Working Area 2: Model-based performance evaluation of STCA and ACAS operations - Final report

Performance and safety Aspects of Short-term Conflict Alert – full Study

PASS Project

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RECORD OF CHANGES

Issue	Date	Detail of changes
0.1	29-07-2010	Draft outline of the PASS/WA2 final report
0.2	23-08-2010	Material added in all chapters building on the PASS/WA2 Interim report (Phase 2) and the latest simulation results (Phase 3)
0.3	09-09-2010	Reworked section 4.7 (STCA-ACAS interaction). Editorial changes following internal review. Completion of recommendations.
1.0	10-09-2010	First version delivered to EUROCONTROL
1.1	26-10-2010	Revised version taking into account comments received from EUROCONTROL and consolidation work for Final Report

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

Executive Summary

In the context of Short-Term Conflict Alert (STCA) standardisation in Europe, EUROCONTROL has launched the PASS project (**P**erformance and safety **A**spects of **S**hort-term Conflict Alert – full **S**tudy), based on the recommendations of the EUROCONTROL's RA downlink study (FARADS project) and the ACAS-STCA workshop held on 27 and 28 March 2007 in Zürich. The project falls within the scope of the SPIN (Safety nets Performance Improvement Network).

The second Work Area (WA2) of the PASS project specifically addresses the performance and safety benefits evaluation of STCA and ACAS operations. The cornerstone of this work is the refinement of the encounter model-based methodology already used in the ACAS field.

The work conducted within WA2 has enabled the development of a set of models that constitutes a realistic framework in which STCA fast-time simulations can be conducted. These models notably include an encounter model generating theoretical, yet realistic, situations in which STCA might be involved. EUROCONTROL reference STCA system has been implemented in an STCA model that can be configured to suit different approaches towards the operation of STCA. The CNS environment in which STCA is operated is also taken into account, notably with a model of ATC surveillance means. Lastly, the responses brought by human actors involved in STCA occurrences have also been implemented in specific controller and pilot models.

Using the inputs from PASS WA1 monitoring and the description of the European STCA environment conducted earlier in the project, a number of operational scenarios have been defined, that cover both TMA and en-route airspace. These operational scenarios cover a wide range of operationally realistic STCA implementations as observed in Europe. Several STCA families have notably been identified, which supply a greater or lesser frequency of time-critical alerts depending on the ANSP expectations regarding STCA, i.e. significant positive contribution to “collision prevention” mainly or also to “separation protection”. Specific scenarios were also defined to assess the influence of the CNS characteristics on the performance of STCA, as well as the influence of the human behaviour on the potential safety benefits that can be expected from STCA operation.

In parallel with the setting up of this simulation framework, a set of metrics have been defined that allow the performance of STCA in any given scenario to be quantified. These metrics relate to the likelihood of STCA alerts, to their operational relevance, to their potential efficacy and to the level of interaction between STCA and ACAS.

The subsequent fast-time simulations that have been performed show that the strategy followed by an ANSP when implementing and optimising its STCA system has a direct effect on the likelihood of alerts. Although all investigated STCA configurations show comparable alert rates for the most severe encounters, those designed mainly for “collision prevention” result in a rate of alerts in less severe encounters up to 100 less than those designed for “separation protection” as well as “collision prevention”.

A feature common to all investigated STCA configurations is the issuance of unnecessary alerts in encounters with no loss of separation. The frequency of these unnecessary alerts can be reduced either by using the CFL/SFL data, with less conservative separation and warning time parameter values, or, to a much lesser extent, with improved surveillance means.

The operational relevance of STCA alerts is dependant on the extent of aircraft proximity that an ANSP considers as requiring an alert, and thus on the strategy it follows when implementing and optimising its STCA system. While STCA systems designed for “separation protection” as well as “collision prevention” provide a high rate of alert (i.e. 90% or more) for encounters with a significant loss of separation (i.e. less than 80% of applicable minima), STCAs designed mainly for “collision prevention” provide comparable rates in encounters one order of magnitude more severe (i.e. less than 50% of applicable minima).

The behaviour of a given STCA system with regard to both rates of genuine and nuisance alerts can be more precisely tuned with the addition of optional features (use of CFL/SFL, additional filters, …). However, a balance always has to be struck between genuine and nuisance alert rates whatever the level of sophistication of the STCA.

The efficacy of STCA alerts is mostly linked to the warning time afforded by the STCA to the controller for him/her to assess the situation and take action to ensure that separation will not be infringed or will be restored. STCA systems designed for “separation protection” as well as “collision prevention” issue fewer time-critical alerts than those designed only for “collision prevention”. For a given STCA system, the use of optional features (use of CFL/SFL, additional filters, …) can provide additional warning time to the controller in a few specific circumstances.

These general trends are of course susceptible to be influenced by the performance of human actors involved in the responses to STCA alerts, with prompter controller responses or the use of avoiding phraseology reducing the final number of separation infringements. However, STCA systems designed for “separation protection” as well as “collision prevention” are less sensible to this influence of controller (and pilot) performances.

The simulations performed have also demonstrated that STCA families fundamentally designed for “collision prevention” significantly increase the likelihood of interaction with ACAS, compared to those families designed for “separation protection” as well. For the former STCA families, avoiding instructions should be preferably given in the vertical dimension so as to reduce the likelihood of a subsequent ACAS RA (since horizontal instructions are less effective in increasing safety margins, and hence to prevent RA issuance). However, belated vertical avoiding instructions have a greater potential for being contrary to a subsequent RA if and when it happens.

The comprehensive range of simulations conducted within WA2 of PASS have led to the recommendation of a set of performance metrics that can help quantify the qualitative requirements expressed in EUROCONTROL Specification of Short-Term Conflict Alert. Depending on the exact strategy adopted by an ANSP with regard to the role of its STCA system (i.e. focused on “collision prevention” or on “separation protection”), appropriate thresholds for these metrics can be established so as to set up minimum performance requirements for this STCA system.

Table of Contents

List of Figures

List of Tables

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 impeding collision.

Hereafter, ACAS always refers to ACAS II – a system that generates traffic advisories (TAs) and also resolution advisories (RAs) in the vertical dimension, and whose carriage and operation is mandatory for many aircraft in Europe.

Alert Indication of an actual or potential hazardous situation that requires particular attention or action (Source EUROCONTROL Specification of Short-Term Conflict Alert).

Hereafter, the term “alert” may refer to either an STCA alert or an ACAS alert.

Conflict Converging of aircraft in space and time which constitutes a predicted violation of a given set of separation minima.

Source EUROCONTROL Specification of Short-Term Conflict Alert (derived from ICAO Doc 9426)

CPA Closest Point of Approach – point of minimum physical distance between two aircraft (slant range) involved in an encounter.

This point is used by ACAS for the determination of its alerts.

CPP Closest Point of Propinquity – point of minimum ‘propinquity’ between two aircraft involved in an encounter.

The ‘propinquity’ metric (Rho) scales the horizontal and vertical distances (Hsep and Vsep) between the aircraft according to the respective separation minima (Hmin and Vmin) applicable by ATC.

$$Rho = \sqrt{(Hsep/Hmin)^2 + (Vsep/Vmin)^2}$$

This metric is used by the PASS encounter model for the building of the aircraft trajectories.

Encounter A traffic situation involving two (or more) aircraft in which STCA and/or ACAS may issue an alert.

Encounter severity An indication of the extent with which applicable ATC separation minima have been infringed in a given situation if a loss of separation occurred.

False alert Alert which does not correspond to a situation requiring particular attention or action (e.g. caused by split tracks and radar reflections).

Source EUROCONTROL Specification of Short-Term Conflict Alert

Ground-based safety net A ground-based safety net is functionality within the ATM system that is assigned by the ANSP with the sole purpose of monitoring the environment of operations in order to provide timely alerts of an increased risk to flight safety which may include resolution advice.

Source EUROCONTROL Specification of Short-Term Conflict Alert

Human performance Human capabilities and limitations which have an impact on the safety and efficiency of aeronautical operations.

Source EUROCONTROL Specification of Short-Term Conflict Alert

LOS Loss of Separation – point where the separation minima applicable by ATC are first infringed during an encounter.

Miss Distance Horizontal and vertical distances between two aircraft involved in an encounter at the 'Closest Point of Approach'.

Distance at Minimum Propinquity Horizontal and vertical distances between two aircraft involved in an encounter at the 'Closest Point of Propinquity'.

Minimum Separation Horizontal and vertical distances between two aircraft involved in an encounter at the 'Point of Minimum Separation'.

Nuisance alert Alert which is correctly generated according to the rule set but is considered operationally inappropriate.

Source EUROCONTROL Specification of Short-Term Conflict Alert

See also Appendix C.2 about possible performance-oriented definitions about to the operational relevance of alerts used in the PASS WA2 study

PoMS Point Of Minimum Separation – point of minimum 'separation factor' between two aircraft (slant range) involved in an encounter.

The 'separation factor' ('mu' or μ) is the maximum scale factor of the horizontal and vertical distances (Hsep and Vsep) between the aircraft according to the respective separation minima (Hmin and Vmin) applicable by ATC.

$$\mu = \text{MAX (Hsep/Hmin, Vsep/Vmin)}$$

This metric is proposed to be used in the PASS study for the severity determination of safety-net related encounters.

RA Resolution Advisory – an ACAS alert that indicates to a pilot how to adjust or regulate the vertical rate of the aircraft so as to avoid a mid-air collision

Separation Spacing between aircraft, levels or tracks.

Source EUROCONTROL Specification of Short-Term Conflict Alert

Separation minima Horizontal and vertical separation minimum applicable by ATC in a given environment.

In radar controlled airspace, typical separation minima are:
- 3 NM or 5 NM in the horizontal dimension; and
- 1,000 feet (or 2,000 feet) in the vertical dimension.

Short duration alert Short-Term Conflict Alert that ends less than 20 seconds after having been generated.

This definition is derived from an FAA Human Factor study ([HFFAA]), which suggested that "alerts lasting less than 20 seconds that do not result in operation errors can be considered nuisances because they deactivated before a response by the controller could have taken effect".

Split alert Alert that is temporarily switched-off (at least once) during the alert time window.

STCA Short-Term Conflict Alert – a ground-based safety net intended to assist the controller in preventing collision between aircraft by generating, in a timely manner, an alert of a potential or actual infringement of separation minima.

Source EUROCONTROL Specification of Short-Term Conflict Alert

TA Traffic Alert – an ACAS alert warning the pilot of the presence of another aircraft that may become the subject of an RA.

TCAS Traffic alert and Collision Avoidance System – an aircraft equipment that is an implementation of an ACAS

Hereafter, TCAS refers to TCAS II – the only equipment so far that is compliant with the ACAS II standards.

Warning time The amount of time between the first indication of an alert to the controller and the predicted hazardous situation.

Note – The achieved warning time depends on the geometry of the situation.

Note – The maximum warning time may be constrained in order to keep the number of nuisance alerts below an acceptable threshold.

Source EUROCONTROL Specification of Short-Term Conflict Alert

See also Appendix C.3 about possible performance-oriented definitions related to warning time of alerts used in the PASS WA2 study

Acronyms

ACAS	Airborne Collision Avoidance System
ACASA	ACAS Analysis
ANSP	Air Navigation Service Provider
ASARP	ACAS Safety Analysis – post-RVSM Project
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATM	Air Traffic Management
ATS	Air Traffic Services
CAS	Collision Avoidance System
CFL	Cleared Flight Level
CPA	Closest Point of Approach
CPF	Current Proximity Filter
CPP	Closest Point of Propinquity
ECIP	European Convergence and Implementation Plan
FARADS	Feasibility of ACAS RA Downlink Study
FL	Flight Level
I-AM-SAFE	IAPA – ASARP Methodology for Safety net Assessment – Feasibility Evaluation
IAPA	Implications on ACAS Performances due to ASAS Implementation
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
LoS	Loss of Separation (from an ATC perspective)
MRT	Multi-Radar Tracker
MTOM	Maximum Take-Off Mass
NMAC	Near Mid-Air Collision
PANS-OPS	Procedures for Air Navigation Services - Aircraft Operations
PASS	Performance and safety Aspects for Short-term conflict alert – full Study
PoMS	Point Of Minimum Separation
PoR	Point Of Risk
RA	Resolution Advisory
r.m.s.	Root Mean Square
RVSM	Reduced Vertical Separation Minima
SARPs	Standards And Recommended Practices
SIR	Separation Infringement Ratio
SPIN	Safety nets Performance Improvement Network
STCA	Short-term Conflict Alert
SRC	Safety Regulation Commission
SSR	Secondary Surveillance Radar
TA	Traffic Advisory
TCAS	Traffic alert and Collision Avoidance System
TFL	Target Flight Level
TLS	Target Level of Safety
TMA	Terminal Control Area
TPF	Turning Prediction Filter
VFR	Visual Flight Rules
WA	Work Area
WP	Work Package

1. Introduction

1.1. Background and context

1.1.1. In the context of Short-Term Conflict Alert (STCA) standardisation in Europe, EUROCONTROL has launched the PASS project (**P**erformance and safety **A**spects of **S**hort-term Conflict Alert – full **S**tudy).

1.1.2. The project was undertaken based on the recommendations of the EUROCONTROL's RA downlink study (FARADS project) and the ACAS-STCA workshop held on 27 and 28 March 2007 in Zürich. It falls within the scope of the SPIN (Safety nets Performance Improvement Network) and is intended to help establish quantified performance requirements for STCA, and to define a consistent overall concept for ground-based and airborne Safety Nets (SNET).

1.1.3. The project ([D01]) is divided into three main phases, as follows:

- Phase 1: Monitoring & understanding of current situation;
- Phase 2: European STCA environment modelling & safety and performance analysis; and
- Phase 3: Enhanced modelling and analysis, synthesis and guidelines.

1.1.4. The monitoring activities conducted in Phase 1 of the project (October 2007 – April 2009) provided a better understanding of the typical sequence of events during Air Traffic Management (ATM) occurrences in which STCA and/or Airborne Collision Avoidance System (ACAS) played a role, and of the factors that have a major influence on the features of this sequence.

1.1.5. Phase 2 of the project (November 2008 – December 2009) progressed on two main Work Areas (WA) addressing respectively the performance evaluation of STCA and ACAS operations (WA2), and a preliminary operational safety analysis of these operations (WA4). Both Work Areas were completed and finalised during the Phase 3 of the project (year 2010).

1.2. Document scope and objectives

1.2.1. The second Work Area (WA2) of the PASS project specifically addresses the performance and safety benefits evaluation of STCA and ACAS operations. The cornerstone of this work is the refinement of the encounter model-based methodology used in the ACAS field to support the evaluation of the performance and safety benefits of STCA while taking into account the effect of ACAS operations.

1.2.2. The work was essentially conducted in two main steps, as follows:

- Step 1: Investigation of European STCA environment (Phase 1); and
- Step 2: Performance evaluation and requirement determination (Phases 2 and 3);

1.2.3. This second step requires setting up an STCA simulation framework, which uses at its core an encounter model that is specifically tailored to generate artificial (but realistic) encounters where STCA might be involved. The behaviour of actual STCA systems in these encounters is reproduced using an implementation of the EUROCONTROL specification for STCA ([ES11]). Human actors involved in STCA alerts are also taken into account through dedicated controller and flight crew models replicating typical responses to STCA alerts. Using this framework, it is possible to run a given STCA configuration on an arbitrarily large number of encounters (typically representing several years of traffic within an ATC unit) and quantify the system performance through the computation of pre-defined metrics on the output of the simulation. One aspect of the STCA performance is the level of interaction with the ACAS system ([ACAS]) currently in operation worldwide. To evaluate such interaction, the simulation framework set in place also includes a model of the ACAS system, as well as a model of pilot responses to ACAS RAs.

1.2.4. Such SNET simulation framework was set in place during the Phase 2 of the PASS project. It enabled a first model-based performance evaluation of STCA operations ([D137]), which pointed out the need for a series of model improvements. These improvements were further specified and implemented during the Phase 3 of the project. The refined simulation framework supported a comprehensive performance evaluation of combined STCA and ACAS operations [(W161]).

1.2.5. This document summarises the main achievements and findings of the PASS Working Area 2 including the modelling of current STCA and ACAS operations in Europe, the evaluation of STCA performance in realistic operational scenarios and the sensitivity analysis of factors influencing this performance.

1.3. Document overview

1.3.1. Following this introduction, section 2 provides some elements on the role of STCA and ACAS as safety nets in the current ATM environment, and on the evaluation of their performances. Section 2 also recaps the outcome of the “IAPA – ASARP Methodology for Safety net Assessment – Feasibility Evaluation” (I-AM-SAFE) study which assessed the feasibility of using, for STCA, the encounter model-based methodology that has been used to quantify the performance of ACAS.

1.3.2. Section 3 gives some insight into the simulation process that has been set up to adapt the ACAS encounter model-based methodology to the context of STCA, and notably on the different models that have been implemented to take into account the key factors influencing STCA performance.

1.3.3. Section 4 contains the most significant results of the model-based evaluation of STCA performance that has been conducted on a number of operational scenarios representative of current STCA operations in Europe.

1.3.4. Lastly, section 5 draws some conclusions from the PASS WA2 study and provides some recommendations to support the future development of quantified performance requirements for STCA operations (including increased compatibility with ACAS operations).

1.3.5. In addition, three appendices are included that complement the main document on the key elements from EUROCONTROL guidance material on STCA that are applicable to the study, on the definition of the operational scenarios that have been investigated during Phase 3 and on key elements of the STCA performance evaluation framework used in the study.

2. Background on STCA and ACAS operations and performance evaluation in Europe

2.1. Role of STCA in the ATM system

2.1.1. The EUROCONTROL specification [ES11] defines STCA as: "a ground-based safety net intended to assist the controller in preventing collision between aircraft by generating, in a timely manner, an alert of a potential or actual infringement of separation minima."

2.1.2. The EUROCONTROL Safety Regulation Commission (SRC) policy [SRC28.06] clarifies the specific role that ground based safety nets have within the ATM system with the three following basic principles:

- "2. Ground based safety nets by themselves should have the sole objective to contribute to safety.
- 3. Ground based safety nets should not be relied upon for separation assurance in the provision of Air Traffic Services.
- 12. The effect and contribution of ground based safety nets may be taken into account when an ANSP determines the achieved level of safety."

2.1.3. Unlike the airborne safety net for which standards have been developed by the International Civil Aviation Organization (ICAO), there exist several STCA implementations with no uniform procedures for operational use, optimisation and validation.

2.1.4. Regarding the procedures in the event of an STCA, the ICAO Procedures for Air Navigation Services – Air Traffic Management (PANS-ATM) ([Doc4444]) nevertheless requires that:

"15.7.2.2 In the event an STCA is generated in respect of controlled flights, the controller shall without delay take action to ensure that the applicable separation minimum will not be infringed."

2.1.5. As a reminder, the ICAO Annex 11 about Air Traffic Services ([Annex 11]) states that:

"3.3.1 In order to provide air traffic control service, an air traffic control unit shall: […] C) issue clearances and information for the purpose of preventing collision between aircraft under its control and of expediting and maintaining an orderly flow of traffic"

2.1.6. For the purpose of preventing collision, clear distinction is thus made between: 1) clearances (or instructions) that aims at providing separation, and 2) traffic information (and traffic avoidance advice) that aims to assist the pilot to avoid a collision.

2.2. Current state of STCA performance evaluation in Europe

2.2.1. In Europe, a major milestone has been achieved to ensure the effectiveness of ground-based safety nets with the release by EUROCONTROL of specifications and supporting guidance material. The material relating to STCA ([ES11], [GM20]) has recently been updated for alignment with the other EUROCONTROL specifications for ground-based safety nets.

2.2.2. The notion of STCA performance is tackled by the EUROCONTROL Guidance Material. In a few words, Appendix A describing the Reference STCA System advocates that "STCA performance is measured by the numbers of genuine and nuisance alerts which are displayed to controllers, together with the amount of warning time provided for genuine alerts."

2.2.3. The EUROCONTROL Specification for STCA specifies minimum qualitative requirements ([ES11]), some of which are of particular interest in the context of STCA performance evaluation.

Requirements defined in the EUROCONTROL Specification for STCA	
STCA-05	In the event an alert is generated in respect of controlled flights, the controller ***shall*** without delay assess the situation and if necessary take action to ensure that the applicable separation minimum will not be infringed or will be restored.
STCA-07	STCA ***shall*** detect and alert operationally relevant conflicts involving at least one eligible aircraft.
STCA-08	STCA ***shall*** provide alerts for operationally relevant conflicts.
STCA-10	The number of nuisance alerts produced by STCA ***shall*** be kept to an effective minimum.
STCA-11	The number of false alerts produced by STCA ***shall*** be kept to an effective minimum.
STCA-12	When the geometry of the situation permits, the warning time ***shall*** be sufficient for all necessary steps to be taken from the controller recognising the alert to the aircraft successfully executing an appropriate manoeuvre.
STCA-13	STCA ***shall*** continue to provide alert(s) as long as the alert conditions exist.

Table 1: Requirements from the EUROCONTROL Specification for STCA

2.2.4. It is worthwhile noting that the overall performance of STCA is not only related to the STCA system itself, but also to the use of the STCA system by the air traffic controllers ([STCA-05]).

2.2.5. These requirements constitute the foundations for the STCA performance evaluation framework used in the present study.

2.3. Monitoring of STCA operations in PASS (Phase 1)

2.3.1. The monitoring activity conducted in Phase 1 of the PASS project (cf. [D08], [D64]) collected and analysed a significant number of ATM occurrences where an ACAS alert and/or an STCA alert were triggered. The airspace covered by this monitoring was as wide as possible in order to reflect all types of Air Traffic Control (ATC) operations over Europe.

