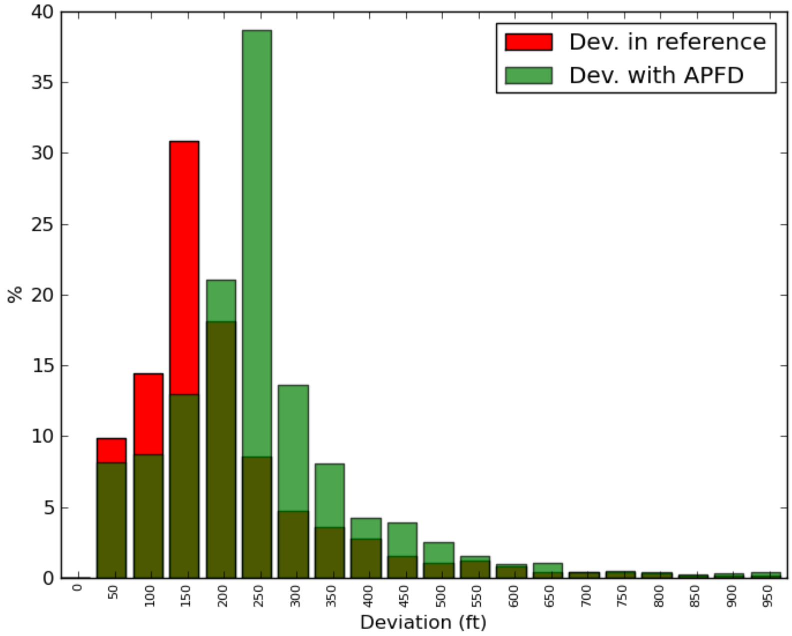


Figure 21: Deviation distributions - AP/FD with 4s delay and 0.25g acceleration - Full equipage - Full compliance – Comparison against standard reference scenario

This figure confirms that overall, deviations are increased, but only by a small amount.

When considering the benefits brought to safety by AP/FD, this increase in deviations is a minor issue. One must also remember that the comparison is made against the reference standard scenario, which assumes a perfect response to RAs, which are rarely observed operationally.

The following figures show the same AP/FD scenario but this time compared to the typical reference scenario, which is closer to what can be observed operationally.

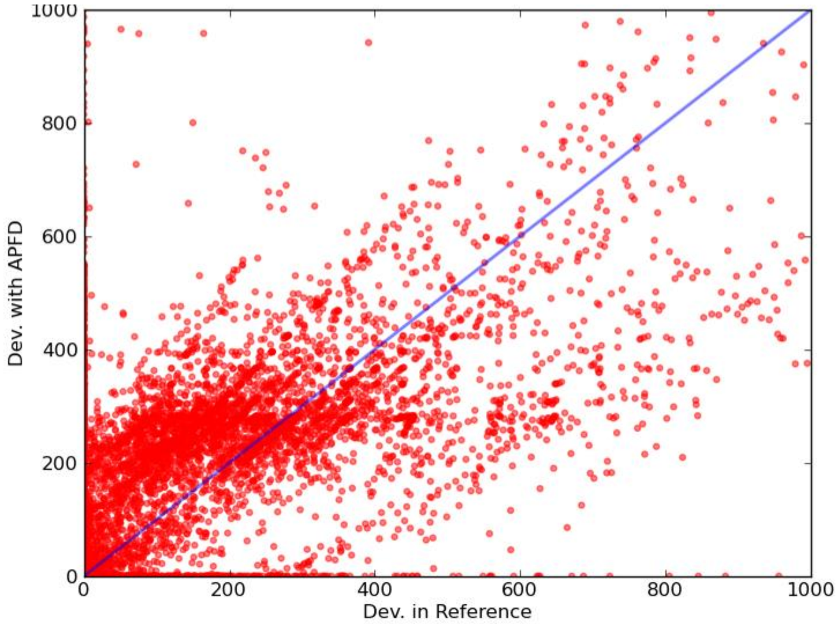


Figure 22: Deviation diagram - AP/FD with 4s delay and 0.25g acceleration - Full equipage - Full compliance – Comparison against typical reference scenario

In this case, the deviation diagram is more widespread. This is explained by the fact that with the typical scenario, the delays and accelerations used for the responses to RAs range from 0.09g – 730 fpm to 0.22g – 3900 fpm.

There are more situations with deviations decreased by the AP/FD than when comparing to the standard scenario (deviation ratio equal to 0.5).

The following figure shows the distributions of deviation with the reference scenario and with the AP/FD scenario.

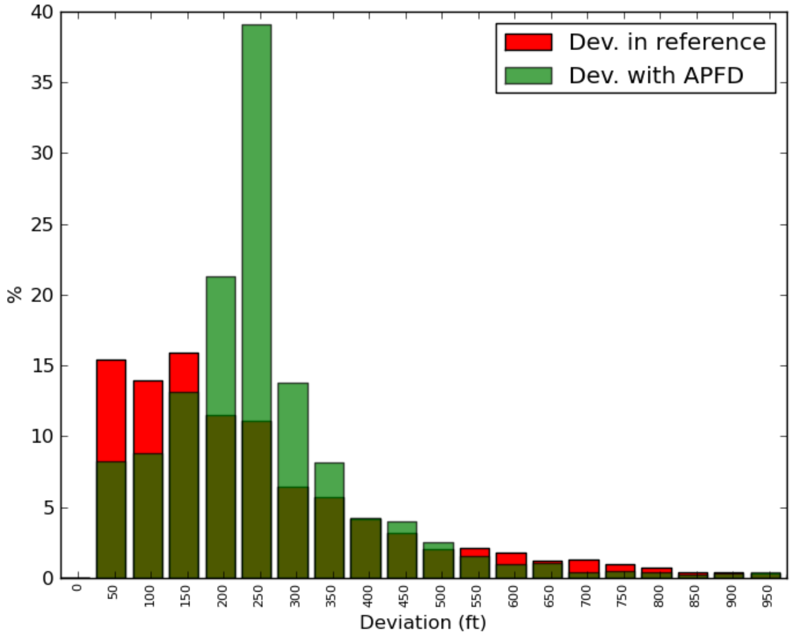


Figure 23: Deviation distributions - AP/FD with 4s delay and 0.25g acceleration - Full equipage - Full compliance – Comparison against typical scenario

We observe the same trend than with the comparison against the standard scenario. However it is noticeable that the AP/FD reduces the proportion of deviations above 550 ft.

3.3.2 Crossing RAs

The following figure shows a diagram representing the gains on the standard scenario, expressed as a percentage of the number of crossing RAs in the reference scenario, when using the AP/FD with different parameters:

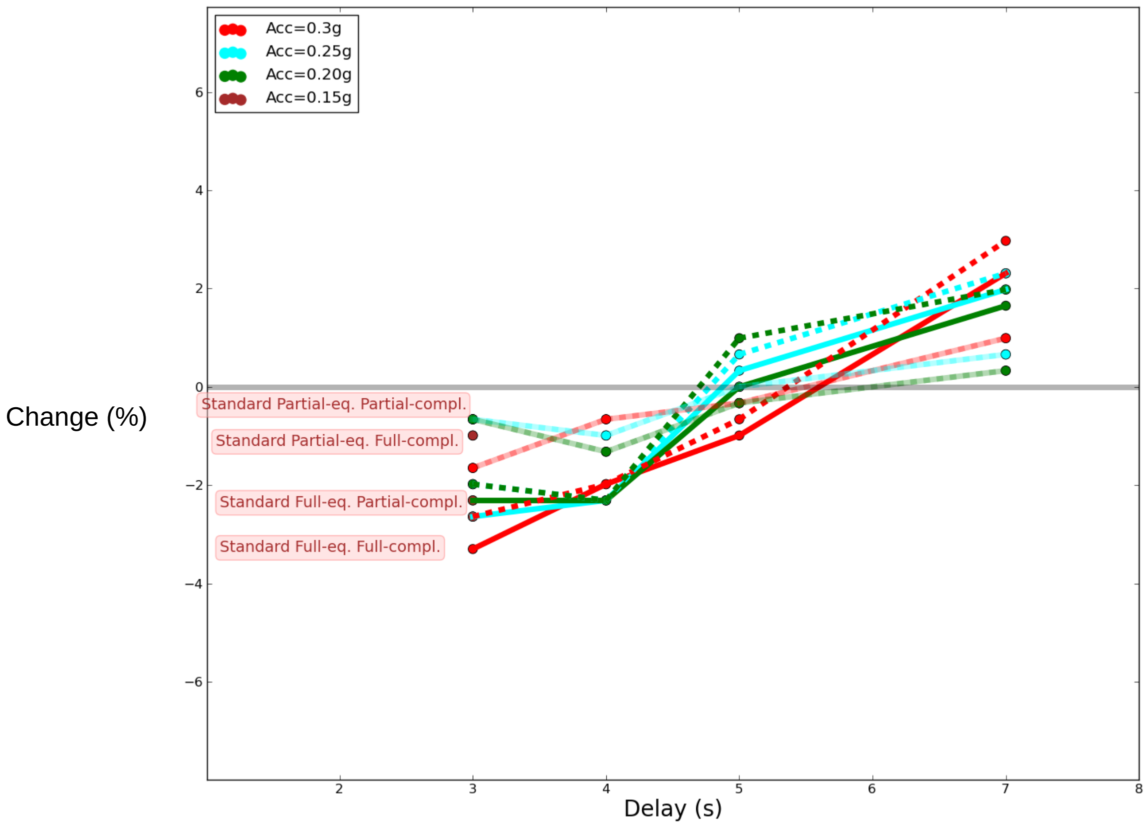


Figure 24: Crossing RAs - Gains with AP/FD - Standard scenario - Airspace perspective

The following figure shows the same results but this time for the typical scenarios.

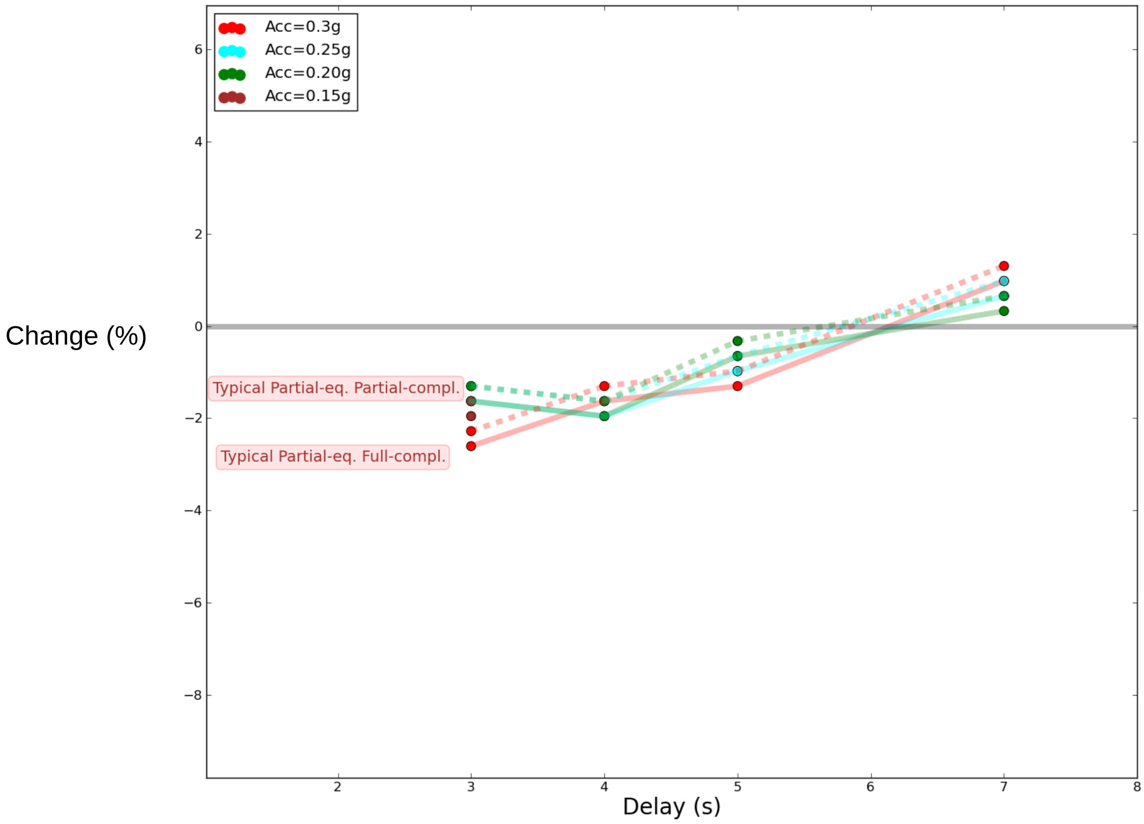


Figure 25: Crossing RAs - Gains with AP/FD - Typical scenario - Airspace perspective

The AP/FD scenarios have a very limited effect on the number of crossing RAs, as the variations are below 4%. Indeed, shorter delays of response to RAs can avoid the triggering of secondary RAs announced as crossing RAs.

On the contrary, the 7 s delay can result in an increase of the number of crossing RAs.

