



Safety benefits of ACAS in the future European ATM environment with Very Light Jets – AVAL final report

ACAS on VLJs and LJs – Assessment of safety Level AVAL Project

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Executive Summary

The 'Airborne Collision Avoidance System (ACAS II)' is now an integral part of ATM operations in Europe, and represents an essential element of safety in the airspace. The carriage of ACAS II has been mandated in Europe by January 2005 for civil fixed-wing turbine-engined aircraft having a Maximum Take-Off Mass (MTOM) exceeding 5,700 kg or a maximum approved passenger seating configuration of more than 19.

The advent of Very Light Jets (VLJ) and small Light Jets (LJ) (i.e. jet aircraft weighing less than 5,700 kg) means that in the near future there may be a significant population of aircraft which fall outside the thresholds of the current European ACAS II mandate and need to be integrated into the European Air Traffic Management (ATM) environment.

EUROCONTROL has initiated the AVAL project (ACAS on VLJs and LJs – Assessment of safety Level) to assess the impact of VLJ and LJ operations on the safety benefits delivered by ACAS II, and whether it is appropriate to extend the ACAS II mandate to include these aircraft.

Since it has been suggested in some quarters that the appropriate level of ACAS equipage for VLJs and small LJs is TCAS I (an ACAS I providing only traffic advisories (TAs) on a cockpit display of traffic information) rather than TCAS II (an ACAS II providing resolution advisories (RAs) in addition to TAs and a cockpit display of traffic information), the AVAL project also evaluated the option of a TCAS I equipage of VLJ and small LJ aircraft (as an alternative to ACAS II equipage).

The evaluation conducted during the project had a specific focus on the safety aspects, but not exclusively. Other elements that were also brought to light and examined include operational, economic and technical aspects.

The cornerstone of the safety evaluation was the encounter model-based methodology used in the development of the ACAS II performance standards and in past evaluations of ACAS II performance and safety benefits in Europe. The existing models were adapted to simulate the future European ATM environment where a significant proportion of VLJ and small LJ operations will occur (viz. in the '2015 timeframe'), as well as the possible pilots' responses to ACAS RAs onboard VLJ and small LJ aircraft. To evaluate the option of a TCAS I equipage by VLJs and small LJs (as an alternative to ACAS II equipage), a model of visual acquisition has also been implemented, and the evasive manoeuvres possibly resulting from visual acquisition prompted by TCAS I were modelled for use in the simulations.

With the proportion of VLJ and small LJ operations assumed in the study, there will be a small influence on the overall ACAS II performance in the 2015 European airspace. The study results demonstrated that the extension of the current European ACAS II mandate to these aircraft would slightly improve the mid-air collision risk reduction afforded by ACAS II (at airspace level).

In addition, from the perspective of each VLJ or LJ aircraft, the study results demonstrated a net safety benefit when equipping with ACAS II: almost halving the risk of mid-air collision. This benefit is considerable even when only the most common VLJs and small LJs aircraft equip and even greater when less common VLJs and LJs equip as well.

Regarding the option of a TCAS I equipage of VLJ and small LJ aircraft (as an alternative to ACAS II equipage), the study demonstrated that TCAS I equipage can undoubtedly enhance the prospect of visually acquiring a collision threat but only in certain scenarios. It was also highlighted that the enhanced probability of visually acquisition ironically brings with it an increase in the probability of simultaneous, potentially incompatible, evasive manoeuvres. This effect is most marked against threats which are equipped with ACAS II, and might be detrimental to the overall safety in the airspace.

The study results also show that, when considering the efficiency of the evasive manoeuvres prompted by TCAS I, their likelihood of occurrence, as well as any resulting deviations, TCAS I does not perform as well as ACAS II, and markedly so. The study finally highlighted how much the TCAS I performance is much more influenced (than that of ACAS II) by the meteorological conditions and the pilot's ability to execute an effective avoidance manoeuvre. It is worth noting that it was beyond the scope of the study to fully quantify the potential safety benefits delivered by TCAS I although some aspects of TCAS I operation have been investigated. Notably the study produced no evidence that TCAS I equipage was better than no ACAS equipage.

Finally, the TCAS I option would require specific attention from the regulatory standpoint as no framework currently exists for TCAS I carriage in Europe, unlike for ACAS II carriage.

Overall the project findings support the conclusion that modifying the criteria for ACAS II equipage in Europe so as to include at least the mainstream VLJs, and preferably all light jets under 5,700 kg (not subject to the current mandate), is the most effective option for safe and effective VLJ operations in Europe. The project also concluded that equipping VLJs and other light jets under 5,700 kg with TCAS I is the least preferred option. Indeed, it might be better not to equip these aircraft with TCAS I in order to minimise disruption of ATC and ACAS II operations.

In light of these findings, it is recommended to extend the European ACAS II mandate to include all civil fixed-wing turbine-engined aircraft with a maximum cruising speed of over 250 kt.

It is also recommended that proper attention be given to ACAS II training for pilots of light jets under 5,700 kg regardless of the extension date of the European ACAS II mandate (as some aircraft might equip sooner on a voluntary basis).

Finally, the study produced no evidence on which to base any recommendation for equipping light jets under 5,700 kg with TCAS I. Should any operator decide to equip with TCAS I (before the extension of the ACAS II mandate), it is recommended that the safety benefits of TCAS I in the European airspace be demonstrated and quantified, with a particular focus on the potential impact on the mid-air collision risk reduction delivered by ACAS II.

Table of Contents

EXECUTIVE SUMMARY.....	III
GLOSSARY	VII
ACRONYMS	IX
1. INTRODUCTION.....	1
1.1. BACKGROUND AND CONTEXT	1
1.2. STUDY SCOPE AND OBJECTIVES	1
1.3. DOCUMENT OVERVIEW	2
2. BACKGROUND ON AIRBORNE COLLISION AVOIDANCE	3
2.1. THE 'SEE-AND-AVOID' PRINCIPLE	3
2.2. AIRBORNE COLLISION AVOIDANCE SYSTEMS.....	3
2.3. THE ROLE OF ACAS II IN THE ATM SYSTEM.....	5
2.4. EVALUATION OF ACAS II PERFORMANCES IN EUROPE.....	6
2.5. KEY FACTORS INFLUENCING THE SAFETY BENEFITS OF ACAS II.....	7
2.6. CURRENT STATE OF TCAS I	8
3. ANALYSING AND MODELLING THE FUTURE ATM ENVIRONMENT WITH VLJ AIRCRAFT.....	10
3.1. DEFINITION OF VLJs	10
3.2. PERFORMANCE OF VLJs AND SMALL LJs.....	11
3.3. FORESEEN OPERATIONS OF VLJs AND SMALL LJs IN EUROPE	12
3.3.1. Nature of possible VLJ operations	12
3.3.2. Options for VLJ and small LJ type of operations	13
3.3.3. Growth forecast for VLJs and small LJs	14
3.4. MODELLING ACAS II OPERATION BY PILOTS OF VLJs AND SMALL LJs	14
3.4.1. Background of VLJ and small LJ pilots.....	14
3.4.2. Observed pilot responses to RAs in larger commercial aircraft	15
3.4.3. Probable pilot responses to RAs on board VLJs and small LJs.....	16
3.5. MODELLING TCAS I OPERATION BY PILOTS OF VLJs AND SMALL LJs	17
3.5.1. Visual acquisition prompted by TCAS I	17
3.5.2. Evasive manoeuvre following visual acquisition	18
3.6. MODELLING SAFETY-RELATED ENCOUNTERS CONSEQUENT TO FUTURE VLJ OPERATIONS IN EUROPE	19
3.6.1. General.....	19
3.6.2. Building of the pre-VLJ and post-VLJ European safety encounter models	20
3.6.3. Overview of the AVAL safety encounter model	22
4. EVALUATION OF THE IMPLICATIONS OF COLLISION AVOIDANCE EQUIPAGE OF VLJS AND SMALL LJS.....	24
4.1. EVALUATION OF THE SAFETY IMPLICATIONS OF ACAS II EQUIPAGE	24
4.1.1. Scope and approach.....	24
4.1.2. Operational scenarios under evaluation	24
4.1.3. Effect on the ACAS II safety benefits from an airspace perspective	25
4.1.4. Safety benefits of ACAS II equipage from an airborne perspective	27
4.2. EVALUATION OF THE SAFETY IMPLICATIONS OF TCAS I EQUIPAGE.....	29
4.2.1. Scope and approach.....	29

4.2.2. Operational scenarios under evaluation	29
4.2.3. Comparative analysis of the safety benefits of TCAS I and TCAS II equipage	30
4.2.4. Extent of the evasive manoeuvres prompted by TCAS I compared to TCAS II resolution advisories	31
4.2.5. Efficiency of the evasive manoeuvres prompted by TCAS I compared to TCAS II resolution advisories	32
4.3. PROS AND CONS OF COLLISION AVOIDANCE EQUIPAGE OF VLJS AND SMALL LJS	34
4.3.1. Options for ACAS equipage	34
4.3.2. Safety considerations	36
4.3.3. Operational considerations	37
4.3.4. Economic considerations	37
4.3.5. Technical considerations	38
5. CONCLUSIONS AND RECOMMENDATIONS	39
5.1. MAIN ACHIEVEMENTS AND FINDINGS	39
5.1.1. General	39
5.1.2. Safety evaluation approach	39
5.1.3. Main safety evaluation results	39
5.1.4. Other study results	40
5.2. RECOMMENDATIONS	41
6. REFERENCES	42
6.1. AVAL INTERNAL REFERENCES	42
6.2. EXTERNAL REFERENCES	42
APPENDICES	I
A. BACKGROUND ON VLJS AND SMALL LJS	II
A.1. EXAMPLES OF VLJS	II
A.2. EXAMPLES OF LJS UNDER 5,700 KG	IV
A.3. SALES AND GROWTH FORECAST OF VLJS AND SMALL LJS	V
B. BACKGROUND ON TCAS I AND TCAS II LOGICS	VI
B.1. GENERAL	VI
B.2. TCAS I LOGIC	VI
B.3. TCAS II LOGIC VERSIONS	VI
B.4. SUMMARY OF TCAS ALERT THRESHOLDS	VII
C. MODELS OF VLJ AND LJ PILOT'S RESPONSE TO RAS	VIII
C.1. EXISTING PILOT RESPONSE MODELS	VIII
C.2. KEY ASSUMPTIONS FOR PILOTS OF VLJS AND SMALL LJS	IX
C.3. SUMMARY OF PILOT'S RESPONSE MODELS FOR VLJS AND SMALL LJS	X
D. MODEL OF VISUAL ACQUISITION PROMPTED BY TCAS I	XI
D.1. FACTORS AFFECTING VISUAL ACQUISITION RATE	XI
D.2. PROBABILITY OF VISUAL ACQUISITION	XI
D.3. CROSS-SECTIONAL AREA OF THE THREAT	XII

Glossary

ACAS	Airborne Collision Avoidance System – a system standardised in the ICAO SARPs that uses transponder replies from other aircraft to warn the pilot of a risk of impending collision. Three types of ACAS been defined by ICAO as follows: <ul style="list-style-type: none">- ACAS I – an ACAS which provides information as an aid to “see and avoid” action but does not include the capability for generating resolution advisories (RAs).- ACAS II – an ACAS which provides vertical resolution advisories (RAs) in addition to traffic advisories (TAs).- ACAS III – an ACAS which provides vertical and horizontal resolution advisories (RAs) in addition to traffic advisories (TAs). ACAS I is not intended for international implementation and standardization by ICAO. ICAO defines which aeroplanes required to be equipped with an ACAS II. No requirements exist for ACAS III implementation at ICAO level.
ACASA project	ACAS Analysis – a project commissioned by EUROCONTROL in support of the mandate for the carriage of ACAS II in Europe, before implementation of RVSM. Work Package 1 of ACASA investigated the safety of ACAS II and developed a European safety encounter model based on pre-RVSM radar data, i.e. the ACASA safety encounter model.
ASARP project	ACAS Safety Analysis post-RVSM Project – a project commissioned by EUROCONTROL to investigate the safety of ACAS II following the introduction of RVSM in Europe. The ASARP project used post-RVSM radar data to update the ACASA safety encounter model and produced the post-RVSM European safety encounter model, viz. the ASARP safety encounter model.
CPA	Closest Point of Approach – point of minimum physical distance between two aircraft (slant range) involved in an encounter.
Close encounter	For the purpose of the study, a pair of aircraft for which, at some point, the horizontal separation is less than 0.5 NM and simultaneously the vertical separation is less than 200ft.
Encounter	A traffic situation involving two (or more) aircraft. Hereafter, an encounter always refers to pair-wise encounter (involving two aircraft only). Furthermore, an encounter can either be an ‘actual’ encounter extracted from radar data recordings according to agreed capture criteria, or an encounter generated from a safety encounter model.
HMD	Horizontal Miss Distance – horizontal distance between two aircraft involved in an encounter at the ‘Closest Point of Approach’ (CPA).
LJ	Light Jet – For the purpose of the study, turbofan-powered aircraft with a maximum takeoff mass between 4,500 kg (10,000 lbs) and 9,000 kg (20,000 lbs). The industry long ago defined the upper end of the “light” segment at less than 20,000 lbs, but with the development of the “very light jet” segment, a lower bound is now required for the “light jet” segment” at more than 10,000 lbs. For the study purpose, there is a also need to distinguish between the light jets with a maximum takeoff mass below and above 5,700 kg (12,500 lbs), i.e. the small LJs currently not covered by the European ACAS II mandate and the other LJs.
NMAC	Near Mid Air Collision – a pair of aircraft for which, at some point, the horizontal separation is less than 500ft and simultaneously the vertical separation is less than 100ft.
Pilot response model	A set of parameters which characterise the pilot responses to ACAS II RAs and which can be used to simulate pilot behaviour during ACAS II simulations. The ICAO ACAS II SARPs defines the nominal response to initial RAs, known as the ‘standard pilot response’, used by the ACAS II logic to determine the proper resolution of a given collision risk.

	<p>In the early stages of ACAS II implementation in Europe, the ACASA project identified two distinct groups of actual pilot responses to RAs, i.e. an 'aggressive pilot response' and a "slow pilot response".</p> <p>A few years after, the ASARP project established the 'typical pilot response' applicable to current ACAS II operations in Europe.</p>
RA	Resolution Advisory – an ACAS II alert providing advice to a pilot on how to modify or regulate his vertical speed to avoid a potential mid-air collision.
Risk ratio	<p>The ratio of the risk of mid-air collision when ACAS II is deployed to the risk that would exist without ACAS II.</p> <p>A risk ratio of 0% would indicate a perfect system that would eliminate the risk of collision; a risk ratio of 100% would indicate an ineffective system that would make no change to the risk of collision</p>
Safety encounter model	<p>A mathematical model which reproduces the distributions and interdependencies of the parameters characterising risk bearing encounters likely to occur in ATM operations.</p> <p>The encounters that matter are those in which (at least) two aircraft are on a close encounter course in which there exist a risk of mid-air collision or in which the response of pilots to RAs can result in a risk of mid-air collision.</p> <p>The AVAL project used recent radar data recordings to update the ASARP safety encounter model and produced the pre-VLJ European safety encounter model for 2008, as well as the post-VLJ European safety encounter model for 2015, viz. the 2008 and 2015 instances of the AVAL safety encounter model.</p>
SIRE project	<p>Safety Issue Rectification Extension – a project commissioned by EUROCONTROL to improve the TCAS II collision avoidance logic and specifically address TCAS II safety issues.</p> <p>The most notable of the issues addressed by the SIRE project have been the failure of TCAS to reverse some RAs when a reversal is required to resolve the collision threat (referred to as SA01), and the observation that, not infrequently, flight crews unintentionally manoeuvre in the wrong direction to a specific type of RA (referred to as SA-AVSA). The SIRE project also investigated the TCAS II performance in European TMAs providing up-to-date elements on the RA response rate by pilots. Finally, the SIRE project developed supporting material to progress with the mandatory carriage of TCAS II version 7.1 in Europe.</p>
Standard pilot response	The pilot response model described in the ACAS II SARPS and implicitly assumed in the ACAS II collision avoidance algorithms, viz. an initial delay of 5s before the pilot responds with an acceleration of 0.25g to achieve the required vertical rate.
TA	Traffic Advisory – an ACAS alert warning the pilot of the presence of another aircraft that may become the subject of an RA in case of an ACAS II system.
TCAS	<p>Traffic Alert and Collision Avoidance System – an aircraft equipment that is an implementation of an ACAS.</p> <p>Hereafter, reference is made to two kinds of TCAS equipment:</p> <ul style="list-style-type: none"> - TCAS II, version 7.0 or the future version 7.1 – the equipment that complies with the ICAO SARPS for ACAS II and whose operation is mandatory in Europe for civil fixed-wing turbine-engined aircraft having a Maximum Take-Off Mass (MTOM) exceeding 5,700 kg or a maximum approved passenger seating configuration of more than 19; and - TCAS I – an equipment that complies with the ICAO SARPS for ACAS I and whose operation is mandated in the USA for certain smaller aircraft.
VIP	Very Light Jet Integration Platform – a EUROCONTROL initiative to ensure a safe and efficient integration of the VLJs in the European ATM environment.
VLJ	Very Light Jet – For the purpose of the study, turbofan-powered aircraft with a maximum takeoff mass not exceeding 4,500 kg (10,000 lbs), certified for single pilot operations and that typically seat between 3 to 8 passengers.
VMD	Vertical Miss Distance – Vertical distance between two aircraft involved in an encounter at the 'Closest Point of Approach' (CPA).

Acronyms

ACAS	Airborne Collision Avoidance System
ACASA	ACAS Analysis
ASARP	ACAS Safety Analysis post-RVSM Project
ATC	Air Traffic Control
ATM	Air Traffic Management
AVAL	ACAS on VLJs and LJs – Assessment of safety Level
CAS	Collision Avoidance System
CPA	Closest Point of Approach
ECAC	European Civil Aviation Conference
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FL	Flight Level
GA	General Aviation
HF	Human Factors
HMD	Horizontal Miss Distance
IBAC	International Business Aviation Council
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
JAR	Joint Aviation Regulations
LJ	Light Jet
MTOM	Maximum Take-Off Mass
NBAA	National Business Aviation Association
NMAC	Near Mid-Air Collision
RA	Resolution Advisory
RF	Radio Frequency
RFL	Requested Flight Level
RVSM	Reduced Vertical Separation Minima
SARPs	Standards And Recommended Practices
SIRE	Safety Issue Rectification Extension
TA	Traffic Advisory
TCAS	Traffic Alert and Collision Avoidance System
TLS	Target Level of Safety
TMA	Terminal Control Area
VFR	Visual Flight Rules
VIP	Very Light Jets Integration Platform
VLJ	Very Light Jet
VMD	Vertical Miss Distance
WA	Work Area

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1. Introduction

1.1. **Background and context**

- 1.1.1. The ‘**Airborne Collision Avoidance System (ACAS II)**’ is a last resort safety net against the risk of mid-air collision that operates independently of ATC. In Europe, the carriage of ACAS II is currently mandatory for civil fixed-wing turbine-engined aircraft having a Maximum Take-Off Mass (MTOM) exceeding 5,700 kg or a maximum approved passenger seating configuration of more than 19.
- 1.1.2. The advent of Very Light Jets (VLJ) and small Light Jets (LJ) (*i.e.* jet aircraft weighing less than 5,700 kg) means that in the near future there may be a significant population of aircraft which fall outside the thresholds of the current European ACAS II mandate and need to be integrated into the European Air Traffic Management (ATM) environment.
- 1.1.3. To ensure the safe and efficient integration of VLJs in the European ATM environment, EUROCONTROL has set in place the ‘**Very Light Jets Integration Platform (VIP)**’. The platform has initiated the dialogue amongst stakeholders around the issues related to such integration, including the potential requirement for VLJs to be equipped with a collision avoidance system.
- 1.1.4. As ACAS II is now an integral part of ATM operations in Europe, and represents an essential element of safety, there is a need to identify and quantify the effect of an increased proportion of VLJs and LJs under 5,700 kg on the existing performance of the ACAS II safety net. The safety implications if VLJs and small LJs are eventually not required to be equipped with ACAS II need to be evaluated, as well as the potential safety benefits of extending the current ACAS II mandate to the VLJs and small LJs.
- 1.1.5. In some quarters it has been suggested that the appropriate level of equipage for VLJs and small LJs is TCAS I (an ACAS I providing only traffic advisories on a cockpit display of traffic information) rather than TCAS II (an ACAS II providing resolution advisories in addition to traffic advisories and a cockpit display of traffic information). The TCAS I equipage of VLJs and small LJs therefore merits specific attention.

1.2. **Study scope and objectives**

- 1.2.1. The objective of the present study was to perform a comprehensive assessment of the impact of VLJ and LJ operations on the safety benefits delivered by ACAS II in the European environment, *i.e.* the AVAL study.
- 1.2.2. **AVAL** stands for **ACAS on VLJs and LJs – Assessment of safety Level**.
- 1.2.3. The study was initiated by the Mode S & ACAS Programme of EUROCONTROL, and was conducted in two phases by Egis Avia (ATM domain, SSS Skill Unit) with the support of DSNA/DTI and QinetiQ in Phase 2 of the study.
- 1.2.4. The safety benefits of ACAS II have been demonstrated to be very sensitive to a set of factors that include the traffic characteristics in the airspace in which it is being operated, the level of ACAS II equipage in the airspace, as well as the actual pilot’s response to RAs.