2.3.2. This activity was essential for the understanding the typical sequence of events during ATM occurrences in which STCA and/or ACAS played a role, as well as the factors that have a major influence on the features of this sequence.

2.3.3. More specifically, for the prospect of WA2 STCA performance evaluation through models of these influencing factors, the Phase 1 monitoring enabled the establishment of the parameters and distributions that would most accurately reflect actual STCA, ACAS, controller and pilot behaviour in situations where STCA plays a role.

2.3.4. This Phase 1 monitoring activity was complemented with a review of European STCA implementations that identified the approach towards the operation of STCA by various Air Navigation Service Providers (ANSPs). The key features of individual STCAs and their parameters were collected and analysed during this step.

2.4. The role of ACAS in the ATM system

2.4.1. The ICAO Annex 2 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 conflicting[1] aircraft that are equipped with SSR transponders” (cf. ICAO Annex 2 – Rules of the Air).

2.4.2. 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. ACAS provides two levels of alert to the pilot, viz. Traffic Advisories (TAs) and vertical Resolution Advisories (RAs). A TA is a cue for the pilot to try to visually acquire the potential threat and to prepare for a possible RA. 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.

2.4.3. As stated in the ICAO Procedures for Air Navigation Services – Aircraft Operations (PANS-OPS) ([Doc8168]), 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.

2.4.4. 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.

2.4.5. 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.

2.4.6. This reduction is measured through a ‘risk ratio’ which compares the risk of a ‘Near Mid-Air Collision[2]’ (NMAC) both with and without ACAS.[3] 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.

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[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 ATC services.

[2] 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.

[3] ‘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

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

2.4.7. 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’[4] (cf. ICAO Standards And Recommended Practices (SARPs) ([ACAS])).

2.4.8. ICAO also defines an ‘ATM encounter model’ whose structure derives from that of the ‘safety encounter model’, but which enlarges the scope of the featured encounters to situations where the aircraft pass each other with some horizontal miss distance. This encounter model has been used to standardise ATM compatibility requirements for ACAS through the definition of target levels of nuisance alerts and the deviations caused by responding to RAs.

2.5. The evaluation of ACAS performance in Europe

2.5.1. The methodology consisting of evaluating ACAS performance based on encounter models was initially used in Europe to support the introduction of ACAS. As the encounter models specified in the ICAO SARPs are not representative of any particular airspace, EUROCONTROL sponsored the “ACAS Analysis” (ACASA) project in 1998 to 2001 which notably developed a European safety encounter model representative of actual operations at that time and which was a cornerstone in the establishment of the European ACAS mandate.

2.5.2. This European safety encounter model was subsequently updated in the EUROCONTROL-sponsored “ACAS Safety Analysis – post-RVSM Project” (ASARP) study, between 2003 and 2005, following the introduction of Reduced Vertical Separation Minima (RVSM) in European airspace. ASARP also used airborne recordings to analyse the pilot responses to actual ACAS alerts, which were notably different from those observed during ACASA, just after the introduction of ACAS.

2.5.3. Lastly, the European safety encounter model has been the key tool used for the development and the validation of TCAS II version 7.1 logic conducted within the EUROCONTROL “Safety Issue Rectification” initiative, under the auspices of the Mode S & ACAS Programme. The safety improvements quantified with version 7.1 on the encounter model led to the endorsement of this revised version of TCAS II by RTCA and EUROCAE, respectively through the DO-185B and ED-143 document standards.

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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.

[4] 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.

2.5.4. The encounter model-based methodology has also been used in forward looking studies that aimed at assessing the safety and operational performance of ACAS in novel ATM operations. Notably, the “Implications on ACAS Performances due to ASAS Implementation” (IAPA) project implemented a European ATM encounter model to support the analysis of the possible interaction between ACAS and future ASAS operations. As for the safety encounter models, the ICAO SARPs ATM model is not representative of any particular airspace, while the IAPA ATM model replicated actual operations in Europe.

2.6. The I-AM-SAFE feasibility study

2.6.1. The objective of the I-AM-SAFE study was to assess the applicability and usefulness of the encounter model-based methodology used in the ACAS field, for establishing quantified performance requirements for STCA ([I-AM-SAFE]). The methodology was demonstrated to be applicable and useful to evaluate the performance of STCA, and the possible interaction issues with ACAS, although some adaptations would be required to specifically address STCA.

2.6.2. Although quite simple, the STCA performance metrics evaluated during the study have shown the influence of the encounter characteristics (i.e. risk bearing situations or day-to-day conflicts in Terminal Control Area (TMA) or en-route), the STCA configuration (e.g. with or without the use of the Cleared Flight Level (CFL)) and parameters, as well as the quality of the data provided to STCA, on the likelihood and relevance of the alerts is significant.

2.6.3. Taking into account the main study findings, a more sophisticated framework that would enable the evaluation of STCA performance and safety benefits while also taking into account the effect of ACAS operations has been proposed and is illustrated in Figure 1.

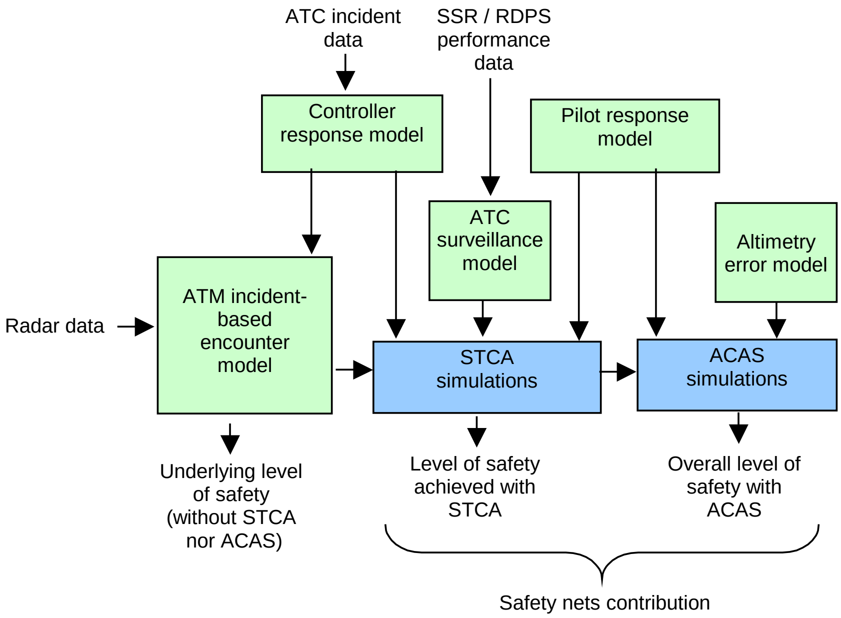

Figure 1: Possible framework for STCA performance evaluation from the I-AM-SAFE feasibility study

2.6.4. This framework builds upon the encounter model-based methodology and the various areas of improvement identified during the study. It requires the development of a series of models to simulate operationally realistic scenarios of STCA environment and use.

2.6.5. The cornerstone of the approach is the development of an ATC incident-based encounter model (derived from real incidents that occurred in Europe) that would encompass the scope of both the previous safety and ATM encounter models without their limitations.

2.6.6. To allow the ability of STCA to alert the controller with sufficient warning time to be evaluated, the study results also pointed out the interest in modelling the controller interventions in response to STCA alerts separately from the encounter model itself.

3. Modelling of current STCA and ACAS operations in Europe

3.1. General

3.1.1. The I-AM-SAFE feasibility study identified a number of key factors that influence the performance of STCA. These include the STCA system itself, for which numerous implementations are used currently in Europe. The typical situations where STCA is involved, resulting from the airspace nature and structure where it is operated, also play a significant role. As the effects of STCA alerts are implemented by human actors, i.e. Air Traffic Control Officers (ATCO) and flight crews, the way they respond to these alerts is of particular significance.

3.1.2. All of these factors influencing the performance of STCA are represented by specific models in the encounter model-based methodology. Models are in essence a limited representation of reality and, in order for them to be representative, a number of assumptions have to be made regarding the scope in which they are used.

3.1.3. The approach adopted for PASS WA2 regarding the evaluation of STCA performance through the encounter model-based methodology focuses on European airspace where surveillance services are provided by Air Traffic Services (ATS) and with an implementation and an operational use of a “Level 2” STCA (cf. Pan-European European Convergence and Implementation Plan (ECIP) Objective ATC02.2 with implementation completion date of December 2008). This notably translates into the following stakeholder lines of action for ANSPs:

- ATC02.2-ASP01: “Implement STCA in line with EUROCONTROL Specification for STCA”
- ATC02.2-ASP02: “Align ATCO training with EUROCONTROL Specification for STCA”

3.1.4. Also, the choice has been made to concentrate on scenarios where ATC is aiming to prevent collision by the issuance of clearances (or instructions) to at least one flight in order to provide separation (cf. requirements STCA-05, STCA-07 from Table 1). The use of STCA to assist the controller in preventing collision through the provision of traffic or flight information was outside of scope of the present study.

3.1.5. Regarding the airborne safety net, i.e. ACAS, the modelling framework assumes carriage and operation of TCAS II equipment by civil aircraft as defined by the current European ACAS mandate (cf. Phase 2 of this mandate with an implementation completion date of 31st March 2006).

3.1.6. It is also assumed that pilots follow the RAs and do not resort to exercising “their best judgment and full authority in the choice of the best course of action to resolve a traffic conflict or avert a potential collision” (cf. PANS-OPS 3.1.2). This assumption also extends to ACAS RAs precedence over ATC instructions (cf. ICAO Procedures for Air Navigation Services since November 2007).

3.2. Modelling ATC surveillance means

3.2.1. Scope and approach

3.2.1.1. The model for ATC means of surveillance ([W36]), or surveillance model, is based on the minimum requirements for surveillance data quality established in Work Package 1 (WP1) of the project.

3.2.1.2. The precise surveillance environment varies both between and within the airspaces of individual ANSPs. No unique surveillance environment can characterise the range of different conditions that can be found in core European airspace. Within the PASS project, the precise details of the simulated surveillance environment are subordinate to the details of the tracker model and STCA model which are employed in the study.

3.2.1.3. In order to realistically represent the characteristics of most typical surveillance means in Europe, the surveillance model is able to work with both 25ft and 100ft altitude quantisation (i.e. as supplied by Mode C and Mode S transponders), includes a multi-radar tracker (which may or may not be used) and uses an accuracy (measured through the r.m.s. value (i.e. square-root of the mean of the squared differences) around five times better than EUROCONTROL minimum requirement (i.e. 100m for en-route airspace and 60m for terminal airspace) ([SUR]).

3.2.1.4. The development of the surveillance model was initiated in the Phase 2 of the PASS project ([D88]) and completed during the Phase 3 with the introduction of a set of improvements addressing deficiencies identified during the Phase 2 simulations.

3.2.2. Insight into the ATC surveillance model

3.2.2.1. The surveillance model takes the precise positions and altitudes of aircraft in artificial encounters and with these constructs output track data of a similar quality and form as that used by an operational STCA system. This is achieved by using a simplified model of the processes occurring in an operational multi-radar tracking (MRT) system.

3.2.2.2. The model can be configured to accept input from 1, 2 or 3 radars, each of which can have a rotation period of 4s, 6s, or 8s, and each of which can perform either Mode C interrogations only or joint Mode C/Mode S interrogations. The positions of the radars relative to the encounter can also be configured.

3.2.2.3. The model allows for each of the aircraft in the encounter to be either Mode C equipped or Mode S equipped, and in the latter case reporting altitude with either 25-ft or 100-ft precision.

3.2.2.4. The probability of successful position plot extraction and altitude report extraction from each aircraft on each rotation of each radar is determined on a stochastic basis taking account of whether a Mode C or Mode S reply is involved.

3.2.2.5. The MRT in the model consists of separate vertical and horizontal trackers, which estimate positions and velocities based on the history of position plots.

3.2.2.6. In the horizontal plane the range and azimuth of each successfully extracted position plot are constructed from the Cartesian coordinates of the aircraft and radar. Realistic measurement noise and the effect of measurement quantisation are included before the plots are provided to the horizontal tracker.

3.2.2.7. Horizontal tracking is performed by a Kalman filter (in which the assumed equation of motion is that aircraft are either travelling in a straight line or turning with a constant turn rate). The Kalman filter is configured to take account of noise arising from both plot position 'noise' and potential departures from the assumed equation of motion (aircraft accelerations). Using a Kalman filter introduces a realistic lag in the detection of heading or attitude changes (which can affect the timing of STCA alerts).

3.2.2.8. In the vertical plane altitude reports with the appropriate quantisation (25-ft or 100-ft) are constructed. For Mode C altitude reports errors due to incorrect decoding (caused by garbling with fruit) and, when aircraft are close together (precisely the situations investigated in PASS WA2), 'Mode C swaps' are included on a stochastic basis.

3.2.2.9. A credibility check on reported altitudes is performed, on the basis of the tracked altitude and vertical rate and the known typical performance of civil air traffic, allowing the rejection of those which are diagnosed as being unlikely to reflect the genuine altitude of the aircraft.

3.2.2.10. Vertical tracking is performed by an adaptive alpha-beta filter which takes account of the altitude quantisation and uses different modes depending on whether aircraft are diagnosed as climbing/descending or flying level. Specific tests allow the tracker to recognise transitions between the two modes (aircraft levelling-off or breaking out of level flight).

3.2.2.11. The tracker recognises that aircraft frequently fly level at standard cruising altitudes. Minor variations in tracked altitude and vertical rate in these circumstances are suppressed in the output of the vertical tracker (so called "rate clamping") and avoid unrealistic fluctuations in tracked vertical rate and altitude for nominally level aircraft.

3.2.2.12. Finally, the tracked positions and velocities and turn rates of the two aircraft are regularly output (with a period that reflects the radar rotation rates) and constitute the input to the STCA model.

3.3. Modelling the range of STCA systems in Europe

3.3.1. Scope and approach

3.3.1.1. For the I-AM-SAFE study purposes, a simplified STCA model was implemented, which complies with the essential features of the reference STCA system defined by EUROCONTROL ([GM20]). The study results demonstrated the operational realism of this STCA model despite its simplicity. It also pointed out the potential interest of implementing other optional features described in the EUROCONTROL guidance material for STCA, in addition to the development of a surveillance model that would be representative of current surveillance performances in Europe ([IAMSAFE]).

3.3.1.2. A refinement of the simplified STCA model was therefore carried out in the PASS project, which took into consideration the most significant features of the reference STCA system. The EUROCONTROL guidance material for STCA also describes more specific features and parameters, but these are of relatively minor importance when describing the overall performance and behaviour of an STCA system.

3.3.1.3. The features added to the initial I-AM-SAFE STCA model consist of the use of an arithmetic method and the possible use of uncertainty on vertical speeds in the Linear Prediction Filter, an improved detection of altitude busts, an optional Current Proximity Filter (CPF) and an optional Turning Prediction Filter (TPF) ([D116]).

3.3.1.4. As the behaviour of a given STCA implementation is highly dependent on the parameters used for its configuration, it is also required for WA2 to know the typical values taken by these parameters for the STCA model to perform realistically. To this effect, a review of current STCA systems has been compiled ([D31]) in order to summarise the optional features they use and the range of values used by their most significant parameters (separation thresholds, warning time, etc.).

3.3.2. Insight into the reference STCA model

3.3.2.1. As described by the specification for EUROCONTROL reference STCA system, the PASS STCA model consists of three main functions used in sequence: a Coarse Filter, a series of Fine Filters (including optional ones) and an Alert Confirmation stage (see Figure 2).

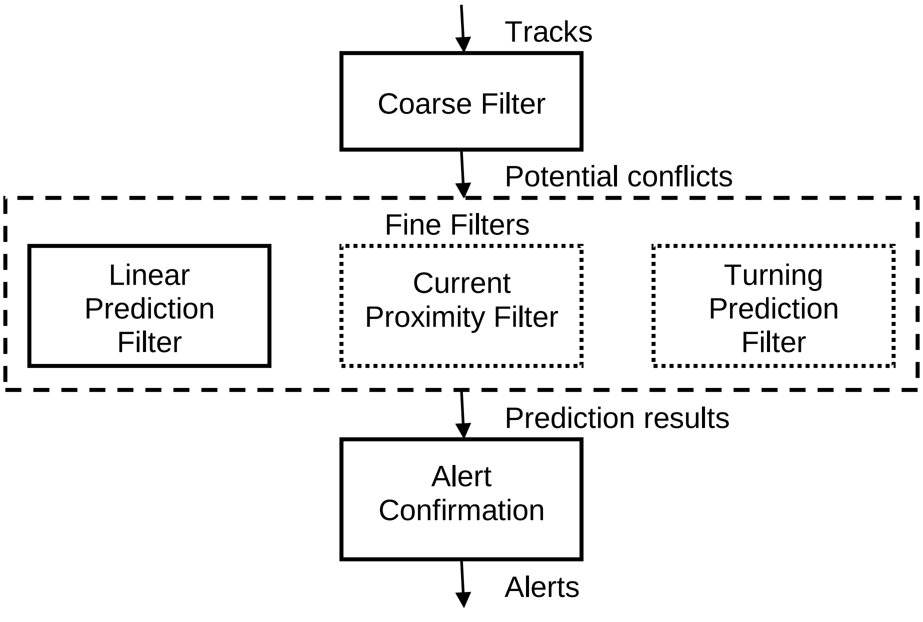

Figure 2: Main functions of the reference STCA model

3.3.2.2. The purpose of the Coarse Filter is to identify tracks that have the potential to result in a conflict and that require further processing. Tracks are projected linearly and have to breach both a lateral and a vertical threshold within a look-ahead time in order to be retained.

3.3.2.3. The Linear Prediction Filter projects tracks linearly and determines the time interval during which lateral separation is predicted to be infringed and the time interval during which vertical separation is predicted to be infringed. If these two intervals overlap within a look-ahead time, a predicted conflict is declared.

3.3.2.4. If so configured, the Linear Prediction Filter is able to use the Target Flight Level (TFL) associated to a track (i.e. the Cleared Flight Level (CFL) given by ATC or the onboard Selected Flight Level (SFL) received through Mode S surveillance) and thus improve its vertical prediction by considering potential level-offs and reduce the number of alerts issued in encounters with no separation infringement. In addition, it is possible to configure the use of a degree of uncertainty on the tracks' vertical speed in the vertical prediction.

3.3.2.5. The optional Current Proximity Filter is designed to detect slow closure conflicts in a timely manner. A late manoeuvre by one or both aircraft in a slow closure geometry can cause the predicted time to infringement to rapidly shorten in which case the Linear Prediction Filter would provide only a low warning time.

3.3.2.6. The optional Turning Prediction Filter makes use of the turn data supplied by the surveillance model and models the turn performed by turning aircraft. In situations where one aircraft is turning toward another, this results in an earlier detection of the conflict than the Linear Prediction Filter alone would achieve.

3.3.2.7. Lastly, the Alert Confirmation function consolidates the conflict predictions from the different fine filters and issues an STCA alert if the conflict is predicted to occur within a given warning time.

3.3.2.8. As indicated above, the STCA model uses a significant number of parameters and options, whose effect on the overall system performance can only be assessed through a sensitivity study.

3.4. Modelling controller's and pilot's behaviour following STCA alerts

3.4.1. Scope and approach

3.4.1.1. The objective of the controller behaviour model in response to STCA alert is to emulate in a simple, yet realistic, manner the responses of ATCOs to STCA alerts. Taking advantage of the large set of ATC incidents analysed in WA1, actual ATCO responses have been categorized and defined through a set of parameters.

3.4.1.2. A similar analysis has been conducted on pilot responses to ATCO instructions following STCA alerts. These pilot responses have been defined through a set of parameters, each with a range of observed values.

3.4.1.3. The development of the controller and pilot models ([D115]) were initiated in the Phase 2 of the PASS project and completed during the Phase 3 with the introduction of a set of refinements to these models.

3.4.1.4. During the Phase 2 of the project, only the most significant parameters have been varied from one simulated scenario to another, in order to reduce the number of variables influencing the outcome of the simulations ([W123]). This was no longer the case during the Phase 3 simulations, which included specific scenarios to evaluate the influence of key parameters of the controller's and pilot's response models on STCA performance ([W145]).

3.4.1.5. Although fairly realistic, the modelled controller's and pilot's behaviour following STCA alerts has some recognised limitations. Notably, only one aircraft in a given encounter is given an instruction following an STCA alert, while the WA1 incident analysis showed that both aircraft involved in an STCA alert received an ATC instruction in 60% of the cases ([D64]). As for the pilot model, it always models a response to ATCO instruction, although Phase 1 monitoring found 4% of non-responding aircraft ([D64]).

3.4.2. Insight into the controller response model to STCA alerts

3.4.2.1. Depending on the configuration of the ATCO model, it will try to solve a given conflict either through an instruction in the horizontal dimension or in the vertical dimension. However, the same principles apply in both cases:

- Try and achieve the separation standard at minimum separation;
- Minimise the deviation;
- Give priority to the slower aircraft.

3.4.2.2. In the horizontal dimension, these principles result in the modelling of increasingly larger heading alterations. If some of these enable the applicable separation minima to be restored, then the selected instruction is the one minimising the deviation from the initial track, with a preference for a pass-behind manoeuvre.