3.4 Indicators related to pilot acceptability

3.4.1 Complex sequences of RAs

The following figure shows a diagram representing the gains on the standard scenario, expressed as a percentage of the number of complex sequences of RAs in the reference scenario, when using the AP/FD with different parameters:

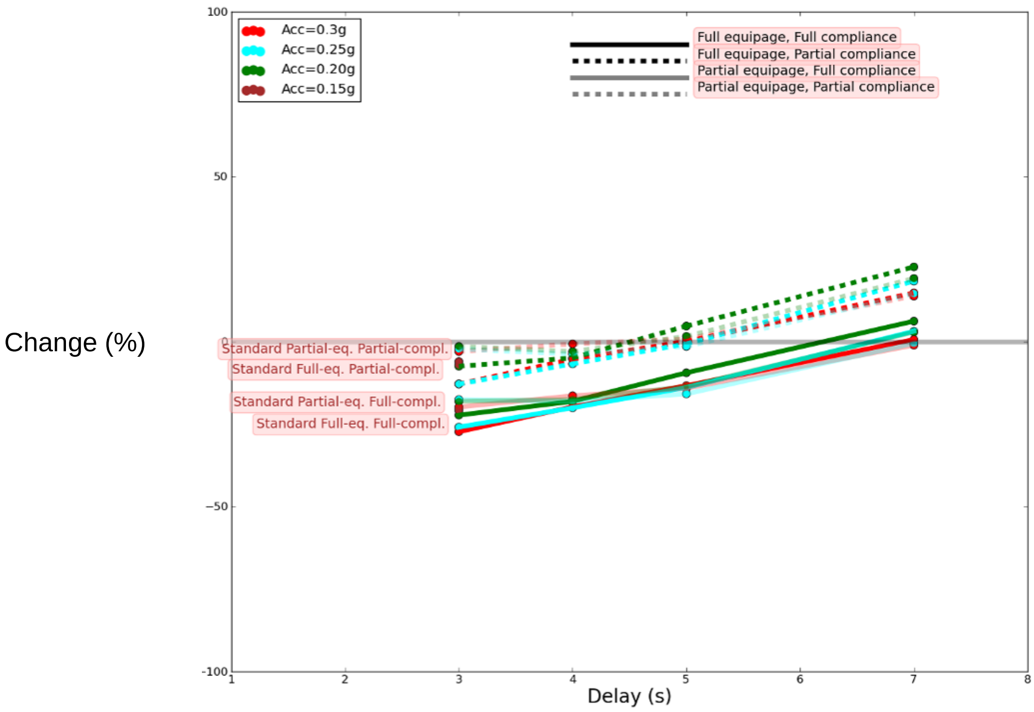


Figure 26: Complex sequences of RAs - Gains with AP/FD - Standard scenario - Airspace perspective

The following figure shows the same results but this time for the typical scenarios.

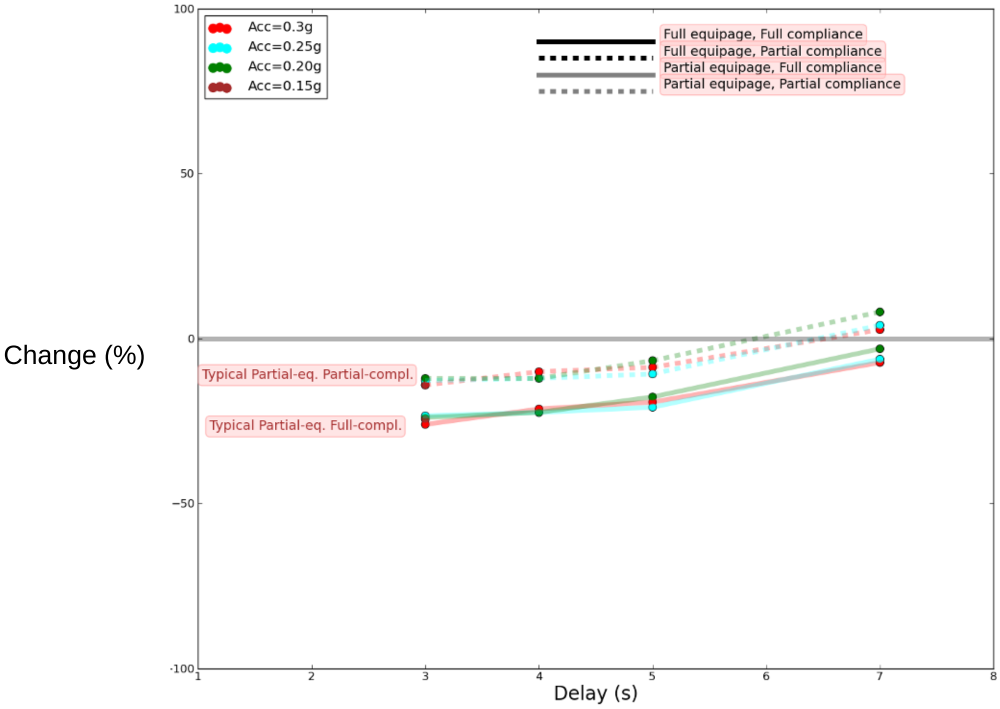


Figure 27: Complex sequences of RAs - Gains with AP/FD - Typical scenario - Airspace perspective

The number of complex sequences of RAs decreases as the delay decreases and the acceleration increases. As for the previous indicators shown, the benefit with full compliance and full equipage with a 3 s or 4 s delay is significant.

With a 7s delay, an increase of the number of complex sequences of RAs can be observed, showing that with this delay, the initial RAs are more often inefficient than with shorter delays and require updates.

4 CAS logic threshold reduction scenario

4.1 Introduction

A specific AP/FD scenario was studied, to check the effect of reducing by 3s the CAS logic thresholds to trigger RAs. This CAS logic threshold reduction is coupled with a reduced delay of response to RAs to 2 s and with an acceleration of 0.25 g.

This scenario is the one with which there are, overall, the most performance indicators for which we observe a gain when compared to the reference scenario. This part aims at detailing these results.

4.2 Indicators related to safety performance

4.2.1 Risk ratio

The following figure shows, with full equipage and full compliance, the risk ratio gains obtained with several AP/FD scenarios when compared to the reference scenario, including the CAS logic threshold reduction scenario, shown with a delay of 2s (left most point).

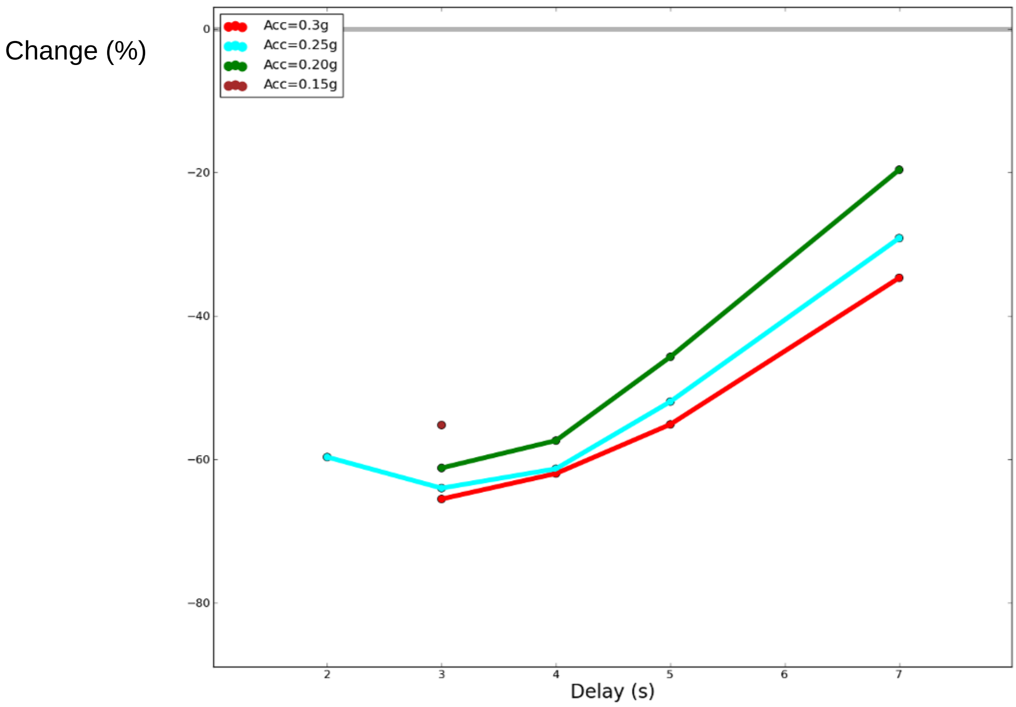


Figure 28: Risk ratios - Gains with AP/FD - CAS logic threshold reduction

The CAS logic threshold reduction scenario provides significant safety benefits when compared to the reference scenario (i.e., gain of 60%), even though a few other AP/FD scenarios provide slightly larger safety benefits. However the difference with the best performing scenarios is minor.

This slightly lower performance can be explained by one specific geometry, shown hereafter. In this example of this geometry, only aircraft 2 (black aircraft) is equipped with TCAS. The following figure shows the encounter without TCAS contribution.

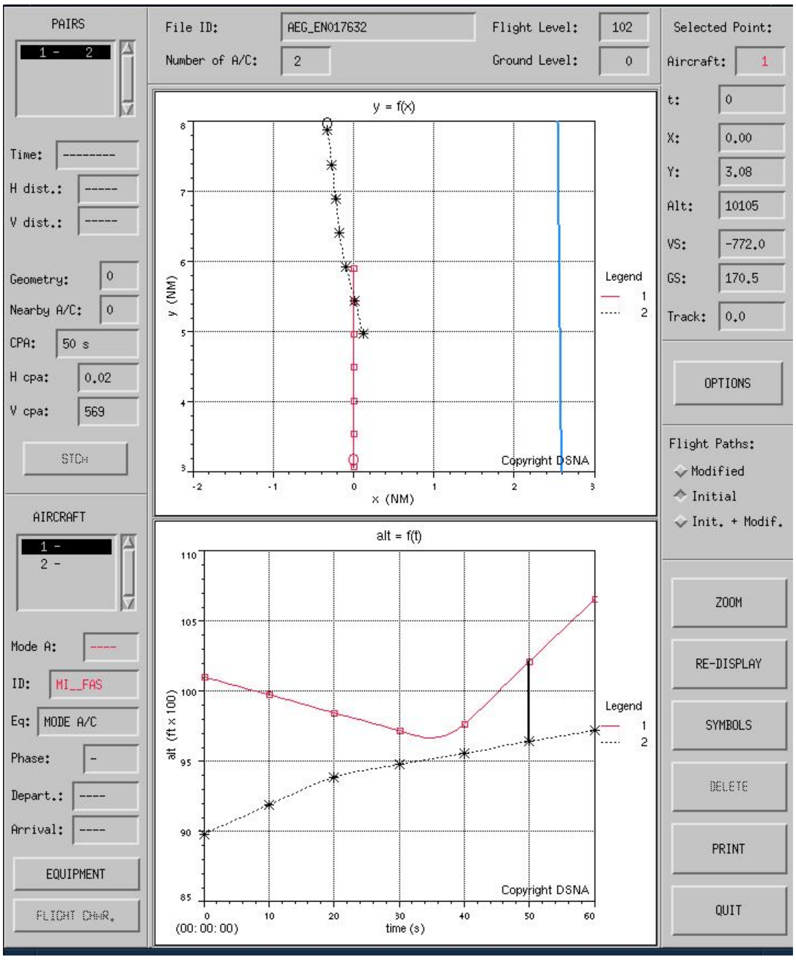


Figure 29: Encounter without TCAS contribution

The following figure show the encounter simulated with an AP/FD scenario (4 s delay, 0.25g acceleration) with the current CAS logic threshold and with the reduced thresholds.

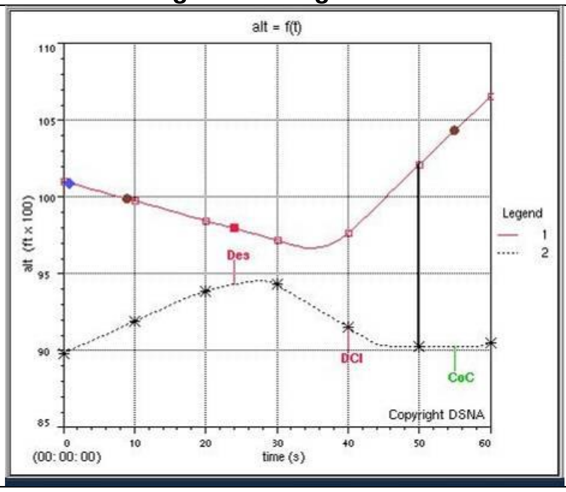
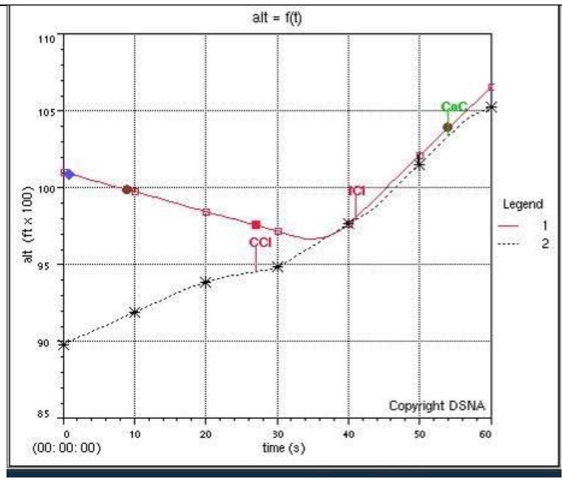
Unchanged CAS logic thresholds	**Reduced thresholds**
	
VMD=1200ft	VMD=50ft

Figure 30: Encounter with TCAS contribution
Legend: Des: Descend RA, CCl: Crossing climb RA, ICl: Increase climb RA, DCl: “Level-off’ RA, CoC: Clear of conflict

With the current CAS logic thresholds, aircraft 2 receives a descend RA, which results in vertical separation at CPA of 1200 ft.