- 1.2.5. With the prospect of an increase in the number of light jet aircraft not subject to the European ACAS II mandate, all these areas need to be investigated. This was the purpose of the Phase 1 of the study, which concluded there was a need to quantify the safety implications of equipping, or not, VLJ and small LJ aircraft with ACAS II ([D7]).
- 1.2.6. Phase 2 of the study concentrated, therefore, on the evaluation the potential safety benefits of ACAS II equipage, as well as the impact on the overall performance of ACAS II in the future European environment where a significant proportion of VLJ and small LJ operations will occur (viz. in the '2015 timeframe' in the context of the study). The option of a TCAS I equipage of VLJ and small LJ aircraft (as an alternative to ACAS II equipage) was also evaluated, assuming that TCAS I alerts would aid visual acquisition of collision threats by pilots exercising the 'see-and-avoid' procedure.
- 1.2.7. Based on a comprehensive set of simulation results, the study eventually determined the best approach for the VLJ and small LJ aircraft in terms of ACAS equipage.

1.3. Document overview

- 1.3.1. Following this introduction chapter, Chapter 2 provides background information on airborne collision avoidance principles and systems, i.e. the 'see-and-avoid' procedure, the ACAS II and ACAS I systems and their contribution to safety.
- 1.3.2. Chapter 3 is an analysis of the available literature on VLJ with regard to their expected performances, their foreseen type of operations and pilot's background. This analysis was the preamble to the development of a set of models that aim to simulate the future European ATM environment with VLJs. The chapter thus reviews the key assumptions used during this modelling process.
- 1.3.3. Chapter 4 presents the main simulation results and discusses the safety benefits that can be expected from equipping VLJs and small LJs with either ACAS II or an ACAS I. The chapter ends with an evaluation of the various options of ACAS equipage of VLJs and small LJs taking into account not only safety considerations, but also operational, technical and economic considerations.
- 1.3.4. Finally, Chapter 5 draws conclusions on the present study, and provides a set of recommendations to secure the continued safety benefits of ACAS II in the future European ATM environment with VLJs, while ensuring safe and cost-effective VLJ operations in that environment.

2. Background on airborne collision avoidance

2.1. *The 'see-and-avoid' principle*

- 2.1.1. The exercise of 'see-and-avoid' is required by ICAO Annex 2 – Rules of the Air ([ANN2]). See-and-avoid is the principle by which the pilot of an aircraft conducts a continuous visual scan of the surrounding airspace in order to detect hazards including other traffic, that might constitute a threat to his own aircraft, in a timely manner and undertake any avoidance manoeuvre that may be necessary in order to assure the safety of his own aircraft – see, for example, the guidance given by the UK CAA and the FAA ([CAA] [FAA]).
- 2.1.2. Since the early 1970s, much evidence has emerged that suggests that 'see-and-avoid' is insufficiently effective as a mitigation of the risk of mid-air collision – see, for example, the research reports published by the Australian Bureau of Air Safety Investigation about the 'limitations of the see-and-avoid principle' ([BASI]). Much of the evidence is circumstantial or anecdotal (and therefore qualitative) and most is primarily concerned with see-and-avoid without the aid of a traffic display or alerting device.
- 2.1.3. The principle of 'see-and-avoid' is therefore very much a last line of defence against the risk of mid-air collision and it is in no way a substitute for Air Traffic Control (which aims to prevent collision, through the process of separation provision, by issuing clearances or instructions to controlled flights) or ACAS.

2.2. *Airborne collision avoidance systems*

- 2.2.1. ICAO defines ACAS as "*an aircraft system based on secondary surveillance radar (SSR) transponder signals which operates independently of ground-based equipment to provide advice to the pilot on potential conflicting¹ aircraft that are equipped with SSR transponders*" (cf. ICAO Annex 2 – Rules of the Air).
- 2.2.2. There are various levels of ACAS capability currently implemented:
 - ACAS II provides two levels of alert to the pilot: Traffic Advisories (TAs) and Resolution Advisories (RAs) in the vertical plane;
 - ACAS I provides TAs only and does not recommend any manoeuvres.
- 2.2.3. ACAS II is specified by ICAO Annex 10, volume IV through the Standards And Recommended Practices (SARPs) for Surveillance and Collision Avoidance Systems ([ACAS]), and currently the only implementation is TCAS II Version 7

¹ In the context of ACAS, 'conflicting aircraft' is related to a risk of collision and not to the predicted violation of the separation minima applicable in the airspace by the Air Traffic Control (ATC) services.

specified in RTCA Minimum Operational Performance Standards (MOPS)² ([TCAS2], [TCAS3]).

2.2.4. There is currently only one implementation of ACAS I, viz. TCAS I. TCAS I is specified in RTCA MOPS ([TCAS1]) – SARPs for ACAS I are published in ICAO Annex 10, volume IV but are limited to interoperability with ACAS II and interference limiting issues. No international implementation of ACAS I is planned at the ICAO level, but TCAS I is mandated in the USA for certain smaller aircraft.

2.2.5. Both ACAS II and ACAS I can generate a TA when a tracked intruder is diagnosed as being on a potential collision course. A TA is a cue for the flight crew to try to visually acquire the potential threat with the aid of the traffic display and, in the case of ACAS II only, to prepare for a possible RA (cf. Appendix B for further details on the ACAS II and ACAS I logics).

2.2.6. An RA is an indication to the pilot on how to modify or regulate his vertical speed so as to avoid a potential mid-air collision. It is either “*a manoeuvre intended to provide separation from all threats; or a manoeuvre restriction intended to maintain existing separation*” (cf. ICAO SARPS Volume IV).³ A coordination process also exists by which two ACAS II-equipped aircraft select compatible RAs by the exchange of resolution advisory complements (see e.g. Figure 1).

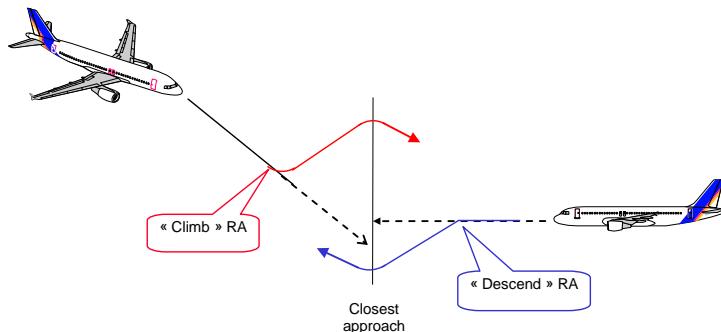


Figure 1: Illustration of a coordinated ACAS II resolution

2.2.7. As stated in the ICAO PANS-OPS, in the event of an RA, pilots have to respond immediately by following the RA as indicated, unless doing so would jeopardize the safety of the aeroplane. The nominal response to initial RAs is defined by the ICAO ACAS II SARPS as reaching a vertical speed as required by the RA (e.g., 1,500 fpm for a Climb RA) within a delay of 5 seconds and with a vertical acceleration of 0.25 g.

² The current version of the TCAS II MOPS was published in June 2008. The document is RTCA DO-185B. A change document was approved in July 2009. This latest revision to the system is referred to as "Version 7.1". These MOPS have also been published by EUROCAE as ED-143.

While these revised MOPS are now recognized and accepted by US and European regulatory authorities, current mandates for TCAS equipage for most civilian aircraft still cite DO-185A compliant systems. The version of these systems is referred to as "Version 7.0".

³ A guide to the use of ACAS II and its functionality can be found in the EUROCONTROL ACAS brochure ([ACA4]).

2.3. ***The role of ACAS II in the ATM system***

- 2.3.1. The role of ACAS II is to mitigate the risk of mid-air collision. It serves as a last resort safety net irrespective of any separation standards.
- 2.3.2. Naturally the safety benefits of ACAS II depend on the efficacy of the collision avoidance system (CAS) logic, but is also affected by the environment in which ACAS II is being operated, the way it is operated by the pilots, and the possible interaction between ACAS II and other lines of defence against the risk of mid-air collision, i.e. clearances and instructions issued by ATC in controlled airspace and the manoeuvres resulting from the application of the see-and-avoid principle.
- 2.3.3. ACAS II is not designed, nor intended, to achieve any specific 'Target Level of Safety' (TLS). Instead, the safety benefit deriving from the deployment of ACAS II is expressed in terms of reduction in the risk of mid-air collision.
- 2.3.4. This reduction is measured through a 'risk ratio' which compares the risk of a 'Near Mid-Air Collision⁴' (NMAC) both with and without ACAS.⁵ Any risk ratio that is less than unity indicates that the deployment of ACAS II reduces the risk of collision and thus provides a safety benefit.

$$\text{risk ratio} = \frac{\text{NMAC rate with ACAS II}}{\text{NMAC rate without ACAS II}}$$

- 2.3.5. ICAO has defined a set of target 'risk ratios' for different scenarios of aircraft equipage in a theoretical airspace described by a 'safety encounter model'⁶ (cf. ICAO SARPs ([ACAS])). An essential property of the 'safety encounter model' is the level of risk (the NMAC rate) in the absence of ACAS II, usually given per flight-hour. This underlying NMAC rate is crucial to the determination of the risk that remains when ACAS II is being operated.
- 2.3.6. In the context of this study, the notion of 'close encounter ratio' has also been introduced, in order to compare the safety benefits of ACAS II with the 'see-and-avoid' actions of the pilots assisted by TCAS I alerts. This 'close encounter ratio' compares the number of 'close encounters'⁷ with and without the effect of the evasive manoeuvres prompted by TCAS I (cf. section 4.2.3 for further details).

⁴ An NMAC is defined as a pair of aircraft for which, at some point, the horizontal separation is less than 500ft and simultaneously the vertical separation is less than 100ft.

⁵ 'NMAC' is used as a surrogate for 'collision' in the analysis, as it is an objective measure that is independent of the physical size of specific aircraft types. In such encounters the separation is so small that it can be assumed that whatever separation does exist is fortuitous, in which case the ratio of NMACs is equivalent to the ratio of collisions.

⁶ The ICAO encounter model is derived from a blend of different airspaces. While not atypical it does not represent any specific airspace, and is intended primarily as a tool for comparing different CAS logic implementations of the ACAS SARPs.

⁷ In the context of the present study, a 'close encounter' is defined as a pair of aircraft for which, at some point, the horizontal separation is less than 0.5 NM and simultaneously the vertical separation is less than 200ft.

2.4. Evaluation of ACAS II performances in Europe

2.4.1. ICAO states that “ACAS can have a significant effect on ATC (Air Traffic Control). Therefore, the performance of ACAS in the ATC environment should be monitored” (cf. ICAO PANS-ATM – Procedures in regard to aircraft equipped with airborne collision avoidance systems (ACAS)).

2.4.2. In that prospect, the framework initiated at ICAO level when defining ACAS II minimum performances has been further developed through various ACAS-related projects in Europe. These projects include the ‘full-system safety study’ completed in the ‘ACAS Analysis’ (ACASA) project ([ACA1], [ACA2], [ACA3]) performed in support to the mandate for the carriage of ACAS II in Europe, and more recently the ‘ACAS Safety Analysis post-RVSM’ (ASARP) Project ([ASAR]) and the ‘Safety Issue Rectification Extension’ (SIRE) project ([SIRE]).

2.4.3. These projects delivered a comprehensive framework that includes a set of models allowing the replication of the environment in which ACAS II is being operated in Europe. These models consist essentially of a ‘European safety encounter model’, models of pilot reaction in response to RAs and a model of altimetry errors applicable in the European airspace.

2.4.4. These models make possible the determination of the ACAS II safety benefits in operationally realistic scenarios of ACAS II equipage and operation by simulating the behaviour of the Collision Avoidance System (CAS) logic on a large number of encounters representing, as a whole, the typical encounters between two aircraft that one can, or will, observe in the European airspace at different times.

- For typical operations in the European airspace in 2003, ACAS II has thus been demonstrated to provide a risk ratio of 22% ([SIRE+1]), i.e. it reduced the risk of mid-air collision by a factor of about five.
- Based on more recent observations of the traffic characteristics in Europe and RA compliance rate by the pilots, the present study evaluated the mid-air collision risk reduction afforded by ACAS II for the 2008 European environment at about two-thirds, i.e. a risk ratio of 32%.
- Finally, for anticipated typical operations in the post-VLJ European environment in 2015, the present study has estimated that with no change in the current rules for ACAS II equipage the risk ratio would be about 40% (cf. section 4.1.3 for further details), i.e. ACAS II would reduce the risk of mid-air collision by a factor of about two and a half.

2.4.5. As shown in Figure 2, the different risk ratios determined for the 2003, 2008 and 2015 timeframes evolved in a similar manner to the average number of flights per day in European airspace.

2.4.6. It is however worth noting that these risk ratios were determined using different operational assumptions in terms of traffic characteristics in the airspace, ACAS equipage of the fleet and ACAS operation by the pilots. As such they are not directly comparable, but rather reflect the effect of key influencing factors on the safety benefits delivered by ACAS II.

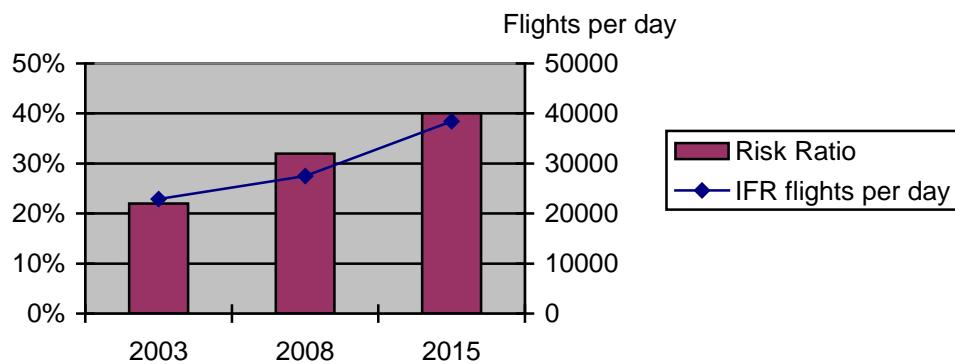


Figure 2: Evaluation of the safety benefits of ACAS II in Europe

2.4.7. Finally, it is worth mentioning that these risk ratios were determined using a conservative assumption regarding the underlying risk without ACAS II contribution in the airspace, of 3×10^{-7} NMACs per flight-hour, notwithstanding the traffic growth in the period. Under the assumption that the future airspace is “safer”, there is less opportunity for ACAS II to reduce the risk of mid-air collision. As a consequence these risk ratios are likely to underestimate the contribution of ACAS II in the current and future European airspace.

2.5. Key factors influencing the safety benefits of ACAS II

2.5.1. Previous safety studies have shown that ACAS II performance is very sensitive to the characteristics of the airspace: ostensibly small changes in ‘encounter’ types can have a significant effect on ACAS II performance. It is therefore essential to appropriately describe the properties of the safety-related encounters that can occur in the airspace of interest.

2.5.2. The level of ACAS II equipage in the airspace as implied by the applicable mandate, as well as the operating mode of ACAS II (i.e. standby, TA-only or TA/RA) by equipped aircraft, are also key factors that influence the safety benefits delivered by ACAS II. The transponder equipage of aircraft is also of significance since this has an effect on the ACAS II surveillance and on the altitude reports that aircraft can provide.

2.5.3. The pilot behaviour is another key factor for the safety benefits delivered by ACAS II and, in particular, the actual pilot response to the RAs issued by the CAS logic. Previous studies ([ACA1], [ASAR]) have demonstrated that the RAs should be followed, and followed promptly, for best benefits. These studies also defined several models of pilot’s response to RAs to reflect the evolution observed in the actual pilots’ behaviour in Europe (cf. section 3.4.2 for further details).

2.5.4. The possibility of the encounter being influenced by a late controller intervention (possibly incompatible with the sense of a coordinated RA) or being resolved by ‘see-and-avoid’ also needs to be considered. Previous studies ([ASAR]) have however indicated that visual acquisition has little influence on the overall mid-air collision risk reduction achieved by ‘typical pilots’ (who sometimes do not respond to their RAs) and for ‘conscientious pilots’ (who always follow their RAs).

2.5.5. Finally, for any vertical separation at closest approach diagnosed by ACAS II, there is a finite probability that this separation will be negated by altimetry error and that a collision occurs. This probability has to be calculated taking into account altimetry system performances and summed to determine the overall risk in a set of encounters.

2.6. Current state of TCAS I

2.6.1. From the regulatory standpoint, the deployment of TCAS I onboard VLJ aircraft in Europe (as an alternative to ACAS II) would require specific attention.

2.6.2. TCAS I was developed in the United States (US) for smaller, lower performance aircraft. Since 1997, TCAS I has been required by Federal Aviation Regulation for civil aircraft, which have ten to thirty passenger seats, in scheduled revenue service. Neither ICAO nor any ICAO member State, other than the US, requires ACAS I compliant equipment for some aircraft, although operations are permitted in some states.

2.6.3. Consequently there is currently no published guidance for the use of TCAS I in Europe. At this stage, only the existing ICAO provisions related to ACAS operation by pilots would apply, which notably state that "*pilots shall not manoeuvre their aircraft in response to traffic advisories only*" (cf. ICAO PANS-OPS – Operation of Airborne Collision Avoidance System (ACAS) Equipment).

2.6.4. With regard to the safety benefits of TCAS I equipage, and although in operation in the US airspace, no quantitative evidence is apparent on the mid-air collision risk reduction afforded by TCAS I. In particular the authors are not aware of any programmes in which pilots have provided inputs on TCAS I system performance or which have monitored or quantified TCAS I system performance.

2.6.5. Any safety benefit delivered by TCAS I would be in the form of an improvement in the probability of the visual acquisition of other aircraft that constitute a collision hazard, and the subsequent avoidance of these aircraft through 'see-and-avoid' exercised by the pilot following visual acquisition prompted by TCAS I. The shortcomings of visual acquisition, along with the fact that visually acquiring a threat is no guarantee that a collision will be avoided, are factors affecting the potential safety benefits of TCAS I.

2.6.6. The added value of visual acquisition prompted by TCAS I compared to un-alerted 'see-and-avoid' consists of the active surveillance of transponder-equipped aircraft (and only those) in the vicinity, the automatic detection of threat aircraft and the increased and earlier awareness of the pilots resulting from the TCAS I traffic advisories and use of the traffic display (described in the next paragraph).

2.6.7. The surveillance and threat detection functions of TCAS I operate in a similar way to ACAS II, but with different threat detection thresholds. Both systems provide a 'traffic display': a plan-position indicator showing the relative positions, altitudes, and vertical trends of nearby aircraft ('intruders') using standard symbology. ICAO however recognises that "*because of design limitations, the bearing displayed by ACAS is not sufficiently accurate to support the initiation of horizontal manoeuvres based solely on the traffic display*" (cf. ICAO PANS-OPS – ACAS Training Guidelines for Pilots).

- 2.6.8. The traffic display is designed to aid visual acquisition of an intruder: it is not designed nor certified for any other use. Limitations of the display and in its interpretation mean that manoeuvres based on the traffic display can degrade flight safety (see EUROCONTROL's ACAS Bulletin No. 6, 'Incorrect use of the TCAS traffic display' [ACA6]).
- 2.6.9. Abuse of, or incorrect use of, the TCAS I traffic display can result in a number of hazardous event types including:
 - 1) unnecessary manoeuvres initiated by the pilots on their own judgement which may disrupt ATC strategy in controlled aircraft or even create a collision hazard with a third party aircraft,
 - 2) ineffective evasive manoeuvres initiated in the wrong direction or against the wrong aircraft resulting in a reduction (instead of an increase) of the miss distance with the threat aircraft, or
 - 3) un-coordinated evasive manoeuvres against intruders fitted with ACAS II which may defeat the ACAS II initial resolutions.
- 2.6.10. Other shortcomings related to the operational use of TCAS I derive from the inherent limitations of visual acquisition. These limitations are related to physical limits, human perception and other external factors that can reduce a pilot's effective visual field including the meteorological conditions or the cockpit field of view (cf. section 3.5.1 for further details).
- 2.6.11. Finally, TCAS I operation raises some radio frequency (RF) spectrum issues. The TCAS I interference algorithms are not as robust as those of ACAS II: in some circumstances excessive use of the RF spectrum by TCAS I units can adversely affect the operation of ACAS II; in other circumstances the proximity of clusters of aircraft can severely degrade the surveillance of TCAS I so that threats may be detected late, or in many cases, not at all ([ACA5]). In the highest density of traffic, when TCAS I needs to be most effective, it may have serious problems detecting other aircraft. This supports a conclusion that TCAS I would be of limited help to collision avoidance on VLJs. Further consideration of these issues was outside the scope of the present study.

3. Analysing and modelling the future ATM environment with VLJ aircraft

3.1. Definition of VLJs

- 3.1.1. There is currently no internationally agreed definition of a VLJ category. Several definitions exist in the literature, which do not radically differ from each others.
- 3.1.2. According to [AVBU], “*It seems the industry consensus is forming around the VLJ maxing out at under 10,000 lbs [4,500 kg]. By extension, it then seems, the “light” segment begins at 10,000 lbs [4,500 kg] – something of a change when “light” meant anything under 20,000 lbs [9,000 kg] fairly recently.*”
- 3.1.3. According to [MIT], “*the 10,000 lbs [4,500 kg] threshold between very light and light jets has emerged from an historical perspective, distinguishing two generations of aircraft, with the Cessna CJ1 (10,600 lbs [4,800 kg]), certified in 1992, being the lightest twin turbofan-powered aircraft in the current business jet spectrum. The entry of VLJs expected in 2006 will lower the current business jet spectrum under 10,000 lbs [4,500 kg].*”
- 3.1.4. This [MIT] investigation also notes that an alternative threshold of 12,500 lbs (5,700 kg) may also be appropriate as it “*separates aircraft that are certified under JAR/FAR [Joint Aviation Regulations/Federal Aviation Regulations] Part 23 airworthiness standards for normal, utility, aerobatic and commuter category aircraft from those air transport category aircraft certified under JAR/FAR Part 25.*”
- 3.1.5. For the present study, the 5,700 kg threshold is also of particular interest as it determines whether the carriage and operation of ACAS II is required or not according to the current ACAS II mandate in the ECAC member States.