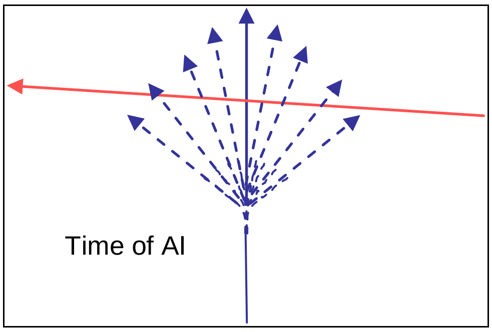

Figure 3: Simulation of horizontal avoiding instructions by the ATCO model

3.4.2.3. The selection of an instruction in the vertical dimension is a more complex process, as it takes into account the vertical trends of the two aircraft both at the time of the STCA alert and at minimum separation. Depending on the geometry of the encounter, one to three favoured manoeuvres, pre-determined by operational experts, can be applied and the most efficient one is selected. These favoured manoeuvres are detailed in [D115].

3.4.2.4. The selection process of horizontal and vertical manoeuvres has been refined in Phase 3 of the project to increase the efficiency of the selected avoiding manoeuvres. Although fairly realistic, the simulation results ([W161]) have shown that the current implementation of the ATCO model could still be improved (in particular to correctly manage split alerts).

3.4.3. Insight into the pilot response model to ATC avoiding instructions

3.4.3.1. The pilot model implements the instruction supplied by the ATCO model, after an initial delay that accounts for the transmission on the frequency and the reaction of the pilot.

3.4.3.2. If the instruction selected by the ATCO model would include avoiding action phraseology, the pilot response is slightly quicker and the requested manoeuvre is performed with increased intensity.

3.4.3.3. The pilot model has been refined in Phase 3 of the project to increase the realism of the response delays (using either standard fixed values or typical delay distributions) and of the climb / descent rates used, taking into account the aircraft performances (see [D115] for further details).

3.5. Modelling pilot's action in response to ACAS RAs

3.5.1. Background on pilot models used in previous ACAS studies

3.5.1.1. ICAO ACAS SARPs ([ACAS]) define a "standard pilot response" to ACAS RAs, which in fact corresponds to the response model used by the Collision Avoidance System (CAS) logic when predicting the outcome of a given RA. This RA response model is defined through an initial delay, a target vertical rate and a vertical acceleration to achieve the target vertical rate.

3.5.1.2. A monitoring of actual pilot responses to RAs has been conducted in various EUROCONTROL studies, showing significant variation from the standard pilot model and enabling the definition of a more realistic model of pilot behaviour.

3.5.1.3. In 2001, following the introduction of TCAS operation in Europe, the ACASA project identified two distinct families of responses ([ACASA]), which were characterized as "slow" (long delay, low vertical rate) and "aggressive" (high vertical rate). This study was repeated in 2005 during the ASARP project and showed that the range of pilot responses to RAs was not as clear-cut as four years earlier. Indeed, 32 classes of responses, rather than 2, were defined ([ASARP]), but the average response was very close to the standard response.

3.5.2. Insight into the pilot response model to RAs

3.5.2.1. Two options have been retained regarding the pilot response model to RAs. In Phase 2, only the standard pilot response was applied on ACAS RAs, with a 100% response rate. The more refined "typical response" model, which includes a 20% non-response rate as observed in actual operations (cf. Figure 4), has been used in for a specific sensitivity study in Phase 3 of the project.

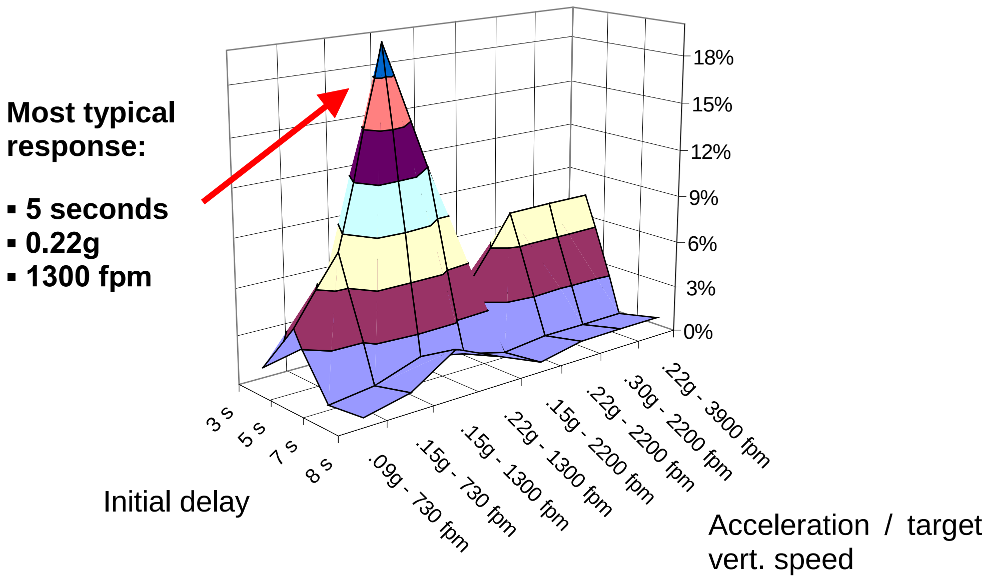

Figure 4: Model of typical pilot response to RAs

3.5.2.2. Whatever the response model used on ACAS RAs, the pilot model always responds to RAs in priority to ATCO instructions.

3.6. Modelling safety-net related encounters in European airspace

3.6.1. General

3.6.1.1. An ‘encounter model’ is a model of traffic situations (involving two aircraft only) that captures the properties of encounters of interest as a series of statistical distributions (defined as histograms and implemented as tables) describing the parameters of a typical encounter and their interdependencies. The encounter model approach is a powerful technique by which a large set of risk bearing encounters (which are rare events) can be stochastically generated to assess the safety benefits of any ATM safety nets.

3.6.1.2. The PASS ATC incident-based encounter model ([D75]) has been designed to generate encounters with a focus on losses of ATC separation in order to create situations with a potential for STCA alerts to be issued. It is able to focus on encounters where both aircraft are eligible for STCA alerts (typically two IFR aircraft) or on encounters where only one aircraft is eligible for STCA alerts (for e.g. an IFR and a VFR aircraft, an IFR and a military aircraft).

3.6.1.3. The development of the encounter model was initiated during the Phase 2 of the PASS project and completed during the Phase 3 with the progressive introduction of a set of improvements to increase the realism of the generated encounters (e.g. more operationally relevant altitude layers, new proportions of aircraft performance classes, refined altitude distribution within layers, more realistic distribution of aircraft turns and vertical rates, etc.).

3.6.2. Building the PASS encounter model using European radar data

3.6.2.1. The initial step in the development of the PASS encounter model was the collection of a sufficient amount of radar data that would provide the real encounters that would populate the statistical distributions (i.e. tables) of the model. To this effect, radar data have been collected from five ANSPs over an area corresponding to most of the European Core Area from 12th October 2007 to 31st March 2008 and 77 days of recordings were processed so as to extract close to 144,000 pair-wise encounters of interest.

3.6.2.2. These radar encounters have subsequently been analysed in order to discard those that involved two aircraft that would not be eligible for an STCA alert, i.e. military aircraft and aircraft flying in uncontrolled airspace. This resulted in the identification of close to 110,000 radar encounters suitable for the development of the PASS encounter model. As a last step prior to populating the model tables, operational experts removed manoeuvres resulting from STCA or TCAS alerts from captured encounters, so that these would not appear in encounters generated from the model.

3.6.3. Insight into the PASS encounter model

3.6.3.1. The model generates an individual encounter between two aircraft only, by selecting the positions and velocities of the two aircraft at the point of minimum separation. Trajectories are then incrementally expanded from that point, 2 or 3 minutes backward and 1 minute forward, integrating the equations of motion as one goes. The model allows each aircraft to perform at most one vertical and one horizontal manoeuvre both before and after the point of minimum separation. These manoeuvres are decided based on their probabilities of occurrence indicated by the model tables.

3.6.3.2. Many of the properties of encounters and individual aircraft trajectories have a dependence on altitude. To capture these dependencies within the model the airspace is divided into 5 altitude layers each with a different set of properties. For convenience, the two lower altitude layers, which go from 1,000ft to Flight Level (FL) 135, have been labelled ‘TMA’, while the three upper ones, from FL135 to FL415, have been labelled ‘en-route’.

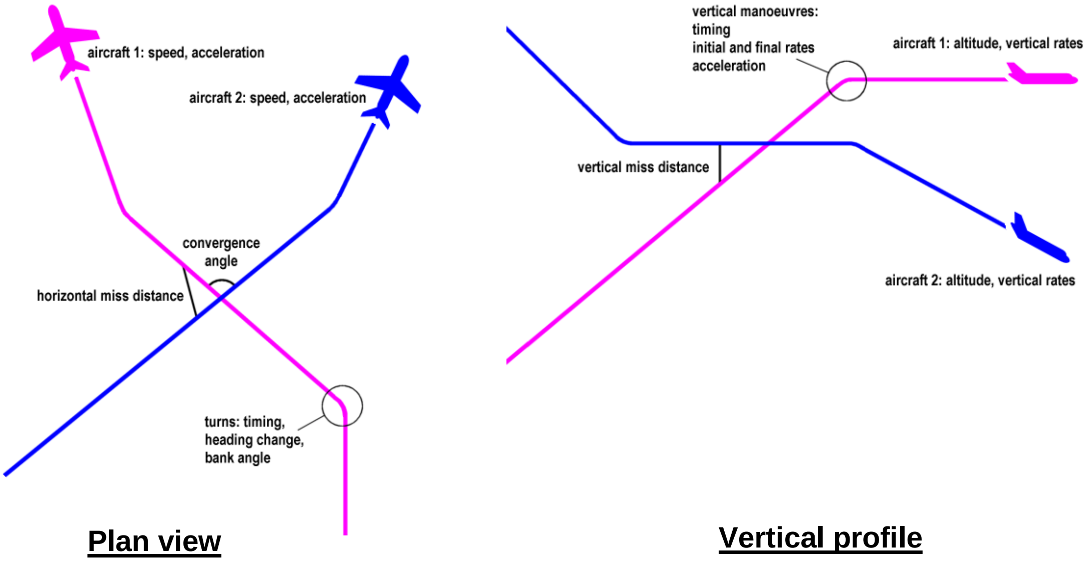

Figure 5: Key characteristics of encounters generated from the PASS model

3.6.3.3. In order to illustrate the key features of the encounters generated from the PASS model, Table 2 provides the distribution of encounters altitudes measured at the point of minimum separation, on TMA altitude layers first, and then for en-route layers. These sets of encounters, which have been used for the Phase 2 STCA simulations, all involve two aircraft that are eligible for STCA alerts.

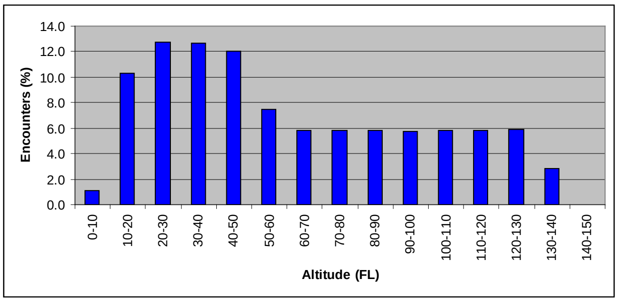	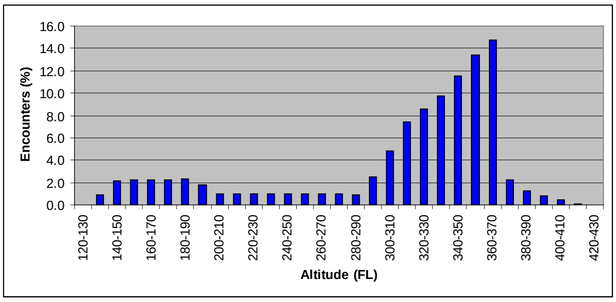
TMA	En-route

Table 2: Distribution of average altitude at minimum separation

3.6.3.4. Table 3 shows the distribution of vertical separation between aircraft at the point of minimum separation, both for TMA and en-route altitude layers. The noticeable peak around 1,000 ft corresponds to encounter in which aircraft are flying level at adjacent standard ATC flight levels. Similarly, two secondary peaks at 0 and 2,000 ft correspond to encounters where aircraft are respectively at co-altitude or separated by twice the standard vertical separation.

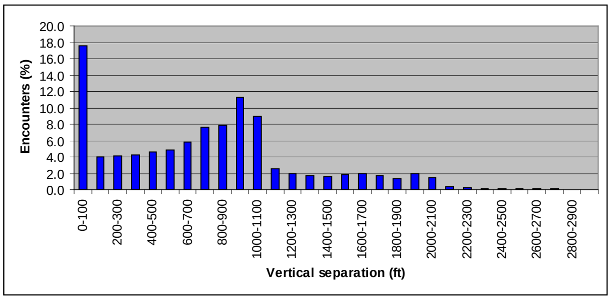	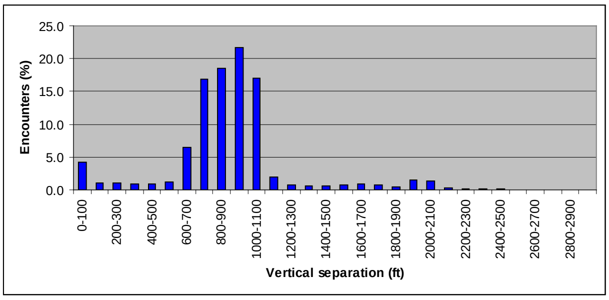
TMA	En-route

Table 3: Distribution of vertical separations at minimum separation

3.6.3.5. Last, Table 4 provides the distribution of lateral separation between aircraft at the point of minimum separation, both for TMA and en-route altitude layers. In both cases, the peak for the distribution can be observed around the applicable ATC separation minimum for the airspace under consideration.

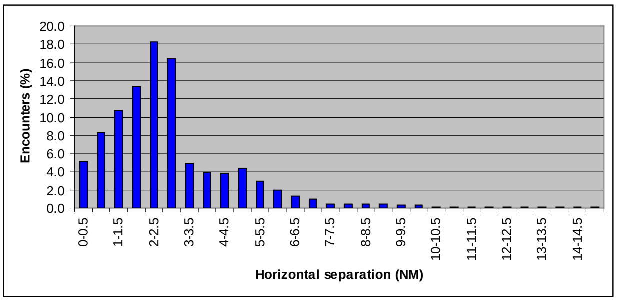	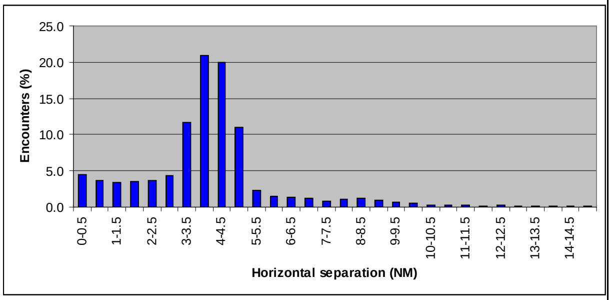
TMA	En-route

Table 4: Distribution of lateral separations at minimum separation

3.6.3.6. The above distributions, computed on encounters generated from the PASS encounter model, correspond to similar distributions computed on the radar encounters that have been used to build the model ([D71]).

4. Evaluation of STCA operations in simulated operational scenarios

4.1. Overview of the simulation framework

4.1.1. In order to measure the performance of STCA with the encounter-model based methodology, two key elements are required. The first one is a large set of encounters generated from the PASS ATC incident-based model, which is described in the previous chapter and which consists of at least 400,000 encounters within the context of Phase 2. The second required element is a set of operational scenarios that describe a series of assumptions related to the ATC surveillance environment, to the STCA and ACAS systems and to the human performance. All of these are parameters to the different models constitutive of the PASS STCA and TCAS simulation framework.

4.1.2. In a first step, an STCA simulation is performed on the generated encounters using one of the agreed operational scenarios. The output of this simulation is a set of modified encounters which, in the case that an STCA alert has been issued by the STCA model, contains the manoeuvre performed by the pilot model in response to the instruction determined by the ATCO model. Comparing these modified encounters to the initial ones enable the computation of STCA performance metrics ([D120]) indicative of the level of safety achieved with STCA alone.

4.1.3. In a second step, an ACAS simulation, using an implementation of TCAS II, is performed on the encounters modified with the responses to any STCA alerts. Any resulting RA is responded to by the pilot model according to the response scheme defined in the operational scenario under investigation. The result of this second step is thus a set of encounters containing potential responses to both STCA and ACAS alerts. Comparing these modified encounters to the initial ones enables the computation of performance metrics on the combination of both safety nets, and is indicative of the level of safety achieved with both STCA and ACAS.

4.1.4. These two steps and the simulation framework that has been set up to conduct PASS Phase 2 STCA and ACAS simulations are summarized in Figure 6 below.

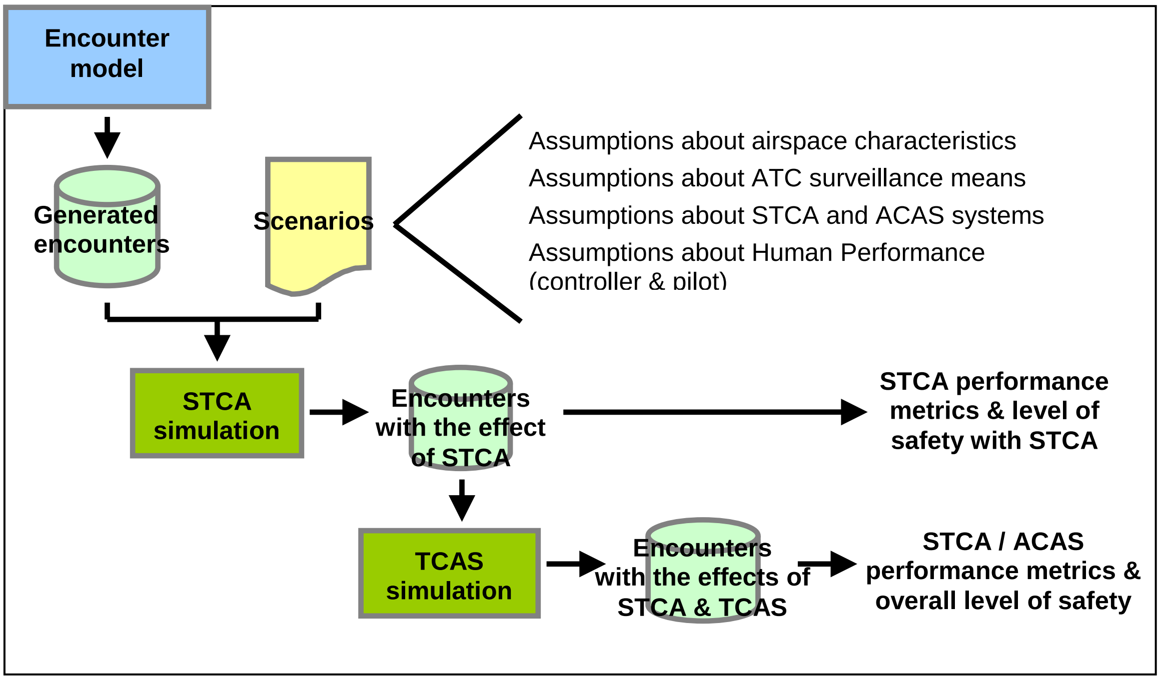

Figure 6: Overview of the STCA and ACAS simulation framework

4.1.5. In principle, the framework described above could be enhanced to allow the simulation of both STCA and TCAS in one sweep, thus better addressing situations where both STCA alerts and ACAS RAs occur. The I-AM-SAFE feasibility study however indicated that these situations are rare ([IAMSAFE]). In addition, the desired outcome of encounters triggering both types of alert generally corresponds to what is achieved with the two-step approach described in Figure 6, given the priority of ACAS RAs over ATC instructions and the different time horizons of the two systems.

4.2. Operational scenarios under evaluation

4.2.1. General

4.2.1.1. The PASS study focuses on the scenarios where ATC aims to prevent collision by the issuance of clearances (or instructions) to at least one of flights involved in order to preserve or restore separation (cf. requirements STCA-05 (and STCA-07) of the EUROCONTROL specification for STCA). The use of STCA to assist the controller in preventing collision through the provision of traffic (or flight) information, or traffic information advice, to help the pilot to avoid a collision is out of scope.

4.2.1.2. Regarding the ATC environment in which STCA is being used, STCA implementations generally distinguish between TMA and en-route controlling environments in order to take account of different procedures and separation standards. This is principally achieved through the values assigned to various parameters, but also in the features that the STCA system incorporates. TMA and en-route airspace also potentially differs in terms of surveillance characteristics.

4.2.1.3. Actual STCA systems generally define specific areas, or regions, within the airspace in which they are used, where particular values of parameters are used (e.g. holding patterns, approach paths, etc.). Given the generic nature of the PASS encounter model, no such distinction is made in the configuration of the PASS STCA model and only one set of parameter values is used for a given operational scenario.

4.2.1.4. A series of operational scenarios have been investigated during the PASS study starting with basic scenarios in Phase 2 in order to determine the parameters having the most significant impact on STCA performance, carrying on in Phase 3 with the simulation of a wide range of realistic STCA implementations assuming first perfect CNS characteristics, as well as standard controller's and pilot's behaviour, and finally investigating operationally realistic scenarios specifically tailored for the sensitivity analysis of the environmental and human factors possibly affecting STCA performance ([W145]).

4.2.2. Families of STCA systems in TMA and en-route airspace

4.2.2.1. Using the outputs from WA1 monitoring activities ([D64])) and the report on "European STCA environment" ([D31]), several approaches to the use of the STCA model have been identified and categorized. Five STCA families have been identified for en-route airspace and four families for TMA, corresponding to the use of more time-critical or less time-critical parameter values and smaller or larger reduced separation parameter values.