When introducing the CAS logic threshold reduction, the descend RA becomes a crossing climb RA triggered 3 s later, which results in an NMAC.

The crossing RA is triggered because the delayed RA is triggered at a time where the vertical separation is lower than with the unchanged thresholds. Thanks to this reduced vertical separation, a crossing RA is possible. However as the intruder starts to climb just after the triggering of the crossing climb RA, this RA becomes inefficient.

4.2.2 Vertical miss distances

The following figures shows the VMD diagram comparing the VMDs with the AP/FD scenario (4s delay, 0.25g acceleration) with the current CAS logic thresholds, with the VMDs with the reduced CAS logic thresholds.

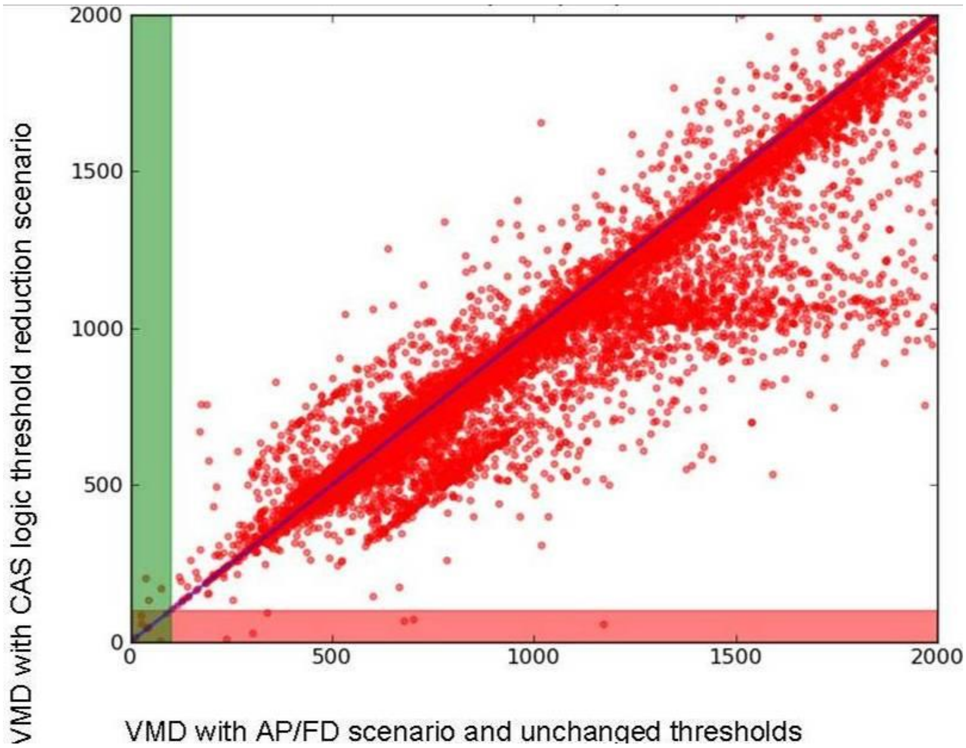


Figure 31: VMD diagram

Overall, there are more VMDs decreased than VMDs increased with the CAS logic threshold reduction. This is an expected result, as the RAs are triggered 3 s later with the CAS logic threshold reduction, and because the shorter delay of response of 2 s does not compensate the 3 s difference in the RA triggering when compared to the 4 s delay response of the AP/FD scenario without CAS logic threshold reduction. However it is noticeable that in the lower VMDs, there are very few changes on the diagram, which confirms that with this threshold reduction, the safety brought by TCAS II is not debased, and that the problem geometry discussed in the previous paragraph is a rare issue.

One notices a cluster of encounters for which the VMD with the CAS logic threshold reduction is around 1000 ft, and for which the VMD with the current CAS logic threshold is over 1000 ft. These are 1000 ft level-off encounters, in which reducing the CAS logic threshold results in no RAs being triggered. This is illustrated in the example below.

In this example, both aircraft are TCAS equipped, but only aircraft 1 (red aircraft) receives RAs.

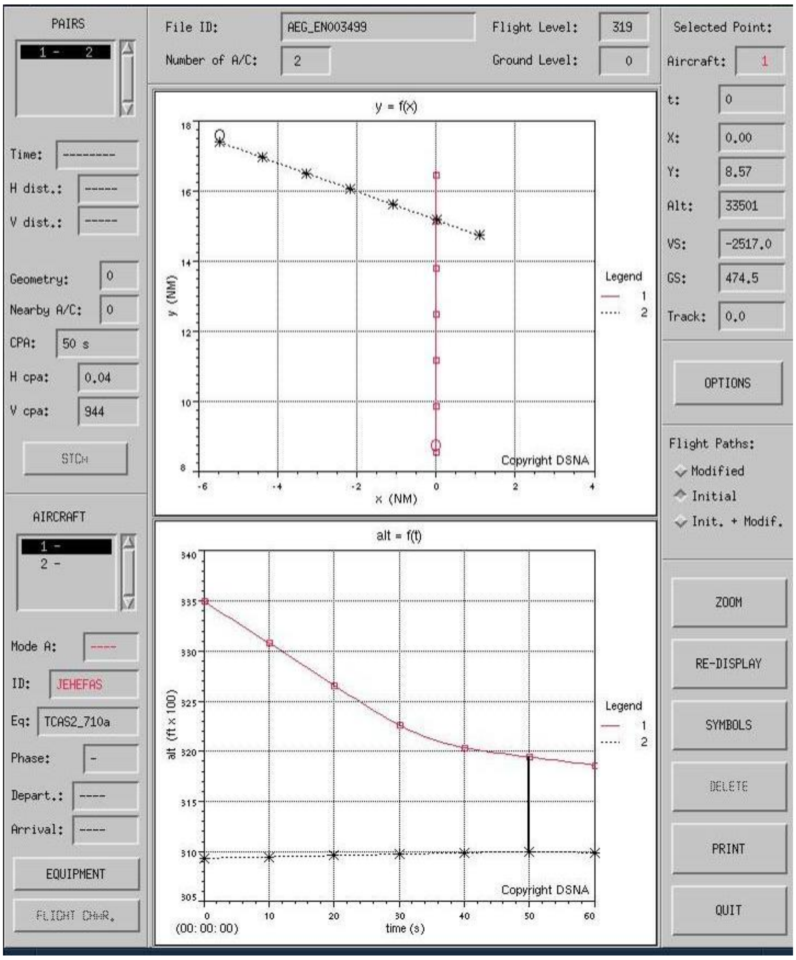


Figure 32: Encounter without TCAS contribution

The following figure shows the encounter simulated with an AP/FD scenario (4s delay, 0.25g acceleration) with the current CAS logic thresholds, and with the reduced CAS logic thresholds.

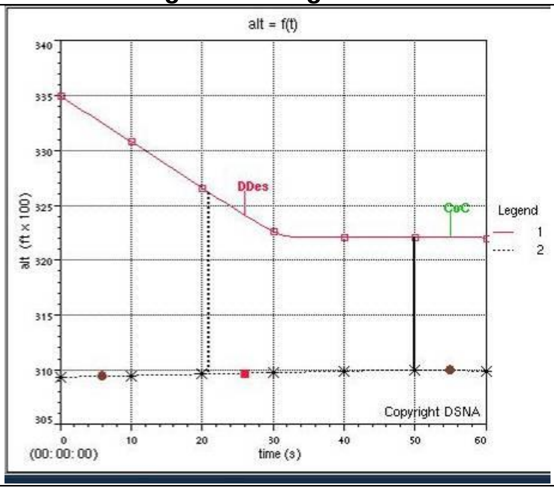
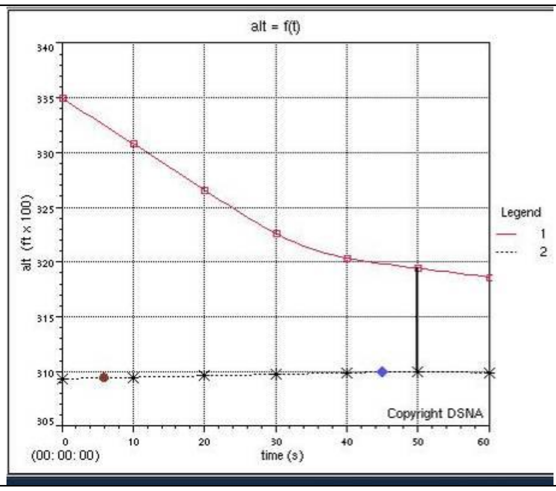
<table>
<tr><th>Unchanged CAS logic thresholds</th><th>Reduced thresholds</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>VMD=1200ft</td><td>VMD=900ft</td></tr>
</table>

Figure 33: Encounter with TCAS contribution
Legend: DDes: "Level-off" RA, CoC: Clear of conflict

With the AP/FD and the unchanged CAS logic thresholds, a "level-off" RA is triggered. With the reduced thresholds, the RA is no more triggered. This is a significant benefit from the CAS logic threshold reduction, as RAs triggered in 1000 ft level-off encounters is a well known operational issue since these RAs are often perceived as operationally undesired. This would be an additional benefit to the possible introduction of the new altitude capture law detailed in [4].

4.2.3 Increase RAs

The following figure shows, with full equipage and full compliance, reductions of the number of increase RAs obtained with several AP/FD scenarios when compared to the reference scenario, including the CAS logic threshold reduction scenario, shown with a delay of 2s (left most point).

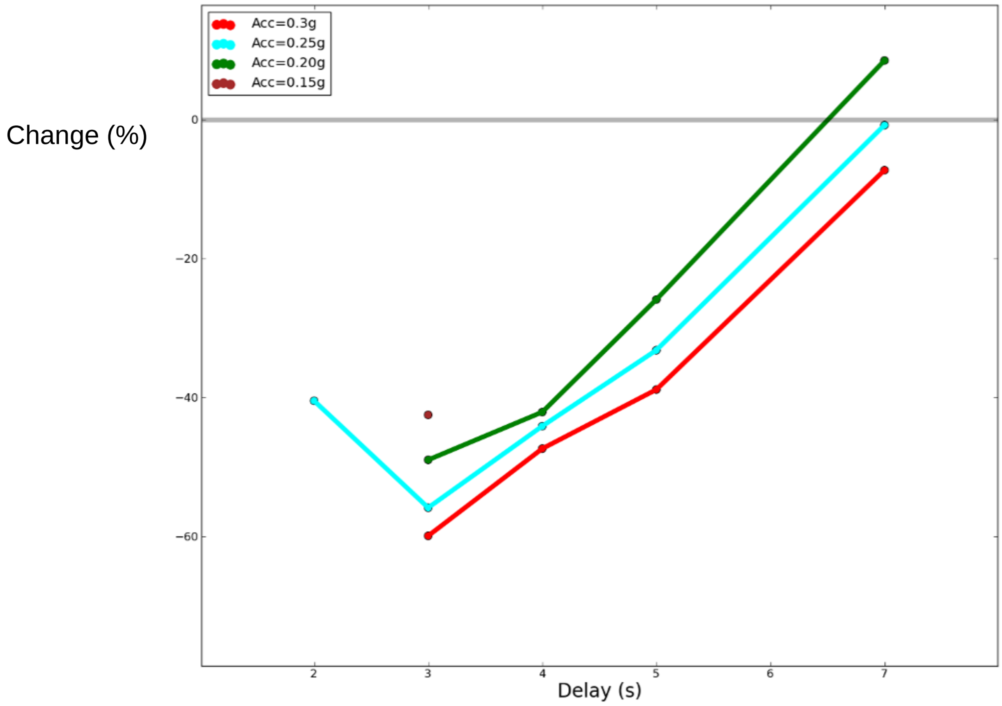


Figure 34: Increase RAs - Gains with AP/FD - CAS logic threshold reduction

With the CAS logic threshold reduction, the number of increase RAs is significantly reduced when compared with the reference scenario, but some AP/FD scenarios show a better performance.

The number of increase RAs is comparable to that of the 4s delay and 0.25g acceleration. Indeed, there is only a 1 s difference with this AP/FD scenario in the timing of start of manoeuvre following the triggering of an RA.

4.2.4 Reversal RAs

The following figure shows, with full equipage and full compliance, reductions of the number of reversal RAs obtained with several AP/FD scenarios when compared to the reference scenario, including the CAS logic threshold reduction scenario, shown with a delay of 2s (left most point).