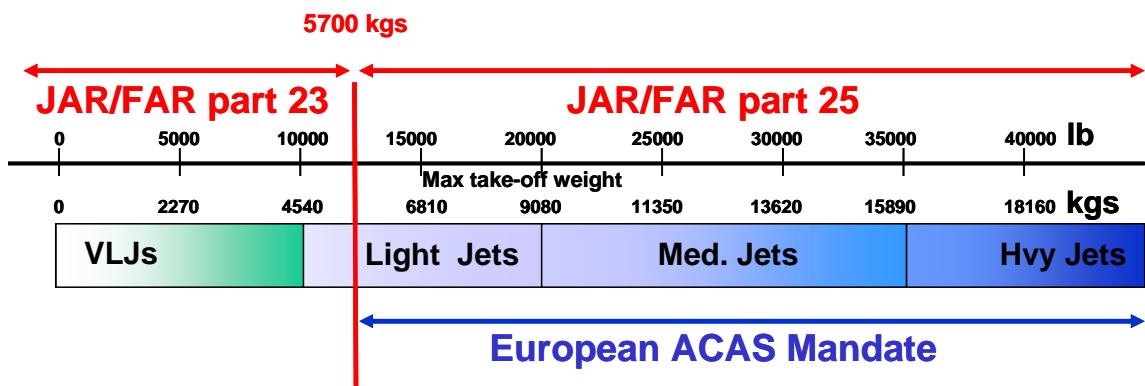


Figure 3: Current airworthiness regulation and ACAS II mandate versus MTOM

- 3.1.6. On these bases, the definition of VLJs used in the present study is as follows:

VLJs are turbofan-powered aircraft with a maximum takeoff mass not exceeding 4,500 kg (10,000 lbs), that can be certified for single pilot operation and that typically seat from 3 to 8 passengers.

- 3.1.7. In addition, the light jets with a maximum takeoff mass between 4,500 kg and 5,700 kg, are referred to as ‘small LJs’ in the present study.

3.2. Performance of VLJs and small LJs

3.2.1. One difficulty to deal with when assessing the performances of VLJs is linked to the scarcity of information, as only manufacturer figures are available and those readily available are not always comprehensive.

3.2.2. For comparison purposes, Figure 4 presents ceiling altitude versus speed figures (which are often maximum cruise speeds) as provided by manufacturers ([WEB]), for several VLJs, LJs, turboprops and a few medium jets. LJs with a MTOM below and above 5,700 kg are shown with different colours to differentiate them.

Note: Only the names of representative aircraft are indicated. Aircraft names in bold correspond to LJs weighing less than 5,700 kg. A brief description of the most representative VLJ and small LJ aircraft is provided in Appendix A.

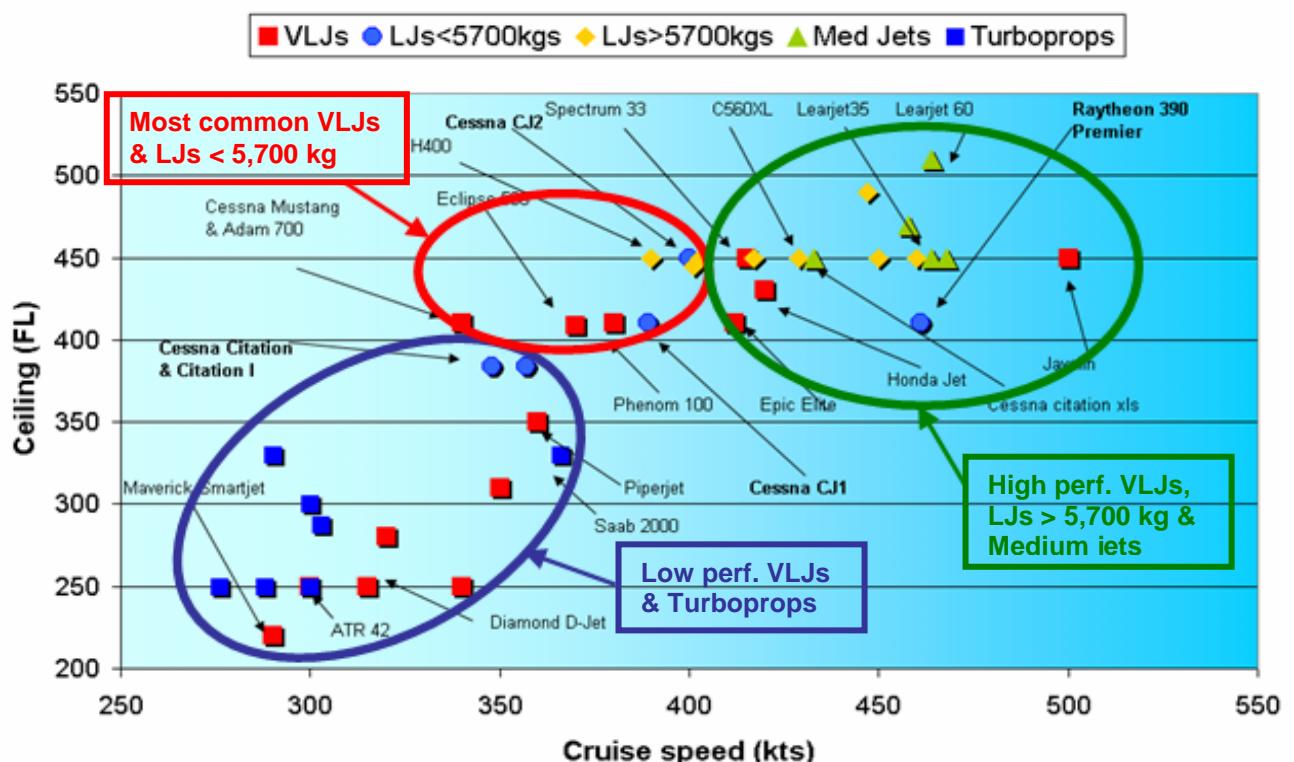


Figure 4: Speed performances of VLJs and small LJs provided by manufacturers

3.2.3. The analysis of these speed performances ([D1]) has shown that VLJs can be classified into three categories:

- **The first category (in blue)** corresponds to VLJs with a ceiling below Flight Level (FL) 350, and often below FL300, and with cruise speeds below 360 kt. These performances are similar to turboprop aircraft.
- **The second category (in green)** corresponds to some VLJs with characteristics similar to those of LJs weighing more than 5,700 kg and to medium jets, with a ceiling above FL400 and cruise speeds above 410 kt.
- **The third category (in red)** includes VLJs with a ceiling above FL400, and with cruise speeds between 340 kt and 380 kt. LJs weighing less than 5,700 kg and these VLJs can be considered as having similar performances.

3.2.4. This third category composed of mid-range VLJs is likely to create greater difficulties in traffic handling, as they are slightly slower than LJs and medium jets, while they can fly at similar altitudes. This category includes the Adam 700, the Eclipse 500, the Embraer Phenom 100 and the Cessna Mustang, for which there are currently orders in Europe, and which are likely to be the most represented. These VLJs are roughly 15% slower than LJs over 5,700 kg.

3.2.5. According to manufacturers' figures, the maximum ranges of operation of VLJs are often close to 1,250 NM (e.g. roughly the distance between Brussels and Moscow). It is likely that the actual range of VLJ operations would be lower than this maximum range of operation.

3.2.6. Because the most common VLJs expected in Europe show performances comparable to LJs under 5,700 kg, the study extrapolated that their operations will also be similar. Therefore to balance the maximum performances put forward by the VLJ manufacturers, the study also analysed current light jet operations in the European core area. This analysis showed that their operations can be classified into three categories ([D2]):

- **short-range operations** close to those of turboprop aircraft, along routes of less 200 NM and cruise FLs around FL180;
- **mid-range operations** along routes between 100 NM and 300 NM and cruise FLs around FL270-280 just below the RVSM airspace; and
- **high-performance light jet operations** spanning a wide range of possible distances from 200 NM to 700 NM and cruise FLs between FL300 and FL400.

3.2.7. Finally, with regard to vertical performances, manufacturers' figures could not be found for as many VLJs and small LJs as other performance data. The present study nevertheless anticipated that the vertical rates of VLJs would be somewhat lower than those of LJs.

3.3. *Foreseen operations of VLJs and small LJs in Europe*

3.3.1. *Nature of possible VLJ operations*

3.3.1.1. The International Business Aviation Council (IBAC) has classified business aviation operations, of which VLJ aircraft will be a part, into three main categories (see also 'EUROCONTROL Trends in Air Traffic | volume 1, Getting to the Point: Business Aviation in Europe' [SFO1]):

- Commercial: aircraft flown for business purposes by an operator having a commercial operating certificate. Typically, these flights are related to air-taxi operations, 'fractional aircraft' operations, but 'per seat, on demand' service is also envisaged for VLJs.
- Corporate: non-commercial flights operated by professional crews employed to fly the aircraft.
- Owner-operated: flights operated for business purposes by the owner of the aircraft.



Figure 5: Business aviation ([SFO1])

- 3.3.1.2. Geographically, the business aviation network in Europe is more spread out than the network of scheduled flights. Specific customer demand and difficulties in accessing larger airports mean that business aviation often flies to different, yet sometimes close by, airports than scheduled flights. Business traffic typically concentrates traffic along the London-Rome axis, taking in Paris, Geneva, Cannes and Milan on the way. There is also a number of more specialised market of which Moscow, the Norwegian fjords and some island services are obvious examples.
- 3.3.1.3. Because the business airports often share the same Terminal Control Areas (TMA) as major airports, VLJs and small LJs operating at these airports are expected to interact with scheduled commercial flights in these locations, as well as in the upper airspace.
- 3.3.1.4. In addition to these business aviation operations, VLJ aircraft will also be flown for leisure purposes by owner-pilots or private pilots, as part of General Aviation (GA).

3.3.2. Options for VLJ and small LJ type of operations

- 3.3.2.1. Several aircraft operators intending to focus on VLJs have already described the type of operations they foresee. These operators notably include Jetbird ([JETB]) and ETIRC Aviation ([ETIR]). There are however many unknowns still needed to obtain a full picture of the future VLJ and small LJ operations in Europe.
- 3.3.2.2. Four different scenarios were selected for specific analysis in the present study. These combine in different ways the possible types of VLJ flights and are as follows:
 - **Balanced scenario:** This first scenario assumes a balanced mix of VLJ and small LJ operations with 33% of commercial flights, 33% of corporate flights and 33% of GA flights;
 - **Business aviation scenario:** This second scenario puts the focus on business aviation operations with 45% of commercial flights, 45% of corporate flights and 10% of GA flights;
 - **Commercial operation scenario:** This third scenario puts the focus on commercial operations with 70% of commercial flights, 20% of corporate flights and 10% of GA flights;

- **Corporate operation scenario:** This fourth scenario puts the focus on corporate operations with 20% of commercial flights, 70% of corporate flights and 10% of GA flights.

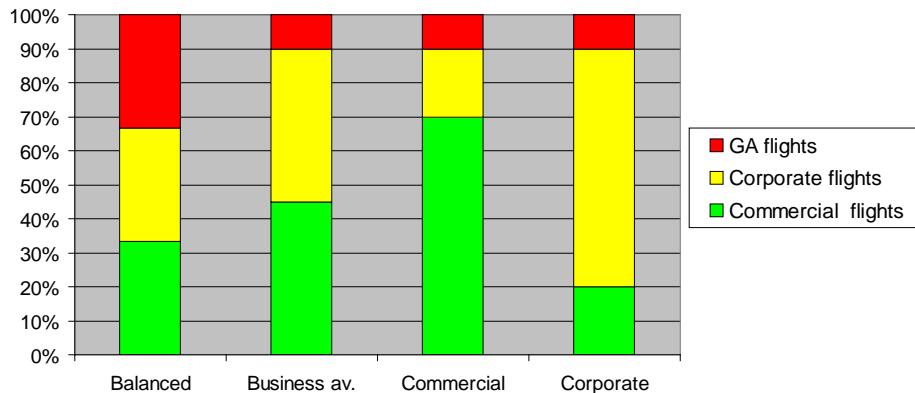


Figure 6: Options for VLJ and small LJ type of operations

3.3.2.3. As a whole these scenarios are intended to cover a wide range of possible options for VLJ and small LJ operations in Europe, and to permit verification of the robustness of the study results despite the uncertainties that exist with regard to the future VLJ operations.

3.3.3. **Growth forecast for VLJs and small LJs**

3.3.3.1. Based on different available forecasts on VLJ sales and business traffic growth before the onset of the global recession in the second half of 2008, it was estimated that VLJ and small LJ operations in Europe might result in 110,000 to 170,000 additional flights each year between 2008 and 2015 (cf. Appendix A.3 for further details).

3.4. **Modelling ACAS II operation by pilots of VLJs and small LJs**

3.4.1. **Background of VLJ and small LJ pilots**

3.4.1.1. When envisaging the operation of ACAS II by less experienced pilots, as with VLJ and small LJ aircraft, it is essential that the elements that might affect their behaviour when responding to an RA be anticipated so that the impact on the performance of ACAS II can be evaluated (cf. section 2.4.5).

3.4.1.2. From the perspective of pilots, VLJs and small LJs present two specific issues compared to larger commercial aircraft. First, most of these light aircraft are certified for single pilot operation and second, they may be operated by a mixed population of pilots with different backgrounds. Three categories of VLJ and small LJ pilots can thus be distinguished, viz. airline pilots with past experience of TCAS II, airline pilots without⁸ past experience with TCAS II, and pilots from General Aviation with close to no experience with TCAS II.

⁸ Those airline pilots without past experience with TCAS II include pilots from business aviation or commercial airlines operating small aircraft not subject to the current European ACAS II mandate.

3.4.1.3. By combining these three categories of VLJ / LJ pilots with the two types of aircraft operation (either single crew or two-member crew), six different pilot configurations have been proposed to characterise the responses that can be expected from VLJ and small LJ pilots to TCAS II RAs ([D5]). It is worth noting that these pilot configurations were assumed to be differently represented in each of the four scenarios related to VLJ and small LJ type of operations as shown in Figure 7.

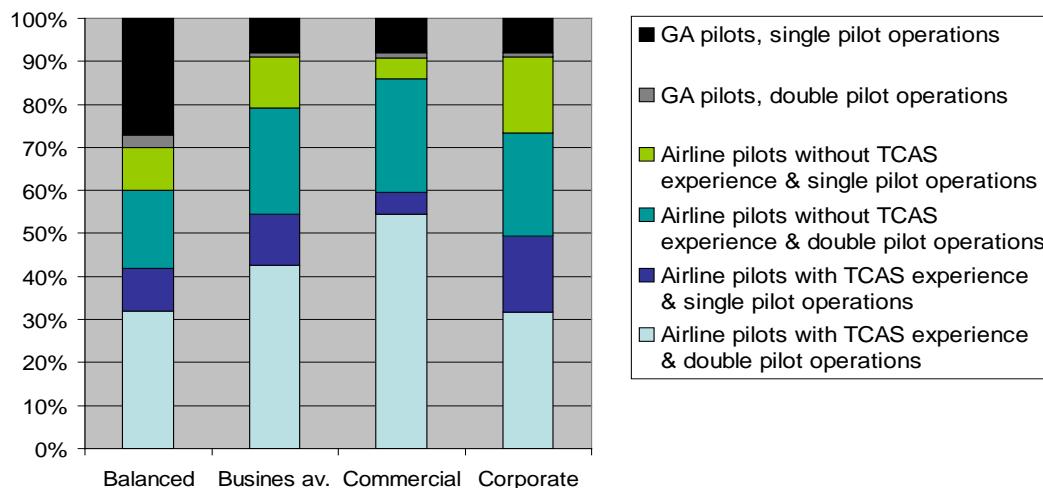


Figure 7: Options for pilot background onboard VLJs and small LJs

3.4.2. Observed pilot responses to RAs in larger commercial aircraft

3.4.2.1. In the early stages of ACAS II implementation in Europe, the ACASA study ([ACA1]) has shown, based on the analysis of airborne recorded data, that the actual pilot responses to RAs fall into two distinct groups:

- ‘aggressive response’ in which pilots achieved a vertical rate in excess of that required by the RA; and
- ‘slow response’ in which the delay before a response was initiated was longer than standard, the acceleration was lower than standard, and the vertical rate attained was less than required by the RA.

3.4.2.2. A few years later, a subsequent analysis of airborne recorded data conducted in the ASARP study ([ASAR]) demonstrated that pilot behaviour in response to ACAS II had improved. Notably, their responses to corrective RAs were generally very close to the standard response expected by the ACAS II logic, although the reactions adopted spanned over a range of reaction times, vertical rates, and vertical accelerations.

3.4.2.3. The RA compliance rate by pilots is a key factor influencing the safety benefits actually provided by ACAS II. In the ASARP study, the analysis of airborne-recorded data collected from two major European airlines and the two European regional airlines evaluated the non-response rate to RAs at about 10% ([ASAR]). The recent analysis of TCAS II operations in European TMAs has further demonstrated that non-response rate actually varies from 30% at very low altitudes (i.e. below FL50) and 10% above ([SIRE+2]).

3.4.3. Probable pilot responses to RAs on board VLJs and small LJs

- 3.4.3.1. The operation of VLJs and small LJs by single pilots has the potential to affect one or more of the factors⁹ that are representative of how human errors can intrude into normally robust procedures and lead to accidents ([NASA]). When envisaging the operation of ACAS II in aircraft being operated by a single pilot, it is likely that the rate of non-response and late response to RAs on board these aircraft will therefore be greater than that observed in current ACAS II operations.
- 3.4.3.2. The other key factor that might influence the RA responses on board VLJs and small LJs is the level of pilots' training or past experience on ACAS II. Although VLJ stakeholders have taken steps to try and bring the population of GA pilots on par with airline pilots through a dedicated initial training, less emphasize seems to be put on recurrent training ([NBAA], [BARN]). Consequently, this is likely to increase the rate of non-standard responses from VLJ pilots if these aircraft would be fitted with ACAS II.
- 3.4.3.3. By combining the effects of the VLJ and LJ pilot's background and past experience of ACAS II with the possible effects of single pilot operation, six different models of pilot responses to RAs were defined in the present study. These six models derive from the existing ACASA and ASARP pilot response models as described in Table 1.

Pilot background	Pilot response to RAs in case of double pilot operation	Additional effects in case of single pilot operation
Airline pilot with ACAS II experience	As observed in ASARP, with typical rate of non-response	- Higher non-response rate - Increased initial delay - Increased risk of opposite response - Increased probability of high vertical rate (e.g. higher rate of aggressive responses compared to slow responses)
Airline pilot without ACAS II experience	As observed in ACASA, with balanced mix of slow and aggressive responses and typical rate of non-response	
GA pilot	As observed in ACASA, with increased rate of non-response and non-standard manoeuvres	

Table 1: Anticipated pilot responses to RAs on board VLJs and small LJs

- 3.4.3.4. As shown in Figure 8, the various types of pilot responses to RAs are differently represented in each of these VLJ and LJ pilot models (cf. Appendix C for further details).

Note: Typical responses (observed in current ACAS II operations in Europe) include a sophisticated mix of slow, prompt, aggressive, nominal and smooth pilots' responses to RAs.

⁹ These factors notably relate to lapses in the execution of procedures, failures of the crew to successfully be alerted by airborne systems and psychological phenomena related to human error.

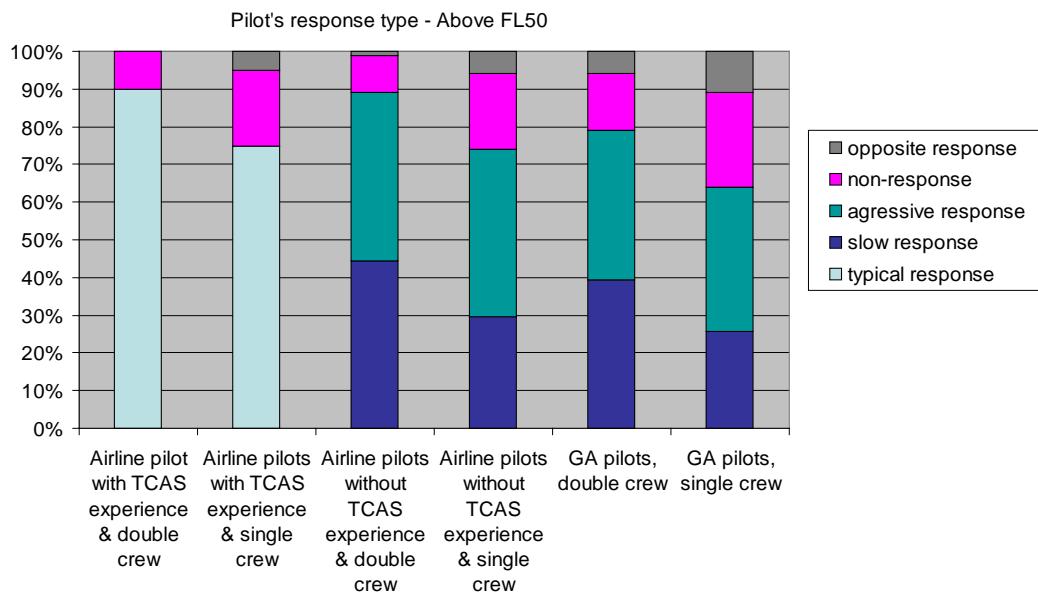


Figure 8: Assumptions for pilot's response to RAs onboard VLJs and small LJs

3.5. Modelling TCAS I operation by pilots of VLJs and small LJs

3.5.1. Visual acquisition prompted by TCAS I

- 3.5.1.1. As a first step towards the comparison of the safety benefits of TCAS I and ACAS II quantitatively, the study investigated the probability of a pilot visually acquiring the threat aircraft when two aircraft are on a collision course ([D8]).
- 3.5.1.2. The probability of visual acquisition in various scenarios (with and without the aid of TCAS I) was calculated using an implementation of the visual acquisition model developed at Lincoln Laboratory ([LLAB]). This model combines the principal factors that affect visual acquisition to form a comparatively simple mathematical representation of the 'visual acquisition rate', viz. the chance of visually acquiring a target in any given instant of time (cf. Appendix D for further details).
- 3.5.1.3. From the analysis of illustrative scenarios (that cover a range of encounter altitudes, own aircraft speed, threat aircraft type and equipage) the study demonstrated that TCAS I equipage can undoubtedly enhance the prospect of visually acquiring a collision threat but only in certain scenarios.
- 3.5.1.4. TCAS I is naturally more effective in prompting visual acquisition against larger aircraft (like medium and large passenger aircraft), and less effective against smaller aircraft types (like GA, military fast jets or VLJ aircraft). It is particularly ineffective against small-sized threats with high closing speeds in which there is virtually no prospect of visual acquisition, even when equipped with TCAS I, at the highest closing speeds.
- 3.5.1.5. Although effective in certain scenarios when the meteorological visibility is unlimited, this effectiveness is markedly decreased when the visibility decreases. Even at the limit of visibility for VFR the usefulness of TCAS I as an aid to visual acquisition is severely curtailed, even against large-sized threats. This effectiveness is obviously further reduced (ultimately to nil) in IMC. It is worth noting that many of the risk-bearing encounters in the European airspace occur at

low altitudes (cf. section 3.6.3) where the effect of the meteorological conditions on the visibility is more noticeable.