4.2.2.2. For en-route airspace, the five families identified correspond to increasingly tighter parameters for both the separation thresholds and the warning time used by the STCA in its trajectory prediction, and hence in its determination of alerts. These families and the different approaches to the use of STCA in en-route airspace are illustrated in Figure 7 below.

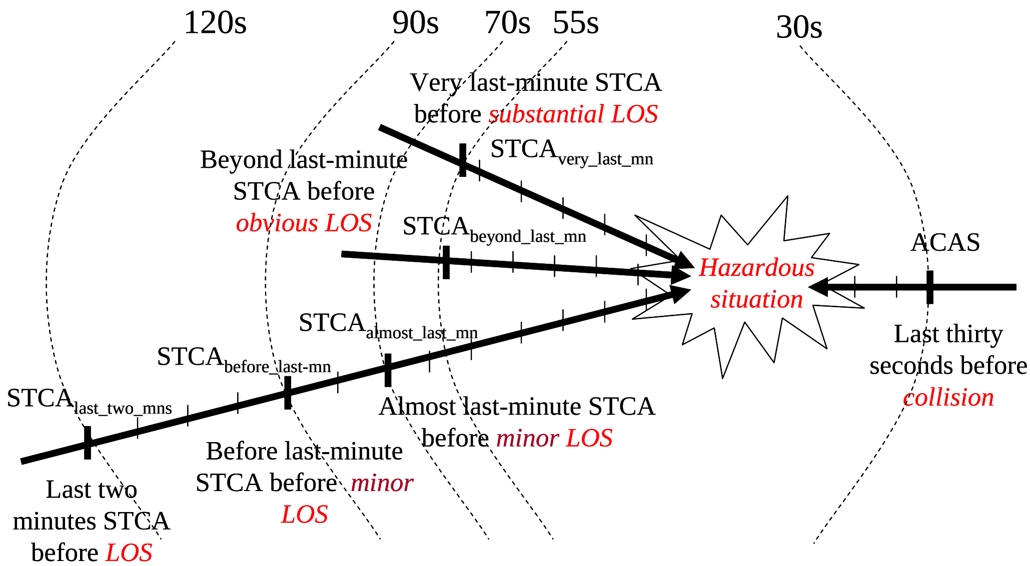

Figure 7: Families of simulated STCA systems in en-route airspace

4.2.2.3. For TMA, the identified families of STCA appear to use only two sets of parameters for separation thresholds, but with each two different warning times. These families and the different approaches to the use of STCA in TMA are illustrated in Figure 8.

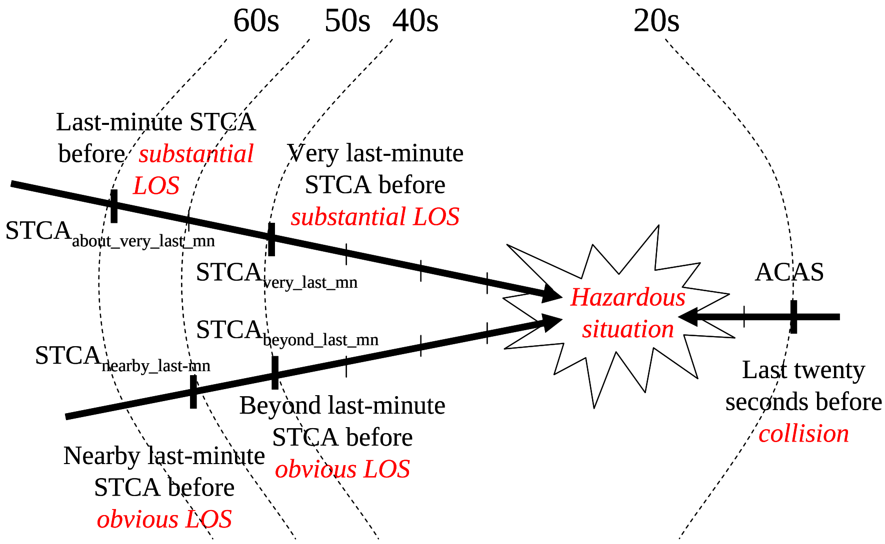

Figure 8: Families of simulated STCA systems in TMA airspace

4.2.2.4. These different families of been implemented as nine different sets of parameters for the tuning of the STCA model. The most significant parameters are given in Table 5, while the details on the parameters used for the fine tuning of the STCA model can be found in Appendix B.2.

	STCA family	Lateral threshold	Vertical threshold	Warning time
En-route	Last_two_mns	5 NM	800 ft	120 s
En-route	Before_last_mn	4.9 NM	800 ft	90 s
En-route	Almost_last_mn	4.9 NM	750 ft	70 s
En-route	Beyond_last_mn	3.7 NM	700 ft	55 s
En-route	Very_last_mn	2.5 NM	500 ft	55 s
TMA	About_very_last_mn	2 NM	500 ft	60 s
TMA	Nearby_last_mn	3 NM	740 ft	50 s
TMA	Beyond_last_mn	2.9 NM	725 ft	40 s
TMA	Very_last_mn	1.5 NM	500 ft	40 s

Table 5: Main STCA model parameters in simulated operational scenarios

4.2.2.5. In particular, it is worth noting that three different system configurations were defined for each STCA family, i.e. a ‘basic’ one with no optional features, a ‘standard’ one with optional features (e.g. ‘Turning Prediction Filter, ‘the Current Proximity Filter, or use of uncertainty on vertical rates) as currently used by one or more ANSPs in Europe, and an ‘extended’ one with other envisaged or potential optional features (like the use of CFL or SFL).

4.2.3. Assumptions on STCA environment and operational use

4.2.3.1. With regard to the assumptions related to the CNS environment and the operational use of the STCA system, a stepwise approach was adopted in the simulations in order to identify the factors that really influence the performance of the safety-net.

4.2.3.2. Regarding ATC surveillance aspects, a 'perfect' surveillance model configuration was first used to simulate good quality surveillance data. With this configuration, there are no gross errors in the measurements performed by the surveillance model, although aircraft manoeuvre are still perceived with a few seconds of lag (due to the update rate of the surveillance model output). A sensitivity analysis on the surveillance characteristics was carried out in a second step using four different surveillance scenarios respectively for TMA and en-route airspace. These scenarios vary the number of radars, their interrogation mode (i.e. Mode C or Mode S) and their rotation period. These scenarios have been implemented as different configurations of the surveillance model (see Appendix B.1 for further details).

4.2.3.3. The transponder equipage scheme of aircraft uses an aircraft performance class approach, as this notion exists in the PASS encounter model. As a general rule, 95% of aircraft are equipped with transponders reporting altitude in 25ft quanta, except aircraft under 5,700 kg Maximum Take-Off Mass (MTOM) for which this proportion has been reduced to 20% (see Appendix B.1 for further details). An 'ideal' scenario in which all Mode S transponders report altitude in 25ft quanta has also been evaluated for comparison purposes. Regarding the navigation characteristics, and although the PASS encounter model includes features specific to modelled RVSM and RNP-1 compliant aircraft ([D75]), the simulations have been performed assuming 'perfect' navigation characteristics. [5]

4.2.3.4. Lastly, for the modelling of controller's and pilot's behaviour following an STCA alert, simple assumptions have first been taken in the simulations with the use of the 'standard' configuration of the controller and pilot models. This 'standard' scenario notably uses fixed delays before the controller's response to STCA and pilot's response to the ATC avoiding instructions (if any). A sensitivity analysis on the controller's and pilot's behaviour was carried out in a second step using four different operational scenarios. These scenarios vary the response delays of controllers and pilots and the use or not of avoiding phraseology by the controller. Two distinct simulations were systematically performed using a controller model configured to issue either horizontal or vertical avoiding instructions (see Appendix B.3 for further details).

4.3. STCA performance evaluation framework

4.3.1. Encounter severity

4.3.1.1. As a preamble to the definition of "operationally relevant conflicts" (cf. requirements STCA-08 of the EUROCONTROL specification for STCA), the performance evaluation framework ([W120]) set in place in the PASS study considers the degree of severity of the encounters. The notion of "encounter severity" is directly related to the extent of separation margins that exist between the aircraft.

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[5] These relatively simple assumptions in terms of communication and navigation characteristics were necessary to limit the simulation runs to a number compatible with the project constraints (in terms of available efforts and schedule).

4.3.1.2. As shown in Figure 9, five severity classes are distinguished ranging from "serious" separation infringements (SC1) to "safe" encounters (SC5) without any separation infringement (see Appendix C.1 for further details).

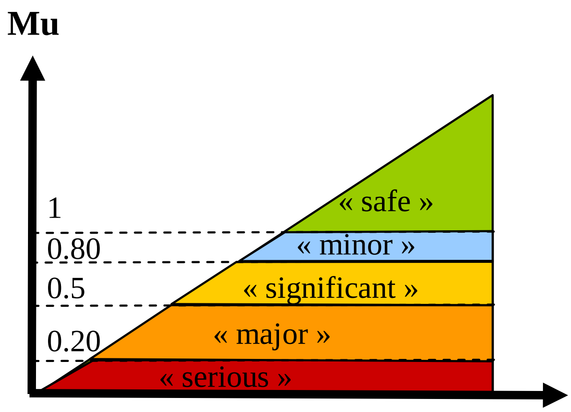

Figure 9: Overview of the encounter severity classes used in PASS study

4.3.1.3. For a safety-net related encounter as generated by the PASS encounter model, the effect of STCA, possibly combined with the effect of ACAS, can be qualified by comparing the "initial" severity of the encounter (before any safety-net contribution) and the "final" severity (without the effect of the controller's avoiding instruction prompted by STCA, possibly combined with the pilot's response to any ACAS RA).

4.3.1.4. A decrease in the encounter severity can be interpreted as a safety enhancement provided by the safety-net(s), whereas an increase in the encounter severity would mean a negative effect on safety.

4.3.2. Key performance areas

4.3.2.1. The PASS performance evaluation framework also identifies a series of key performance areas of STCA to be investigated as follows:

- the likelihood of STCA alerts (in terms of alerts per flight-hour);
- the operational relevance of STCA alerts, notably through the likelihood of "genuine" alerts, the trade-off between "missed", "genuine" and "nuisance" alerts (see Appendix C.2 for performance-oriented definitions for these alert categories). From an operational perspective, the quality of the alerts (in terms of alert duration and continuity) is also of importance.
- the efficacy of "genuine" alerts, notably with respect to the time left to the controller to intervene (see Appendix C.3 for performance-oriented definitions related to "warning time" of alerts), and achievable separation margins assuming realistic controller's and pilot's behaviour; and finally
- the level of STCA and ACAS interaction (in terms of combined alerts and relative timing) assuming both safety-nets are being operated in the airspace.

4.3.2.2. These performance areas are intended to support the definition of quantified performance requirements for STCA in relationship with the high-level requirements contained in the EUROCONTROL specification for STCA ([ES11]), while taking into account the outcomes of the WA1 monitoring results ([D64]).

4.4. Likelihood of STCA alerts

4.4.1. General

4.4.1.1. Since too frequent alerts may foster an incorrect use of STCA (in support to separation provision) or be detrimental to the controller's acceptance and confidence in the STCA system (if not "operationally relevant"), the likelihood of alerts is one of the key performance areas of STCA to be investigated.

4.4.1.2. With the prospect of defining quantified performance requirements for STCA, it has been proposed ([W120]) to evaluate the likelihood of alerts (in terms of alerts per flight-hours) depending on the "initial" severity of the encounters (i.e. without the effect of STCA or ACAS).

4.4.2. Influence of STCA parameters and configuration

4.4.2.1. The likelihood of STCA alerts in TMA and en-route airspace was demonstrated to significantly vary depending on the simulated STCA system. The observed frequency of alert per flight-hour could thus vary by a factor of five in TMA (i.e. between 4.2×10^{-3} and 1.9×10^{-2} alerts per flight-hour) and a factor of about fifty in en-route (i.e. between 7.0×10^{-4} and 3.3×10^{-2} alerts per flight-hour) depending on the STCA parameters and configuration used in the simulations.

4.4.2.2. Despite such discrepancies in the frequency of alerts, the various STCA implementations show some general trends in both TMA and en-route airspace. In particular, the alert rate always increases when the encounter severity decreases. As shown in Figure 10, the alert rates observed in en-route airspace vary from 9.1×10^{-5} alerts per flight-hour for "serious" encounters (SC1) whatever the STCA implementation up to 1.9×10^{-2} alerts per flight-hour for "safe" encounters (SC5) with the more conservative STCA implementation, i.e. the 'basic' configuration of the "last_two_mns" STCA family. Similarly in TMA, it varies from 6.2×10^{-4} alerts per flight-hour for "serious" encounters (SC1) whatever the STCA implementation up to 7.7×10^{-3} alerts per flight-hour for "safe" encounters (SC5) with the more conservative STCA implementation, i.e. the 'standard' configuration of the "nearby_last_mn" STCA family.

4.4.2.3. For a given STCA family, the different simulated configurations (i.e. 'basic', 'standard' and 'extended') typically provide similar results for the "serious" and "major" separation infringements (SC1 and SC2), but show different behaviours during less severe encounter situations. The 'extended' and 'standard' configurations are notably more effective in alerting "significant" and "minor" separation infringements (SC3 and SC4), while reducing the likelihood of unnecessary alerts during "safe" encounters (SC5).

4.4.2.4. The reduced frequency of unnecessary alerts is either obtained with the STCA configurations that use the CFL or the SFL or with the less conservative STCA families that use reduced separation and warning time parameter values. The alert rate for "safe" encounters (SC5) is thus reduced to 4.7×10^{-3} alerts per flight-hour in en-route with the 'standard' configuration of the "last_two_mns" STCA family which uses the CFL, and reduced respectively to 1.1×10^{-4} alerts per flight-hour in en-route, and to 1.9×10^{-5} alerts per flight-hour in TMA, with the 'extended' configuration of the "very_last_mn" STCA family.

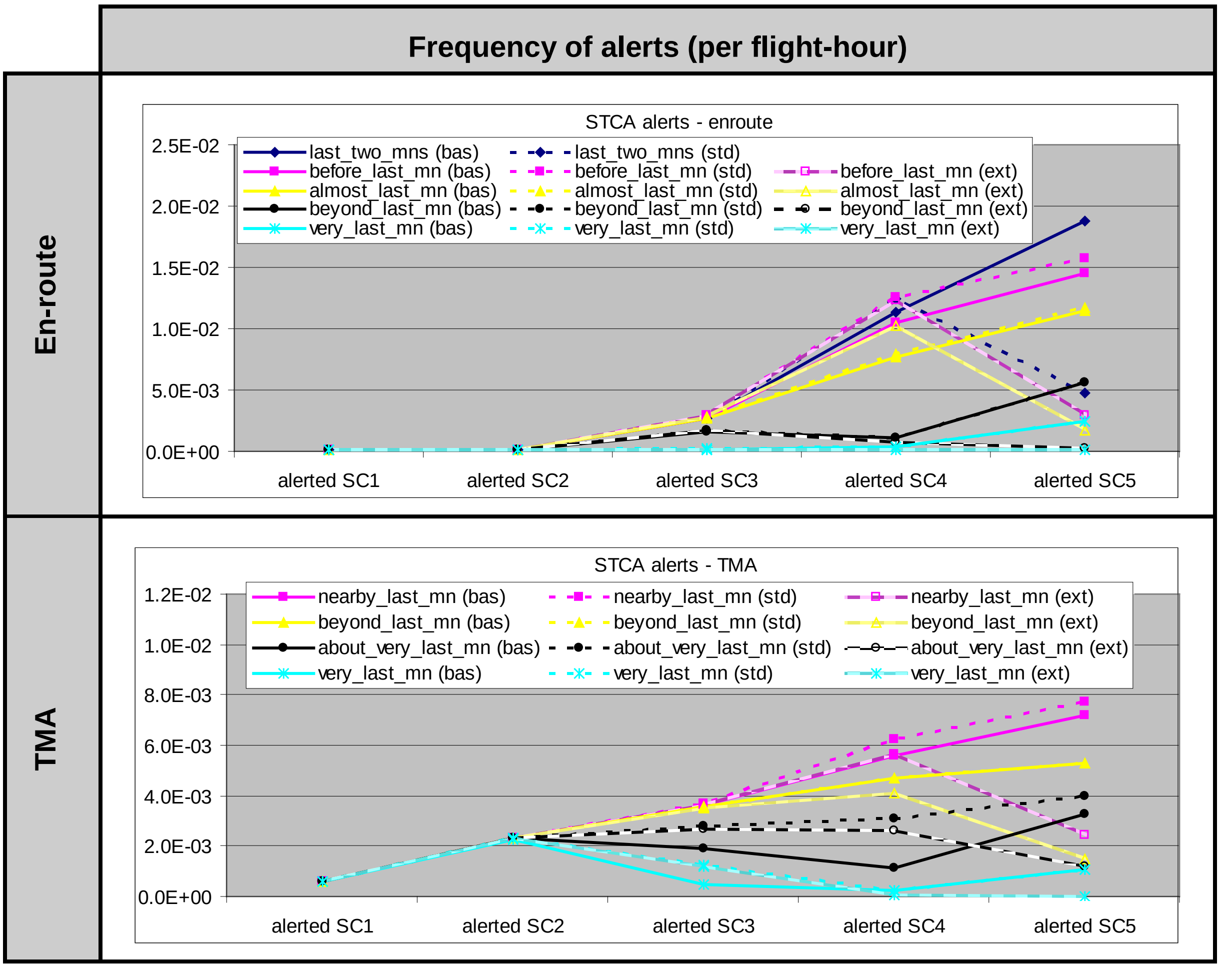

Figure 10: Influence of STCA design on the frequency of alerts

4.4.2.5. These simulation results point out the alternative strategies that ANSPs might follow when implementing and optimising their STCA system. Three main strategies can be identified as follows:

- A minimalist strategy in favour of an STCA primarily designed to "**make a significant positive contribution to the effectiveness of collision prevention essentially**" by alerting the controller of only potentially "major" separation infringements (i.e. less than half the separation minima applicable by ATC) and consequently quite effective in reducing the likelihood of alerts in case of encounters with only "significant" separation infringements;

- A balanced strategy in favour of an STCA primarily designed to "**make a substantial positive contribution to the effectiveness of both separation protection and collision prevention**" by alerting the controller of potentially "significant" separation infringements (i.e. less than four fifths of the separation minima applicable by ATC) with more or less unnecessary alerts in case of encounters without separation infringement or with "minor" separation infringements;

- A conservative strategy in favour of an STCA primarily designed to "**make a significant positive contribution to the effectiveness of separation protection essentially (and consequently to collision prevention)**" by alerting the controller of potentially any separation infringements with more or less unnecessary alerts in case of encounters without separation infringement.

4.4.2.6. The first strategy typically corresponds to the "very_last_mn" STCA family, but also the "about_very_last_mn" STCA family in TMA. The second strategy is illustrated by the "beyond_last_mn" STCA family in en-route or the "nearby_last_mn" and the "beyond_last_mn" STCA families in TMA. Finally, the third strategy essentially exists in en-route as illustrated by the "almost_last_mn", the "before_last_mn" or the "last_two_mns" STCA families.

4.4.3. Influence of CNS characteristics

4.4.3.1. The quality of the surveillance data used by STCA was demonstrated to have an effect on the STCA alert rate, but not to the same extent as the STCA parameters and main features.

4.4.3.2. For a given STCA implementation in either TMA or en-route, the alert rate increased from 9% to 58% depending on the simulated surveillance environment. It is also worth noting that the influence of the surveillance data on the STCA alerting rate was particularly noticeable in case of "safe" encounters involving aircraft eventually separated or in case of "minor" separation infringements (cf. section 4.5.3 for further details).

4.4.3.3. Regarding the communication aspects, the transponder equipage scheme was shown to only have a marginal effect on the number of alerts issued by STCA.

4.4.4. Main results related to the likelihood of STCA alerts

4.4.4.1. The simulations performed show that the strategy followed by an ANSP when implementing and optimising its STCA system has a direct effect on the likelihood of alerts. Although all investigated STCA configurations show comparable alert rates for the most severe encounters, those designed only for "collision prevention" result in a rate of alerts in less severe encounters up to 100 less than those designed for "separation protection" as well as "collision prevention".

4.4.4.2. A feature common to all investigated STCA configurations is the issuance of unnecessary alerts in encounters with no loss of separation. The frequency of these unnecessary alerts can be reduced either with use the CFL or the SFL, or with less conservative separation and warning time parameter values.

4.4.4.3. The quality of the surveillance data used by STCA also has an effect on the STCA alert rate, but to a considerably lesser extent than the STCA parameters and main features. Indeed, the different surveillance environments that have been simulated led to a variation of the alert rate by a factor of at most 1.6.

4.5. Operational relevance of STCA alerts

4.5.1. General

4.5.1.1. Since safety benefits can only be expected from genuine alerts, whereas nuisance or false alerts might be detrimental to safety, the relevance of STCA alerts is another key performance area investigated during the study.

4.5.1.2. In the prospect of defining quantified performance requirements for STCA, it has been proposed ([W120]) to use the following metrics to evaluate the operational relevance of the generated alerts:

- Severity of the genuine alerts established using the “initial” severity of the encounters in order to evaluate the ability of STCA to provide alerts for “operational relevant conflicts” (cf. STCA-08);
- Quality of the genuine alerts in terms of duration and continuity of the alerts in order to evaluate the ability of STCA to provide alerts “as long the alert conditions exist” (cf. STCA-13);
- Trade-off between nuisance and missed alerts in order to evaluate the ability of STCA to provide alerts for “operational relevant conflicts” (cf. STCA-08), while minimising the number of “nuisance” alerts (cf. STCA-10) and consequently avoiding the well known “cry wolf” syndrome ([Guide]).