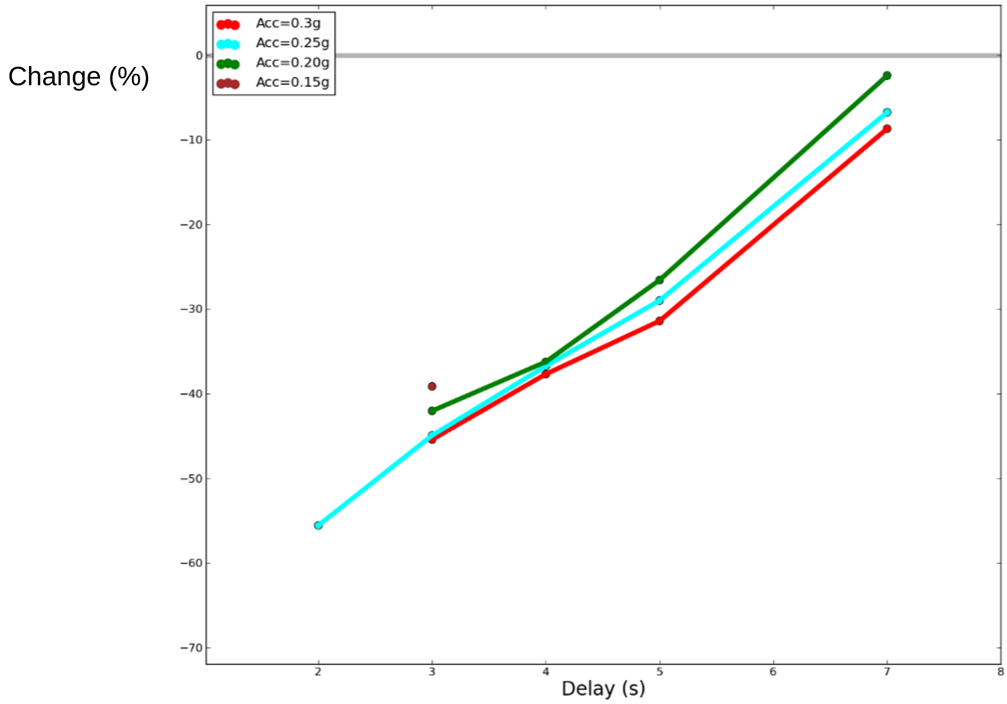


Figure 35: Reversal RAs - Gains with AP/FD - CAS logic threshold reduction

With the CAS logic threshold reduction, the number of reversal RAs is significantly reduced when compared with the reference scenario. In addition, the CAS logic threshold reduction scenario outperforms all the other AP/FD scenarios.

Having less reversal RAs is a significant benefit as it highlights the fact that the initial sense chosen by the CAS logic is less often thwarted. This result is all the more interesting than it was observed in 4.2.3 that the number of increase RAs was higher with the CAS threshold reduction scenario than with a few other AP/FD scenarios. This shows that this increase of the number of increase RAs can be explained by the fact that with the reduced thresholds, it is slightly more difficult to reach ALIM, but also that additional reversal RAs are not needed.

4.3 Indicators related to operational compatibility with ATC

4.3.1 Deviations

The following figure shows, with full equipage and full compliance, the deviation ratios obtained with several AP/FD scenarios when compared to the reference scenario, including the CAS logic threshold reduction scenario, shown with a delay of 2s (left most point). As a reminder, the deviation ratio is computed as the number of deviations decreased divided by the number of deviations increased.

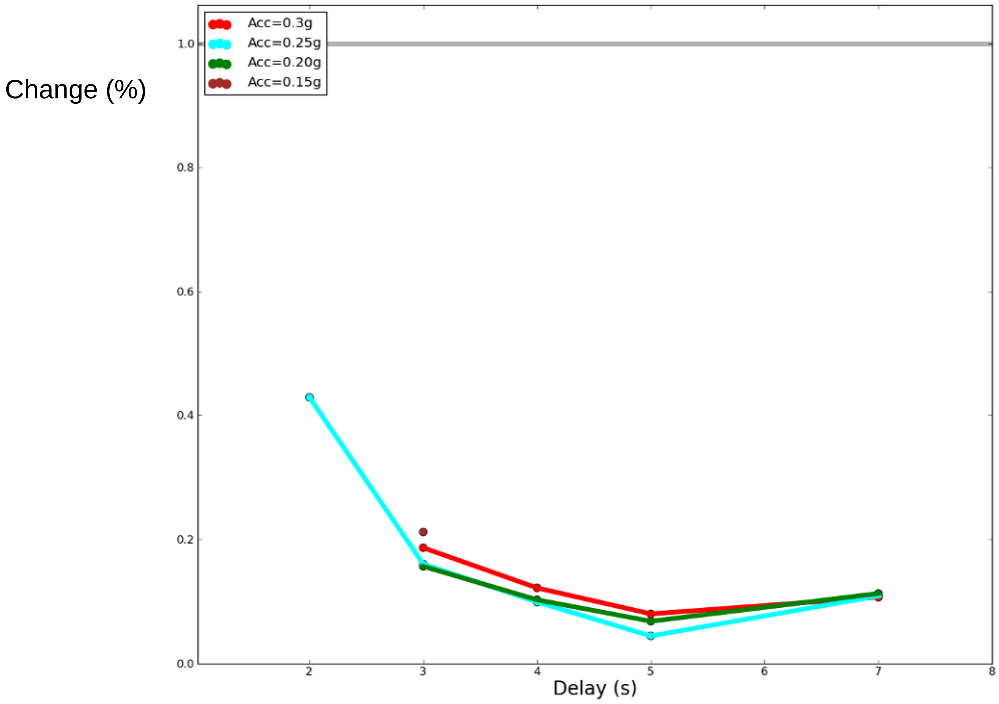


Figure 36: Deviation ratio – Gains with AP/FD - CAS logic threshold reduction

The CAS logic threshold reduction scenario performs much better than the other AP/FD scenarios.

The following figure illustrates this by showing the deviation diagram comparing the deviations obtained in the AP/FD scenario with a 4 s delay and 0.25g acceleration with the deviations obtained in the CAS logic threshold reduction scenario.

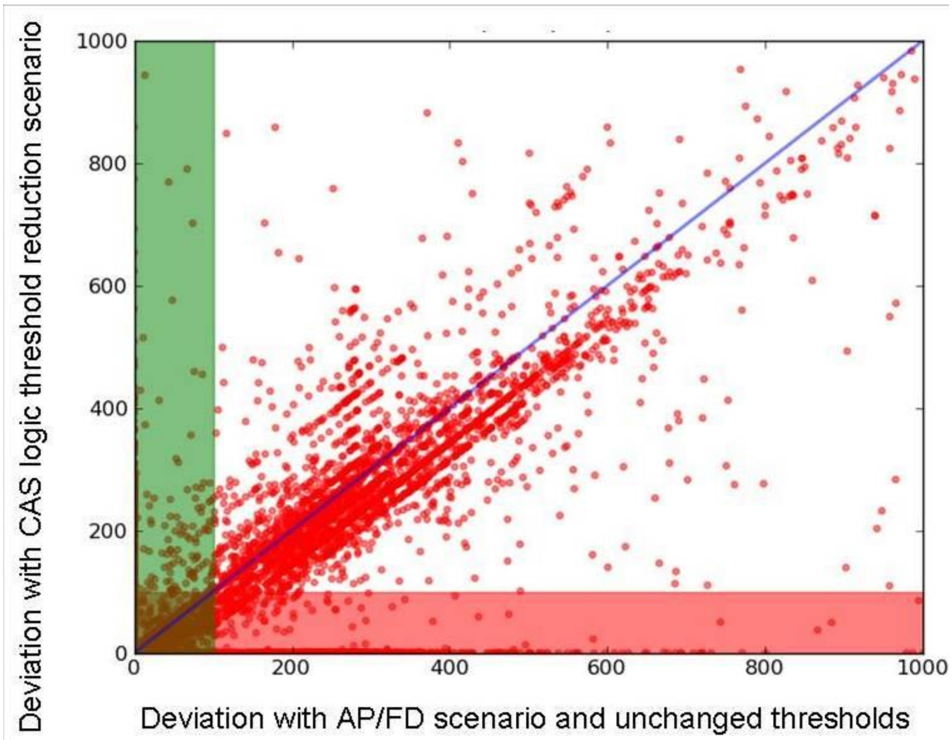


Figure 37: Deviations diagram - APFD (4s, 0.25g) vs CAS threshold reduction scenario

The CAS logic threshold scenario often reduces the deviations when compared to the AP/FD scenario with unchanged thresholds. This shows the better compatibility of this solution with ATC practices.

The CAS logic threshold reduction would increase the compatibility with ATC, by a reduction of deviations, when compared to other AP/FD scenarios with unchanged CAS logic thresholds.

4.3.2 Crossing RAs

The following figure shows, with full equipage and full compliance, reductions of the number of crossing RAs obtained with several AP/FD scenarios when compared to the reference scenario, including the CAS logic threshold reduction scenario, shown with a delay of 2s (left most point).

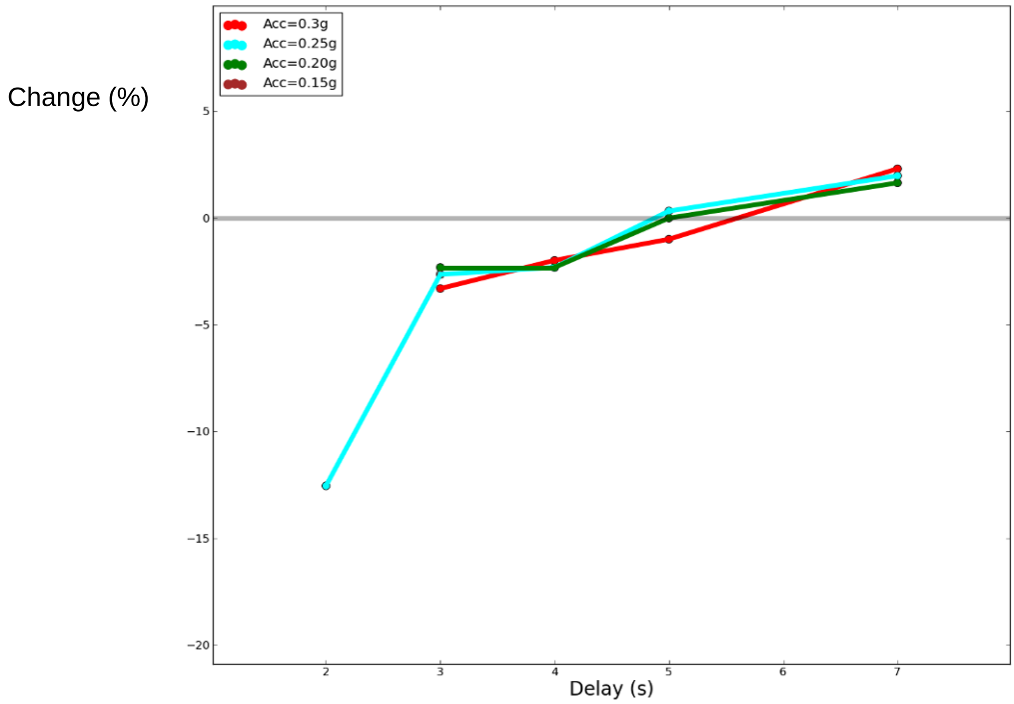


Figure 38: Crossing RAs - Gains with AP/FD - CAS logic threshold reduction

With all the AP/FD scenarios not including the CAS logic threshold reduction, the number of aircraft receiving crossing RAs is never reduced by more than 3%.

When introducing the CAS logic threshold reduction, the number of aircraft receiving crossing RAs is decreased by 13%. This is a noticeable benefit of this solution. This also shows that the scenario for which the reduced threshold adds changes a descend RA to a crossing climb RA (see 4.2.1) is not a common scenario as overall, the reduced thresholds tends to favour the opposite behaviour.

4.4 Indicators related to pilot acceptability

4.4.1 Number of aircraft receiving RAs

The following figure shows, with full equipage and full compliance, reductions of the number of aircraft receiving RAs obtained with several AP/FD scenarios when compared to the reference scenario, including the CAS logic threshold reduction scenario, shown with a delay of 2s (left most point).