3.5.1.6. Figure 9 is an example of a visualisation of how the probability of visual acquisition at an instant of time before collision varies with the encounter geometry and the meteorological visibility. In the example, own aircraft (a VLJ) is travelling at a speed of 300kt at an altitude between FL100 and FL200. At these altitudes the nominal TCAS I TA warning time is 30s and the nominal ACAS II RA warning time is also 30s. The limit of visibility for flying VFR is 8 km. The threat aircraft is taken to be an Airbus A320 (a medium-sized passenger aircraft) flying at a speed in the range 200kt to 500kt.

Legend: The diagrams show the effect of closing speed and angle of approach on the probability of visual acquisition by a VLJ aircraft when unequipped (on the left) or TCAS I equipped (on the right). For each diagram, the effect of the meteorological visibility can be seen by comparing the left-hand side of the diagram (unlimited visibility) with the right-hand side of the diagram (with visibility at the limit of VFR) which would otherwise be symmetrical.

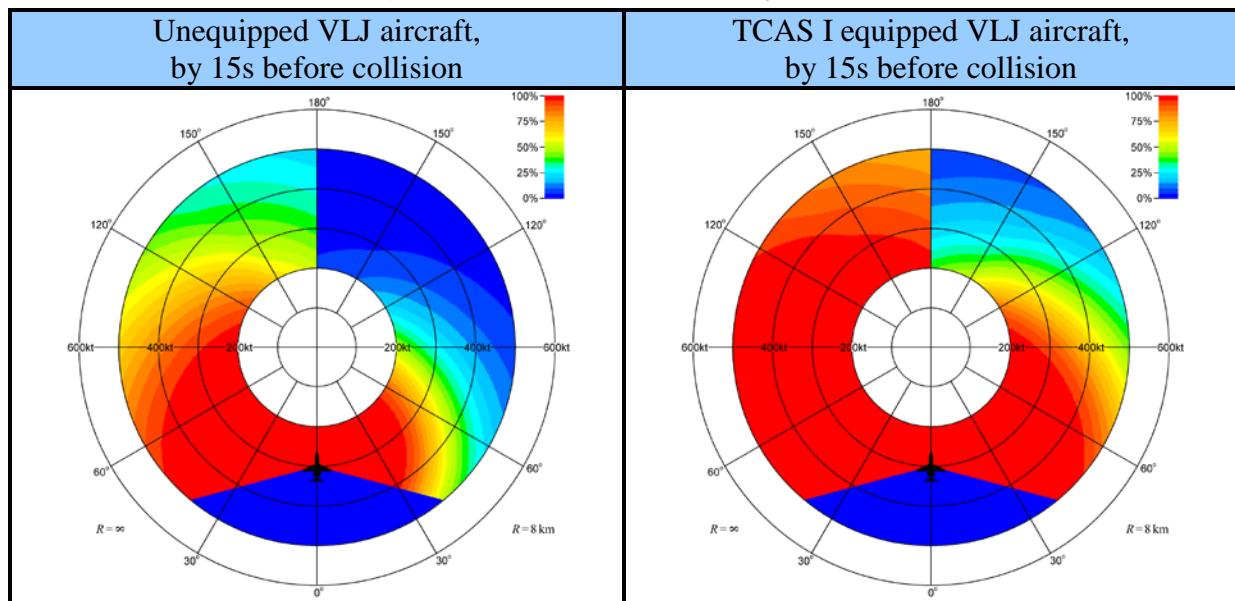


Figure 9: Illustration of the probability of visual acquisition at an instant of time before collision

3.5.1.7. Finally, TCAS I is naturally of no benefit in visually acquiring collision threats which approach from behind (see blue areas behind own aircraft symbol in the diagrams).

3.5.2. Evasive manoeuvre following visual acquisition

3.5.2.1. The analysis of illustrative scenarios also highlighted that the enhanced probability of visually acquiring a collision threat thanks to TCAS I ironically brings with it an increase in the probability that the two aircraft will initiate an evasive manoeuvre in a similar timeframe and potentially employ incompatible avoidance manoeuvres. The effect is most marked against threats which are equipped with ACAS II since the interval around the time at which an RA will be generated corresponds to times at which the occurrence of visual acquisition is high.

- 3.5.2.2. To fully assess the consequences of the competing effects of enhanced visual acquisition and an increased probability of incompatible manoeuvres, it was necessary to model also the evasive manoeuvres initiated in response to TCAS I alerts. In accordance with the rules of 'right-of-way' defined by ICAO Annex 2 – Rules of the Air ([ANN2]), these evasive manoeuvres were assumed to happen in the horizontal plane.
- 3.5.2.3. The evasive manoeuvres were modelled as starting following the probable visual acquisition of the threat (and not before) in line with the ICAO provisions that forbid any manoeuvre based on TAs only (cf. section 2.6.3). A delay of 5 seconds was applied between visual acquisition and the turn initiation. The turn itself was achieved by reaching a maximum bank angle of 45 degrees below FL250 and 30 degrees above, using a roll rate of 15 degrees per second.
- 3.5.2.4. Finally, the evasive manoeuvre ceased when the range between own aircraft and threat aircraft started to increase or when the relative bearing of the threat was greater than the threshold allowing visual acquisition (viz. ± 105 degrees).

3.6. *Modelling safety-related encounters consequent to future VLJ operations in Europe*

3.6.1. General

- 3.6.1.1. When envisaging a change in ATM operations, as may be the case with the introduction of VLJs in the European airspace, it is essential that the effect on traffic patterns and safety-related encounters be anticipated so that the impact on the performance of ACAS II can be properly evaluated (cf. section 2.4.5).
- 3.6.1.2. The encounter model approach is a powerful technique that supports such evaluation of ACAS II safety benefits. A 'safety encounter model' is a model of traffic situations (involving two aircraft) that captures the properties of risk-bearing¹⁰ encounters as a series of statistical distributions (implemented as probability tables) describing the parameters of a typical encounter and their interdependencies in a given airspace. The encounter model can then be used to stochastically generate an arbitrarily large set of risk bearing encounters (even though these are rare events) replicating the encounters observed in the considered airspace.
- 3.6.1.3. The AVAL safety encounter model ([D4]) builds upon the 'European safety encounter model' developed in the ACASA project of EUROCONTROL ([ACA2]) and later enhanced and updated in the ASARP project to reflect typical operations under Instrument Flight Rules (IFR) in the European RVSM airspace ([ASAR]). The structure of the former 'European safety encounter model' was adapted to incorporate performance characteristics of VLJ and LJ aircraft. Contemporary radar data was then analysed to update the probability tables of the AVAL safety encounter model. Two instances of the encounter model were actually produced to compare the performance of ACAS II in the current European environment ('2008 timeframe') and in a future airspace environment where a significant proportion of VLJ and small LJ operations are anticipated to occur ('2015 timeframe').

¹⁰ The encounters that matter are those in which (at least) two aircraft are on a close encounter course in which there exist a risk of mid-air collision or in which the response of pilots to RAs can result in a risk of mid-air collision.

3.6.1.4. A traffic growth had to be assumed between 2008 and 2015, to establish the probable likelihood of safety-related encounters involving VLJs and small LJs in the future European ATM environment. Forecasts made before the onset of the global recession in the second half of 2008 predicted a 4.9% annual increase in overall world passenger traffic (GFOR). Revised forecasts now predict a 16% (instead of 40% initially) growth of IFR traffic in the ECAC area between 2008 and 2015 ([SFO2]). Assuming that sales will favour VLJs instead of larger aircraft, because of economic constraints for airlines, the present study assumed an increase of 4.9% per year for the VLJs and small LJs, and 2.14% for the other aircraft.

3.6.2. Building of the pre-VLJ and post-VLJ European safety encounter models

3.6.2.1. The AVAL safety encounter model was developed using the same methodology as for the ACASA and the ASARP safety encounter models, i.e., the extraction and analysis of actual encounters from European radar data recordings ([D3]).

3.6.2.2. For the 2008-timeframe safety encounter model, contemporary radar data has been gathered from countries within the core European area (France, United Kingdom, Netherlands, Switzerland, and Czech Republic). The geographical coverage is shown in Figure 10 and it can be seen that the coverage extends into neighbouring states. Radar data was gathered between October 2007 and March 2008, corresponding to 1.3×10^6 flight-hours.

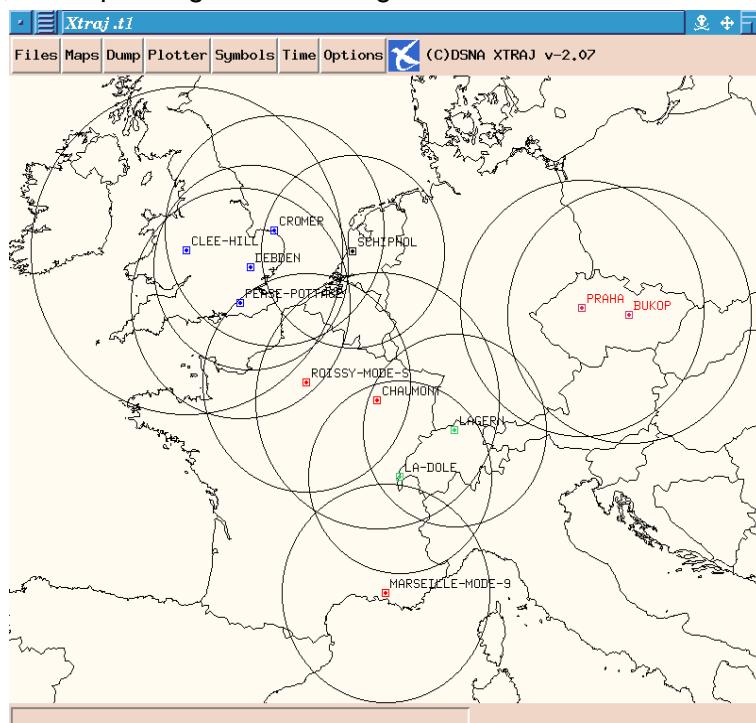


Figure 10: European radar data used for the AVAL safety encounter models

3.6.2.3. The contemporary radar data was analysed to identify and capture those encounters in which the aircraft came sufficiently close that they could be used to populate the tables of the safety encounter model. The captured encounters were subjected to a quality control process to remove unwanted or inappropriate

encounters¹¹. Finally, some encounters were modified to remove any reactions by the pilots to ACAS RAs since reaction to ACAS II is modelled in the simulations. A total of 2,154 radar encounters contributed to the 2008-timeframe probability tables. The ‘2008-radar-data encounters’ were combined with the set of 1,040 encounters observed in RVSM airspace in 2002-2004 during the ASARP project to improve the statistics of the 2008-timeframe safety encounter model.

- 3.6.2.4. The process to produce the 2015-timeframe safety encounter model took as its starting point the contemporary radar data gathered for the 2008-timeframe encounter model. The captured encounters (i.e. the ‘2008-radar-data encounters’) were augmented by further appropriate encounters to represent the extra encounters involving LJ and VLJ aircraft expected to occur due to the presence of these aircraft in the future ATM environment.
- 3.6.2.5. To that end, the 2008-radar-data encounters were passed through a ‘VLJ filter’ that identified VLJ-like encounters in which the profile of at least one of the aircraft was considered to be representative of the characteristics of a VLJ aircraft. The VLJ-like encounters that were identified were then combined with the 2008-radar-data encounters, in proportions reflecting the expected VLJ traffic levels in 2015. Thus was a set of ‘2015-radar-data encounters’ obtained, which is estimated to correspond to 1.5×10^6 flight-hours. A total of 2,324 encounters contributed to the 2015-timeframe probability tables.
- 3.6.2.6. To circumvent the paucity of encounters with ‘Horizontal Miss Distance (HMD)’ less than the NMAC threshold (500 feet = 0.082 NM), the capture criteria used to extract close encounters from the radar data employs a larger threshold. The safety encounter model is then built under the general assumption that the captured encounters have the same properties as encounters with HMD less than the NMAC threshold. The one exception is the ‘Vertical Miss Distance (VMD)’ distributions which determine the number of NMACs that are generated by the safety encounter model (without ACAS). To properly assess the performance of ACAS it is essential that this NMAC rate is realistic (as explained in section 2.3). The VMD distributions were therefore adjusted using an objective and statistically valid technique to ensure that they imply a realistic underlying NMAC rate.
- 3.6.2.7. The analysis of airprox data for the 2001–2008 period determined that an underlying NMAC rate of 3×10^{-7} NMACs per flight-hour (as adopted in the ACASA study for the 2001 timeframe) was not inconsistent with the reported events. This implies that the underlying NMAC rate in core European airspace has remained stable between 2001 and 2008 despite the increase in the traffic levels. It is therefore conceivable that the same NMAC rate would also be applicable in the 2015 timeframe following a further rise in traffic levels. Consequently, the same underlying NMAC rate (viz. 3×10^{-7} per flight-hour) was imposed to the two instances of the AVAL safety encounter model.

¹¹ These removed encounters include: spurious encounters due to tracking errors, encounters between two aircraft which are not potentially ACAS equipped (e.g. military fast jets and GA); and duplicate encounters (due to the overlap of radar coverage).

3.6.3. Overview of the AVAL safety encounter model

- 3.6.3.1. The AVAL safety encounter models consist of five altitude layers with boundaries at operationally significant altitudes (viz. Layer 1 from 1,000 feet to FL50, Layer 2 from FL50 to FL135, Layer 3 from FL135 to FL215, Layer 4 from FL215 and FL285, and Layer 5 above FL285).
- 3.6.3.2. As shown in Figure 11, the 2015-timeframe safety encounter model has a slightly higher number of encounters in the three upper altitude layers (viz. above FL135), when compared to the 2008-timeframe encounter model. In contrast, the 2008-timeframe encounter model has a higher number of encounters in the lower layer (viz. between 1,000 feet and FL50). This reflects the fact that the introduction of VLJs is more likely to add encounters at high altitudes where VLJs have lower performances than other aircraft (e.g. the speed differential can cause more overtaking events).

Legend: The figure shows the altitude distribution of the encounters generated by the model for the 2008-timeframe (in light green) and the 2015-timeframe (in blue), respectively. The dark green colour indicates that the 2008 and 2015 distributions overlap.

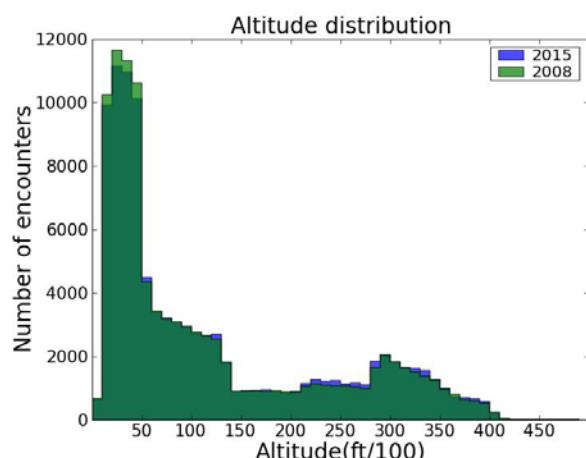


Figure 11: Altitude distribution in the AVAL safety encounter models

- 3.6.3.3. The behaviour of an aircraft in a modelled encounter needs to be subject to the limitations of its aerodynamic performance. The ACASA study ([ACA1]) showed that this feature can be adequately captured by using a limited number of aircraft performance classes based on aircraft engine type (i.e. piston engine, turboprop, or jet) and MTOM (e.g. below or above 5,700 kg), and employing a simplified set of aircraft performance limits that vary with the altitude layers of the model.
- 3.6.4. To reflect the particular concern of the speed at which LJs and VLJs operate (which can be markedly lower than the speeds of other aircraft operating at the same altitudes as illustrated in Figure 4), the performance classes in AVAL also discriminate on the basis of maximum cruising speed using four categories: 'very slow (vs)' (<250kt); 'slow (s)' (250kt – 350kt); 'medium (m)' (350kt – 450kt); and 'fast (f)' (> 450kt). The full range of performance classes in the AVAL safety encounter model is shown in Table 2. These performance classes only address relevant combinations of engine type, MTOM and maximum cruising speeds (i.e. grey cells were not considered as they are not operationally meaningful).

MTOM or type	max cruising speed				engine
	< 250kt	250kt – 350kt	350kt – 450kt	> 450kt	
All weight	P _{VS}	P _S			piston
< 5,700kg		T _{Ls}	T _{LM}		
> 5,700kg	T _{Hvs}	T _{HS}	T _{HM}		turboprop
< 5,700kg	J _{Lvs}	J _{Ls}	J _{LM}	J _{LF}	
> 5,700kg			J _{HM}	J _{HE}	jet
All weight				M _F	military jet

Table 2: Aircraft performance classes in the AVAL safety encounter models

3.6.4.1. Class JL_s corresponds to slow VLJs, such as the Diamond Jet. Class JL_M corresponds to average VLJs and current LJs, such as the Cessna Mustang. This class therefore encompasses already existing aircraft, and also VLJs. Class JL_F corresponds to the fastest of VLJs, such as the Javelin. Finally, class JL_{vs} has been defined, but recent developments in the market suggest that aircraft in this class will not be produced in operationally significant numbers.

3.6.4.2. Modelling of the future VLJ and small LJ operations also has a visible effect on the ground speed distributions in the two instantiations of the AVAL safety encounter model. As illustrated in Figure 12, the differences are mainly observed at high altitudes (i.e. Layer 4 and 5) with a greater proportion of 250 kt – 400 kt interval in the 2015-timeframe compared to the 2008-timeframe. This is due to the introduction of VLJs flying in these altitude bands which fly at slower ground speeds than other aircraft.

Legend: The figures show the ground speed distributions in the two upper altitude layers (viz. above FL215) for the 2008-timeframe model (in light green) and the 2015-timeframe model (in blue), respectively. The dark green colour indicates that the 2008 and 2015 distributions overlap.

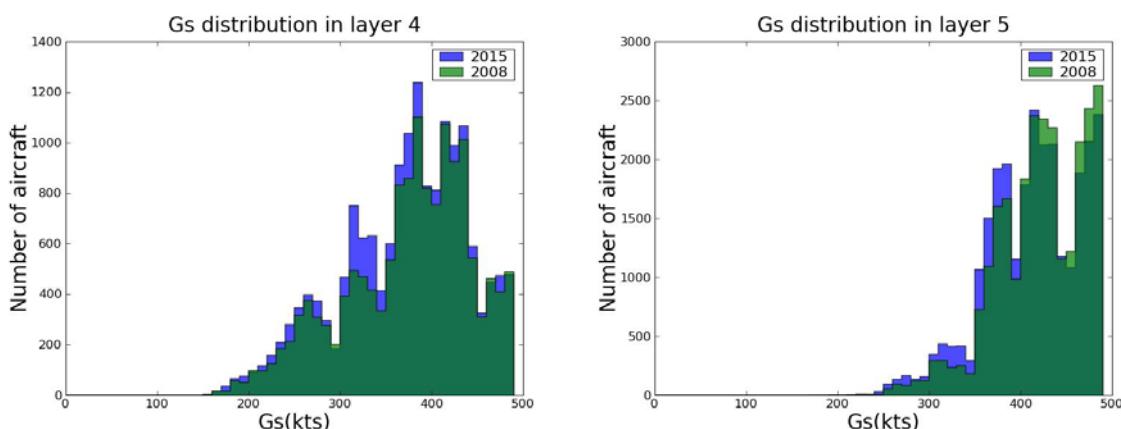


Figure 12: Ground speed distribution in the AVAL safety encounter models

4. Evaluation of the implications of Collision Avoidance equipage of VLJs and small LJs

4.1. Evaluation of the safety implications of ACAS II equipage

4.1.1. Scope and approach

- 4.1.1.1. The AVAL study has evaluated, quantitatively, the safety implications of modifying the criteria for the ACAS II mandate in Europe to include the VLJ and small LJ aircraft ([D6]). This was done for a wide range of possible operational scenarios for the 2015-timeframe, which are described in the subsequent section.
- 4.1.1.2. Using the post-VLJ safety encounter model for the 2015 timeframe developed during the study, ACAS II simulations were performed on each of these scenarios to evaluate the safety implications, from an airspace perspective depending on whether VLJs and small LJs were ACAS II equipped or not.
- 4.1.1.3. By focusing on those generated encounters that involved at least one VLJ or small LJ, the study also evaluated the safety implications of ACAS II equipage from an airborne perspective, viz. from the perspective of the future VLJ and small LJ fleet ([D6]).