4.5.1.3. Sensitivity analysis allowed the identification of the factors influencing most the trade-off between “nuisance” and “missed” alerts.

4.5.1.4. The simulation results also highlighted that the notion of “missed”, “genuine” and “nuisance” alerts is likely to depend on the expectations of a given ANSP with respect to STCA, i.e. a safety net fundamentally designed for “collision prevention” only or also designed for “separation protection”. This idea is illustrated in Table 6, which defines three possible classifications of STCA alerts based on the encounter severity.

Minimalist strategy for STCA implementation and optimisation	Balanced strategy for STCA implementation and optimisation	Conservative strategy for STCA implementation and optimisation
Genuine alerts : alerts generated for “serious” and “major” encounters (alerted SC1-SC2)	**Genuine alerts** : alerts generated for “serious”, “major” or “significant” separation infringements (alerted SC1-SC3)	**Genuine alerts** : alerts generated for any separation infringements (alerted SC1-SC4)
Missed alerts: alerts not generated for “serious” or “major” separation infringements (un-alerted SC1-SC2)	**Missed alerts**: alerts not generated for “serious”, “major” or “significant” separation infringements (un-alerted SC1-SC3)	**Missed alerts**: alerts not generated for any separation infringements (un-alerted SC1-SC4)
Nuisance alerts: alerts generated for “significant” or “minor” separation infringements or “safe” encounters (alerted SC3-SC5)	**Nuisance alerts**: alerts generated for “minor” separation infringements or “safe” encounters (alerted SC4-SC5)	**Nuisance alerts**: alerts generated “safe” encounters (alerted SC5)

Table 6: Possible classifications of STCA alerts based on encounter severity

4.5.2. Influence of STCA parameters and configuration

4.5.2.1. The ability of STCA to provide alerts for “operationally relevant conflicts” while minimising the “nuisance” alerts was demonstrated to vary significantly depending on the simulated STCA system.

4.5.2.2. As an illustration, Figure 11 shows the distributions of encounter severity when there is an alert for the ‘standard’ configurations of each STCA family, in TMA and en-route airspace respectively. These distributions are characterised by a more or less significant proportion of alerts for “minor” separation infringements or “safe” encounters (SC4 and SC5), which are more likely to be considered as nuisance (or at least unnecessary) alerts by the controller. The proportions of alerts for “serious” or “major” separation infringements (SC1 and SC2), which are likely to be considered genuine alerts, also vary significantly.

Note: The hatched zones denote possible performance requirements on the acceptable maximum proportion of “nuisance” alerts (e.g. no more than 75% of the alerts) to avoid the well-known “cry wolf” syndrome.

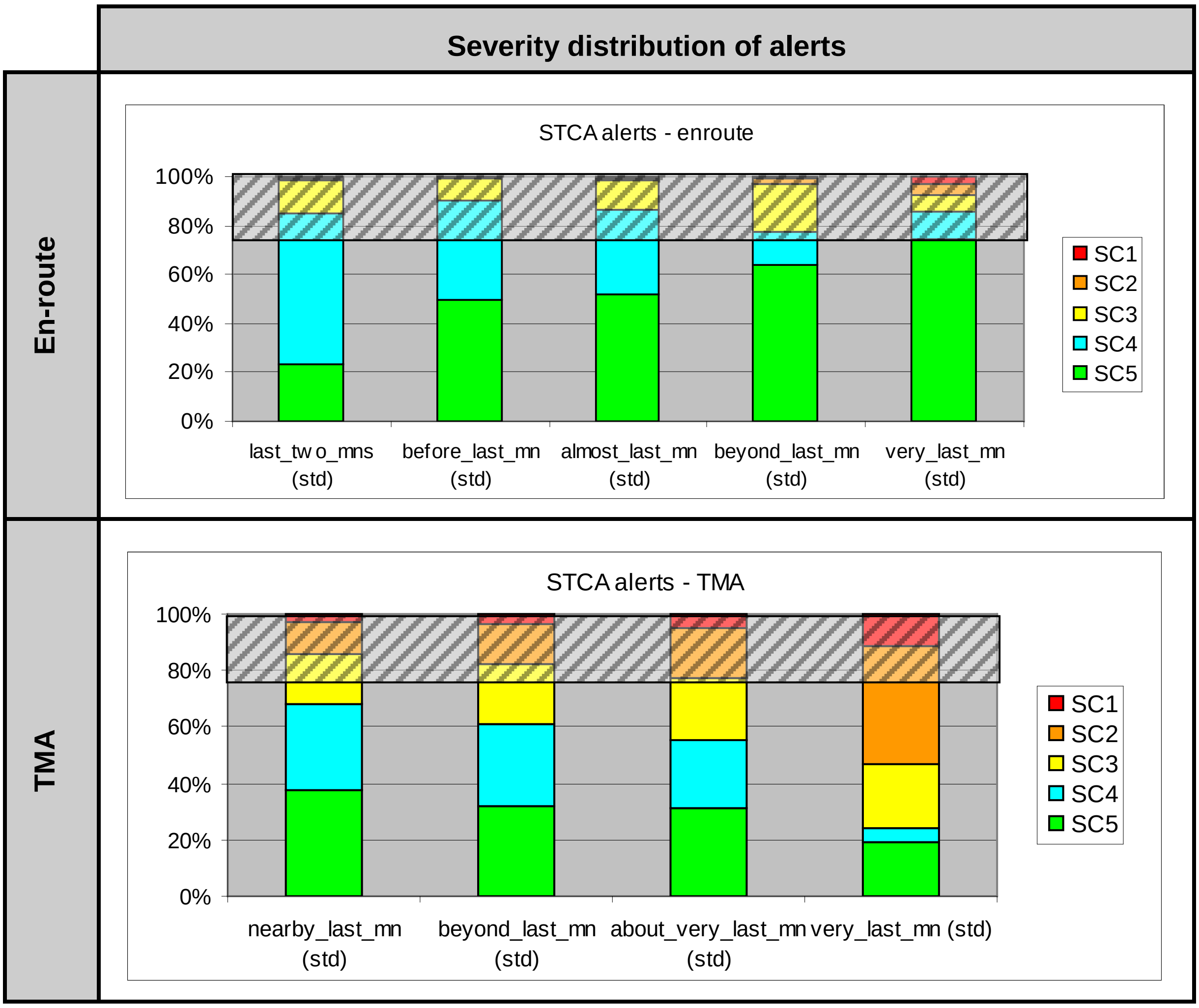

Figure 11: Influence of STCA design on the severity distribution of alerts

4.5.2.3. These above figures also show that the range of 'standard' STCA configurations in en-route airspace lead to more disparity in the severity of encounters leading to STCA alerts, than in TMA where the severity distributions of alerts are more similar from one STCA family to another.

4.5.2.4. In addition to the severity distribution of alerts, another key performance metric on the ability of STCA to provide "genuine" alerts while minimising the "missed" and "nuisance" alerts are the ratios of alerted encounters per severity class. Indeed, these ratios could well be used to define acceptable minimum ratios of hazardous encounters with necessary alerts, as well as acceptable maximum ratios of safe encounters with unnecessary alerts.

4.5.2.5. As an illustration, Figure 12 shows the ratios of alerted encounters observed in the simulations with the various STCA implementations in en-route and TMA airspace respectively.

Note: The hatched zones denote possible performance requirements on the acceptable minimum ratios of alerted separation infringements for two different options regarding the safety contribution expected from the use of STCA.
In the upper figure, assuming that a substantial "separation protection" is expected from the operational use of STCA, the depicted minimum ratios of alerted separation infringements are related to all kind of separation infringements except the "minor" ones (e.g. more than 95% of the "serious" and "major" encounters, and more than 80% of the "significant" ones, with alerts).
In the lower figure, assuming that "collision prevention" is primarily expected from the operational use of STCA, the depicted minimum ratios of alerted separation infringements are only related to the most severe ones (e.g. 95% of the "serious" encounters, and 80% of the "major" ones, with alerts).

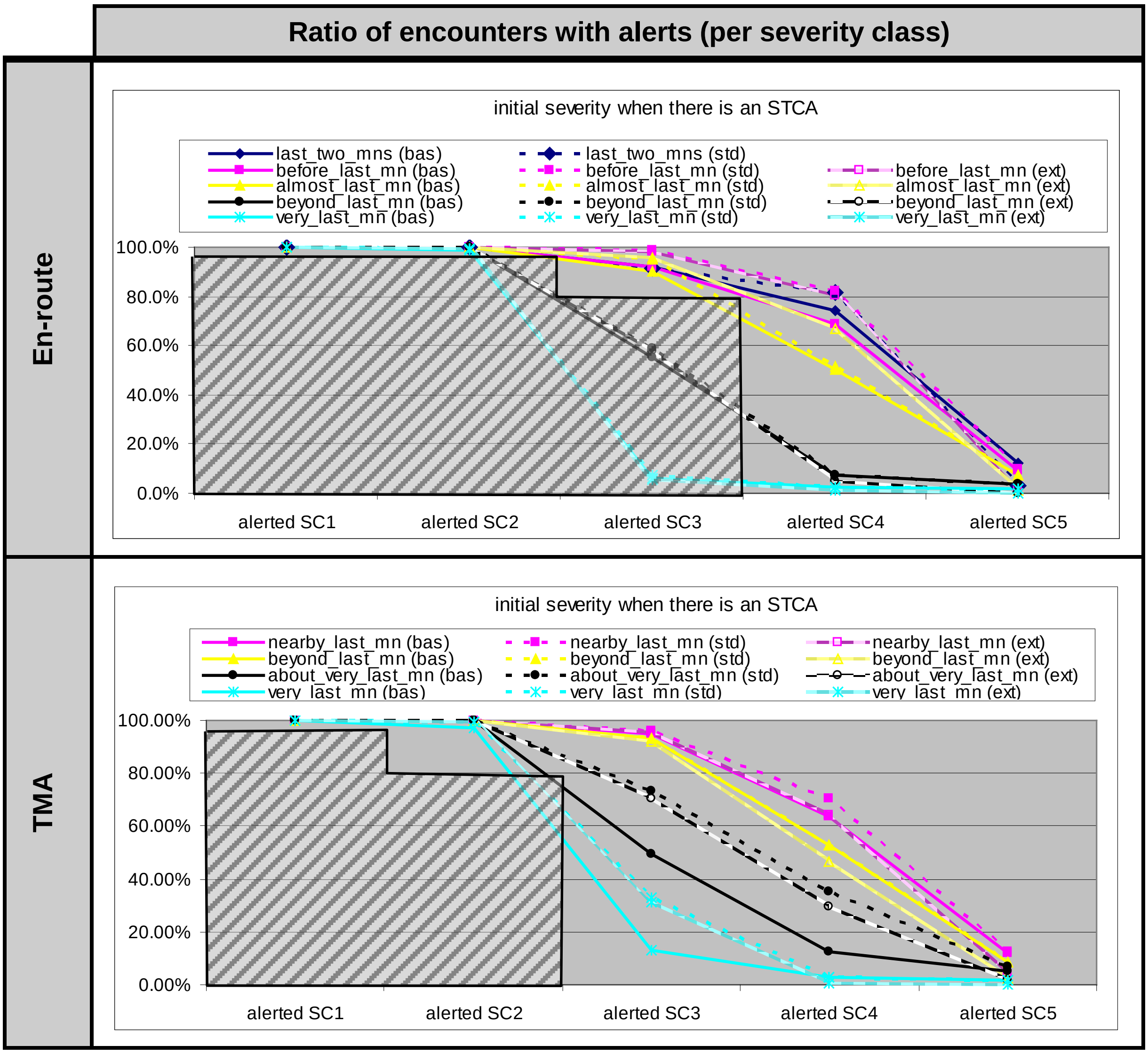

Figure 12: Influence of the STCA design on the ratio of encounters with alerts

4.5.2.6. As shown, for a given STCA family in a given airspace, the various STCA configurations (i.e. ‘basic’, ‘standard’ and ‘extended’) provide fairly similar results, although some positive effect on the STCA performance could be measured from the optional features added in the ‘standard’ and ‘extended’ configurations. General trends highlighted by the simulation results include the following:

- Positive effect of the use of CFL or SFL in reducing the ratio of alerted encounters involving vertically separated aircraft (SC5), typically during 1,000 ft level-off geometries. This is indicated by the reduced ratios of alerted SC5 encounters when improving from ‘standard’ to ‘extended’ configuration of “before_last_mn”, “beyond_last_mn” and “very_last_mn” STCA families in en-route airspace and all STCA families in TMA (cf. Appendix B.2 for the detailed features of each STCA family). This positive effect is comparatively limited for the less conservative STCA families (like the “very_last_mn” family) that use reduced separation and warning time parameter values.
- Positive, yet limited, effect of the ‘Current Proximity Filter’ and ‘Turning Proximity Filter’ in increasing the ratio of alerts for “major” separation

infringements (SC2) during specific encounter situations like slow convergence situations or sudden turn towards another aircraft. This is indicated by the increased ratio of alerted SC2 encounters when improving from the 'basic' to 'standard' configuration of the "very_last_mn" STCA family in TMA airspace, for example.

- Positive, yet not systematic, effect of the 'Current Proximity Filter' and 'Turning Proximity Filter' in increasing the ratio of alerts for "significant" and / or "minor" separation infringements (SC3 and / or SC4). This is indicated by the increased ratio of alerted SC3 and SC4 encounters when improving from the 'basic' to 'standard' configuration of the "almost_last_mn" STCA family in en-route airspace, for example. This positive effect actually depends on the parameter used by these optional features compared to the ones used by the 'Linear Prediction Filter'.
- Positive effect of the use of vertical uncertainties by the 'Linear Prediction Filter' in increasing ratio of "significant" and "minor" separation infringements (SC3 and SC4). This is indicated by the increased ratio of alerted SC3 and SC4 encounters when improving from the 'basic' to 'standard' configuration of the "nearby_last_mn" STCA family in TMA airspace, for example.

4.5.2.7. It is worth noting that depending on the expectations of a given ANSP with respect to STCA, increasing the ratio of alerted "minor" or possibly "significant" separation infringements might either be considered as a positive contribution to "separation protection" or an unnecessary feature that does not contribute much to "collision prevention". Some might even consider that this has the potential for degrading the safety benefits of STCA by increasing the likelihood of the "cry wolf" syndrome.

4.5.2.8. The STCA not only needs to provide alerts for "operationally relevant conflicts", but these alerts need to be maintained "as long the alert conditions exist". The duration and continuity of the alerts were therefore investigated, and demonstrated to vary significantly depending on the STCA family and configuration, as well as the initial severity of the alerted encounters.

4.5.2.9. Whatever the STCA family in either TMA or en-route airspace, the proportion of "short duration"[6] alerts typically increases with the encounter severity. These "short duration" alerts are also comparatively more frequent for the less conservative STCA families (like the "very_last_mn" or the "beyond_last_mn" families in en-route, as shown in Figure 13) due to the use of reduced separation and warning time parameter values. From an operational perspective, it would therefore be essential to relate any performance requirement on the alert duration to the expected safety contribution of STCA, i.e. "collision prevention" or "separation protection".

Note: As an example, the hatched zones denote possible performance requirements on the acceptable maximum ratios of "short duration" alerts (e.g. 20%) assuming that a substantial "separation protection" is expected from the operational use of STCA.

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[6] The definition of "short-duration" alert is derived from an FAA Human Factor study ([HFFAA]), which suggested that "alerts lasting less than 20 seconds that do not result in operation errors can be considered nuisances because they deactivated before a response by the controller could have taken effect".

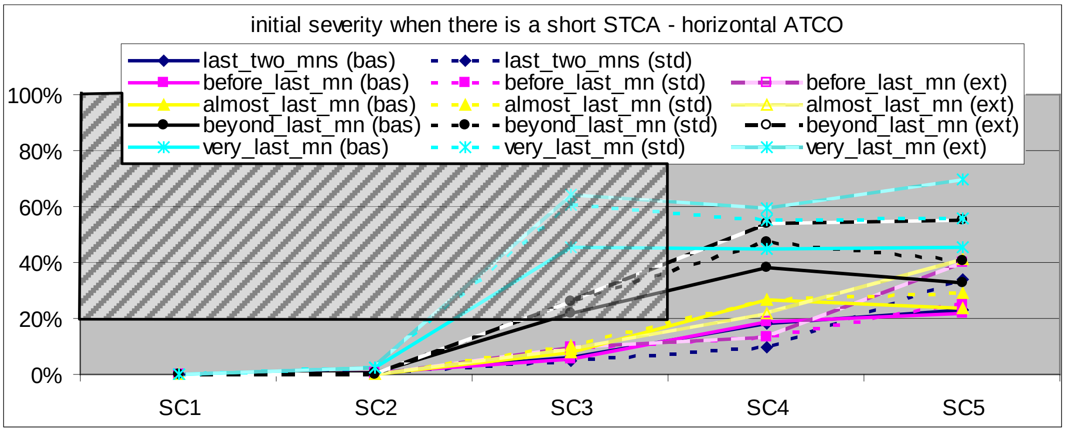

Figure 13: Influence of STCA design on ratio of short duration alerts (en-route)

4.5.2.10. With regard to the continuity of alerts, the proportion of split alerts typically increases for the separation infringements that are close to the separation parameter values used by STCA. Hence, the less conservative STCA families tend to increase the frequency of split alerts for more severe separation infringements. As an illustration, Figure 14 shows the proportions of split alerts observed with the various STCA families and configurations of the en-route airspace.

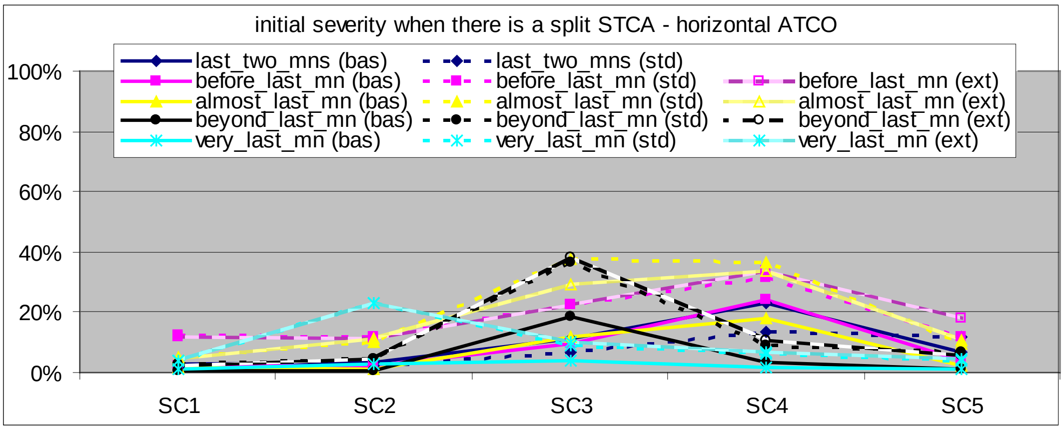

Figure 14: Influence of STCA design on ratio of split alerts (en-route)

4.5.2.11. Finally, it is worth noting that the positive effect on the ratios of alerted separation infringements obtained with the optional features (other than the use of CFL or SFL) of the 'standard' or 'extended' STCA configurations typically brings with it a decrease in the quality of alerts with greater proportions of "short duration" and split alerts.

4.5.3. Influence of CNS characteristics

4.5.3.1. The sensitivity analysis performed on the surveillance environment in which STCA is operated highlighted that the quality of the surveillance data can not only affect the frequency of alerts (cf. section 4.4.3), but can also affect the operational relevance and the quality of the alerts supplied to ATC.

4.5.3.2. It is however worth noting that the influence of the surveillance means on the alerting functionality of STCA was essentially observed in case of "minor" separation infringements (SC4) or "safe" encounters (SC5). Obviously, the effect of the surveillance data was observed to increase with the more conservative STCA implementations (due to the use of greater warning time parameter values that increase the alert duration).

4.5.3.3. As an illustration, Figure 15 shows the different trade-off between missed, genuine and nuisance alerts observed for two STCA implementations (i.e. the 'standard' configurations of the "beyond_last_mn" and "very_last_mn" STCA families) in several surveillance environments (cf. Appendix B.1 for further details). These two STCA families are representative of two different strategies for STCA design and optimisation, i.e. "collision prevention" and "separation protection".

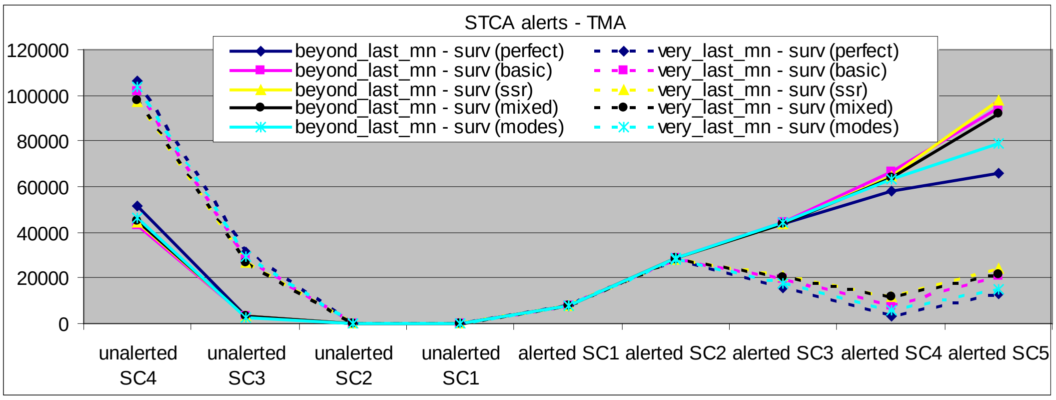

Figure 15: Influence of surveillance data on the trade-off between missed, genuine and nuisance alerts

4.5.3.4. The surveillance means was also observed to potentially significantly affect the number of split alerts. Improving the quality of the surveillance data tend to limit these split alerts, and therefore, to improve the quality of the alerts supplied by STCA to the controllers.