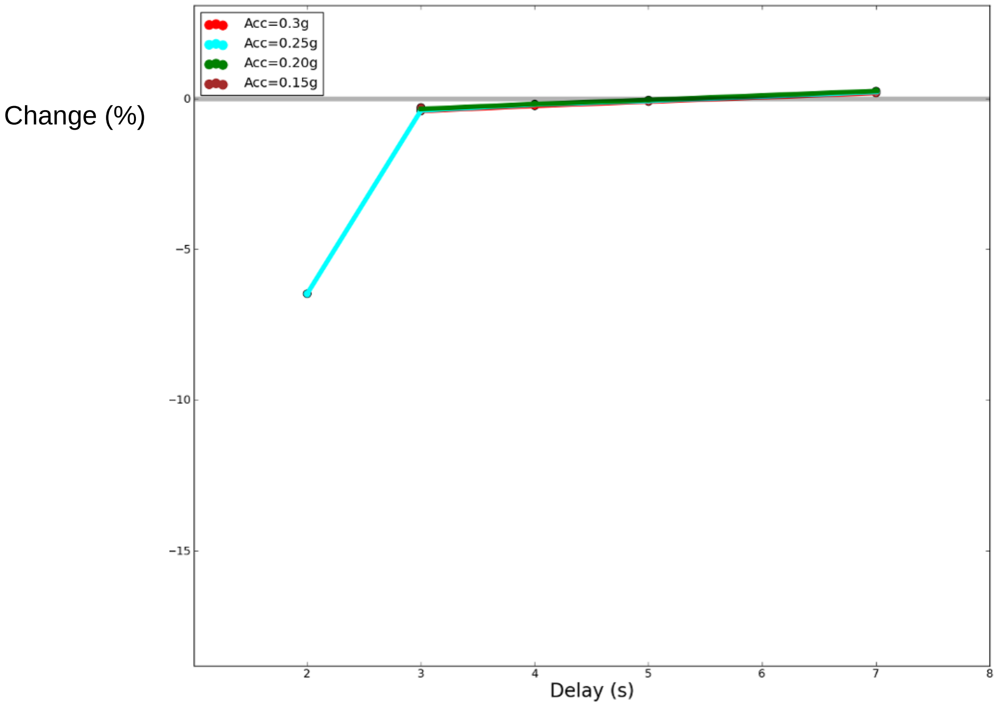


Figure 39: Number of RAs - Gains with AP/FD - CAS logic threshold reduction

With all the AP/FD scenarios not including the CAS logic threshold reduction, the number of aircraft receiving RAs is nearly constant.

When introducing the CAS logic threshold reduction, the number of aircraft receiving RAs is decreased by 7%, which is a significant benefit.

4.4.2 Number of RAs opposite to the trajectory

The following figure shows, with full equipage and full compliance, reductions of the number of RAs opposite to the trajectory obtained with several AP/FD scenarios when compared to the reference scenario, including the CAS logic threshold reduction scenario, shown with a delay of 2s (left most point).

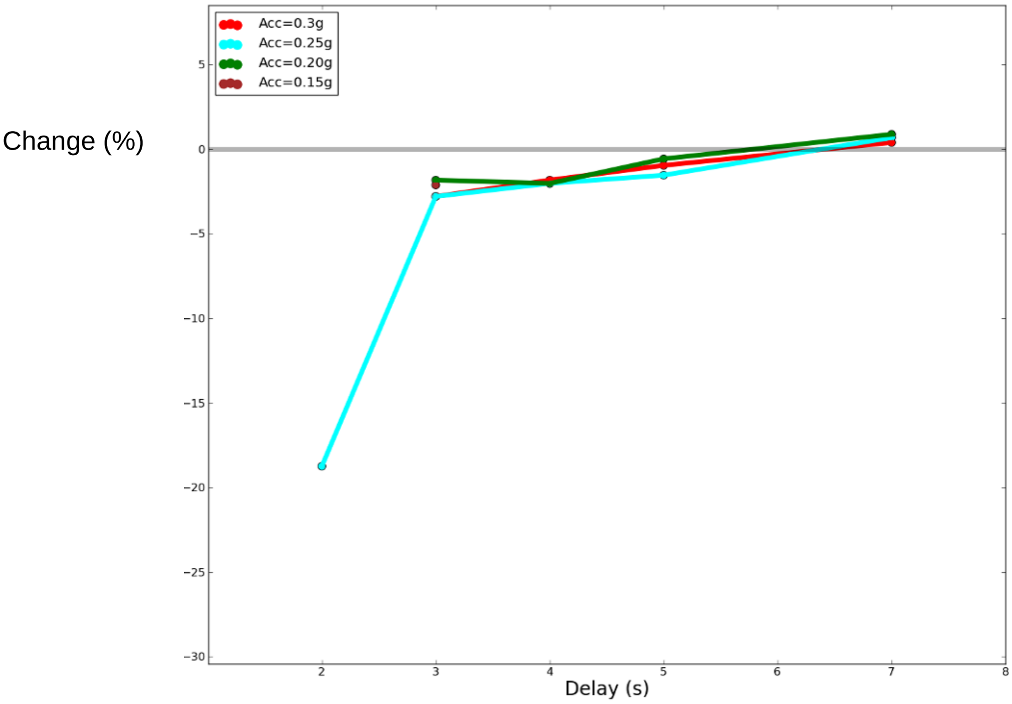


Figure 40: RAs opposite to the trajectory - Gains with AP/FD - CAS logic threshold reduction

With all the AP/FD scenarios not including the CAS logic threshold reduction, the number of aircraft receiving RAs opposite to the trajectory is never reduced by more than 3%.

When introducing the CAS logic threshold reduction, the number of aircraft receiving RAs opposite to the trajectory is decreased by 19%.

4.4.3 Number of initial RAs opposite to the trajectory

The following figure shows, with full equipage and full compliance, reductions of the number of initial RAs opposite to the trajectory RAs obtained with several AP/FD scenarios when compared to the reference scenario, including the CAS logic threshold reduction scenario, shown with a delay of 2s (left most point).

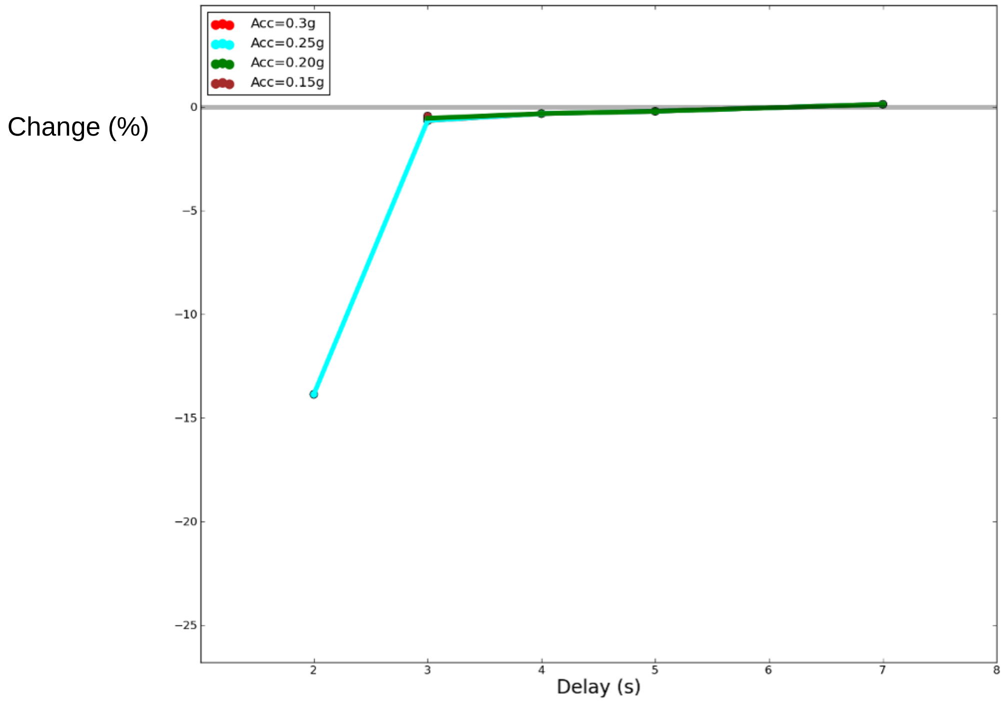


Figure 41: Initial RAs opposite to the trajectory - Gains with AP/FD - CAS logic threshold reduction

With all the AP/FD scenarios not including the CAS logic threshold reduction, the number of aircraft receiving initial RAs opposite to the trajectory is never reduced by more than 1%.

When introducing the CAS logic threshold reduction, the number of aircraft receiving initial RAs opposite to the trajectory is decreased by 14%.

4.4.4 Number of complex sequences of RAs

The following figure shows, with full equipage and full compliance, reductions of the number of complex sequences of RAs obtained with several AP/FD scenarios when compared to the reference scenario, including the CAS logic threshold reduction scenario, shown with a delay of 2s (left most point).

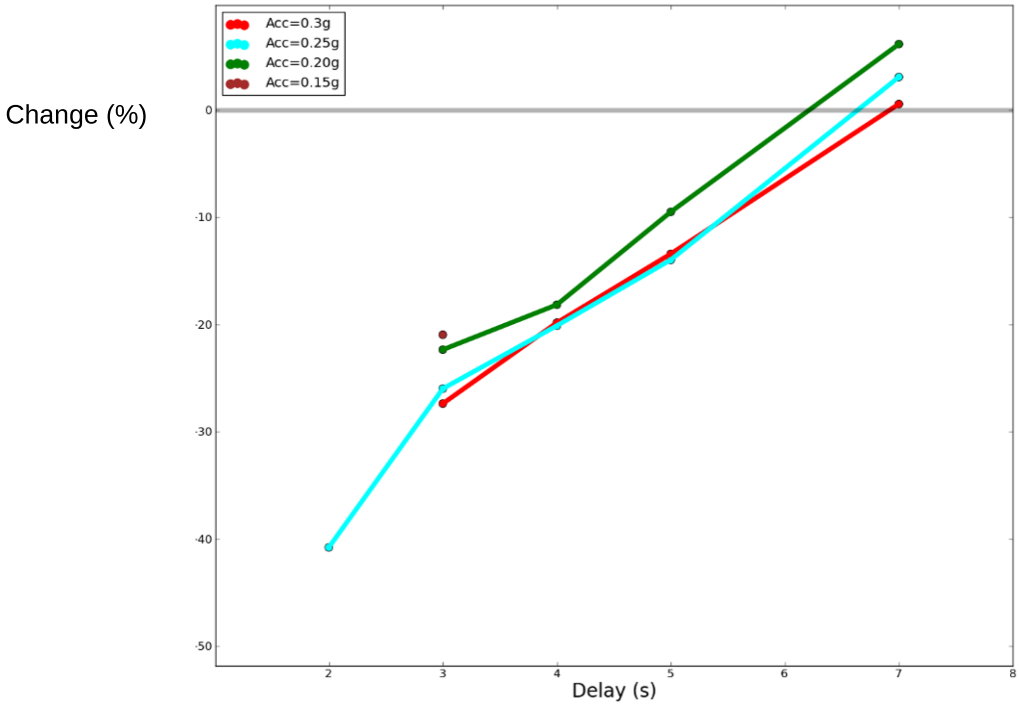


Figure 42: Number complex sequences of RAs - Gains with AP/FD - CAS logic threshold reduction

When introducing the CAS logic threshold reduction, the number of aircraft receiving complex sequences of RAs is decreased by 41%, which is significantly better than all the other AP/FD scenarios.

4.5 Conclusion on the CAS logic threshold reduction scenario

This scenario provides significant gains in safety when compared to the reference scenario. Some AP/FD scenarios have a better performance, however the difference is minimal.

This scenario increases the compatibility with ATC and acceptance by pilots, by generating less RAs (especially in 1000 ft level-off encounters), less crossing RAs, less RAs opposite to the trajectory, and triggering RAs which need to be updated less often.

This scenario appears as a promising improvement to TCAS II, and can be implanted thanks to the availability of the AP/FD functionality.

5 Effect of the performance limitations

5.1 Introduction

TCAS II specifications include the possibility to provide the indication to the logic that the own aircraft is vertical performance limited and cannot achieve the nominal climb rate of 1,500 fpm for a “Climb” RA.

In the MOPS for “Automatic Flight Guidance and Control System and Equipment that includes guidance for Auto-Pilot/Flight Director/autothrust coupled with TCAS” under development by RTCA SC220, consideration is given to a possible requirement of providing TCAS with this information in the case of automatic responses to RAs. It should be noted that this functionality is not currently implemented and in today operations, TCAS can generate RAs that pilots cannot follow manually due to limited performances of aircraft.

The TCAS logic includes two possible inhibitions: Climb RA inhibition and Increase Climb RA inhibition. The worst constraining situation, i.e. Climb RA inhibition, will be investigated in this study.

In this part, a case study is presented. This case study was performed on an empirical basis using a reduced set of encounters to evaluate the impact of implementing this functionality. The objective was to use encounters in which at least a “Climb” RA is generated and to assess the impact of setting the Climb RA inhibition for one TCAS logic (or both). Comparison was made between simulations with and without the provision of the performance limitations to the TCAS logic to assess the consequences on the RAs generated on-board all the aircraft involved in the encounters. Different responses to RAs were investigated in particular to compare simulations without RA climb inhibition and limited climb rate, and simulations with RA climb inhibition.

5.2 Head on encounter at same flight level

In this encounter, two aircraft are head-on, one is level at FL370, the other is not flying perfectly at its flight level and is 200 ft below the first. The following figure shows the encounter without TCAS contribution.