4.1.2. Operational scenarios under evaluation

- 4.1.2.1. The existence of three categories of VLJs with very different speed performances (cf. section 3.1.7) argues for the introduction of speed as a determinant for ACAS II carriage, in addition to the MTOM that is currently used by the European ACAS II mandate.
- 4.1.2.2. Consequently, three different scenarios of ACAS II equipage by VLJs and small LJs were evaluated as follows:
 - Baseline scenario: Aircraft equipage according to the current European ACAS II mandate (i.e., VLJs and small LJs not equipped with ACAS II);
 - Intermediate equipage scenario: Extension of the current European ACAS II mandate to all jet aircraft with maximum cruising speed greater than or equal to 350 kt (i.e. classes JL_F and JL_M) (i.e. the most common VLJs and small LJs equipped with TCAS II);
 - Full equipage scenario: Extension of the current European ACAS II mandate to all jet aircraft with maximum cruising speed greater than or equal to 250 kt (i.e. classes JL_F , JL_M and JL_s) that is to say full VLJs and small LJs equipage with TCAS II (since class JL_{vs} is currently empty).
- 4.1.2.3. Four scenarios were defined and evaluated in the study to reflect different options foreseen for VLJ and small LJ operations: viz. 'Balanced scenario'; 'Business aviation scenario'; 'Commercial operation scenario'; 'Corporate operation scenario' (cf. section 3.3 for further details).
- 4.1.2.4. It should be recalled that these scenarios are characterised by different proportions of business aviation flights, commercial flights, corporate flights and GA flights, as well as different assumptions with regard to the VLJ and small LJ pilot's background and probable responses to RAs (cf. section 3.4).

4.1.2.5. Finally, two different situations were evaluated with regard to the version of the TCAS II system being operated, viz. version 7.0 ([TCAS2]) currently in operations in Europe or version 7.1 ([TCAS3]) which is anticipated to be mandated sometime before 2015, as follows:

- Mix of v7.0/v7.1: assuming 20% version 7.0 and 80% version 7.1, to assess the situation where the implementation of version 7.1 is not complete.
- Full version 7.1 equipage.

4.1.3. Effect on the ACAS II safety benefits from an airspace perspective

4.1.3.1. For each of the scenarios the effect of ACAS II equipage was measured through the computation of the mid-air collision risk reduction delivered by ACAS II in the airspace, as summarised in Table 3.

Scenario	ACAS II equipage scheme (2015)					
	Baseline		Intermediate		Full equipage	
	V7/V7.1 mix	V7.1 only	V7/V7.1 mix	V7.1 only	V7/V7.1 mix	V7.1 only
Balanced	40.0%	39.7%	39.0%	38.7%	39.1%	38.8%
Business av.			39.0%	38.7%	39.0%	38.7%
Commercial			39.2%	38.9%	39.2%	38.9%
Corporate			38.9%	38.6%	38.9%	38.6%

Table 3: Effect of ACAS II equipage of VLJs and small LJs on the airspace risk ratio

4.1.3.2. Whatever the scenario of VLJ and small LJ operations, the gain in airspace risk ratio is estimated at about 1 percentage point when equipping these aircraft with ACAS II, which is a relative gain of 2.5%. Some small variations can be observed in the risk ratios obtained for the different operational scenarios, but they are within the accuracy of the simulation and the results can be considered as comparable.

4.1.3.3. The characteristics of the VLJ and LJ pilot responses to RAs have thus a limited influence on the mid-air collision risk reduction in the airspace, but this is only a consequence of the small proportion of VLJ and small LJ aircraft in the ACAS II-equipped fleet. If these aircraft were to be fitted with ACAS II, their pilots would nevertheless require specific training on the appropriate responses to RAs, for maximum safety benefits.

4.1.3.4. There were at the most 1.7% of additionally ACAS II equipped aircraft when equipping VLJs and small LJs. The relative gain in risk ratio (of 2.5%) is therefore slightly greater than the fraction of additionally equipped aircraft. As this fraction is relatively low, the additional reduction of the mid-air collision risk obtained by extending the ACAS II equipage is limited from an airspace perspective.

4.1.3.5. It is also worth noting that, whatever the ACAS II equipage scheme, the risk ratios with a full TCAS II version 7.1 equipage are lower than those with a mix of version 7.1 and 7.0, which was expected because of the better safety performances of version 7.1.

4.1.3.6. Figure 13 compares the Vertical Miss Distances (VMD) observed with the 'baseline' ACAS II equipage scenario (on the X-axis) and the 'best-case' scenario with full VLJs and small LJs equipage with ACAS II (on the Y-axis) assuming a balanced mix of commercial, corporate and GA flights, viz. the 'balanced scenario'.

Legend: Each plot represents a single simulated encounter. For green plots the best-case scenario provided more vertical separation than the baseline scenario. Dark green plots represent NMACs solved with the best-case scenario, but not with the baseline scenario. For red plots the baseline scenario provided more vertical separation than the best-case scenario. Dark red plots represent NMACs solved with the baseline scenario, but not with the best-case scenario. Blue plots on the diagonal represent encounters for which the vertical miss distance was unchanged. Yellow dots represent NMACs that neither of the two scenarios resolved.

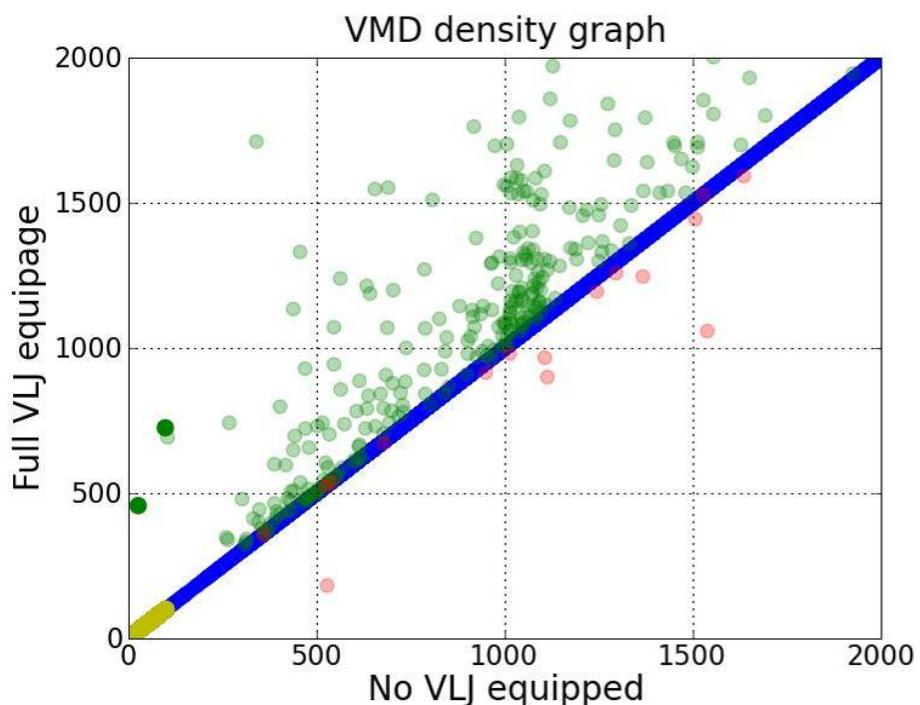


Figure 13: VMD density graph – 'Balanced' scenario, full v7.1 – Airspace perspective

4.1.3.7. This VMD density graph shows that there are, from an airspace perspective, much more safety benefits than drawbacks in equipping VLJs and small LJs with ACAS II. Although very few encounters were modified in the 'full equipage' scenario compared to the 'baseline' scenario, the number of encounters with an increased VMD was indeed far greater than the number of encounters with a decreased VMD.

4.1.3.8. An illustration of such increase of the safety margins thanks to ACAS II is provided in Figure 14. This figure shows an operationally realistic encounter involving a VLJ aircraft against a piston aircraft at low altitudes, with and without the effect of ACAS II equipage. On the left-hand side, without the benefit of ACAS II the encounter ends with a Near Mid Air Collision, while on the right-hand side the RA follow-up by the VLJ pilot when ACAS II equipped ensures a safe vertical separation (of about 600 feet).

Legend: The figure presents the altitude of the aircraft versus time. The vertical profile of the VLJ aircraft is depicted in red; the vertical profile of the light piston aircraft is depicted in black. When ACAS II equipped, the RA updates onboard the VLJ aircraft are shown by tags on its vertical profile, viz. Climb (Cl) RA, Don't Descend (DDes) RA, and Clear of Conflict (Coc). The solid black line shows the relative altitude of the aircraft at the time of closest approach.

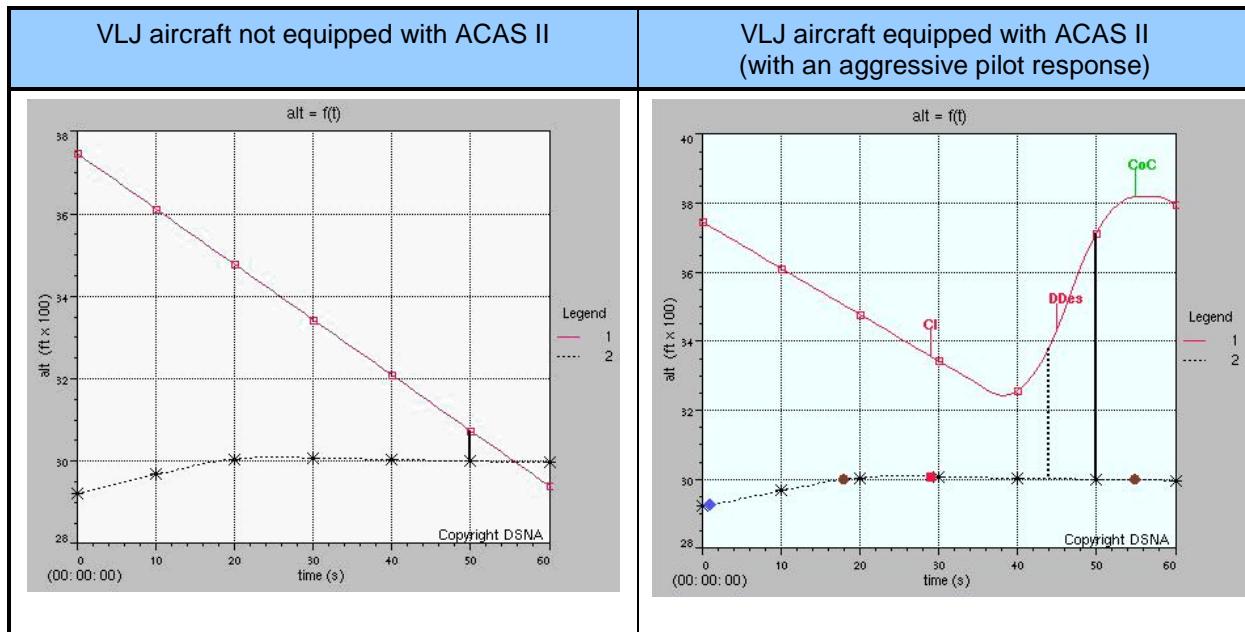


Figure 14: Illustration of the ACAS II safety benefits for a VLJ aircraft

4.1.3.9. Overall the study results tend to demonstrate that the implications of VLJs and small LJs on the overall ACAS II performance in Europe will receive little influence from the nature of their operations, and that the extension of the current European ACAS II mandate to these aircraft would slightly improve the mid-air collision risk reduction afforded by ACAS II in the 2015 airspace.

4.1.4. Safety benefits of ACAS II equipage from an airborne perspective

4.1.4.1. To further evaluate the safety benefits of ACAS II equipage from the perspective of VLJ and small LJ aircraft, the mid-air collision risk reduction delivered by ACAS II was measured on the subset of encounters involving at least one light jet under 5,700 kg. As shown in Table 4, these airborne risk ratios varied a lot depending on the ACAS II equipage scheme.

Scenario	ACAS II equipage scheme (2015)					
	Baseline		Intermediate		Full equipage	
VLJ and small LJ type of operations	V7/V7.1 mix	V7.1 only	V7/V7.1 mix	V7.1 only	V7/V7.1 mix	V7.1 only
Balanced	85.6%	85.6%	51.4%	51.2%	45.9%	45.7%
Business av.			50.7%	50.5%	44.5%	44.2%
Commercial			52.2%	52.1%	47.7%	47.6%
Corporate			52.7%	52.6%	47.2%	47.1%

Table 4: Effect of ACAS II equipage of VLJs and small LJs on the airborne risk ratio

- 4.1.4.2. For the 'baseline' scenario where VLJs and small LJs are not equipped, the airborne risk ratio is quite high (about 85%), yet less than unity thanks to the ACAS II equipage of the threat aircraft in some circumstances. This means that unequipped VLJs and small LJs will nevertheless get some safety benefits from the ACAS II equipage from the rest of the fleet.
- 4.1.4.3. The simulation results also highlighted that equipping VLJ and small LJ aircraft with ACAS II has a very significant effect as it reduces their collision risk by a factor that varies between 1.6 and 1.9 for the 'intermediate' and 'full' equipage scenario, respectively. In both cases this is a very significant benefit in terms of safety for VLJ and LJ aircraft fitted with ACAS II.
- 4.1.4.4. It can also be noted that equipping all the light jets under 5,700 kg instead of equipping the medium and fast light jets only has a limited effect, as the risk of collision only decreases by about an additional 10%, due to the limited number of additional equipped aircraft.
- 4.1.4.5. Figure 15 is the density graph of VMDs for the 'full equipage' scenario compared to the 'baseline' scenario for those encounters that involve at least one VLJ or small LJ aircraft (assuming a 'balanced' mix of commercial, corporate and GA, operations).

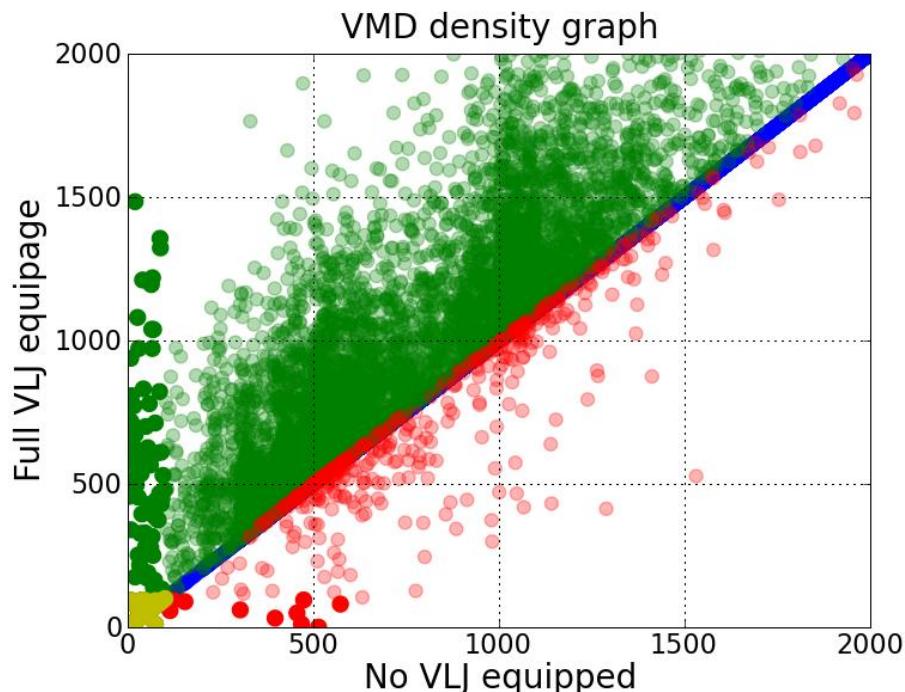


Figure 15: VMD density graph –‘Balanced’ scenario, full v7.1 – Airborne perspective

- 4.1.4.6. This graph shows that a noticeable part of the simulated encounters were modified by equipping VLJs and small LJs with ACAS II. In addition, the number of encounters with an increased VMD was far greater (about 17 times greater) than the number of encounters with a decreased VMD.
- 4.1.4.7. Overall the study results demonstrated that, from the perspective of VLJs and LJs aircraft, there are much more safety benefits than drawbacks in equipping with ACAS II. These benefits are considerable even when only the most common VLJs and small LJs aircraft equip.

4.2. ***Evaluation of the safety implications of TCAS I equipage***

4.2.1. **Scope and approach**

4.2.1.1. The AVAL study also investigated the safety implications of TCAS I equipage by VLJs and small LJs, as an alternative to their equipage with TCAS II ([D9]). This evaluation covered a wide range of possible operational scenarios, which are described in the subsequent section.

4.2.1.2. It was supported by the models of visual acquisition and evasive manoeuvres (cf. section 3.5) developed during the study. The instantaneous visual acquisition rate determined by the former model was used to stochastically determine whether visual acquisition prompted by TCAS I occurred during encounters, and to subsequently simulate a horizontal evasive manoeuvre using the latter model. It also required an adaptation of the post-VLJ safety encounter model for the 2015 timeframe (cf. section 3.6) for generating encounters with small Horizontal Miss Distances (HMD) of less than 1NM, and thus allowing a fair evaluation of the effectiveness of horizontal evasive manoeuvres initiated in response to TCAS I alerts.

4.2.1.3. A series of TCAS I and TCAS II simulations were thus conducted in two steps on generated encounters for each of the scenarios under investigation. The focus was on the encounters that involved at least one VLJ or small LJ aircraft since only these encounters were likely to be impacted. The risk reduction of the mid-air collision risk resulting from the evasive manoeuvres prompted by TCAS I alerts was evaluated. A sensitivity analysis was performed on the effect of the probability of correct turn following visual acquisition of the threat. Finally the mid-air collision risk reduction achieved through the 'see-and-avoid' procedure aided by TCAS I was compared to that provided by the pilots when following TCAS II resolution advisories.

4.2.2. **Operational scenarios under evaluation**

4.2.2.1. Five scenarios corresponding to different ACAS equipage schemes were investigated as follows:

- Three different TCAS I scenarios, which assumed a full VLJs and small LJs equipage with TCAS I with different assumptions regarding the effect of TCAS I on visual acquisition (see below) and a full TCAS II equipage of other aircraft in accordance with the current European ACAS II mandate;
- Two TCAS II scenarios, which assumed the extension of the current European ACAS II mandate to all VLJs and small LJs with different assumptions regarding the VLJ and small LJ pilots' response to RAs (see below).

4.2.2.2. The three TCAS I scenarios covered a wide range of assumptions regarding the meteorological visibility conditions, and their consequences on the visual acquisition prompted by TCAS I:

- TCAS I best case scenario: In this first scenario which assumes clear sky conditions (i.e. unlimited visibility), the visual acquisition is accomplished at the issuance of the TCAS I traffic advisories;

- **TCAS I medium case scenario:** This second scenario assumes that the lower limit of visibility under VFR rules applies and that the visual acquisition is accomplished at an average time of the probable visual acquisition aided by TCAS I (i.e. at a time corresponding to the mean value of a random variable defined by the cumulative distribution of the probability of visual acquisition after the TA issuance);
- **TCAS I worst case scenario:** assuming the lower limit of visibility under VFR rules, the visual acquisition is accomplished at a probable, yet pessimistic, time after the TCAS I alerts (i.e. at a time corresponding to the mean of the 10% lowest values of a random variable defined by the cumulative distribution of the probability of visual acquisition after the TA issuance).

4.2.2.3. The two TCAS II scenarios assumed different pilot's responses to RAs onboard the equipped aircraft:

- **TCAS II operational scenario:** set of operationally realistic assumptions for the pilots of aircraft subject to the current European ACAS II mandate (i.e. typical pilot response model defined in the ASARP project) and for the pilots of VLJs and LJs as defined for the balanced mix of VLJ and small LJ operations (cf. section 3.4).
- **TCAS II best case scenario:** all pilots of TCAS II equipped aircraft (including those of VLJs and small LJs) respond to RAs as expected by the TCAS II logic (i.e. standard pilot model).

4.2.2.4. In accordance with the assumptions made in [SIRE+3], it was further assumed that 100% of the TCAS II equipped aircraft will be fitted with version 7.1 in 2015.

4.2.3. Comparative analysis of the safety benefits of TCAS I and TCAS II equipage

4.2.3.1. The comparative analysis of the TCAS I and TCAS II scenarios was based on the computation of a 'close encounter ratio', which scales the number of close encounters with TCAS contribution (i.e., with TCAS I or TCAS II onboard VLJs, and TCAS II onboard other equipped aircraft) with the number of initially close encounters (i.e., without any TCAS I or II contribution)¹².

$$\text{close encounter ratio} = \frac{\text{close encounters with TCAS}}{\text{close encounters without TCAS}}$$

4.2.3.2. As shown in Figure 16, the TCAS I scenarios resulted in close encounter ratios higher than the TCAS II best case scenario (brown line, ratio equal to 11.0) whatever the probability of correct turn, and greater than the TCAS II operational scenario (black line, ratio equal to 42.0) except for:

- the TCAS I best case scenario (green line), when the probability of correct turn is higher than 80 %; and
- the TCAS I medium case scenario (blue line) when the probability of correct turn is higher than 95%.