4.5.4. Influence of controller's response to STCA

4.5.4.1. The type of controller's response to STCA (i.e. horizontal or vertical avoiding instructions) also potentially affect the quality of the alerts (notably in terms of split alerts) since the execution of the avoiding manoeuvres might affect the various STCA filters. The simulations highlighted that this is particularly the case when the controller issues horizontal avoiding instructions and when STCA uses optional features (like the 'use of vertical uncertainties' or 'Turning Prediction Filter') that increase the sensitivity of the safety-net predictions.

4.5.5. Main results related to the operational relevance of STCA alerts

4.5.5.1. The operational relevance of STCA alerts is dependant on the extent of a loss of separation that an ANSP considers as requiring an alert, and thus on the strategy it follows when implementing and optimising its STCA system. While STCA systems designed for "separation protection" as well as "collision prevention" provide a high rate of alert (i.e. 90% or more) for encounters with a "significant", or worse, loss of separation (i.e. SC1 to SC3), STCAs designed only for "collision prevention" provide comparable rates in encounters one order of magnitude more severe (i.e. SC1 and SC2).

4.5.5.2. This choice is also of importance with regard to the quality of the alerts issued by the STCA system, as higher rates of split and short alerts are generally found for encounters with the first undesired severity (e.g. SC3 severity for STCAs designed for collision prevention).

4.5.5.3. The behaviour of a given STCA system with regard to both target rates of genuine and nuisance alerts can be more precisely tuned with the addition of optional features (use of CFL/SFL, additional filters, …). However, a balance always has to be struck between genuine and nuisance alert rates, whatever the level of sophistication of the STCA. It is worth noting that increasing the sophistication of an STCA system leads to higher rates of split and short alerts, and thus a lesser quality of alerts, although this can be partly counterbalanced by better surveillance means.

4.6. Operational efficacy of STCA alerts

4.6.1. General

4.6.1.1. The potential efficacy of genuine alerts (in terms of time left to the controller to intervene, and achievable safety margins assuming realistic controller's and pilot's behaviour) is another key performance area investigated during the study.

4.6.1.2. The safety benefits provided by STCA themselves can be quantified by evaluating the change in separation metrics with and without the effect of STCA, i.e. with and without the controllers' avoiding instruction prompted by the alert and the subsequent aircraft manoeuvre following the pilot's response to the instruction.

4.6.1.3. With the prospect of defining quantified performance requirements for STCA, it has been proposed ([WP120]) to use the following metrics to evaluate the potential efficacy of the generated alerts:

- Warning time of genuine alerts as an indication of the ability of STCA "to assist the controller […] by generating, in a timely manner, an alert of potential or actual infringement of separation minima" (cf. [ES11]);
- Separation margins achievable with the genuine alerts in order to evaluate the ability of STCA to provide alerts with "sufficient [warning time] for all the necessary steps to be taken" (cf. STCA-12). These separation margins obviously depend on the ability of the controller to "without delay assess the situation and if necessary take action to ensure that the applicable separation minimum will not be infringed or will be restored" (cf. STCA-05).
- Trade-off between warning time and nuisance alerts in order to evaluate the ability of STCA to provide alerts with "sufficient warning time" (cf. STCA-12), while minimising the number of "nuisance" alerts (cf. STCA-10).

4.6.1.4. Sensitivity analysis allowed identifying the factors influencing most the trade-off to be found between "sufficient warning time" and "nuisance" alerts.

4.6.2. Influence of STCA parameters and configuration

4.6.2.1. The ability of STCA to generate "in a timely manner, an alert of potential or actual infringement of separation minima" vary significantly depending on the STCA families, the more conservative ones (that use greater warning time parameter values) supplying much fewer time-critical alerts than the STCA families fundamentally designed to support "collision prevention" rather than to ensure "separation protection".

4.6.2.2. As an illustration, Figure 16 shows the cumulative ratios of the initial warning time[7] of genuine STCA alerts in case of "significant" or worse separation infringements (SC1 to SC3) as simulated for the various STCA implementations for the en-route and TMA airspace respectively. It should be noted that these distributions do not necessarily relate to the same encounter set as the likelihood of STCA alert in case of "significant" separation infringements sensibly varies with the STCA family (cf. Figure 10).

[7] The initial warning time (i.e. the amount of time between the first indication of an alert and the loss of separation in the initial encounter) is a conservative metric for evaluating the time

Note: The hatched zones denote possible performance requirements on the acceptable maximum proportion of "genuine" alerts with insufficient warning time assuming that a substantial "separation protection" is expected from the use of STCA (e.g. no more than 20% of alerted "significant" or worse separation infringements with less than 20 seconds warning time before initial LOS).

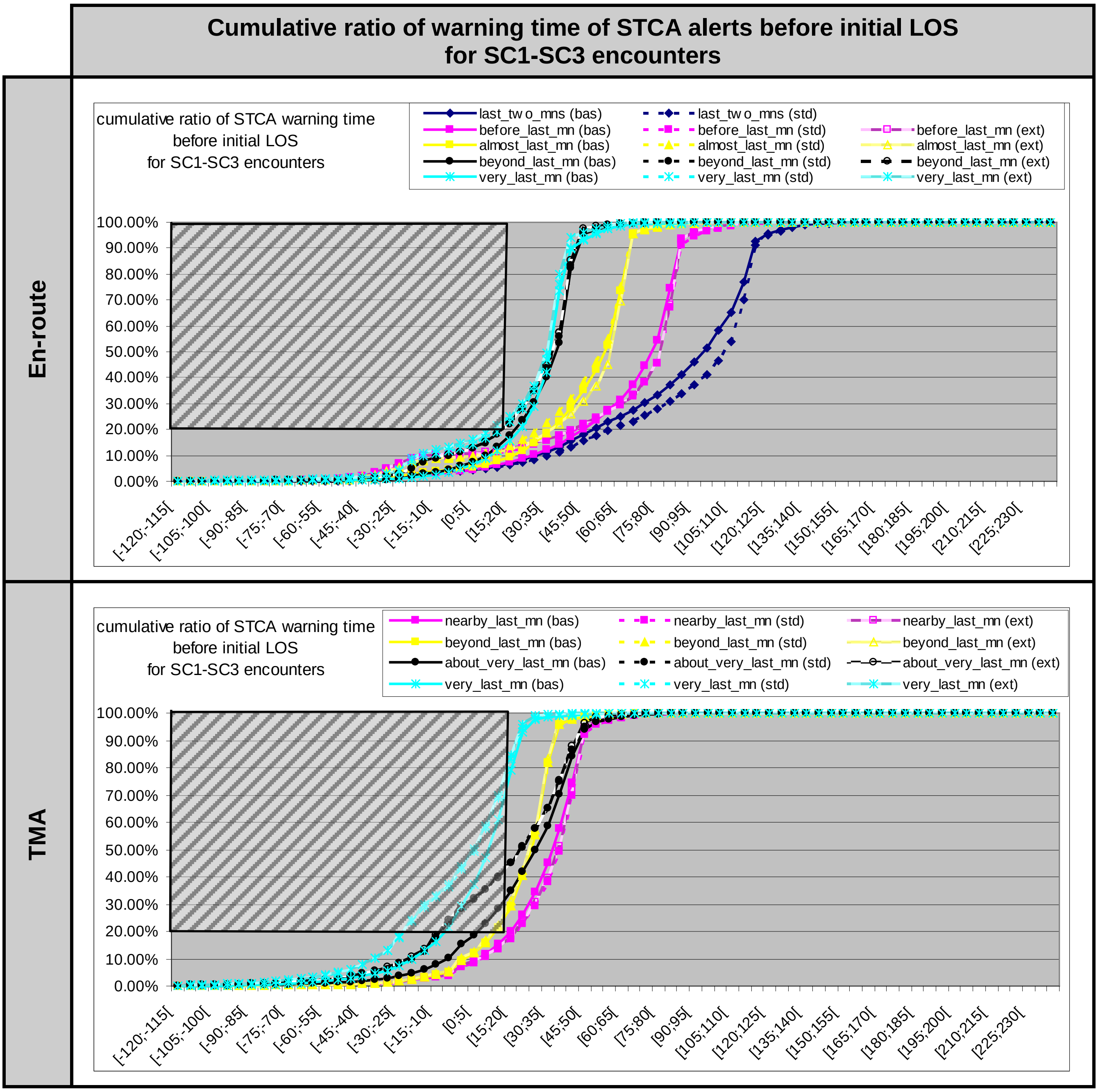

Figure 16: Influence of STCA design on the initial warning time of STCA alerts

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left to the controller to intervene following an STCA alert. This is not the case of the final warning time (i.e. the amount of time between the alert and the loss of separation in the final encounter) since effective controller intervention is likely to maintain separation between the aircraft in conflict.

4.6.2.3. As shown, for a given STCA family in a given airspace, the various STCA configurations (i.e. 'basic', 'standard' and 'extended') provide fairly similar warning time performances, although some influence on the STCA performance could be observed from the optional features added in the 'standard' and 'extended' configurations. The effect of these optional features was most noticeable on the most time-critical alerts. General trends identified include the following:

- Positive effect of the 'Current Proximity Filter', the 'Turning Prediction Filter' or the use of the CFL or SFL in a few specific circumstances (like slow convergence situations, sudden aircraft manoeuvres or level-off at an occupied flight level) with a slight increase in the achieved alert warning time. This is indicated by the increased achieved warning time when improving from the 'basic' to 'standard' configuration of the "about_very_last_mn" STCA family in TMA airspace or from the 'standard' to 'extended' configuration of the "very_last_mn" STCA family in en-route airspace, for example (cf. Appendix B.2 for the detailed features of each STCA family). It is, however, worth noting that this positive effect was not statistically noticeable on the warning time distributions of alerts.
- Negative effect of the 'Current Proximity Filter' on the proportions of alerts with negative warning time, i.e. alerts issued after the separation infringement has occurred. This is indicated by the increased negative warning time when improving from the 'basic' to 'standard' configuration of the "almost_last_mn" STCA family in en-route airspace, for example. This is a side effect of the ability of the 'Current Proximity Filter' to issue an alert in the case of slow convergence situations when the ATC separation is marginally infringed (due to the use of separation thresholds closer to the ATC separation minima than the separation thresholds used by the 'Linear Prediction Filter'). This side effect is amplified with the less conservative STCA families (like the "very_last_mn" family) due to the use of tighter separation parameter values.

4.6.2.4. Regarding the ability of STCA "to assist the controller in preventing collision", the simulation results highlighted, as expected, that the separation margins achievable with genuine STCA alerts (assuming realistic controller and pilot behaviour) significantly increase with the more conservative STCA implementations (as a consequence of the statistical increase of the initial warning time of the alerts).

4.6.2.5. As an illustration, Figure 17 shows the cumulative distributions of the final encounter severity obtained with the various STCA implementations, respectively in en-route and TMA airspace, when simulating a 'standard' controller use of vertical avoiding instructions in response to STCA (and a 'standard' pilot response to the controller's avoiding instruction).

Note: The hatched zones denote possible performance requirements on the acceptable maximum proportions of alerted encounters for which the avoiding instructions prompted by STCA do not enable to preserve separation. Assuming that a substantial "separation protection" is expected from the use of STCA, these requirements are related to all kinds of final separation infringements except the "minor" ones (e.g. no more than 5% of "serious" and "major" separation infringements, and no more than 20% of "significant" or more severe separation infringements).

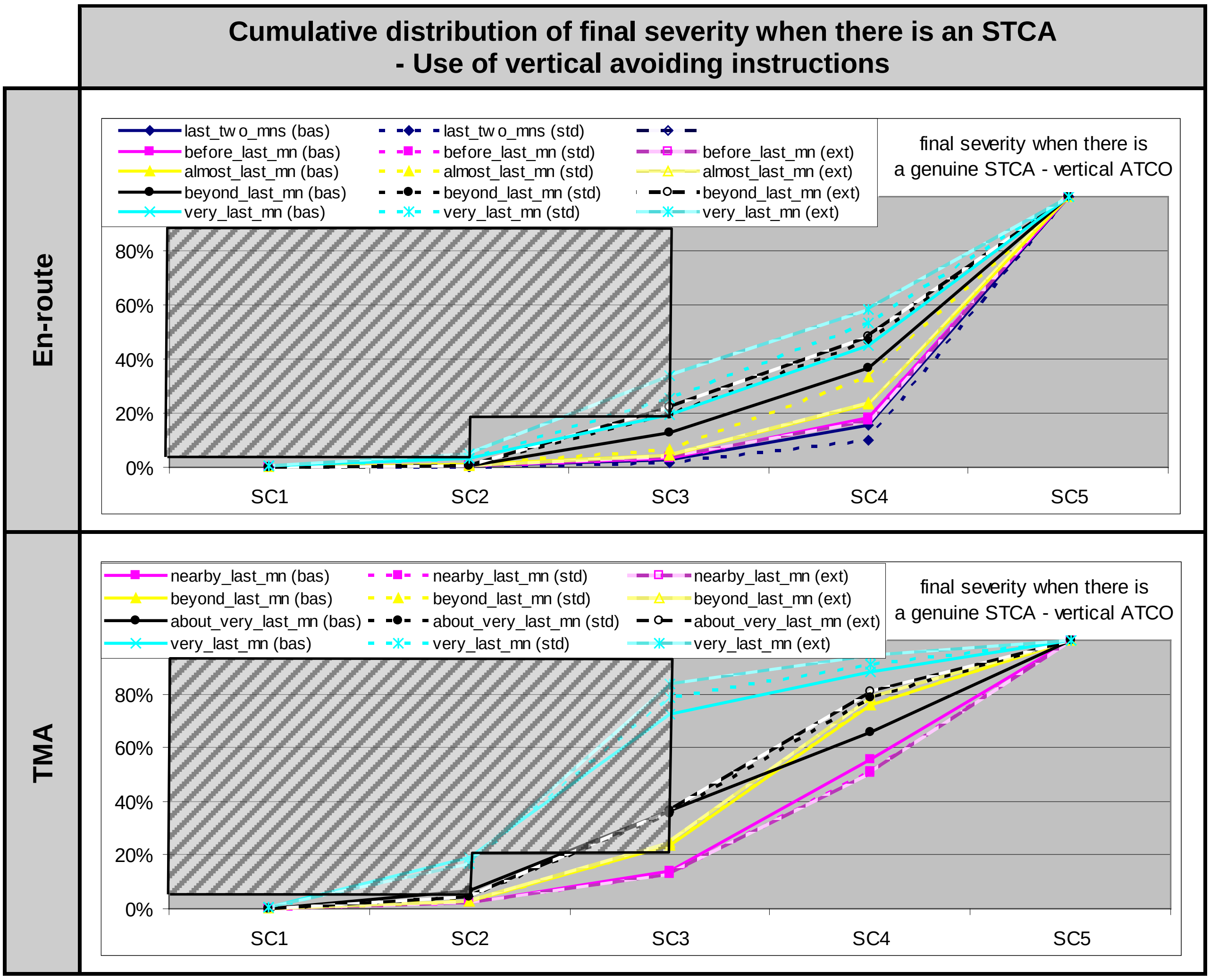


Figure 17: Influence of STCA design on the separation margins achievable by ATC

4.6.2.6. As shown, the less conservative STCA families (like the "very_last_mn" family) tend to statistically increase the ratios of alerted encounter situations in which the separation cannot be maintained by ATC, at least assuming 'standard' avoiding manoeuvres (cf. section 4.6.3 for further details on the influence of the controller's and pilot's behaviour). It is worth noting that this limited efficacy of some of the STCA implementations was more noticeable in TMA than in en-route airspace (due to the use of tighter STCA parameter values in TMA).

4.6.2.7. The overall <u>safety benefits achievable by the operational use of STCA</u> can be quantified by the 'Separation Infringement Ratio' (SIR), i.e. the ratio of the numbers of separation infringements with and without the effect of STCA (or more precisely the effect of the controller's avoiding instructions prompted by STCA). This ratio reflects the ability of STCA to assist the controller in "ensuring that the applicable separation minimum will not be infringed or will be restored".

4.6.2.8. As an illustration Figure 18 shows the Separation Infringement Ratios for different groups of encounter severity (initial severity) obtained with the various STCA implementations of the en-route and TMA airspace respectively when simulating 'standard' horizontal avoiding instructions in response to STCA.

<u>Note</u>: The hatched zones denote possible performance requirements on the acceptable maximum separation infringement ratios expected from the effect of the avoiding instructions prompted by STCA.
Assuming that the operational use of STCA is expected to contribute not only to "collision prevention", but also to a substantial "separation protection", the depicted minimum ratios require a decrease by a factor of at least ten of "serious" separation infringements, by a factor of five of "major" or worse separation infringements and by a factor of two of the "significant" or worse separation infringements (i.e. SIR respectively lower than 10%, 20% and 50%).

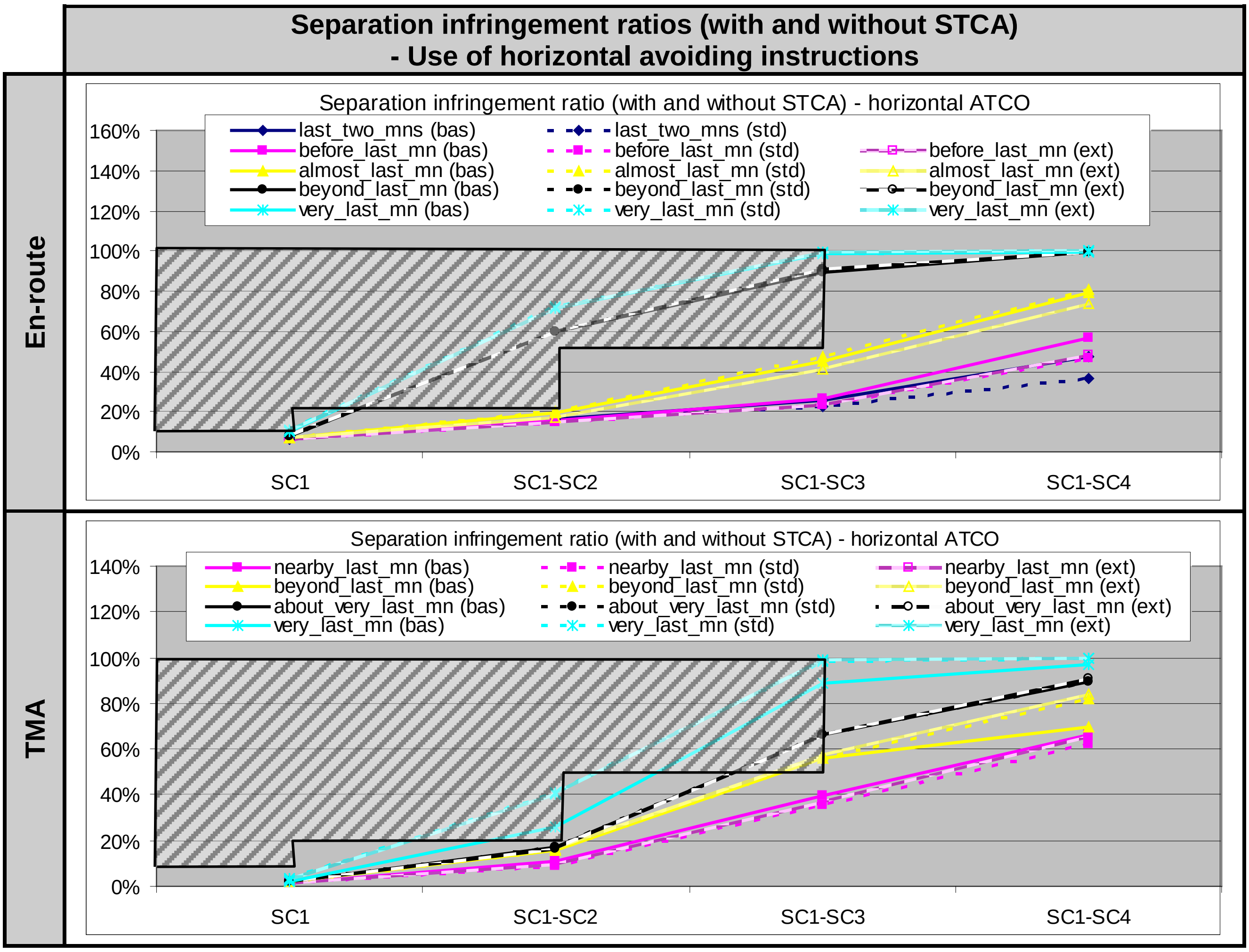


Figure 18: Influence of STCA design on the separation ratios achievable by ATC

4.6.2.9. Once again, the less conservative STCA families appear to be less effective than the other STCA families to help maintain (or restore) separation. It is, for instance, worth noting that for the most severe encounters (SC1 to SC2) the number of separation infringements could be reduced by a factor of at least five (i.e. SIR of 20% or less) with all STCA implementations except with the "very_last_mn" family in either TMA or en-route or with the "beyond_last_mn" family in en-route.