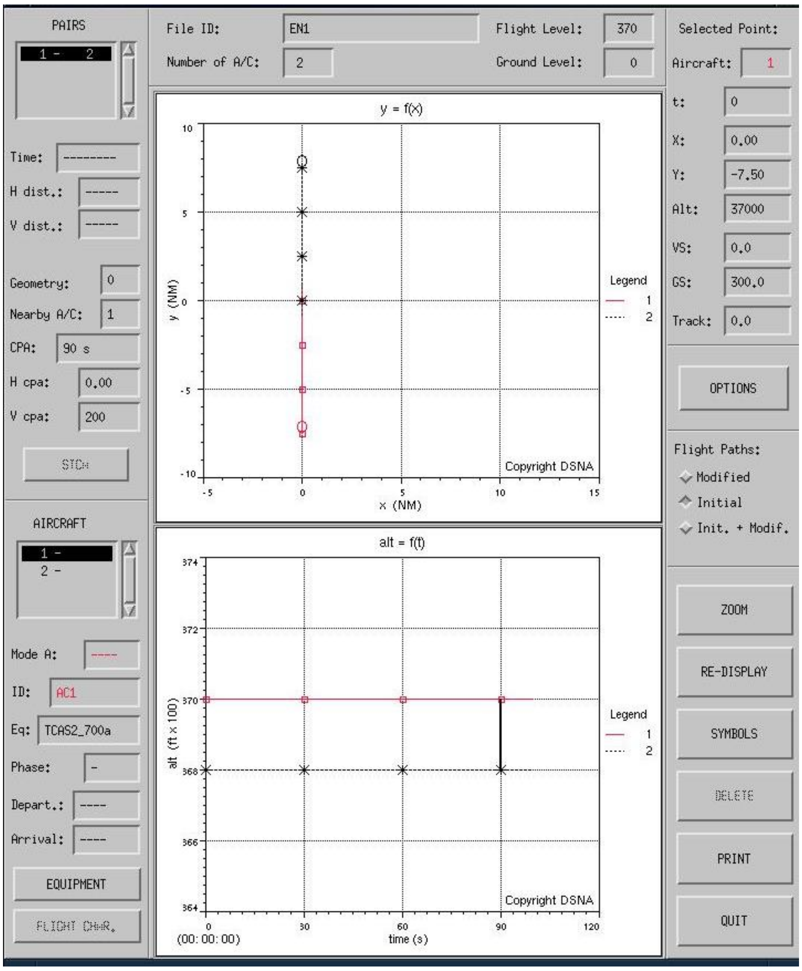
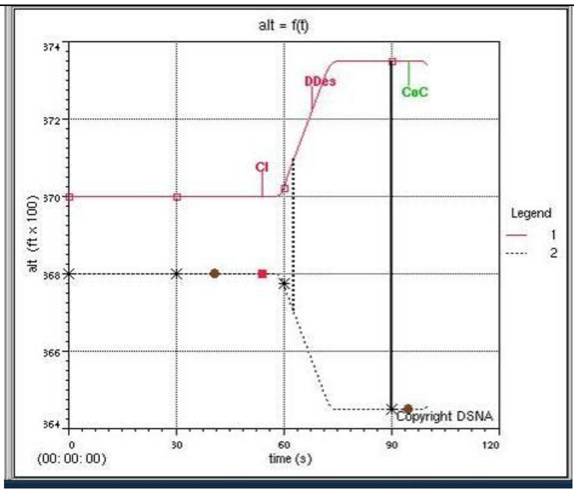
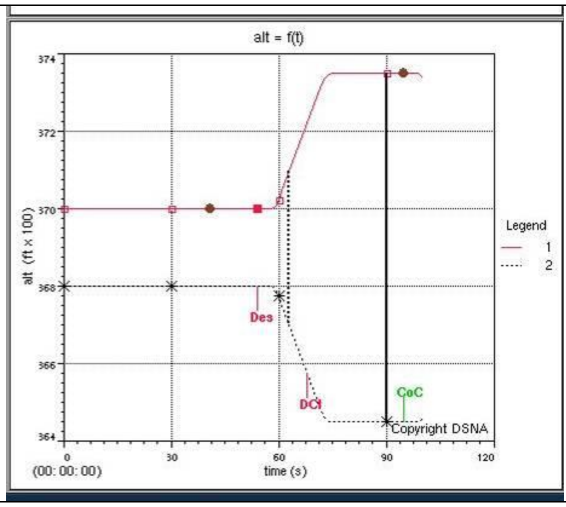


Figure 43: Head-on encounter, without TCAS contribution

The following figures show the same encounter simulated with the APFD with a 4 s delay, and 0.25 g acceleration onboard both aircraft, assuming no vertical limitation and no climb inhibition.

Aircraft 1	Aircraft 2





CPA:0NM/900 ft

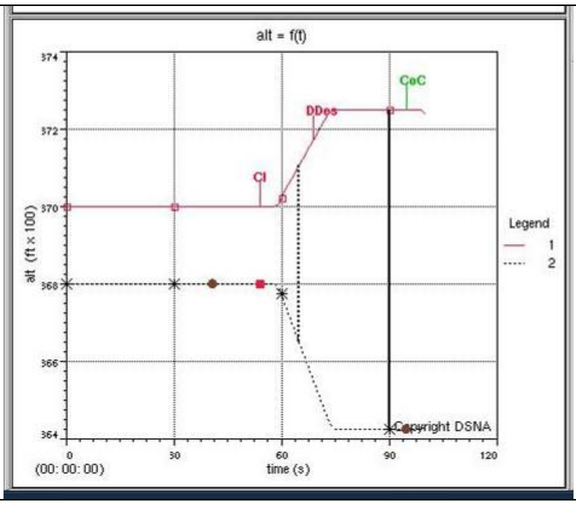
Figure 44: Head-on encounter, with TCAS contribution and no limitation

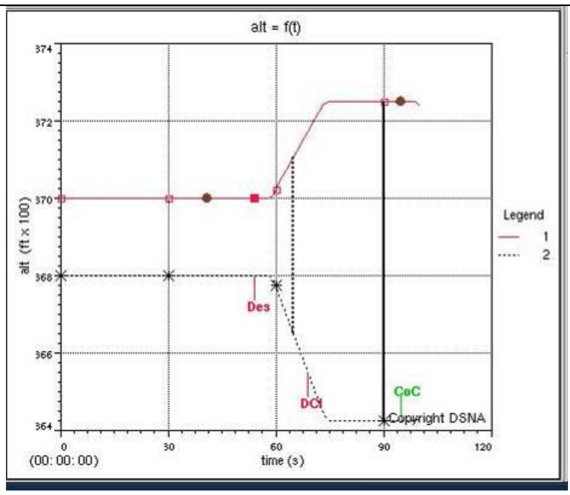
The upper aircraft receives a “Climb” RA, followed by and “Adjust vertical speed, Adjust” RA. The lower aircraft receives a “Descend” RA, followed by an “Adjust vertical speed, Adjust” RA.

The vertical separation at CPA is 900 ft.

The following figure shows the same encounter with a limitation of the vertical rate to 1000 fpm for the upper aircraft.

Aircraft 1	Aircraft 2





CPA:0NM/825 ft

Figure 45: Head-on encounter, with TCAS contribution, aircraft 1 with Vs limitation at 1000 fpm

With a limitation of the vertical rate to 1000 fpm, the vertical separation at CPA is 820 ft. The loss when compared to the situation without any limitation is negligible, and the vertical separation is still higher than ALIM (600 ft).

The following figure shows the same encounter with a climb inhibition for both aircraft.

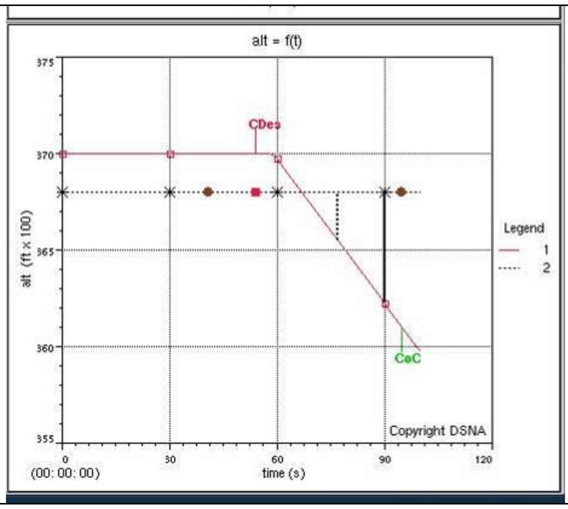
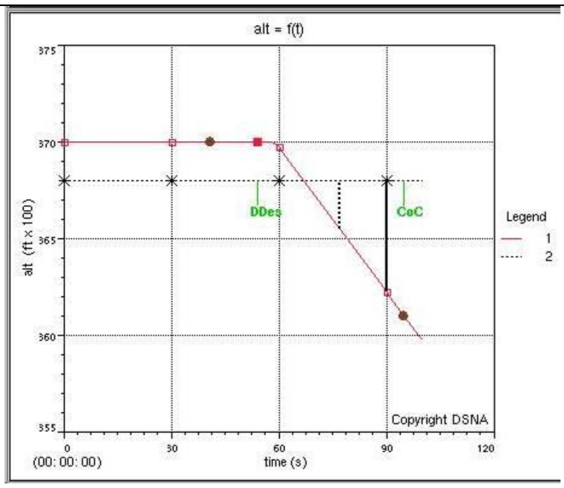
<table>
<tr><th>Aircraft 1</th><th>Aircraft 2</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">CPA:0NM/570 ft</td></tr>
</table>

Figure 46: Head-on encounter, with TCAS contribution, aircraft 1 and 2 with climb inhibition

The upper aircraft receives a “Crossing descend” RA. The intruder receives a monitor vertical speed RA. The vertical separation at CPA is 570 ft, which is below the vertical threshold, referred to as ALIM, which TCAS aims at providing (here, 600 ft).

On this example, it seems that climbing even with a limited vertical rate is better than having the climb inhibition.

5.3 Two aircraft climbing

In this encounter, two aircraft are climbing, one at 300 fpm and the other at 1500 fpm, to the same altitude. They are head on. Aircraft 2 does not follow RAs[3]. The following figure shows the encounter without TCAS contribution.

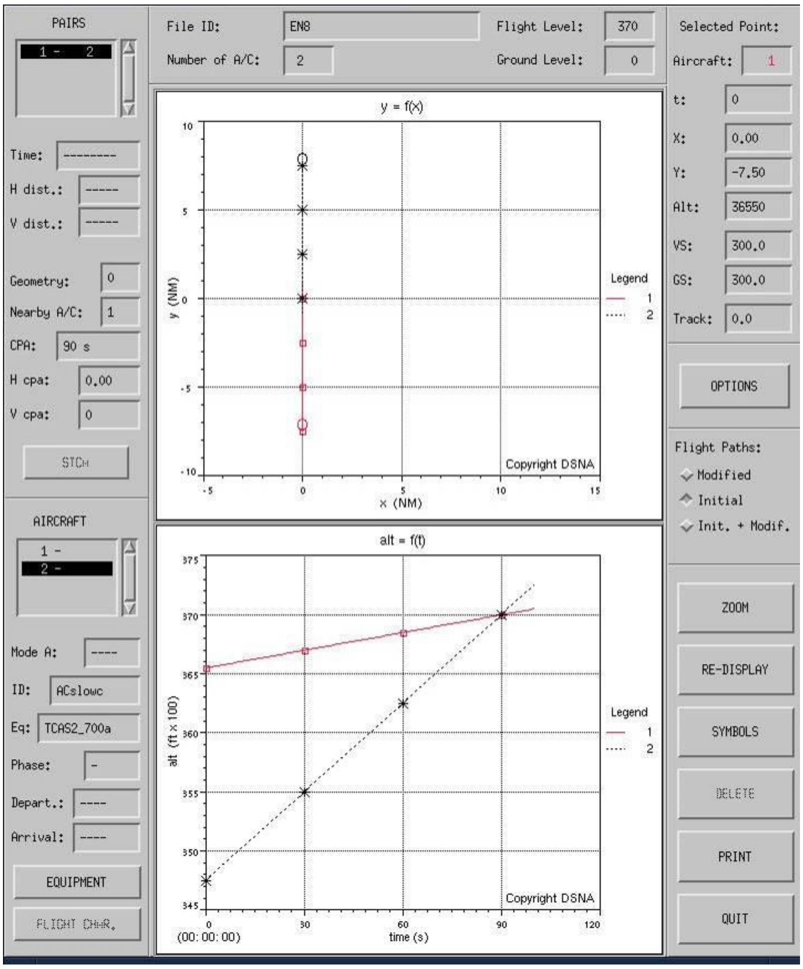
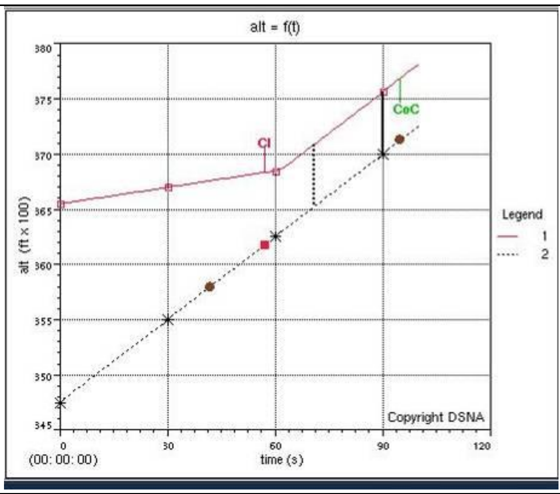


Figure 47: 2 aircraft climbing, without TCAS contribution

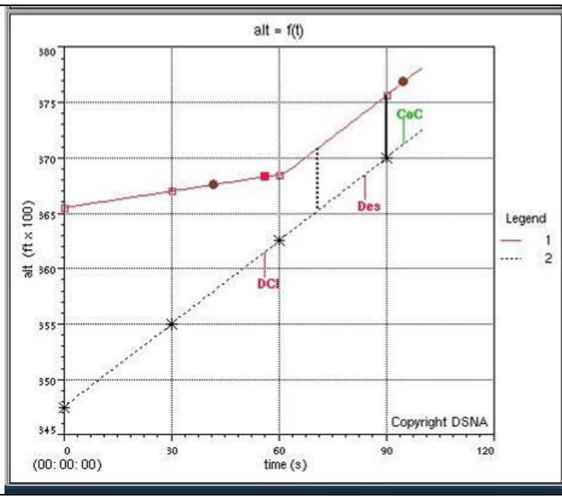
The following figures show the same encounter simulated with the APFD with a 4s delay, and 0.25g acceleration onboard both aircraft, assuming no vertical limitation and no climb inhibition.