¹² If it is assumed that any separation that exists between the aircraft is fortuitous, then by counting close encounters in a sufficiently large set of representative encounters the close encounter ratio produces a measure that is equivalent to a risk ratio.

4.2.3.3. The ratio increase observed between the TCAS II best case scenario and the TCAS II operational scenario shows that the latter is not an overly optimistic scenario, and is probably a fair reference for comparison with the TCAS I scenarios.

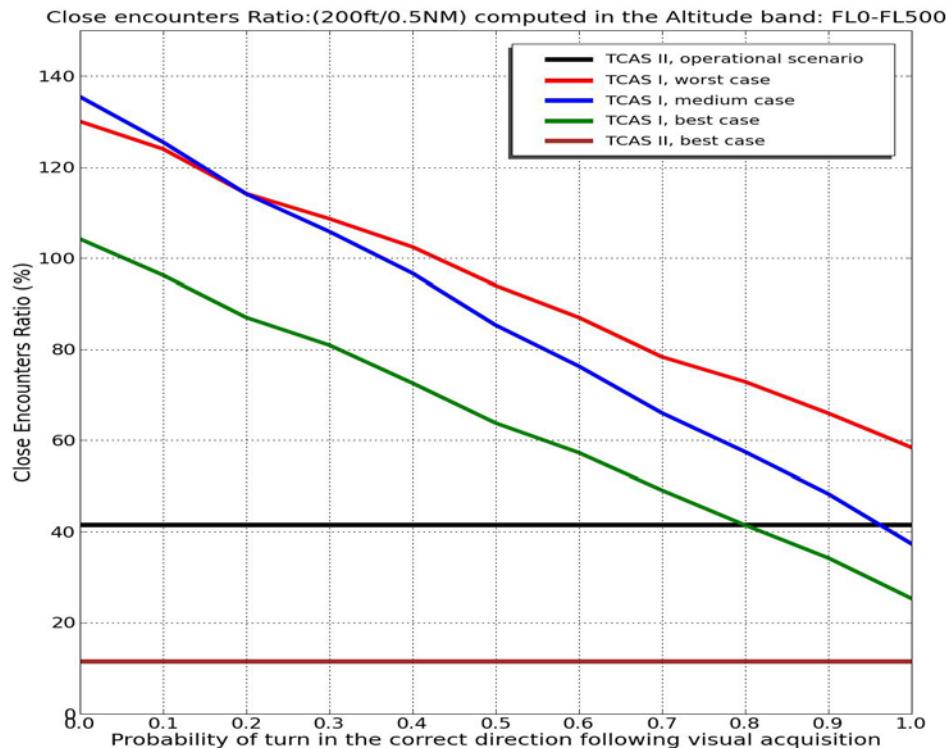


Figure 16: Effect of TCAS I equipage of VLJs and small LJs on close encounter ratio

4.2.3.4. As expected, whatever the probability of turn in the correct direction, the TCAS I best case scenario performs better than the TCAS I medium case scenario and the TCAS I worst case scenario.

4.2.3.5. Furthermore, the TCAS I medium case scenario performs better than the TCAS I worst case scenario, except for low probabilities of correct turn. For these low probabilities of correct turn, it is difficult to conclude anything from the fact that the worst case scenario seems to outperform the TCAS I medium case scenario, as ratios are well over 100%. However, this phenomenon can be explained by the TCAS I worst case scenario having shorter horizontal manoeuvres, giving less time to satisfy the close encounter criteria.

4.2.3.6. In summary, these results indicates that TCAS II offers a better protection than TCAS I, except if one assumes that horizontal evasive manoeuvres performed after a TA and visual acquisition under clear sky are very often made in the correct sense, which seems to be a quite optimistic assumption.

4.2.4. Extent of the evasive manoeuvres prompted by TCAS I compared to TCAS II resolution advisories

4.2.4.1. The trajectory deviations resulting from the evasive manoeuvres prompted by TCAS I traffic advisories (or TCAS II resolution advisories, respectively) are a major metric of the potential disruption caused by TCAS to ATC. Minimising these horizontal or vertical displacements for avoiding action makes the airborne safety net more compatible with the ATC system.

- 4.2.4.2. The crucial element in the calculation of vertical deviation is to identify deviations that have an impact on ATC. An aircraft that is limiting its rate of descent or climb does not deviate from its original flight path in the ATC general sense. A positive vertical deviation is therefore generally associated with a manoeuvre that leads the aircraft to fly outside the altitude band defined by the altitudes at which the aircraft starts to deviate from, and then resumes, its original flight path.
- 4.2.4.3. Similarly, a deviation can be associated to horizontal manoeuvres, and also provides a major metric of the disruption caused by TCAS I to ATC. In this study, this deviation was defined as the maximum distance between the trajectory without any horizontal manoeuvre, and the modified trajectory with the horizontal manoeuvre.
- 4.2.4.4. Figure 17 shows the distributions of deviations in the simulated encounters for the TCAS II 'operational' scenario, and the TCAS I 'medium case' scenario assuming a probability of correct turn by the VLJ and small LJ pilots of 80%. This latter scenario can be considered an optimistic TCAS I scenario compared to the TCAS II operational scenario.

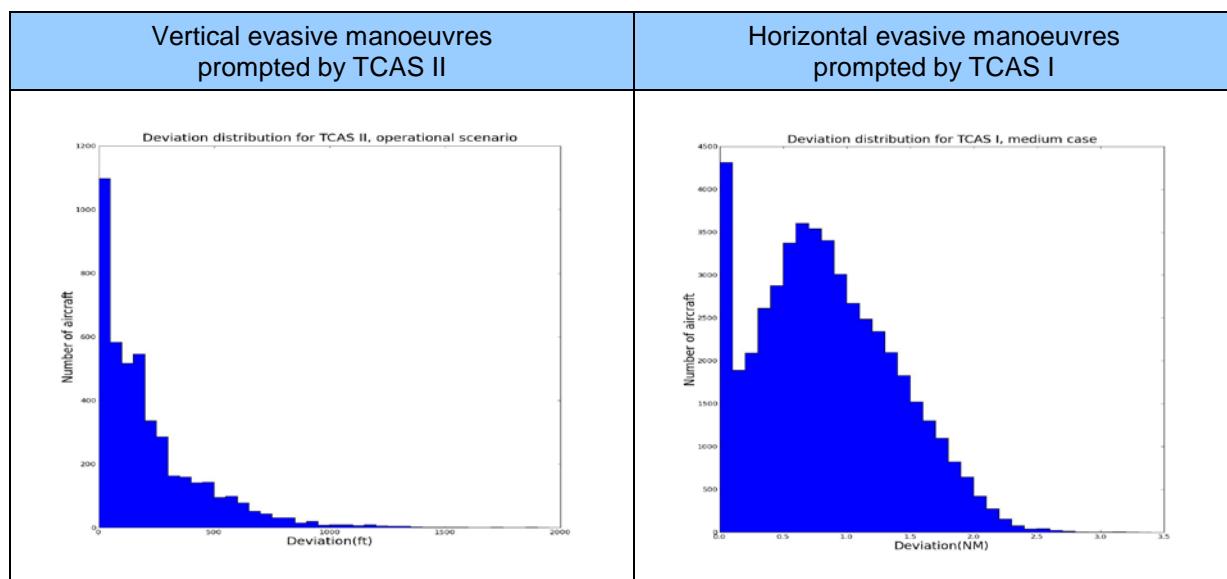


Figure 17: Deviations resulting from evasive manoeuvres prompted by TCAS I

- 4.2.4.5. With TCAS I, the deviations can be over 2 NM, which shows that there is a price to pay in terms of TCAS I compatibility with ATC for safety benefits.
- 4.2.4.6. It is also worth noting that with TCAS I, the number of deviating aircraft is 5 times greater than with TCAS II. This increased number of deviating aircraft could be a nuisance for ATC.

4.2.5. Efficiency of the evasive manoeuvres prompted by TCAS I compared to TCAS II resolution advisories

- 4.2.5.1. For both TCAS I and TCAS II, the manoeuvre efficiency can be defined as the ratio between the gain in the separation achieved at closest approach (either in the horizontal or in the vertical dimension), and the summed deviations of both

aircraft¹³. For a given separation gain, the higher the deviation, the lower the efficiency.

$$Efficiency = \frac{\Delta Separation}{\sum Deviations}$$

4.2.5.2. Figure 18 shows the distribution of the efficiency ratio in the simulated encounters for the various TCAS I scenarios, as well as for the TCAS II operational scenario, for comparison purposes.

Legend: Efficiency ratios are classified in bins of 10%, with ratios higher than 100% classified in the bin $[100, \infty[$, and negative ratios in the left-most bin called “neg”, meaning a loss of separation despite a deviation.

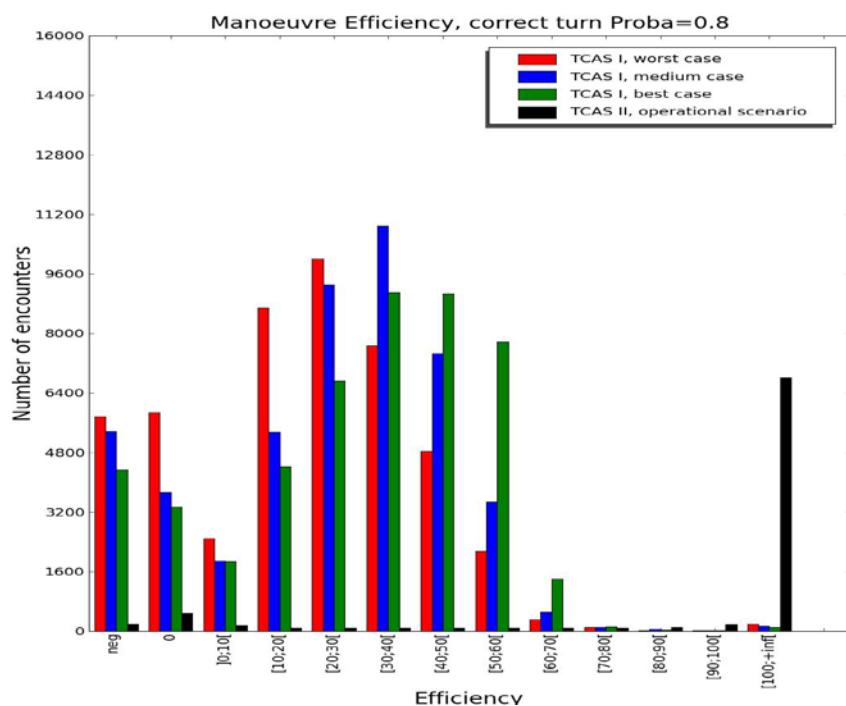


Figure 18: Efficiency of the evasive manoeuvres prompted by TCAS I

4.2.5.3. With the TCAS I scenarios, most of the encounters (i.e., about 78% at the best) end with an efficiency ratio below 50%. With the TCAS II operational scenario, only 12% of the encounters have an efficiency ratio below 50%.

4.2.5.4. Overall the study results show that, when considering the efficiency of the evasive manoeuvres prompted by TCAS I, their likelihood of occurrence, as well as the resulting deviations, TCAS I does not perform as well as TCAS II, and markedly so. Furthermore the TCAS I performance is much more influenced (than that of TCAS II) by the meteorological conditions and the pilot's ability to initiate an effective avoidance manoeuvre.

¹³ For horizontal manoeuvres prompted by TCAS I, the efficiency was computed only taking into account the deviation of the own aircraft, regardless of whether the intruder is a VLJ or not.

4.3. Pros and Cons of Collision Avoidance equipage of VLJs and small LJs

4.3.1. Options for ACAS equipage

4.3.1.1. Four options for Collision Avoidance equipage by VLJ and small LJ aircraft can be envisaged as follows:

- Option 1 – No change in the current European ACAS II mandate (i.e., VLJs and LJs under 5,700 kg not equipped with ACAS II)
- Option 2 – Mainstream VLJ equipage with ACAS II: Extension of the current European ACAS II mandate to VLJs and small LJs with maximum cruising speed of at least 350 kt
- Option 3 – Full VLJ equipage with ACAS II: Extension of the current European ACAS II mandate to VLJs and small LJs with maximum cruising speed of at least 250 kt
- Option 4 – Full VLJ and small LJ equipage with TCAS I: Towards a mandate for TCAS I equipage of VLJs and LJs under 5,700 kg, as an alternative to the extension of the ACAS II mandate.

4.3.1.2. From the study findings, four criteria can be identified that should help deciding between these four options. These criteria, which reflect the expectations of different stakeholders, cover a full range of areas, including safety, operational, technical and economic aspects as listed in Table 5.

Criteria	Stakeholders	Remarks
Overall safety in Europe not degraded following the introduction of VLJs	Regulator, airspace users, ANSPs	Safety of flight operations in the whole airspace, taking into account the safety benefits afforded by the current European ACAS II mandate
Conduct of VLJ operations with a level of safety commensurate to that of mainstream operations	Operators of VLJs, VLJ's users	From a fleet perspective and all type of operations i.e. commercial flights, corporate flights and GA flights
Effectiveness of avoidance manoeuvres by VLJs	ANSPs	From an ATM perspective, with number of avoidance manoeuvres with large deviations kept to an effective minimum for maximum compatibility with ATC
Acceptability of the relative costs	Operators of VLJs	From the economic perspective, relative costs between the options, including both the equipment and training costs

Table 5: Evaluation criteria for options of ACAS equipage of VLJs and small LJs

4.3.1.3. Each of the ACAS options for VLJs and small LJs has been evaluated against the above criteria, first by separately scoring the level of fulfilment of each criterion, and totalling these elementary scores. The level of fulfilment of a given criterion was evaluated using a simple rating mechanism as follows: 'very low' (1), 'Low' (2), 'medium' (3), 'high' (4) or 'very high' (5).

4.3.1.4. The results of this un-weighted multi-criteria analysis are provided in Table 6.

Criteria	Options for ACAS equipage of VLJs			
	Option 1	Option 2	Option 3	Option 4
No ACAS equipage	2	5	5	3
Mainstream VLJs ACAS II equipped	2	4	5	3
Full ACAS II equipage of VLJs	3	4	4	2
Full TCAS I equipage of VLJs	5	1	1	2
Total score	12	14	15	10
Ranking	3	2	1	4

Table 6: Un-weighted multi-criteria analysis of ACAS options for VLJs and small LJs

4.3.1.5. In a second step, trade-off between the various criteria was introduced through a simple weighting mechanism that aims at reflecting the level of importance of each criterion, viz.: 'very high' (5) for the 'overall safety in Europe', 'High' (4) for the 'Safety of VLJ operations', 'Medium' (3) for the 'Effectiveness (from ATM perspective)' and 'high' (4) for the 'relative costs' of a given option.

4.3.1.6. Naturally the 'overall safety' receives a higher weighting than the 'safety within a segment' of the overall flight operations. Obviously, 'effectiveness' from an ATC perspective is subordinate to 'safety' and weighted accordingly. Finally, to address the concerns of VLJ operators, an equal weight is given to 'safety' and 'cost' for their operations (but for the purpose of this analysis only).

4.3.1.7. The results of this weighted multi-criteria analysis are provided in Table 7.

Criteria	Options for ACAS equipage of VLJs			
	Option 1	Option 2	Option 3	Option 4
No ACAS equipage	10	25	25	15
Mainstream VLJs ACAS II equipped	8	16	20	12
Full ACAS II equipage of VLJs	9	12	12	6
Full TCAS I equipage of VLJs	20	4	4	8
Total score	47	57	61	41
Ranking	3	2	1	4

Table 7: Weighted multi-criteria analysis of ACAS options for VLJs and small LJs

4.3.1.8. The un-weighted and weighted multi-criteria analyses provided similar results. Both analyses favour Option 3 (i.e. Full ACAS II equipage of VLJs), although Option 2 (i.e. Mainstream VLJs ACAS II equipped) has very similar scores.

4.3.1.9. Although some credit is given to the potential safety benefits of TCAS I, both analyses ultimately favour Option 1 (i.e. No ACAS equipage of VLJs) compared to Option 4 (i.e. TCAS I equipage of VLJs). This reflects the fact that the gains in safety (in terms of the reduction of mid-air collision risk) that can be expected by TCAS I equipage and operation are offset by the costs and effectiveness from an ATM perspective.

- 4.3.1.10. It can therefore be concluded that equipping VLJs and small LJs with TCAS I (Option 4) is the less preferred option: no ACAS equipage of these aircraft (Option 1) is better. Modifying the criteria of the current European ACAS II mandate to include, at least the mainstream VLJs (Option 2), and preferably all LJs under 5,700 kg (Option 3) remains, however, the most effective option for safe and effective VLJ operations in Europe.
- 4.3.1.11. Key elements that support these study conclusions (and the scores established during the multi-criteria analyses) are provided in the following sections.

4.3.2. Safety considerations

- 4.3.2.1. From the perspective of the overall safety in Europe, the present study has confirmed that equipping light jets under 5,700 kg with ACAS II has the potential to slightly improve the risk reduction afforded by ACAS II in the future European airspace with VLJ operations, and this regardless of the nature of these operations.
- 4.3.2.2. It is worth noting that, if not ACAS II equipped, the operations of VLJs might have a small, yet noticeable, impact on the safety benefits delivered by ACAS II to large aeroplanes already equipped. Indeed, the mid-air collision risk reduction provided by ACAS II is significantly greater in case of coordinated RAs between two equipped aircraft compared to RAs against unequipped aircraft.
- 4.3.2.3. From the perspective of VLJs and LJs aircraft, the study has also demonstrated that there are much more safety benefits than drawbacks in equipping with ACAS II, and that these benefits might be very significant as far as the most common VLJs and small LJs aircraft would be equipped.
- 4.3.2.4. With regard to the alternative of a TCAS I equipage by light jets not subject to the current European ACAS II mandate, the safety implications are much more balanced.
 - On one hand, TCAS I is likely to increase the probability of visual acquisition under certain circumstances, and therefore, increase the chance for the pilot to exercise 'see-and-avoid'.
 - On the other hand, the shortcomings of visual acquisition, along with the fact that visually acquiring a threat is no guarantee that a collision will be avoided, are de-facto impacting the potential safety benefits of TCAS I (cf. section 2.6 for further details). Further the visual acquisition aided by TCAS I brings with it an increase in the probability that the two aircraft will initiate an evasive manoeuvre in a similar timeframe and potentially employ incompatible avoidance manoeuvres.
- 4.3.2.5. Finally, when considering the efficiency of the evasive manoeuvres prompted by TCAS I (i.e. both in terms of likelihood and achieved separation compared to the resulting deviations), the performance of TCAS I was demonstrated to be far from being as effective as the performance of ACAS II. The safety benefits delivered by TCAS I are hence bought at the cost of much more frequent deviations than with TCAS II, and often large deviations, which could be a nuisance for ATC.

4.3.3. Operational considerations

- 4.3.3.1. To deliver the expected safety benefits, the ACAS II equipage and operation by VLJ and small LJ aircraft would however require that their pilots promptly and correctly respond to the RAs issued by the CAS logic.
- 4.3.3.2. Light jets under 5,700 kg present two specific issues compared to larger aircraft currently equipped with ACAS II, i.e. their approved operation by a single pilot for many of these aircraft, and their future operation by a mixed population of pilots with different backgrounds (including pilots with close to no experience with TCAS II). These issues might have an impact on their pilots' behaviour when faced with TCAS II RAs, which are stressful and unusual situations in a cockpit. The training issues should, therefore, not be underestimated when envisaging the extension of the ACAS II mandate to these aircraft.
- 4.3.3.3. The TCAS I alternative raises another set of issues for the future VLJ and small LJ pilots. Unlike ACAS II, there is currently no published guidance for the use of TCAS I in Europe. Such guidance would be required to prevent any abuse of, or incorrect use of, the TCAS I traffic display that might be detrimental to safety.
- 4.3.3.4. The traffic display is designed to aid visual acquisition of an intruder: it is not designed nor certified for any other use. It is essential that pilots be made aware of the limitations of the display and in its interpretation before any operational use. Guidance would also be required to ensure that the pilots will not put overconfidence on TCAS I (which provides alerts only against transponder equipped aircraft). Other shortcomings related to the operational use of TCAS I derive from the inherent limitations of visual acquisition. A preamble to TCAS I operations by light jets would therefore consist of the pilots also being made aware of the limitations of the 'see-and-avoid' procedure.
- 4.3.3.5. TCAS I operations might also raise some safety and interoperability issues. Indeed the enhanced probability of visually acquisition thanks to TCAS I ironically brings with it an increase in the probability that two aircraft will initiate an evasive manoeuvre in a similar timeframe and potentially employ incompatible avoidance manoeuvres. The effect is most marked against threats which are equipped with ACAS II (since the interval around the time at which an RA will be generated corresponds to times at which the occurrence of visual acquisition is high). These issues would need to be solved by appropriate guidance before envisaging TCAS I operations by light jets.

4.3.4. Economic considerations

- 4.3.4.1. When envisaging the extension of the ACAS II mandate to light jets under 5,700 kg, some consideration needs to be given to the costs associated with the mandatory carriage of the ACAS II compliant equipment, viz. the TCAS II system. Similarly for the carriage of the TCAS I system, as an alternative to ACAS II for these aircraft.

4.3.4.2. Figure 19 shows, for a wide range of light jet aircraft, and assuming a price of between 60,000 and 150,000 US dollars¹⁴ for the TCAS II installation (on a new aircraft), the proportion of the aircraft price that TCAS II represents, versus weight.