4.6.3. Influence of controller and pilot behaviour

4.6.3.1. The sensitivity analysis conducted on several operational scenarios addressing a broad range of realistic human performances confirmed that the controller's behaviour, and to a lesser extent the pilot's behaviour, are essential factors influencing the efficacy of STCA.

4.6.3.2. For a given STCA implementation, the safety contribution that can be expected from the operational use of STCA varies depending on the type of controller's response to STCA (i.e. either horizontal or vertical avoiding instructions), the systematic use or not of avoiding phraseology, the delays of the controller's response to STCA and the pilot's response to the controller's avoiding instruction.

4.6.3.3. As an illustration Figure 19 shows the cumulative distributions of the final encounter severity obtained with two distinct STCA implementations in TMA airspace (i.e. the standard configurations of the "before_last_mn" and "very_last_mn" STCA families) when simulating different controller's and pilot's behaviours (cf. Appendix B.3 for further details).

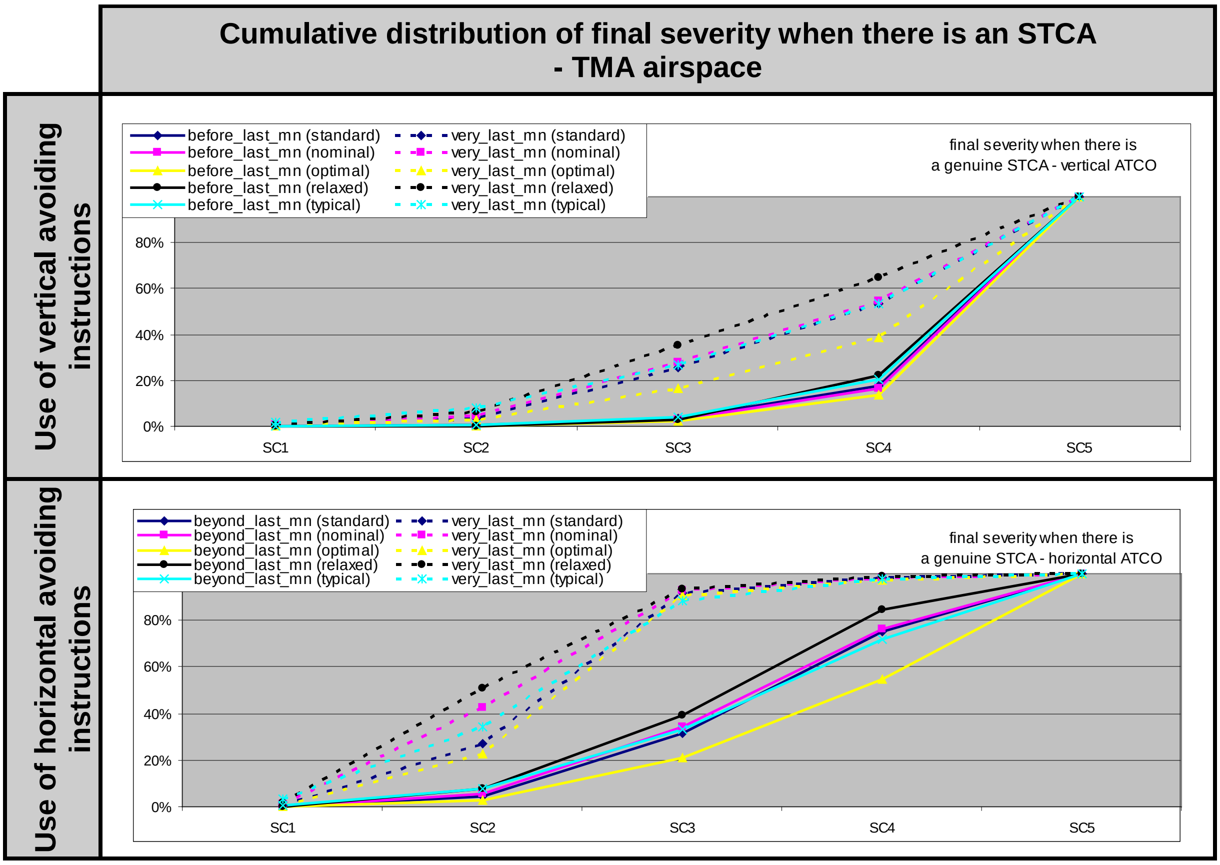


Figure 19: Influence of human behaviour on the separation margins achievable when there is STCA

4.6.3.4. As shown, the "optimal" scenario (which assumes short response delays and systematic use of avoiding phraseology) significantly increases the safety margins achievable thanks to STCA, particularly when STCA uses tight parameter values like with the "very_last_mn" family.

4.6.3.5. It is for instance worth noting that for this specific STCA family fundamentally designed for "collision prevention", when compared to the "relaxed" scenario (which assumes longer delays and no use of avoiding phraseology), the "optimal" scenario enables the reduction by a factor of about two of the proportion of "significant" separation infringements when simulating vertical avoiding instructions, as well as the proportion of "serious" separation infringements when simulating horizontal avoiding instructions.

4.6.3.6. These simulation results also tend to demonstrate that the more conservative STCA implementations (which use greater parameter values, like the "before_last_mn" STCA family in TMA) are less sensible to the human performances, particularly when using vertical avoiding instructions which are typically more effective than horizontal avoiding instructions.

4.6.4. Main results related to the operational efficacy of STCA alerts

4.6.4.1. The efficacy of STCA alerts is mostly linked to the warning time afforded by the STCA to the controller for him/her to assess the situation and take action to ensure that separation will not be infringed or will be restored. STCA systems designed for "separation protection" as well as "collision prevention" supply fewer time-critical alerts than those designed only for "collision prevention". For a given STCA system, the use of optional features (use of SFL/CFL, additional filters …) can provide additional warning time to the controller in a few specific circumstances.

4.6.4.2. As a consequence, STCA systems designed for "collision prevention" only tend to statistically increase the ratios of alerted encounter situations in which the separation cannot be restored by ATC. Indeed, with all STCA implementations except those designed for "collision prevention" only, the number of separation infringements could be reduced by a factor of at least five.

4.6.4.3. These general trends are of course susceptible to be influenced by the performance of human actors involved in the responses to STCA alerts, with prompter controllers or the use of avoiding phraseology reducing the final number of separation infringements. However, STCA systems designed for "separation protection" as well as "collision prevention" are less sensible to the human performances.

4.7. *Level of STCA and ACAS interaction*

4.7.1. General

4.7.1.1. Even though no specific requirement is defined in the EUROCONTROL specification for STCA ([ES11]) to achieve an effective compatibility with ACAS, the level of STCA and TCAS interaction is another key performance area to be investigated in the PASS study.

4.7.1.2. With the prospect of defining quantified performance requirements for STCA, it has been proposed ([W120]) to use the following metrics to evaluate the level of STCA and ACAS interaction:

- Likelihood of STCA and ACAS RAs in order to evaluate the scope of intervention of each safety net, as well as the encounter situations with combined effects of both safety nets;
- Relative timing of STCA and ACAS RAs in order to assess the intervention time of each safety net, as well as the extent of the time window shared by both safety nets;
- Safety benefits achievable by the joint operation of STCA and ACAS in order to evaluate the impact of ACAS on the safety benefits achievable by STCA alone, and vice versa.

4.7.1.3. Sensitivity analysis on the STCA design allowed the identification of the factors influencing most the level of interaction with ACAS in en-route and TMA airspace respectively.

4.7.2. Influence of STCA parameters and configuration on interaction likelihood

4.7.2.1. Figure 20 shows, for encounters in which an STCA and/or an ACAS alert were issued, the proportion of encounters in which either or both safety net issued an alert. This figure shows results obtained with ATCO avoiding instruction issued in the horizontal dimension, which are largely similar to those obtained with vertical instructions. Figure 20 demonstrates the influence of the STCA family (and to a lesser extent, of the controller’s response to STCA) on the proportion of STCA alerts with and without ACAS RA, as well as the proportion of encounters with only an RA. Interaction between STCA and ACAS is expected to be at a minimum when the proportion of encounters leading to both types of alerts is the lowest.

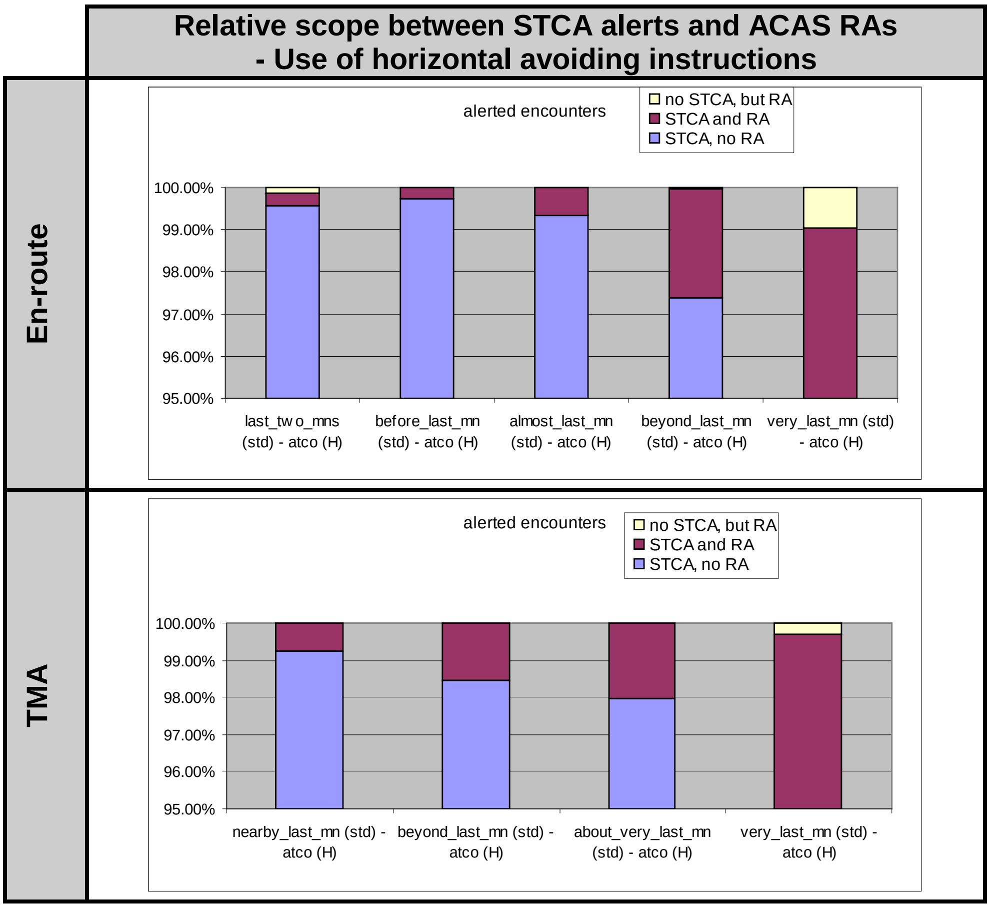


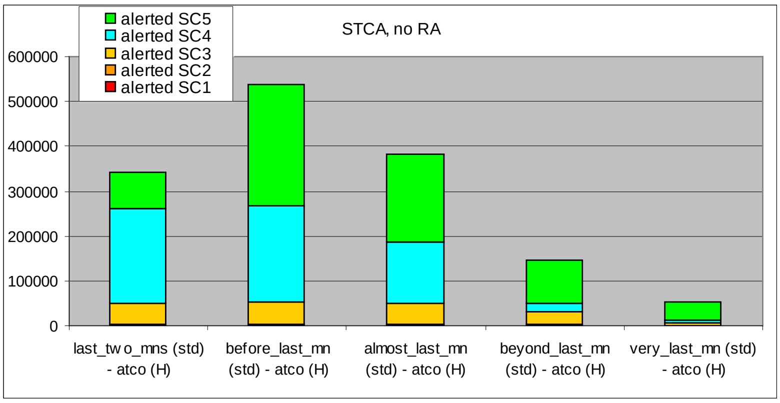
Figure 20: Influence of STCA design on the type of alerts

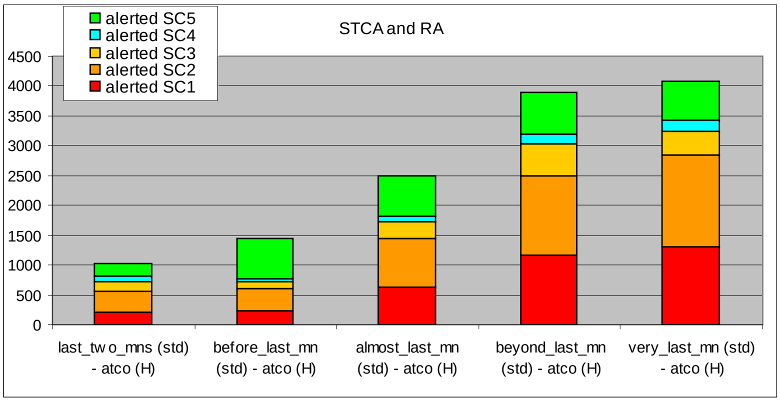
4.7.2.2. The overlap between the scopes of intervention of STCA and ACAS is clearly visible in Figure 20 through the proportion of encounters leading to both an STCA and an ACAS alert. This proportion ranges from 0.3% to 9.1% of encounters, depending on the airspace, the STCA configuration and the sense of the manoeuvres used by the ATCO in response to STCA alerts. General trends highlighted by the simulation results include the following ones:

- Reducing the STCA separation and warning time parameter values increases the proportion of encounters resulting in alerts from both safety nets. This is especially the case with the “very_last_mn” STCA family in both TMA and en-route airspace.
- With the less conservative STCA families (like the “very_last_mn” family), the proportion of encounters resulting in alerts from both safety nets is increased when avoiding instructions are issued in the horizontal dimension. Indeed, vertical manoeuvres provide separation faster than horizontal ones, and are thus more likely to prevent the issuance of an ACAS RA in case of converging aircraft coming close to ACAS thresholds.

4.7.2.3. It is worth noting that the STCA families fundamentally designed for “collision prevention” significantly increase the likelihood of interaction with ACAS, compared to those families designed for “separation protection”. For the former STCA families, avoiding instructions should be preferably given in the vertical dimension so as to reduce the likelihood of a subsequent ACAS RA (since horizontal instructions are less effective in increasing safety margins, and hence to prevent RA issuance). However, belated vertical avoiding instructions have a greater potential for being contrary to a subsequent RA if and when it happens.

4.7.2.4. Figure 21 provides an insight into encounters that result in either, or both, an STCA alert and an ACAS RA, giving their numbers per initial encounter severity for the different STCA families. The dimension (i.e. vertical only or horizontal only) used for ATC instructions in response to STCA alerts has little influence on these numbers. In addition, identical trends are observed in en-route and TMA airspace. Consequently, only simulation results obtained with horizontal ATC instructions in en-route airspace are provided.





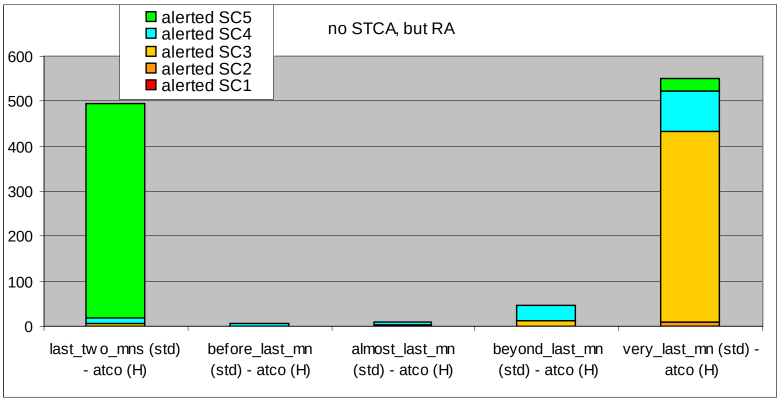


Figure 21: Severity of encounters with STCA and/or ACAS alerts – en-route airspace and horizontal manoeuvres

4.7.2.5. As an initial remark, the "last_two_mns" STCA family shows a specific behaviour, with fewer STCA alerts than other families designed for "separation protection" and mostly for minor losses of separation (i.e. SC4 severity encounters). This comes as a consequence of the use of the CFL in the standard implementation of this particular STCA family. The other STCA families, which do not use the CFL in their standard implementation, result in less and less STCA alerts in encounters of each initial severity category as separation and warning time parameter values are reduced.

4.7.2.6. Two particular categories of encounters have to be considered in the context of STCA and ACAS interaction. "Safe" encounters (i.e. SC5) include a significant proportion of level-off geometries in which ACAS is known to commonly issue RAs, although there is no risk of collision, and "serious" losses of separation (i.e. SC1) in which ACAS is expected to be involved.

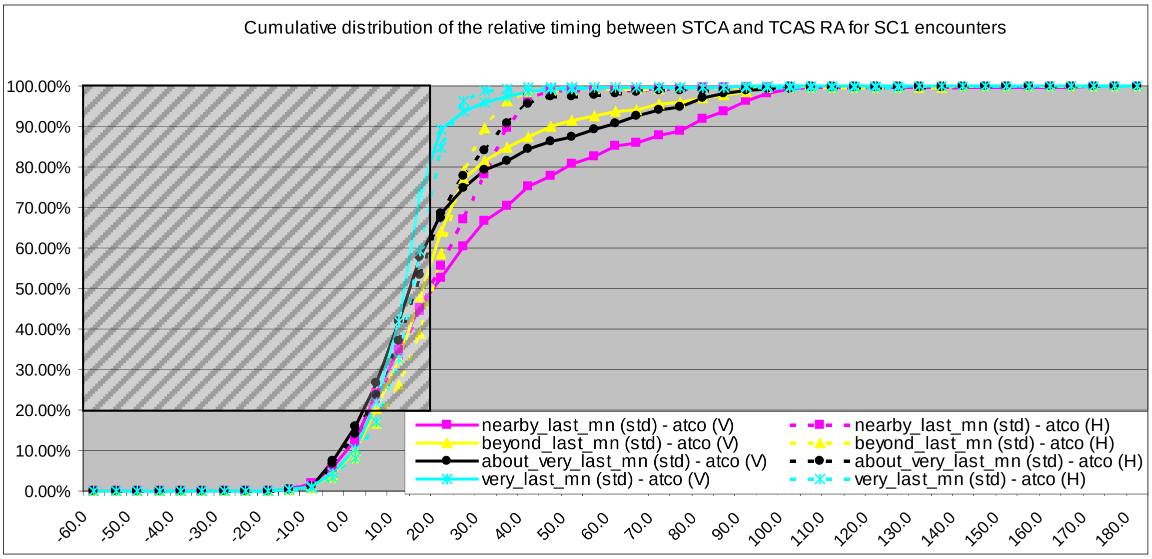
4.7.2.7. As a general trend, the number of STCA alerts in "safe" encounters diminishes with the use of tighter STCA separation and warning time parameter values, but the proportion of these alerts increases, showing that reducing the STCA parameter values is not an efficient solution to address the issue of alerts in "safe" encounters. The use of the CFL is another approach to help mitigate this issue, but at the cost of additional ACAS RAs.

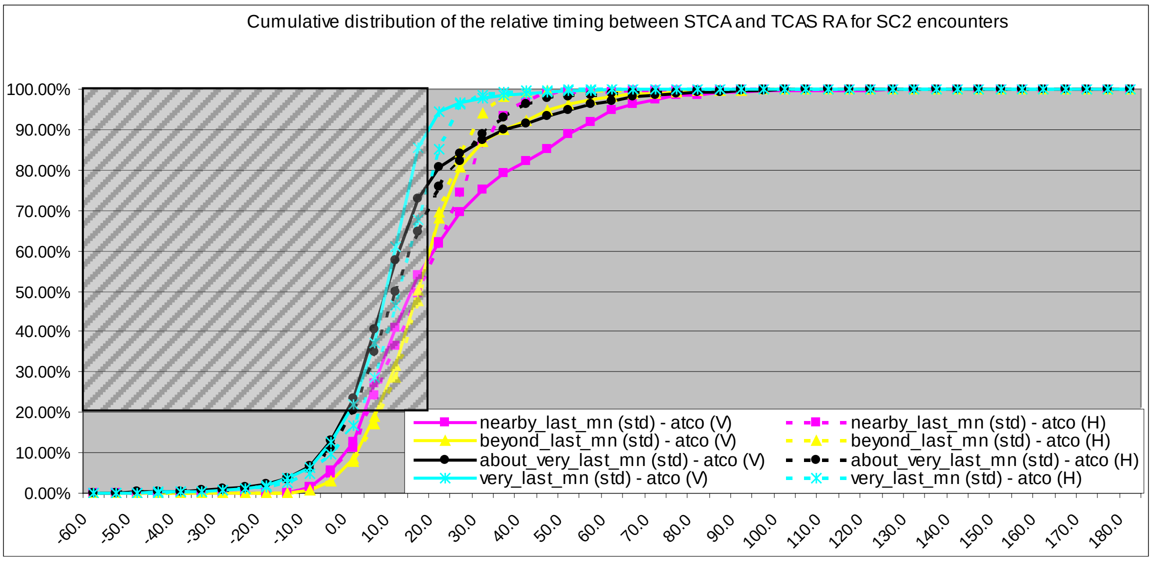
4.7.2.8. As for encounters with a "serious" loss of separation, they lead to both safety nets issue alerts in more cases as STCA is configured with tighter separation and warning time parameter values. This is especially the case with the least conservative STCA family (i.e. "very_last_mn") when horizontal avoiding instructions are issued by the ATCO model, as 84% of en-route SC1 encounters result in alerts from both safety nets. Consequently, when an interaction occurs between an STCA designed for "collision prevention" and ACAS, this interaction is more likely to occur in more severe encounters.