[3] This assumption is not overly pessimistic as it has been shown in the past that the proportion of pilots who do not follow RAs in the European airspace is noticeable

Aircraft 1



Aircraft 2



CPA:0NM/560 ft

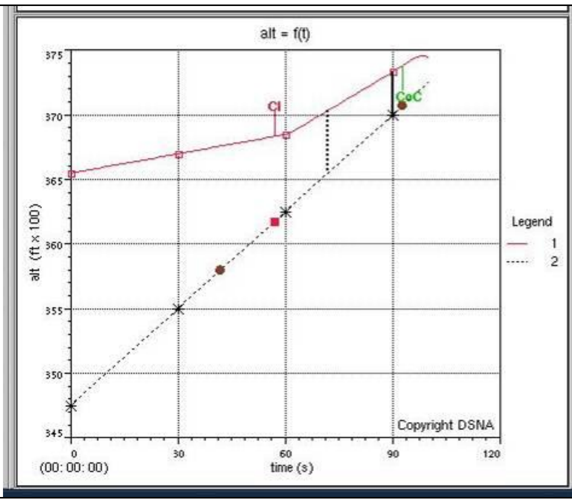
Figure 48: 2 aircraft climbing, with TCAS contribution and no limitation

The upper aircraft receives a climb RA. The lower aircraft receives an “Adjust vertical speed, adjust” RA, followed by a “Descend” RA.

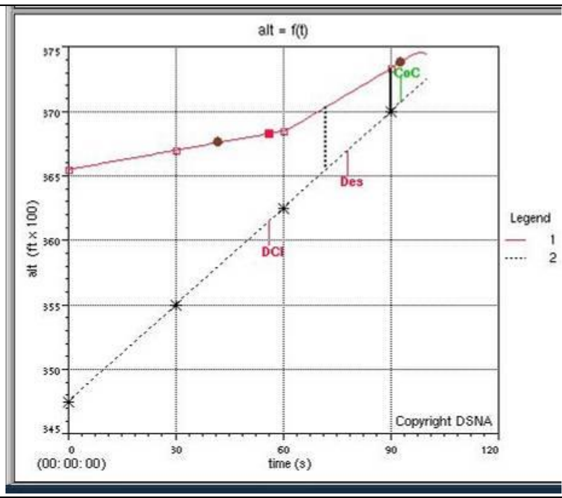
The vertical separation at CPA is 560 ft.

The following figure shows the same encounter with a limitation of the vertical rate to 1000 fpm for the upper aircraft.

Aircraft 1



Aircraft 2



CPA:0NM/335 ft

Figure 49: 2 aircraft climbing, with TCAS contribution, aircraft 1 with Vs limitation at 1000 fpm

The vertical separation at CPA is 330 ft.

The following figure shows the same encounter with a climb inhibition for the upper aircraft.

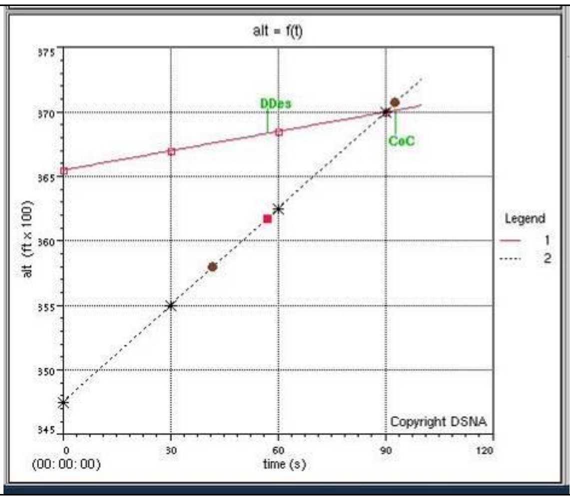
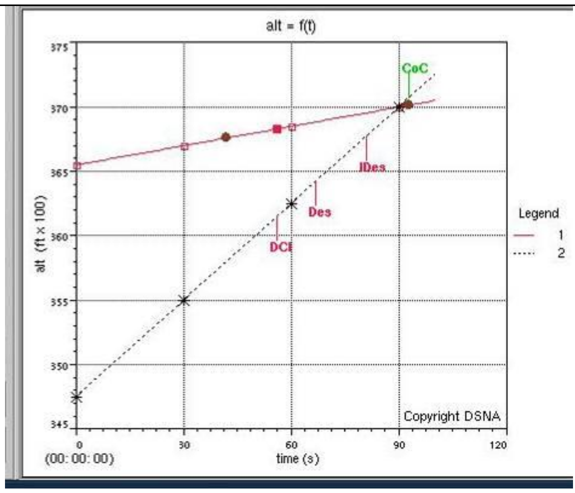
<table>
<tr><th>Aircraft 1</th><th>Aircraft 2</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">CPA:0NM/0 ft</td></tr>
</table>

Figure 50: 2 aircraft climbing, with TCAS contribution, aircraft 1 and 2 with climb inhibition

The upper aircraft receives a “monitor vertical speed” RA. The lower aircraft receives an “Adjust vertical speed, adjust” RA, followed by a “Descend” RA, and then by an “increase descend sense RA”.

The encounter results in an NMAC. **Indeed, it is still better to climb, even by a small amount, than doing nothing**.

5.4 One aircraft level, intruder climbing from below

In this encounter, one aircraft is level at FL370, the intruder is climbing at 1200 fpm, below the same FL. The aircraft are head on. Aircraft 2 does not follow RAs. The following figure shows the encounter without TCAS contribution.

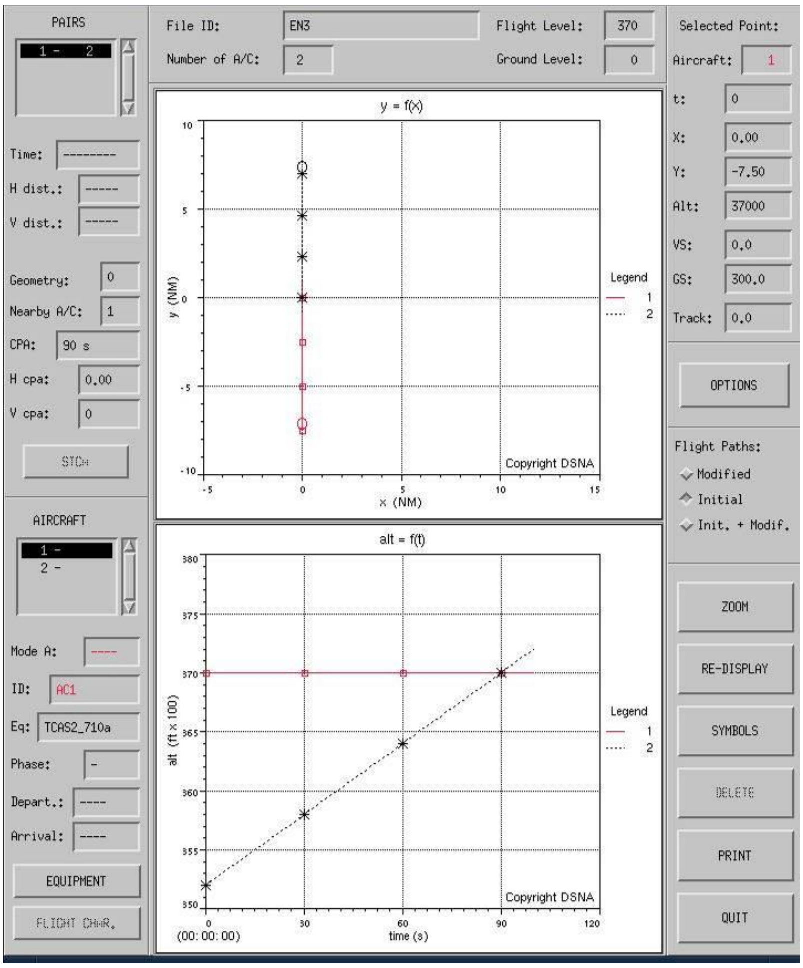


Figure 51: One aircraft level, intruder climbing from below, without TCAS contribution

The following figures show the same encounter simulated with the APFD with a 4s delay, and 0.25g acceleration onboard both aircraft, assuming no vertical limitation and no climb inhibition.

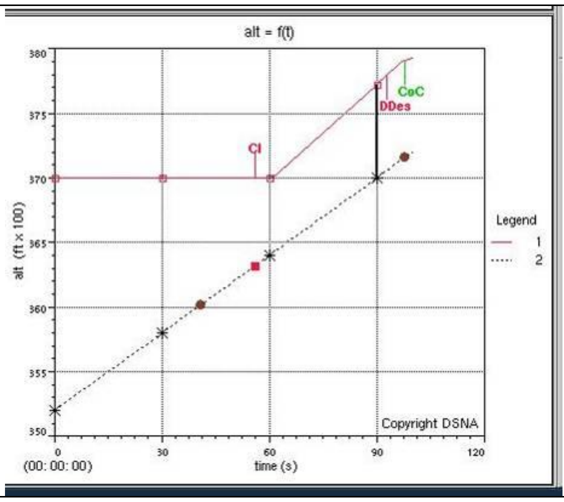
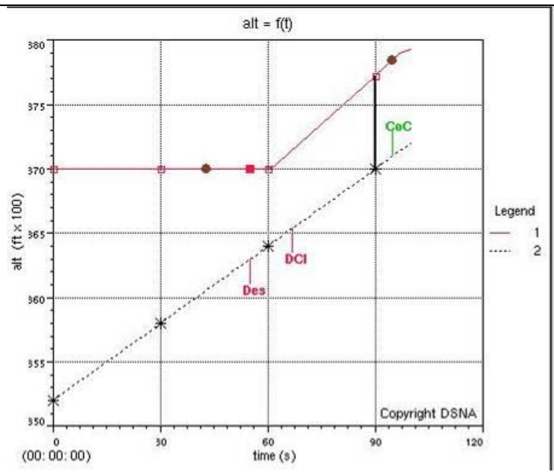
Aircraft 1	Aircraft 2
	
CPA:0NM/600 ft	

Figure 52: One aircraft level, intruder climbing from below, with TCAS contribution and no limitation

The upper aircraft receives a “climb” RA. The lower aircraft receives a “Descend” RA, followed by an “Adjust vertical speed, adjust”, RA.

The vertical separation at CPA is 600 ft.

The following figure shows the same encounter with a limitation of the vertical rate to 1000 fpm for the upper aircraft.