4.3.4.3. These elements show that installing ACAS II on aircraft weighing less than 5,700 kg represents a small, yet not negligible, part of the price of the aircraft. This is especially true for VLJs. This proportion is however never greater than 3.8% of the price.

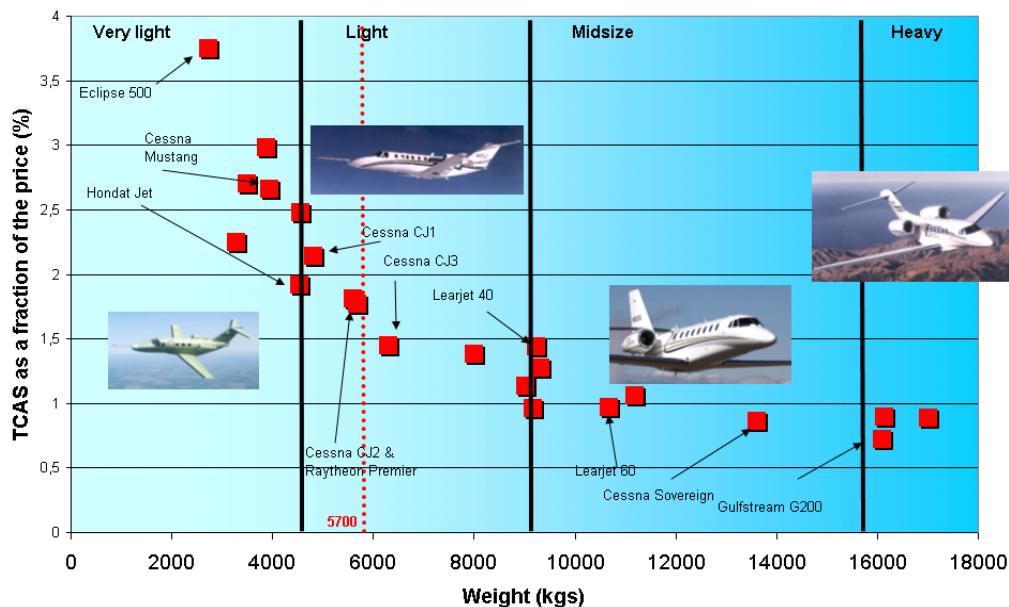


Figure 19: Fraction of the price that TCAS represents for jet aircraft

4.3.4.4. In comparison, and assuming of price of between 25,000 and 35,000 US dollars for the TCAS I installation, this equipment might appear as a cost-effective alternative to TCAS II. However, these reduced equipment costs would need to be balanced with the price to pay in terms of safety.

4.3.4.5. Whatever the option of ACAS equipage (TCAS II or TCAS I), the economic considerations should not only take into account the equipment costs, but possibly the additional costs related to pilot's specific and recurrent training.

4.3.5. Technical considerations

4.3.5.1. The technical feasibility of equipping light jets under 5,700 kg with TCAS II (or TCAS I) is another area to be looked at (which was outside the scope of the present study).

4.3.5.2. In the past, manufacturers have been faced with problem of location and interference issues when equipping small airframes with several advanced avionics with specific antennas. It is also known that TCAS I operation raises some radio frequency spectrum issues that might affect the operations of ACAS II.

¹⁴ The price depends on the weight of the aircraft: the heavier the aircraft, the higher the price in this computation.

5. Conclusions and recommendations

5.1. Main achievements and findings

5.1.1. General

5.1.1.1. The study evaluated several options for ACAS equipage by VLJ and small LJ aircraft with a specific focus on the safety aspects, but not exclusively. Other elements were also brought to light and examined to address operational, economic and technical aspects.

5.1.2. Safety evaluation approach

5.1.2.1. The cornerstone of the safety evaluation was the encounter model-based methodology used in the development of the ACAS II performance standards and in past evaluations of ACAS II safety benefits in Europe.

5.1.2.2. To simulate the future European ATM environment where a significant proportion of VLJ and small LJ operations will occur (viz. in the '2015 timeframe'), the 'European safety encounter model' (developed in past European ACAS II projects) has been adapted to reflect the anticipated VLJ and small LJ operations and to enable the modelling of the performance characteristics of these light jet aircraft. The study hence produced a pre-VLJ and a post-VLJ European safety encounter models addressing the 2008 and 2015 timeframes, respectively.

5.1.2.3. To evaluate the potential safety benefits of ACAS II equipage by VLJs and small LJs, as well as the impact on the overall performance of ACAS II in the future European environment, a series of pilot models were also developed that anticipate (based on past and current experiences) the possible pilots' responses to ACAS RAs onboard VLJ and small LJ aircraft.

5.1.2.4. These models made possible the determination of the ACAS II safety benefits in operationally realistic scenarios of ACAS II equipage and operation by simulating the behaviour of the ACAS II logic on a large number of encounters representing, as a whole, the typical encounters that one can, or would, observe in the European airspace (given a sufficiently long period of observation).

5.1.2.5. Finally, to evaluate the potential safety benefits of a TCAS I equipage by VLJs and small LJs (as an alternative to ACAS II equipage), a model of visual acquisition has been implemented, the probability of visual acquisition in various scenarios (with and without the aid of TCAS I) was investigated, and the evasive manoeuvres possibly resulting from the without acquisition prompted by TCAS I were modelled for use in the simulations.

5.1.3. Main safety evaluation results

5.1.3.1. With the proportion of VLJ and small LJ operations assumed in the study, there will be a small influence on the overall ACAS II performance in the 2015 European airspace. The study results demonstrated that the extension of the current European ACAS II mandate to these aircraft would slightly improve the mid-air collision risk reduction afforded by ACAS II (at airspace level).

- 5.1.3.2. In addition, from the perspective of each VLJ or LJ aircraft, the study results demonstrated a net safety benefit when equipping with ACAS II: almost halving the risk of mid-air collision. This benefit is considerable even when only the most common VLJs and small LJs aircraft equip and even greater when less common VLJs and LJs equip as well.
- 5.1.3.3. Regarding the option of a TCAS I equipage of VLJ and small LJ aircraft (as an alternative to ACAS II equipage), the study demonstrated that TCAS I equipage can undoubtedly enhance the prospect of visually acquiring a collision threat but only in certain scenarios. It was also highlighted that the enhanced probability of visually acquisition ironically brings with it an increase in the probability of simultaneous, potentially incompatible, evasive manoeuvres. This effect is most marked against threats which are equipped with ACAS II, and might be detrimental to the overall safety in the airspace.
- 5.1.3.4. The study results also show that, when considering the efficiency of the evasive manoeuvres prompted by TCAS I, their likelihood of occurrence, as well as any resulting deviations, TCAS I does not perform as well as ACAS II, and markedly so. The study finally highlighted how much the TCAS I performance is much more influenced (than that of ACAS II) by the meteorological conditions and the pilot's ability to execute an effective avoidance manoeuvre.
- 5.1.3.5. Although aspects of TCAS I operation have been investigated, it is worth noting that it was beyond the scope of the study to quantify the potentially safety benefits delivered by TCAS I.
- 5.1.3.6. Finally, the TCAS I option would require specific attention from the regulatory standpoint (as no framework currently exists for TCAS I carriage in Europe, unlike for ACAS II carriage).

5.1.4. Other study results

- 5.1.4.1. The study actually identified four criteria that should help when deciding between the various options for ACAS equipage by VLJ and small LJ aircraft. These criteria, which reflect the expectations of different stakeholders, include naturally safety, but also operational, technical and economic criteria.
- 5.1.4.2. The un-weighted and weighted analyses of the level of fulfilment of each of these criteria for different options of ACAS equipage concluded that equipping VLJs and small LJs with TCAS I is the least preferred option. Indeed, it might be better not to equip these aircraft with TCAS I in order to minimise disruption of ATC and ACAS II operations.
- 5.1.4.3. Finally, modifying the criteria of the current European ACAS II mandate to include, at least the mainstream VLJs, and preferably all LJs under 5,700 kg, was demonstrated to be the most effective option for safe and effective VLJ operations in Europe.

5.2. Recommendations

5.2.1. In light of the study findings and in order to maintain the mid-air collision risk reduction afforded by ACAS II in Europe notwithstanding the anticipated increase in the number of flights operated by light jets under 5,700 kg, the following recommendations are made:

R1: It is recommended to extend the European ACAS II mandate to include all civil fixed-wing turbine-engined aircraft with a maximum cruising speed of over 250 kt.

R2: Proper attention should be given to ACAS II training for pilots of light jets under 5,700 kg regardless of the extension date of the European ACAS II mandate (as some aircraft might equip sooner on a voluntary basis).

5.2.2. With regard to TCAS I, the study produced no evidence on which to base any recommendation for equipping light jets under 5,700 kg. The following recommendation is therefore made:

R3: Before any operator decides to equip with TCAS I, the safety benefits of TCAS I in the European airspace should be demonstrated and quantified, with a particular focus on the potential impact on the mid-air collision risk reduction delivered by ACAS II.

6. References

6.1. AVAL *internal references*

- [D1] 'Performances of VLJs and LJs & Updated European safety encounter model aircraft class definition' – AVAL/WA1/06/D, Version 1.0, February 2008
- [D2] 'Operations of VLJs and LJs in the European airspace' – AVAL/WA2/07/D, Version 1.0, February 2008
- [D3] 'European radar data encounter description' – AVAL/WA3/20/D, Version 1.0, February 2008
- [D4] 'European safety-encounter model incorporating VLJ operations' – AVAL/WA4/30/D, Version 1.1, May 2009
- [D5] 'Modelling of Single Pilot Operations' – AVAL/WA5/08/D, Version 1.0, May 2008
- [D6] 'AVAL TCAS II simulation results' – AVAL/WA6/37/D, Version 1.0, June 2009
- [D7] 'Synthesis of AVAL Phase 1 findings' – AVAL/WA7/09/D, Version 1.3, March 2008
- [D8] 'Illustrative probabilities of visual acquisition with TCAS I and ACAS II' – AVAL/WA8/22/D, Version 1.2, February 2009
- [D9] 'Risk evaluation for TCAS I equipage onboard VLJs' – AVAL/WA9/40/D, Version 1.0, July 2009

6.2. *External references*

- [ACA1] 'Final report on studies on the safety of ACAS in Europe' – EUROCONTROL ACAS Programme – ACASA/WP1.8/210D, Version 1.3, March 2002
www.eurocontrol.int/msa/gallery/content/public/documents/Safety/WP1.pdf
- [ACA2] 'European Encounter Model: Part 1/2 – Specifications' – EUROCONTROL ACAS Programme – ACASA/WP1.1/186, Version 2.1, December 2001
- [ACA3] 'ACAS Safety Study – Safety benefit of ACAS II Phase 1 and Phase 2 in the new European Airspace environment' – EUROCONTROL ACAS Programme – Version 3.0, May 2002
http://www.eurocontrol.int/msa/gallery/content/public/documents/Safety/ACAS_Doc_Safety_Study_in_EE.pdf
- [ACA4] 'ACAS brochure' – EUROCONTROL ACAS Programme – ACASA/WP6.1/015, version 2.0, May 2000
www.eurocontrol.int/msa/gallery/content/public/documents/ACAS_training_ver20.pdf
- [ACA5] 'Electromagnetic environmental effects of and on ACAS' – EUROCONTROL ACAS Programme – ACASA/WP5/211D, Version 1.1, March 2002
www.eurocontrol.int/msa/gallery/content/public/documents/WP5.pdf

[ACA6] 'Incorrect use of the TCAS traffic display' – EUROCONTROL Mode S and ACAS programme – ACAS II Bulletin no. 6, April 2005
www.eurocontrol.int/msa/gallery/content/public/documents/ACAS_Bulletin_6_discaimer.pdf

[ACAS] 'Surveillance Radar and Collision Avoidance Systems' – ICAO, Annex 10, Volume IV, 4th edition, July 2007

[ANN2] 'Rules of the Air' – ICAO, Annex 2, 10th edition, July 2005

[ASAR] 'Final report on the safety of ACAS II in the European RVSM environment' – EUROCONTROL Mode S & ACAS Programme – ASARP/WP9/72/D, Version 1.1, May 2006
www.eurocontrol.int/msa/gallery/content/public/documents/Final_Report_on_the_Safety_of_ACAS_II_in_the_European_RVSM_Environment_v1.1.pdf

[AVBU] 'Light Jets Round-Up 2007' – World Aircraft Sales Magazine – August 2007 – www.avbuyer.com

[BARN] 'The global need for Very Light Jet (VLJ) training best practices' – R. Barnes – EATS 2007

[BASI] 'Limitations of the See-and-Avoid Principle' – Australian Bureau of Air Safety Investigation – April 1991, ISBN 0-642-16089-9
http://www.atsb.gov.au/media/32918/limit_see_avoid.pdf

[CAA] 'Collision avoidance' – UK CAA, Safety Sense Leaflet 13a, June 2005
www.caa.co.uk/docs/33/ga_srg_09webSSL13.pdf

[EMB] 'EUROCONTROL VLJ Workshop - Session 1: What is a VLJ; Its performance; its target market? Phenom100 and the European market' - Marco Túlio Pellegrini VP, Market Intelligence, Embraer - 4th may 2007
www.eurocontrol.int/eatm/public/event/070504_vlj.html

[ETIR] 'EUROCONTROL VLJ Workshop – Taxi Please !!!' - ETIRC Aviation S.à.r.l. Drs. Matthijs de Haan MBA - 4th may 2007

[FAA] 'Pilots' role in collision avoidance' – FAA, advisory circular AC 90-48C, 18th March 1983
rgl.faa.gov/Regulatory_and_Guidance_Library%5CrgAdvisoryCircular.nsf/0/7373CDBC7158F4C286256A03006E1551?OpenDocument

[GFOR] 'Global Market Forecast 2007-2026', Airbus

[JETB] 'EUROCONTROL VLJ Workshop - Transforming Private Jet Travel' – Patrick Raftery, Jetbird - 4th may 2007

[LLAB] 'Air-to-Air Visual Acquisition Handbook' - Andrews, Lincoln Laboratory project report ATC-151, DOT/FAA/PM-87/34, 27th November 1991
www.dtic.mil/srch/doc?collection=t3&id=ADA243807

[MIT] 'Investigation of the Potential Impacts of the Entry of Very Light Jets in the National Airspace System' – Philippe A. Bonnefoy and R. John Hansman, MIT International Center for Air Transportation – Report 2006-02

- [NASA] 'Single pilot commercial aircraft operations' – S. Deutsch, R. Pew – NASA, 2005
- [NBAA] 'Training guidelines for Single Pilot Operations of Very Light Jets and Technically Advanced Aircraft' – NBAA, January 2005
- [RCR] 'Report to Congressional Requesters, VERY LIGHT JETS, Several Factors Could Influence Their Effect on the National Airspace System' – United States Government Accountability Office – GAO-07-1001, August 2007
- [SFO1] 'EUROCONTROL Trends in Air Traffic | volume 1, Getting to the Point: Business Aviation in Europe' – EUROCONTROL Statistics and Forecast Service (STATFOR) Doc176 – Version 1.0, May 2006
http://www.eurocontrol.int/statfor/gallery/content/public/analysis/Business_Aviation_Study_Doc176_v1.0_FINAL.pdf
- [SFO2] 'EUROCONTROL Medium-Term Forecast: IFR Flight Movements 2009–2015' – EUROCONTROL Statistics and Forecast Service (STATFOR) Doc327 – Version 1.0, February 2009
http://www.eurocontrol.int/statfor/gallery/content/public/forecasts/Doc327_MTF09_Report_Vol1_v1.0.pdf
- [SIRE] 'SIRE Project Final Report' – EUROCONTROL Mode S & ACAS Programme – SIRE/WP4/58/D, Version 1.1, December 2005
- [SIRE+1] 'CP115 (LOLO) Evaluation Report' – EUROCONTROL Mode S & ACAS Programme – SIRE+/WP5/40/D, Version 1.0, May 2007
http://www.eurocontrol.int/msa/gallery/content/public/documents/SIRE+_CP115-LOLO.pdf
- [SIRE+2] 'Operational performance of TCAS in European TMAs' – EUROCONTROL Mode S & ACAS Programme – SIRE+/WP1/81/D, Version 1.1, February 2009
http://www.eurocontrol.int/msa/gallery/content/public/documents/Extension_1.pdf
- [SIRE+3] 'Decision criteria for regulatory measures on TCAS II version 7.1' – EUROCONTROL Mode S & ACAS Programme – Version 1.2, July 2008
http://www.eurocontrol.int/msa/gallery/content/public/documents/SIRE+_WP7_69D_v1.2.pdf
- [TCAS1] 'Minimum operational performance standards for an active Traffic alert and Collision Avoidance System I (Active TCAS I)' – RTCA, DO-197A, Change 1, July 1997
- [TCAS2] 'Minimum operational performance standards for Traffic alert and Collision Avoidance System II airborne equipment' – RTCA, DO-185A, 1997
- [TCAS3] 'Minimum operational performance standards for Traffic alert and Collision Avoidance System II airborne equipment' – RTCA, DO-185B, 2008
- [VIP1] 'VIP – Very Light Jets Integration Platform, First meeting summary' - 16 October 2007'
- [WEB] Internet resources, including <http://www.airliners.net/>, manufacturers websites, and <http://www.flug-revue.rotor.com/>

Appendices

A. Background on VLJs and small LJs

A.1. Examples of VLJs

A.1.1. The following table provides some examples of VLJs with information such as weight and ground speed.

Aircraft	Manufacturer	Image	ICAO code	Weight	Ceiling	Cruise speed ¹⁵
A700	Adam Aircraft		not assigned	4,250 kg	FL410	340 kt
D-Jet	Diamond Aircraft		not assigned	2,318 kg	FL250	315 kt (long range: 240 kt)
Eclipse 500	Eclipse Aviation		EA50	2,719 kg	FL410	370 kt
Elite	Epic Aircraft		not assigned	3,495 kg	FL410	412 kt
Honda Jet	Honda		not assigned	4,173 kg	FL430	420 kt
Independence	Spectrum		not assigned	3,402 kg	FL450	415 kt
Javelin	Aviation Tech Group		not assigned	3,100 kg	FL450	500 kt

¹⁵ Often high cruise speeds

Mustang	Cessna Aircraft		not assigned	3,847 kg	FL410	340 kt
Phenom 100	Embraer		not assigned	<4,500 kg	FL410	360 kt
Piper Jet	Piper Aircraft		not assigned	<4,500 kg	FL350	360 kt
Smart Jet	Maverick Jets		not assigned	<4,500 kg	FL220	290 kt
Solo Jet	Maverick Jets		not assigned	<4,500 kg	FL310	350 kt
SPn	Grob Aerospace		not assigned	<4,500 kg	FL410	?
Sport Jet	Excel Jet		not assigned	2,200 kg	FL250	375 kt
The-Jet	Cirrus Design		not assigned	<4,500 kg	FL250	300 kt
Victory	Epic Aircraft		not assigned	2,497 kg	FL280	320 kt

A.2. Examples of LJs under 5,700 kg

A.2.1. The following table provides some examples of small VLJs (i.e. with MTOM under 5,700 kg) with information such as weight and ground speed.

Aircraft	Manufacturer	Image	ICAO code	Weight	Ceiling	Cruise speed ¹⁶
Cessna CJ1	Cessna		C525	4,899 kg	FL410	389 kt
Cessna CJ2	Cessna		C25A	5,585 kg	FL450	357 kt
Cessna Citation I	Cessna		C501	5,380 kg	FL380	357 kt
Cessna Citation	Cessna		C500	4,920 kg	FL380	348 kt
Raytheon Premier I	Raytheon		PRM1	5,670 kg	FL410	461 kt

¹⁶ Often high cruise speeds

A.3. **Sales and growth forecast of VLJs and small LJs**

A.3.1. Several forecasts of VLJ deliveries are available from manufacturers and various groups specialising in the aviation market. These forecasts sometimes use different assumptions with regard to the date for which the forecast is done and the level of traffic growth ([RCR]). The number of forecast deliveries worldwide range from 3,000 to 8,000 depending on the assumptions. **It is also worthwhile to note that these forecasts are sometimes dated and might not take into account the effect of the current economic crisis.**

A.3.2. Figure 20 translates the available figures into sales per year. Sales per year in Europe are also shown, with the rough assumption that they will correspond to 15% of the sales in the world. This figure of 15% is based on [SFO1] which states that for business aviation, the European share will be between 12% and 15%.

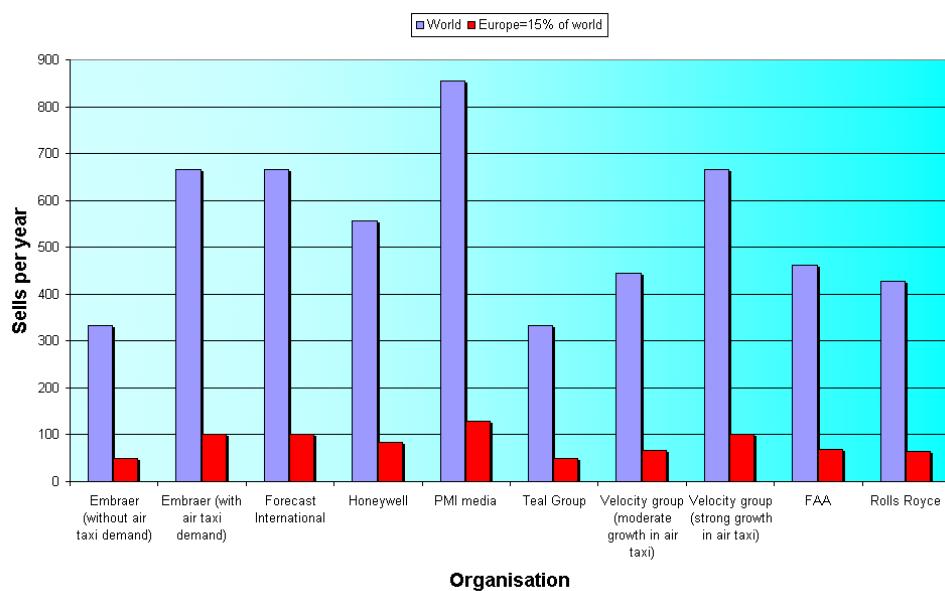


Figure 20: Worldwide and European VLJ delivery forecasts – Per year

A.3.3. With the assumption that Europe will represent 15% of the sales, the sales in Europe can be estimated to about 80 per year on average, ranging from 50 to 130 per year depending on the forecast source. These sales will primarily originate from the business aviation sector, where 25% to 33% of the current fleet is expected to be replaced, largely by VLJs, over the next 10 years.