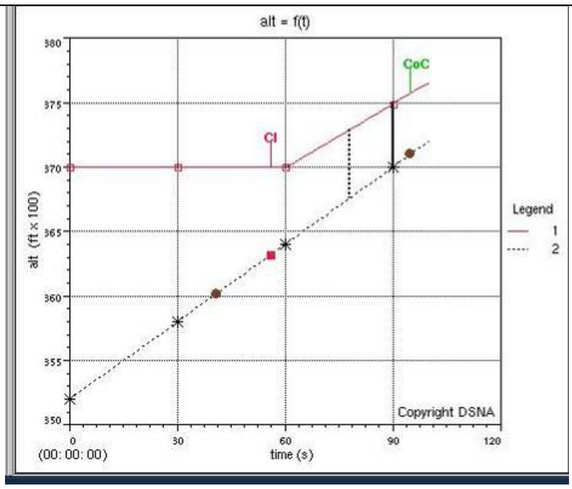
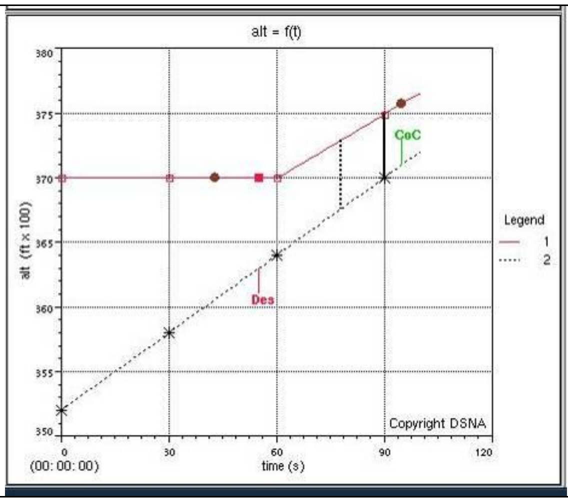
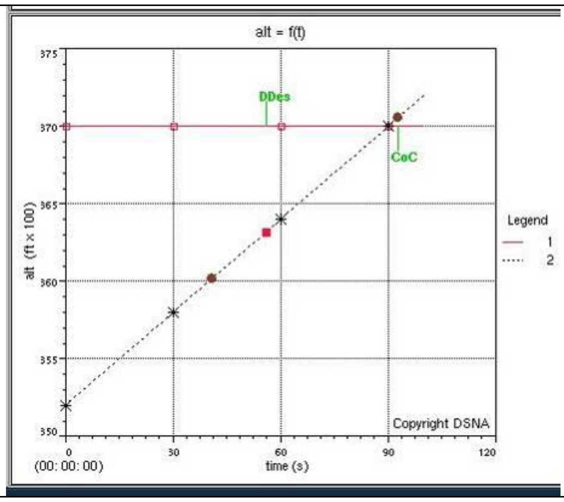
Aircraft 1	Aircraft 2
	
CPA:0NM/500 ft	

Figure 53: One aircraft level, intruder climbing from below, with TCAS contribution, aircraft 1 with Vs limitation at 1000 fpm

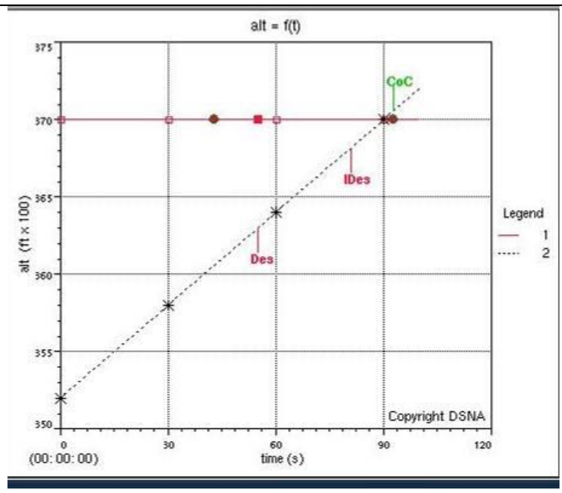
The vertical separation at CPA is 500 ft.

The following figure shows the same encounter with a climb inhibition for the upper aircraft.

Aircraft 1



Aircraft 2



CPA:0NM/0 ft

Figure 54: One aircraft level, intruder climbing from below, with TCAS contribution, aircraft 1 with climb inhibition

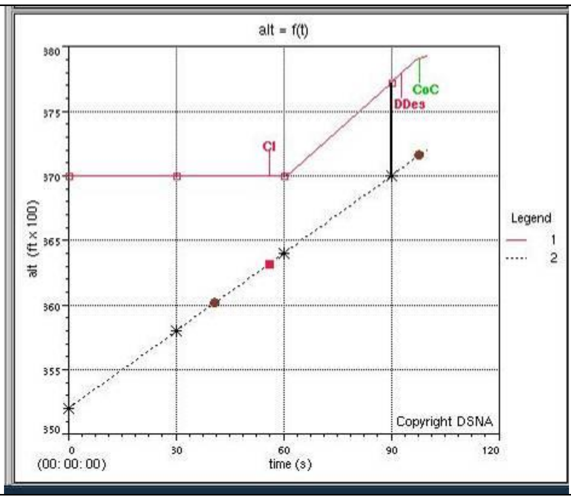
The upper aircraft receives a "monitor vertical speed" RA. The lower aircraft receives a "Descend" RA, followed by an "increase descend" RA.

The encounter results in an NMAC. **Therefore, again, it seems that climbing even with a limited vertical rate is better than having the climb inhibition**.

The following figures show the same situation, but this time the intruder aircraft is not equipped with TCAS.

The first figure shows the encounter with no limitation nor inhibition.

Aircraft 1



CPA:0NM/335 ft

Figure 55: One aircraft level, intruder climbing from below with TCAS contribution and no limitation

The upper aircraft receives a "climb" RA.

With no limitation, the vertical separation at CPA is 600 ft.

With a limitation to climb to 1000 fpm, the result is identical to what is shown above in figure 14.

The following figure shows the same encounter with a climb inhibition for the upper aircraft.

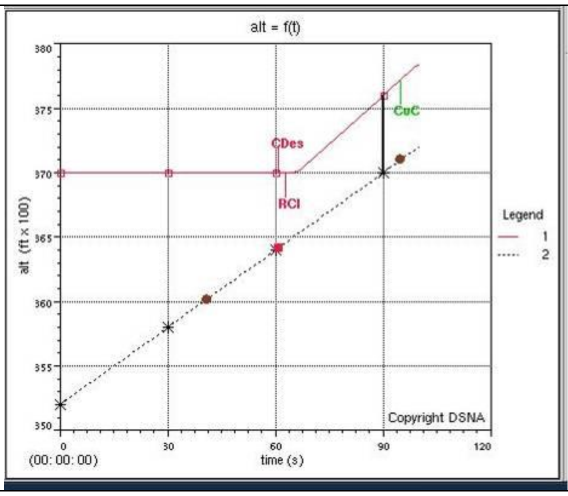
Aircraft 1

CPA:0NM/600 ft

Figure 56: One aircraft level, intruder climbing from below, with TCAS contribution, aircraft 1 with climb inhibition

In this situation, the upper aircraft first receives a crossing descend RA, which is followed by reversal climb RA, despite the climb inhibition. **Therefore, it seems that climb inhibitions are not properly handled in the CAS logic, and should therefore be avoided as much as possible.**

6 Conclusions

The validation has shown that with a delay of response to RAs equal to or below 4 s, the automatic responses to RAs bring significant operational and safety benefits to TCAS II performance, whatever the assumption in terms of equipage and compliance rate.

Furthermore, an initial investigation was conducted on the possibility to enhance the TCAS logic by reducing the initial RA time thresholds thanks to the availability of the automatic response to RAs. Simulations were conducted using a modified TCAS logic including initial RA time thresholds reduced by 3 seconds and an automatic response to RAs after 2 seconds instead of the expected 5 seconds. The reduction of TCAS initial RA time threshold associated to a shortened delay of response to RAs brings additional operational benefits when compared to other AP/FD scenarios, increasing the compatibility with ATC and the acceptability by pilots of the triggered RAs. This solution seems therefore a promising solution.

Finally, a case study was conducted on some encounters to evaluate the impact of providing the TCAS logic with the indication that own aircraft is vertical performance limited and cannot achieve the nominal climb rate of 1,500 fpm for a “Climb” RA. It was also observed through the investigation of several operationally realistic situations that during high altitude encounters it is preferable to perform a manoeuvre even with a vertical rate lower than that expected by TCAS rather than using the existing RA climb inhibition feature. Additionally this study found that climb inhibitions are not properly handled in the CAS logic, and should therefore be avoided as much as possible.

7 References

[1] AVAL, European safety-encounter model incorporating VLJ operations – AVAL/WA4/30/D, Version 1.1, May 2009

[2] ASARP, WP4 – 'Final report on the analysis of airborne recorded data and pilot model specification' – EUROCONTROL Mode S & ACAS Programme – ASARP/WP4/19/D, version 1.0, April 2005

[3] SESAR 4.8.2.2 – Validation Plan – Deliverable 4.8.2.D02, edition 00.01.00, September 2010

[4] SESAR 4.8.2.1 – Validation Report – Deliverable 4.8.2.D03, edition 00.01.00, May 2010

8 Appendix A: General description of OSCAR displays

The OSCAR test bench is a set of integrated tools to prepare, execute and analyse scenarios of encounters involving TCAS II equipped aircraft. It includes an implementation of the TCAS II Version 7.0.
For each encounter, the most relevant results of the TCAS II simulations are provided by screen dumps of OSCAR windows. Several types of information are displayed:

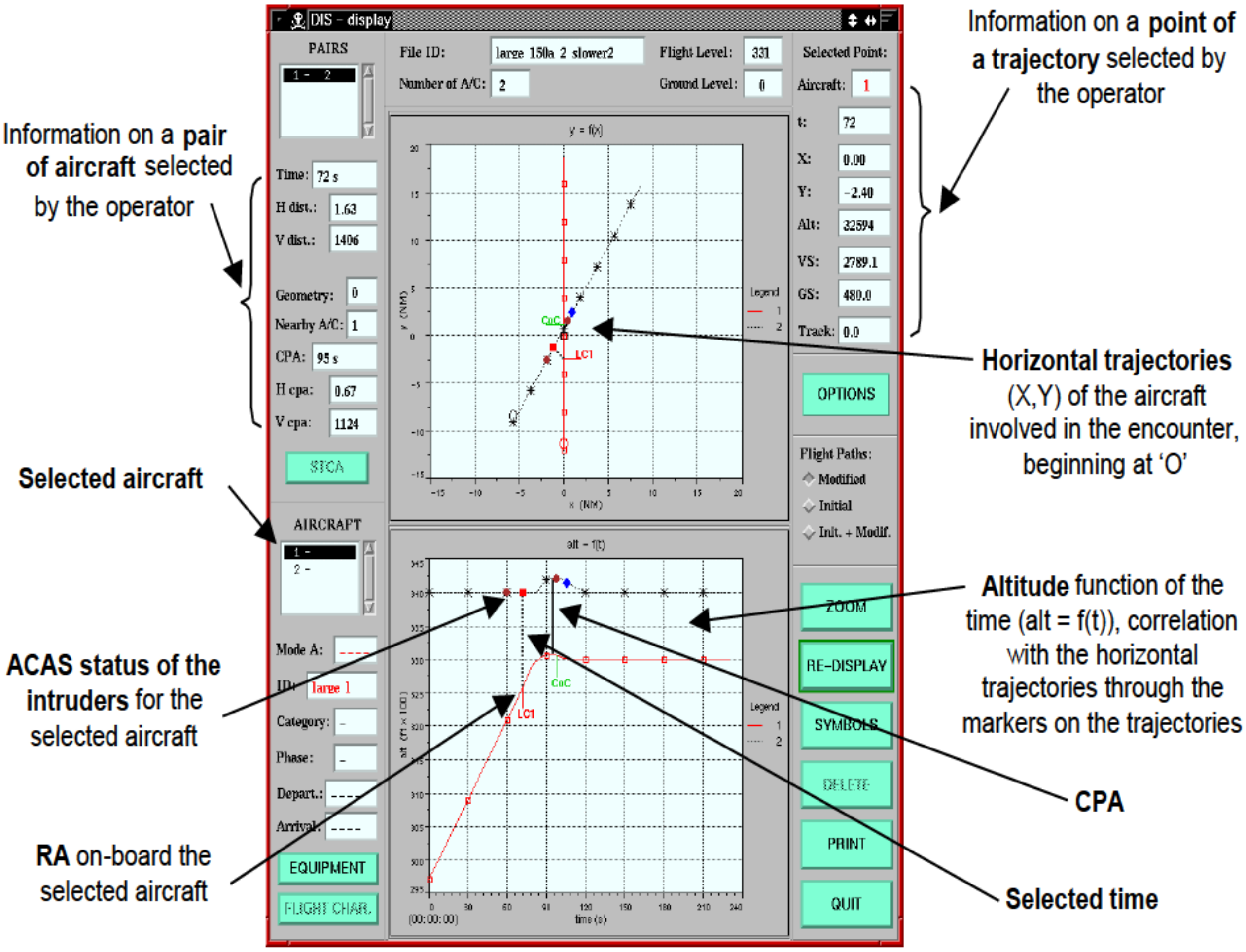


Figure 57: OSCAR display

TCAS II simulation results are displayed on the horizontal and vertical trajectories. RAs are displayed on the trajectory of the selected aircraft and ACAS status of the intruders on their respective trajectories, according to the symbols and labels described hereafter:

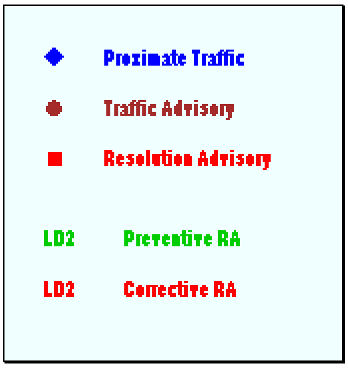


Figure 58: OSCAR symbols

Label	Advisory
CoC	Clear of Conflict
Cl	Climb (1500 fpm)
DDes	Don’t Descend
LD5 / LD1 / LD2	Limit Descent 500 / 1000 / 2000 fpm
Des	Descend (1500 fpm)
DCl	Don’t Climb
LC5 / LC1 / LC2	Limit Climb 500 / 1000 / 2000 fpm
CCl	Crossing Climb (1500 fpm)
RCl	Reverse Climb (1500 fpm)
ICl	Increase Climb (2500 fpm)
MCl	Maintain Climb
CDes	Crossing Descend (-1500 fpm)
RDes	Reverse Descent (-1500 fpm)
IDes	Increase Descent (-2500 fpm)
MDes	Maintain Descent

Table 8: OSCAR labels