A.3.4. Delivery forecasts made in Europe are close to this figure. Based on claims of VLJ sales, there are currently about 230 firm sales of VLJs in Europe, most of which are in 2009 and 2010 ([VIP1]). This can be translated into the figure of about 100 VLJs sold per year. Assuming this sales rate is sustained, about 700 VLJs would be delivered before 2015 in Europe.

A.3.5. Assuming VLJs will fly 3 times a day, this gives a rough estimate of an additional 300 extra flights per day each year ([VIP1]). Applying these same assumptions to the different delivery forecasts available leads to a range of 300 to 470 additional flights per day each year (viz. 110,000 to 170,000 additional flights each year) in Europe related to VLJs and LJs under 5,700 kg.

B. Background on TCAS I and TCAS II logics

B.1. General

- B.1.1. A TCAS system on-board an aircraft continuously tracks the range and altitude of nearby aircraft. Based on these tracked variables TCAS will generate alerts when certain internal tests indicate that there is a risk of impending collision.
- B.1.2. An intruder is declared a threat when it penetrates a protected volume enclosing own aircraft. The protected volume is defined by means of a range test (using range data only) and an altitude test (using altitude and range data).
- B.1.3. In a collision geometry the range test will be satisfied at a time that depends on the closing speed, u , and the values of two detection threshold parameters:
 - T , the nominal warning time; and
 - D , a distance parameter (familiar to some as 'DMOD') – in slow closure collision geometries aircraft can not approach closer than D without the range test being satisfied.
- B.1.4. The objective of the altitude test is to filter out intruders that give a positive result for the range test but are nevertheless projected to be adequately separated in the vertical dimension. The essential feature of the altitude test is that it aims to give a positive result if the projected vertical miss distance (using the same nominal warning time T) is less than a threshold Z (familiar to some as Z-threshold or ZTHR).
- B.1.5. The collision avoidance algorithm parameters are selected in accordance with the Sensitivity Level (SL) which is dependent on the aircraft's altitude, being more sensitive at higher altitude (cf. Table 8 for further details).

B.2. TCAS I logic

- B.2.1. The TCAS I logic only provides Traffic Advisories (TAs) to identify threatening aircraft to assist pilots in visual acquisition of intruder aircraft. The current version of the TCAS I MOPS was published in 1994. The document is RTCA DO-197A. A change document was issued in December 1997.

B.3. TCAS II logic versions

- B.3.1. TCAS II is a more sophisticated system which provides the information of TCAS I, and also includes complex collision avoidance logic to provide vertical Resolution Advisories (RAs) to the flight crew to resolve potential near mid-air collisions. There have been several versions of TCAS II MOPS.
- B.3.2. The first version of the TCAS II MOPS that complied with the ACAS II SARPs published by ICAO was the document DO-185A published in 1997. This version of TCAS II is referred to as "Version 7.0". Compared to the previous version, i.e. "Version 6.04a" which is not ACAS II SARPs compliant, Version 7.0 further improves TCAS II compatibility with the air traffic control system.

B.3.3. The most significant enhancements introduced in Version 7.0 are:

- An horizontal ‘Miss Distance Filter (MDF)’, which permits to inhibit RAs when the sequence of range measurements indicates a significant horizontal miss distance;
- Reduced thresholds, including a ‘Vertical Threshold Test (VTT)’, for improved compatibility with RVSM (Reduced Vertical Separation Minima) operations and 1000 feet level-off geometries;
- Reduced frequency of rate reversing RAs;
- A 25-foot vertical tracking; and
- The reduction of electromagnetic interference.

B.3.4. The current version of the TCAS II MOPS was published in June 2008. The document is RTCA DO-185B. A change document was approved in July 2009. This latest revision to the system is referred to as "Version 7.1". These MOPS have also been published by EUROCAE as ED-143.

B.3.5. Version 7.1 will bring two key changes to the TCAS II logic Version 7.0 as follows:

- Improvement of the reversal logic by detecting geometries close to that of the 2002 Überlingen mid-air collision, and by easing the triggering thresholds of reversal RAs in encounters in which the aircraft remain vertically within 100 ft of each other.
- Replacement of the several “Adjust Vertical Speed, Adjust” RAs with a single “Level-off” RA, and hence simplifying the list of RAs posted by TCAS II.

B.4. Summary of TCAS alert thresholds

B.4.1. The following table summarises the TCAS sensitivity levels and alert thresholds:

altitude ¹⁷		TCAS I				TCAS II						
from	to	SL	T_{TA} (s)	Z_{TA} (ft)	D_{TA} (NM)	SL	T_{TA} (s)	Z_{TA} (ft)	D_{TA} (NM)	T_{RA} (s)	Z_{RA} (ft)	D_{RA} (NM)
	1000ft	A	20	600	0.20	2	20	850	0.30	no RAs		
1000ft	2000ft					3	25	850	0.33	15	600	0.20
2000ft	2500ft		30	800	0.55	4	30	850	0.48	20	600	0.35
2500ft	FL50					5	40	850	0.75	25	600	0.55
FL50	FL100					6	45	850	1.00	30	600	0.80
FL100	FL200					7	48	850	1.30	35	700	1.10
FL200	FL410					7	48	1200	1.30	35	800	1.10
FL410												

Table 8: TCAS sensitivity levels and alert threshold parameters

¹⁷ The values given are the nominal bounds of the altitude bands. In practice a hysteresis of typically 500ft is applied as an aircraft passes from one altitude band to another.

C. Models of VLJ and LJ pilot's response to RAs

C.1. Existing pilot response models

C.1.1. The existing models of pilot response to RAs are mainly described by three parameters:

- the delay between the time of the RA and the start of the response manoeuvre;
- the vertical speed targeted by the modelled pilot; and
- the vertical acceleration with which the modelled pilot achieves the target vertical speed.

C.1.2. The ICAO ACAS II SARPS defines the nominal response to initial RAs with an initial delay of 5 seconds, a vertical speed as required by the RA (e.g., 1500 fpm for a Climb RA) and a vertical acceleration of 0.25 g. This response defines the 'standard pilot' model and is used by the ACAS II logic to determine the proper resolution of a given collision risk.

C.1.3. In the early stages of ACAS II implementation in Europe, the ACASA study ([ACA1]) has identified two distinct groups of pilot responses to RAs:

- 'aggressive response' in which pilots achieved a vertical rate in excess of that required by the RA; and
- 'slow response' in which the delay before a response was initiated was longer than standard, the acceleration was lower than standard, and the vertical rate attained was less than that required by the RA.

C.1.4. A few years later, the ASARP study ([ASA]) demonstrated that pilot behaviour in response to ACAS II had improved. Notably, their responses to corrective RAs were generally very close to the standard response expected by the ACAS II logic, although the reactions adopted spanned over a range of reaction times, vertical rates, and vertical accelerations.

C.1.5. The existing pilot's' response models to RA are summarised below.

Parameter of the pilot's response to RAs	Pilot response type			
	Standard (SARPs)	Slow (ACASA)	Aggressive (ACASA)	Typical (ASARP)
Initial RA delay	5 s	9 s	5 s	3 to 8 s
Initial RA target V/S	1500 fpm	500 fpm	3700 fpm	730 to 3900 fpm
Initial RA acceleration	0.25 g	0.1 g	0.25 g	0.09 to 0.3 g
Subsequent RA delay	2.5 s	2.5 s	2.5 s	2.5 s
Strengthening / weakening RA acceleration	0.25 g	0.1 g	0.25 g	0.09 to 0.3 g
Increase / reversal RA acceleration	0.35 g	0.1 g	0.25 g	0.35 g
Increase RA V/S	2500 fpm	500 fpm	3700 fpm	2500 / 3900 fpm

Table 9: Existing models of pilot's response to RAs

C.2. Key assumptions for pilots of VLJs and small LJs

C.2.1. To represent pilot responses to RAs of VLJs and LJs under 5,700 kg during double pilot operations, the models developed during the former ACASA and ASARP projects were considered as appropriate. The exact probabilities of non-response and non-standard manoeuvres were defined depending on the scenario being investigated.

- Non-response rate: lack of response to an RA varied between 10% and 30% depending on the altitude where the RA occurs (as recently observed in the SIRE project ([SIRE+2]));
- Nominal responses: mix of slow and aggressive responses (as observed in ACASA) for the airlines pilots without ACAS experience and GA pilots, and typical response (as observed in ASARP) for airlines pilots with ACAS experience;
- Opposite responses: commercial airline monitoring has shown opposite responses to RA happen in a few percents of cases. This percentage was estimated at about 1%.

C.2.2. For single pilot operation, the human-related factors that can affect the RA responses of VLJ and LJs under 5,700 kg pilots have been quantified in order to define the corresponding pilot models. These effects have been quantified relatively to the baseline value defined for double pilot operation as follows:

- Non-response rate: it is anticipated that the lack of a second crew member will increase the non-response rate by only 10 percentage points (e.g. 30% if the figure for two-member crews is 20%). Indeed, all types of pilots are now aware of ACAS.
- Opposite responses: it is anticipated that the opposite responses by a single pilot will increase by 5 percentage points due to the lack of cross-check by a second crew member and of the probable reduced available time for the manoeuvre.
- Initial delay: it is anticipated that this delay will increase by 50 percentage points, as a single pilot will have to carry all the tasks currently distributed between two crew members.
- High vertical rate: it is anticipated that this rate will increase by 20 percentage points, as a result of the later manoeuvres in which a single pilot will respond in a stronger manner.

C.3. Summary of pilot's response models for VLJs and small LJs

C.3.1. The resulting pilot's response models to RAs for VLJs and LJs under 5,700 kg are summarised below.

Parameter of the pilot's response to RAs		Pilot background and response type				
		Airline pilot, with ACAS experience	Airline pilot with no ACAS experience		GA pilot	
			slow	aggressive	slow	aggressive
Nominal response rate	Two pilots	70% < FL50 90% > FL50	39% < FL50 44.5% > FL50	39% < FL50 44.5% > FL50	34% < FL50 39.5% > FL50	34% < FL50 39.5% > FL50
	Single pilot	55% < FL50 75% > FL50	25% < FL50 30% > FL50	38% < FL50 44% > FL50	21% < FL50 26% > FL50	32% < FL50 38% > FL50
Initial RA delay	Two pilots	3 to 8 s	9 s	5 s	9 s	5 s
	Single pilot	5 to 12 s	15 s	8 s	15 s	8 s
Initial RA target V/S		730 to 3900 fpm	500 fpm	3700 fpm	500 fpm	3700 fpm
Initial RA acceleration		0.09 to 0.3 g	0.1 g	0.25 g	0.1 g	0.25 g
Subsequent RA delay		2.5 s	2.5 s	2.5 s	2.5 s	2.5 s
Strengthening / weakening RA acceleration		0.09 to 0.3 g	0.1 g	0.25 g	0.1 g	0.25 g
Increase / reversal RA acceleration		0.35 g	0.1 g	0.25 g	0.1 g	0.25 g
Increase RA V/S		2500 / 3900 fpm	500 fpm	3700 fpm	500 fpm	3700 fpm
Non-response rate	Two pilots	30% < FL50 10% > FL50	20% < FL50 10% > FL50		25% < FL50 15% > FL50	
	Single pilot	40% < FL50 20% > FL50	30% < FL50 20% > FL50		35% < FL50 25% > FL50	
Opposite response	Two pilots	No	2% < FL50 1% > FL50		7% < FL50 6% > FL50	
	Single pilot	5%	7% < FL50 6% > FL50		12% < FL50 11% > FL50	
Horizontal manoeuvre		No	No		Yes ¹⁸	

Table 10: Models of pilot's response to RAs for VLJs and small LJs

¹⁸ For the sake of simplicity, the horizontal manoeuvres potential induced by an inappropriate TCAS II operation by GA pilots have not been included in the TCAS II simulations. Instead, the rates of non-response by these pilots have been increased by 5% when compared to airline pilots without ACAS experience.

D. Model of visual acquisition prompted by TCAS I

D.1. Factors affecting visual acquisition rate

D.1.1. The model of visual acquisition originally developed by Lincoln Laboratory combines the principal functional factors in visual acquisition to form a comparatively simple mathematical representation of the instantaneous 'visual acquisition rate' ([LLAB]).

D.1.2. These factors include: the physical size of the threat and the aspect from which it is viewed, the meteorological visibility; the angle of approach of the threat and the closing speed.

D.1.3. The functional relationship between these factors is summarised in Figure 21.

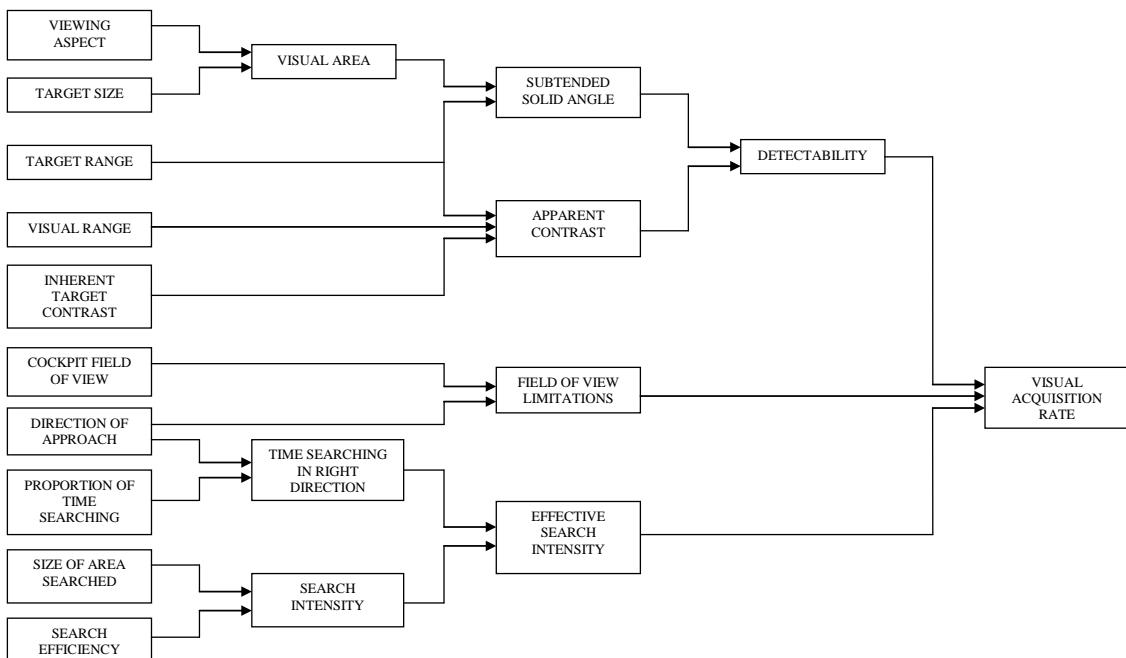


Figure 21: Functional factors determining instantaneous visual acquisition rate

D.2. Probability of visual acquisition

D.2.1. The probability, p , of a given target being visually acquired in a given instant of time t_0 can be computed as follows:

$$p(t_0) = 1 - \exp\left(-\int_{-\infty}^{t_0} \beta \cdot \frac{A}{r^2(t)} \cdot \exp\left(-\frac{3}{R} \cdot r(t)\right) \cdot dt\right) \quad (1)$$

D.2.2. In this equation, the meaning of β , A , u and R is the following:

- $r(t)$ represents the range between the two aircraft at time t ;

- R is the visual range (infinity if clear sky). The lower limit of visibility under VFR rules are 2.7 NM (5km) below 10,000 feet AMSL and 4.3 NM (8km) above 10 000 feet AMSL [5];
- A is the apparent cross-sectional area of the threat;
- β is the search intensity of the pilot, which corresponds to an un-alerted value (17,000 /st.s) or an alerted value (140,000 /st.s).

D.2.3. The instant at which a TA would be generated is calculated on the basis of the encounter geometry assuming perfect surveillance (in practice certain traffic patterns might result in severely degraded surveillance so that the benefit of TCAS I in aiding visual acquisition is overstated here). The 'alerted' value for the search intensity is used after the TA issuance, whereas the 'unalerted' value is used before it.

D.2.4. The cockpit field of view is aircraft type dependent. However, an approximation can be made by assuming that the target is in view if the relative bearing and elevation are within the following fixed thresholds.

$$\begin{cases} -105 \text{ deg} < \text{relative bearing} < +105 \text{ deg} \\ -22.5 \text{ deg} < \text{elevation} < +22.5 \text{ deg} \end{cases} \quad (2)$$

D.2.5. The figure below illustrates the effect of the 'alerted value' and 'un-alerted value' for the search intensity on the probability of visual acquisition with time.

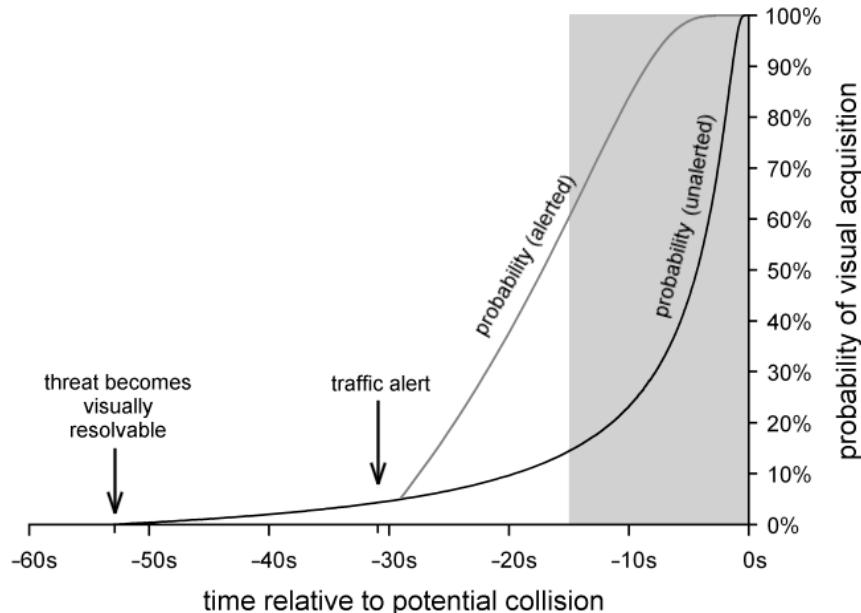


Figure 22: Change in the probability of visual acquisition with time to collision

D.3. **Cross-sectional area of the threat**

D.3.1. The AVAL European safety encounter model distinguishes between 14 aircraft performance classes. The cross-sectional area of each aircraft class is presented on the following table. It has been computed as the average of the cross-sectional areas of the aircraft types listed on the last column.

Aircraft performance class	Cross-sectional area			Aircraft type
	A_x	A_y	A_z	
Piston, Very Slow	5.83m ²	12.2m ²	30m ²	Cessna 421, Piper PA-23, Piper PA-28
Piston, Slow	7.5m ²	15.9m ²	38.7m ²	Cessna 421
TurboProp, Light, Slow	11.8m ²	24.8m ²	55.7m ²	King Air U21
TurboProp, Light, Medium	11.8m ²	24.8m ²	55.7m ²	King Air U21
TurboProp, Heavy, Very Slow	24.92m ²	67.05m ²	135.17m ²	De Havilland Dash 7, Bae ATP, Fokker 50, Beechcraft 1900C
TurboProp, Heavy, Slow	18.56m ²	59.23m ²	101.6m ²	Saab 2000, Dornier 328, BAe Jetstream 41
TurboProp, Heavy, Medium	34.1m ²	80.5m ²	162.3m ²	De Havilland Dash 7
Jet, Light, Very Slow	8.1m ²	20.6m ²	39.5m ²	Embraer Phenom 100
Jet, Light, Slow	8.1m ²	20.6m ²	39.5m ²	Embraer Phenom 100
Jet, Light, Medium	8.1m ²	20.6m ²	39.5m ²	Embraer Phenom 100
Jet, Light, Fast	8.1m ²	20.6m ²	39.5m ²	Embraer Phenom 100
Jet, Heavy, Medium	32.91m ²	105.53m ²	200.4m ²	Boeing 737-300, BAe 146-100, McDonnell Douglas DC9, BAe BAC1-11, Fokker 100, Embraer 145
Jet, Heavy, Fast	84.15m ²	290.21m ²	547.54m ²	Boeing 747-400, Boeing 777, Airbus A340, McDonnell Douglas DC10, Airbus A330, Lockheed L-1011-100 Tristar, Boeing 767-300, Airbus A300, Airbus A310, Boeing 707-320, Boeing 757, Tupolev 154, Airbus A320, Boeing 727, Concorde, Canadair CL-601
Military, Fast	6.75m ²	26.38m ²	57.2m ²	F15 Eagle, Panavia Tornado, BAe Harrier GR9, F18 Hornet, Dassault Mirage F1, BAe Hawk

Table 11: Cross-sectional area of threat aircraft in the present study

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