4.7.3. Influence of STCA parameters and configuration on alert timing

4.7.3.1. When both safety nets are involved in an encounter, the relative timing between STCA alerts and ACAS RAs is a key indicator of the risk that responses to STCA and ACAS alerts occur at about the same time. This relative timing for the most severe encounters is provided in Figure 22 as cumulative distributions, where negative times mean that ACAS RAs occurred before the STCA alerts.

Note: The hatched zones denote possible performance requirements on the proportion of genuine alerts with insufficient warning time for effective controller's intervention preventing the occurrence of an ACAS RA (e.g. STCA alert occurring at least 20 seconds before RA in more than 80% of encounters with both types of alerts).





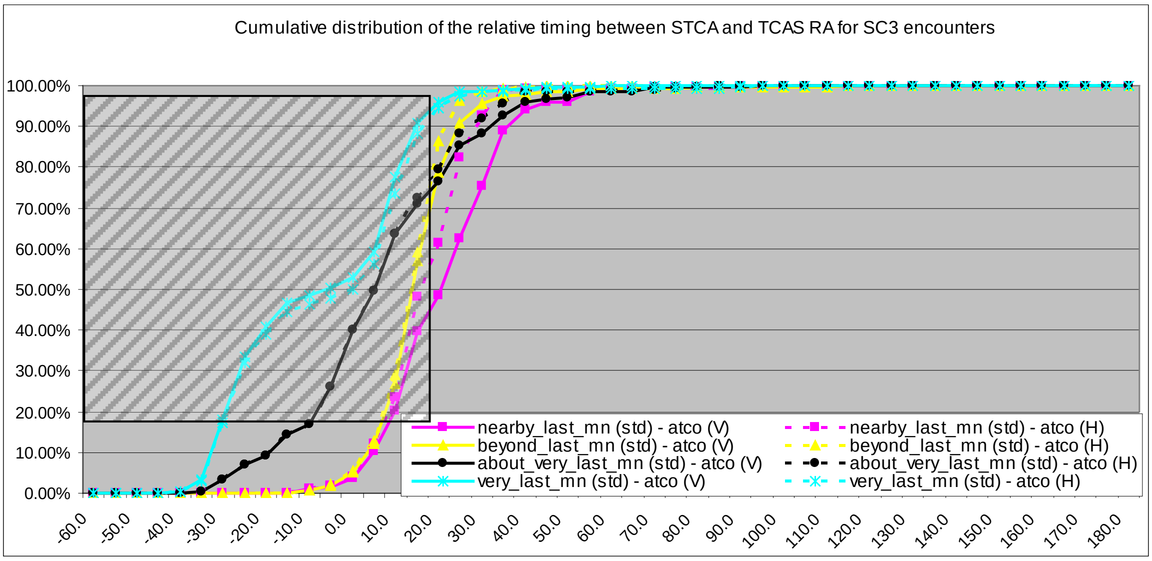


Figure 22: Cumulative distribution of the relative timing between STCA alerts and ACAS RAs – TMA airspace

4.7.3.2. Whatever the STCA family, there is generally little time in "serious" losses of separation (i.e. SC1 severity encounters) after the STCA alert before ACAS issues an RA. ACAS RAs are even issued at the same time as or before STCA alerts in a noticeable proportion of encounters. This means that pilots have to responds to both safety nets at about the same time in these situations.

4.7.3.3. When the severity of losses of separation diminishes, there is a tendency for STCAs designed for both "separation protection" and "collision prevention" to increase the time between both alerts. This increase is however marginal in TMA airspace. STCAs only designed for "collision prevention" perform in a similar manner whatever the encounter severity.

4.7.4. Main results related to the level of STCA and TCAS interaction

4.7.4.1. The simulations performed have demonstrated that STCA families fundamentally designed for "collision prevention" significantly increase the likelihood of interaction with ACAS, compared to those families designed for "separation protection" as well. For the former STCA families, avoiding instructions should be preferably given in the vertical dimension so as to reduce the likelihood of a subsequent ACAS RA (since horizontal instructions are less effective in increasing safety margins, and hence to prevent RA issuance). However, belated vertical avoiding instructions have a greater potential for being contrary to a subsequent RA if and when it happens.

4.7.4.2. In the most severe encounter situations where both safety nets issue an alert, these alerts are generally very close to each other. However, when the severity of losses of separation diminishes, there is a tendency for STCAs designed for both "separation protection" and "collision prevention" to increase the time between both alerts, although this effect is mostly perceived in en-route airspace.

5. Conclusions and recommendations

5.1. Main achievements and findings

5.1.1. Development of the simulation framework

5.1.1.1. Work Area 2 of the PASS project has enabled the development of a set of models that constitutes a realistic framework on which STCA fast-time simulations can be conducted. These models notably include an encounter model generating theoretical, yet realistic, situations in which STCA might be involved. EUROCONTROL reference STCA system ([GM20]) has been implemented in an STCA model that can be configured to suit different approaches towards the operation of STCA. The CNS environment in which STCA is operated is also taken into account, notably with a model of ATC surveillance. Lastly, the responses brought by human actors involved in STCA occurrences have also been implemented in specific controller and pilot models.

5.1.1.2. Using the inputs from WA1 monitoring and the description of the European STCA environment conducted during Phase 1, a number of operational scenarios have been defined, that cover both TMA and en-route airspace. These operational scenarios cover a wide range of operationally realistic STCA implementations as observed in Europe. Several STCA families have notably been identified, which supply a greater or lesser frequency of time-critical alerts depending on the ANSP expectations regarding STCA, i.e. assistance to “collision prevention” only or also to “separation protection”. Specific scenarios were also defined to assess the influence of the CNS characteristics on the performance of STCA, as well as the influence of the human behaviour on the potential safety benefits that can be expected from STCA operation.

5.1.1.3. In parallel with the setting up of this simulation framework, a set of metrics have been defined that allow the performance of STCA in any given scenario to be quantified. These metrics relate to the likelihood of STCA alerts, to their operational relevance, to their potential efficacy and to the level of interaction between STCA and ACAS.

5.1.2. Main results regarding likelihood of STCA alerts

5.1.2.1. The simulations performed show that the strategy followed by an ANSP when implementing and optimising its STCA system has a direct effect on the likelihood of alerts. Although all investigated STCA configurations show comparable alert rates for the most severe encounters, those designed only for “collision prevention” result in a rate of alerts in less severe encounters up to 100 less than those designed for “separation protection” as well as “collision prevention”.

5.1.2.2. A feature common to all investigated STCA configurations is the issuance of unnecessary alerts in encounters with no loss of separation. The frequency of these unnecessary alerts can be reduced by a factor of 3 to 55, depending on the exact STCA implementation, either with use the CFL or the SFL, or with less conservative separation and warning time parameter values.

5.1.2.3. The quality of the surveillance data used by STCA also has an effect on the STCA alert rate, but to a considerably lesser extent than the STCA parameters and main features. Indeed, the different surveillance environments that have been simulated led to a variation of the alert rate by a factor of at most 1.6.

5.1.3. Main results regarding operational relevance of STCA alerts

5.1.3.1. The operational relevance of STCA alerts is dependant on the extent of a loss of separation that an ANSP considers as requiring an alert, and thus on the strategy it follows when implementing and optimising its STCA system. While STCA systems designed for "separation protection" as well as "collision prevention" provide a high rate of alert (i.e. 90% or more) for encounters with a "significant", or worse, loss of separation (i.e. SC1 to SC3), STCAs designed only for "collision prevention" provide comparable rates in encounters one order of magnitude more severe (i.e. SC1 and SC2).

5.1.3.2. This choice is also of importance with regard to the quality of the alerts issued by the STCA system, as higher rates of split and short alerts are generally found for encounters with the first severity considered as not requiring an STCA alert (according to the strategy selected by the ANSP).

5.1.3.3. The behaviour of a given STCA system with regard to both target rates of genuine and nuisance alerts can be more precisely tuned with the addition of optional features (use of CFL/SFL, additional filters, …). However, a balance always has to be struck between genuine and nuisance alert rates, whatever the level of sophistication of the STCA. It is worth noting that increasing the sophistication of an STCA system leads to higher rates of split and short alerts, and thus a lesser quality of alerts, although this can be partly counterbalanced by better surveillance means.

5.1.4. Main results regarding operational efficacy of STCA alerts

5.1.4.1. The efficacy of STCA alerts is mostly linked to the warning time afforded by the STCA to the controller for him/her to assess the situation and take action to ensure that separation will not be infringed or will be restored. STCA systems designed for "separation protection" as well as "collision prevention" supply fewer time-critical alerts than those designed only for "collision prevention". For a given STCA system, the use of optional features (use of SFL/CFL, additional filters …) can provide additional warning time to the controller in a few specific circumstances.

5.1.4.2. As a consequence, STCA systems designed for "collision prevention" only tend to statistically increase the ratios of alerted encounter situations in which the separation cannot be maintained by ATC. Indeed, with all STCA implementations except those designed for "collision prevention" only, the number of separation infringements could be reduced by a factor of at least five.

5.1.4.3. These general trends are of course susceptible to be influenced by the performance of human actors involved in the responses to STCA alerts, with prompter controllers or the use of avoiding phraseology reducing the final number of separation infringements. However, STCA systems designed for "separation protection" as well as "collision prevention" are less sensible to the human performances.

5.1.5. Main results regarding the level of STCA and TCAS interaction

5.1.5.1. The simulations performed have demonstrated that STCA families fundamentally designed for “collision prevention” significantly increase the likelihood of interaction with ACAS, compared to those families designed for “separation protection” as well. For the former STCA families, avoiding instructions should be preferably given in the vertical dimension so as to reduce the likelihood of a subsequent ACAS RA (since horizontal instructions are less effective in increasing safety margins, and hence to prevent RA issuance). However, belated vertical avoiding instructions have a greater potential for being contrary to a subsequent RA if and when it happens.

5.1.5.2. In the most severe encounter situations where both safety nets issue an alert, these alerts are generally very close to each other. However, when the severity of losses of separation diminishes, there is a tendency for STCAs designed for both “separation protection” and “collision prvention” to increase the time between both alerts, although this effect is mostly perceived in en-route airspace.

5.2. Recommendations for future work

5.2.1. Maximum safety benefits should be achieved with maximum “operationally relevant” alerts during the most severe encounter situations (cf. requirement STCA-08 of the EUROCONTROL specification for STCA). To help quantify such performance requirement, it is recommended that:

- Severity of encounters be assessed through the ’separation factor’ (or µ), without the effect of the controller’s instruction prompted by STCA (i.e. initial severity);
- Encounters with a ‘separation factor’ less than 0.5 in the absence of ATCO intervention be considered as severe events for STCA systems designed for “collision prevention’ only;
- Encounters with a ‘separation factor’ less than 0.8 in the absence of ATCO intervention be considered as severe events for STCA systems designed for “collision prevention and ‘separation protection’.

5.2.2. Maximum safety benefits should be achieved with maximum “genuine” alerts with “sufficient” warning time for ATC to preserve separation or minimise the reduction in separation margins (cf. requirements STCA-05 and STCA-12 of the EUROCONTROL specification for STCA). The achieved safety benefits should also be maximised with maximum alerts lasting while the “actual or potential hazardous situation” exists (cf. requirements STCA-13 of the EUROCONTROL specification for STCA). To help quantify such performance requirements, it is recommended that:

- An appropriate threshold be defined to set an acceptable minimum ratio of alerted separation infringements;
- An appropriate threshold be established to set an acceptable maximum proportion of “genuine” alerts with insufficient warning time;
- An appropriate threshold be established to set an acceptable maximum proportion of alerted encounters for which the avoiding instructions prompted by STCA do not enable to preserve separation;
- An appropriate threshold be established to set an acceptable maximum separation infringement ratio expected from the effect of the avoiding instructions prompted by STCA;
- An appropriate threshold be defined to set an acceptable maximum ratio of ”short duration” alert.

5.2.3. Too many nuisance (or false) alerts might be detrimental to the safety benefits expected from the genuine alerts. Consequently their number should be kept to an effective minimum (cf. requirements STCA-10, STCA-11 of the EUROCONTROL specification for STCA). To help quantify such performance requirements, it is recommended that:

- An appropriate threshold be defined to set an acceptable maximum proportion of “nuisance” alerts;
- An appropriate threshold be defined to set an acceptable maximum proportion of “false” alerts.

5.2.4. Finally, maximum safety benefits should be achieved with minimum interaction (or maximum compatibility / interoperability) between the ground-based and airborne safety nets (cf. safety occurrences observed during the WA1 monitoring activity). However, it is conceptually awkward to put a quantified performance requirement on STCA relatively to another system, ACAS, from which it is independent. Nonetheless, simulation results have demonstrated that meeting the above requirements contribute to minimizing the interaction with ACAS.

6. References

6.1. Reference documents

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[Annex11] 'Air Traffic Services', ICAO Annex 11, Thirteenth edition, July 2001

[Doc4444] 'Procedures for Air Navigation Services - Air Traffic Management', ICAO Doc 4444 ATM/501, Fifteenth edition, November 2007

[Doc8168] 'Procedures for Air Navigation Services – Aircraft Operations', ICAO Doc 8168 OPS/611, Fifth edition, November 2007

[ES11] 'EUROCONTROL Specification for Short Term Conflict Alert', Edition 1.1, May 2009

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[D08] 'Monitoring framework description' – PASS/WA1/WP1/08/D, version 1.1, February 2008

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[D64] ‘Monitoring report of SNET performance in Europe’ – PASS/WA1/WP5/64/D, version 1.3, April 2009

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[D75] ‘Encounter model for safety-net related occurrences – Specification‘ – PASS/WA2/WP5/75/D, version 2.3, May 2010

[D88] ‘Surveillance model validation’ – PASS/WA2/WP3/88/D, version 1.0, January 2009

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[D29] ‘Model-based performance evaluation of STCA operations – Interim report (Phase 2)’ – PASS/WA2/WP9/137/D, version 1.1, February 2010

[W36] ‘Surveillance model description’ – PASS/WA2/WP3/36/W, version 2.2, April 2010

[W120] ‘Performance metrics definition’ – PASS/WA2/WP8/120/D, Version 1.2, September 2009

[W123] ‘Operational scenarios for the assessment of STCA performance (slides)’ – PASS/WA2/WP9/123/W, version 1.2, October 2009

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Appendices

Appendix A. EUROCONTROL Guidance Material for STCA

A.1. Optimising STCA

A.1.1. Chapter 5 of the EUROCONTROL Guidance Material for STCA provides guidelines for optimising STCA performance.

A.1.2. This optimisation process consists of the tuning the STCA parameters to meet the STCA requirements laid out in the specifications, i.e. STCA-07, STCA-08, STCA-10, STCA- 12, STCA-13. The goal should be:

"to provide as much warning time as possible, whilst keeping the number of wanted alerts of unwanted alerts to an acceptable level and maximising the number of wanted alerts".

A.1.3. The guidance material distinguishes between five scenario categories "depending on the level to which it is considered relevant to draw the controller's attention to the situation":

- Category 1: "necessary" alert. The situation involved a serious loss of separation or avoided such a loss by a late manoeuvre.
- Category 2: "desirable" alert. Although there was no serious loss of separation, the situation was such that an alert would have been useful in drawing the attention of the controller to a potential conflict.
- Category 3: "unnecessary" alert. An alert was unnecessary for the satisfactory resolution of the situation but would be "predictable" or understandable by the controller
- Category 4: "undesirable" alert. The situation presented little threat of separation loss and an alert would be distracting or unhelpful.
- Category 5: "void" scenario. This situation is not to be used for optimisation. For example. It may be a false situation caused by erroneous track data, or it may occur in a region of airspace not covered by STCA.

A.1.4. As these alert categories are somewhat subjective, it is advocated that "it may be useful to take advice from controllers as to whether an STCA alert is desirable for particular borderline encounter situations".

A.2. Samples of alert categories

A.2.1. Samples of these alert categories are provided in Appendix A of the guidance material relating the Reference STCA system (cf. Figure 23), as well as complementary elements regarding the notion of warning time.

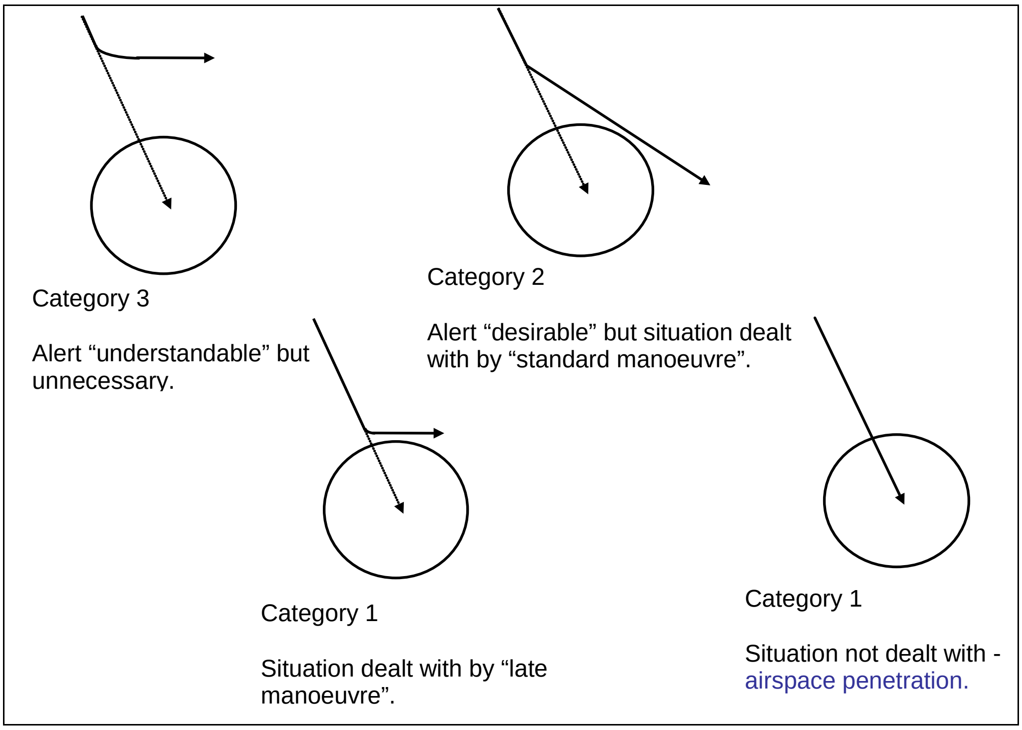

Figure 23: Sample of alert categories in Appendix A of the EUROCONTROL Guidance Material for STCA

A.2.2. Hence, distinction is made between:

- “Adequate” warning time: One which allows sufficient time for controller reaction, communications, pilot reaction and aircraft response.
- “Maximum” warning time: Time between the earliest possible point at which an alert could be given and the Point of Risk (taking into account quality of the surveillance data).
- “Objective” warning time: Optimum time for the alert, i.e. the lesser of the adequate warning time and the maximum warning time
- ”Achieved” warning time: Actual time between the Safety Net alert and the conflict.

A.2.3. Regarding the notion of Point Of Risk (PoR), the guidance material acknowledges that it can be considered as a point on either the actual or predicted aircraft path(s). Further it could be defined as the Closest Point of Approach (CPA) or the breach of some separation minima (such as the ATC standards).

A.3. Requirements for STCA Performance

A.3.1. Finally, the guidance material lists possible quantified performance requirements for STCA (based on expert knowledge and experience in the field):

Performance Indicator	Maximise / Minimise	Required Performance	Preferred Performance
% of Category 1 encounters alerted	Maximise	≥95%	100%
% of Category 2 encounters alerted	Maximise	≥80%	≥90%
% of alerted encounters which are Category 3, 4 & 5	Minimise	≤75%	≤50%
% of Category 3 encounters alerted	Minimise	-	≤30%
% of Category 4 encounters alerted	Minimise	-	≤1%
% of Category 5 encounters alerted	Minimise	-	-
% of Category 1 and 2 encounters where adequate warning time exists which give less than adequate warning time	Minimise	≤45%	≤35%
Mean warning time achieved for Category 1 and 2 encounters where adequate warning time exists	Maximise	≥90% of adequate warning time	≥95% of adequate warning time
Mean achieved warning time for Category 1 and 2 encounters where adequate warning time does not exist	Maximise	≥70% of mean objective warning time	≥75% of mean objective warning time

Table 7: Possible STCA performance indicators in EUROCONTROL Guidance Material

Appendix B. Operational scenarios under investigation

B.1. Set of simulated CNS environments

B.1.1. Four different surveillance environments, respectively for TMA and en-route airspace, were investigated in the study. These surveillance scenarios range from "Basic SSR", in which surveillance data fed to STCA are considered to be supplied by two Mode C radars, to "Full Mode S", where surveillance data comes from three Mode S radars. The two intermediate scenarios correspond to "Typical SSR" (three Mode C radars) and "Mixed Mode S" (three Mode C and Mode S radars) surveillance environments. Table 8 gives the detailed configuration of the surveillance model for each of these scenarios. The default assumption for all simulations apart from the sensitivity analysis on surveillance performances is "Perfect" surveillance.

Scenarios		Number of radars	Radar A		Radar B		Radar C		Output rate	Turn rate threshold
airspace	ATC surveillance		type	rotation	type	rotation	type	rotation		
en-route	Perfect (*)	3	Mode S (no errors)	4s	Mode S (no errors)	4s	Mode S (no errors)	6s	4s	0.6 deg/s
	Basic SSR	2	Mode C	8s	Mode C	8s	-	-	8s	0.6 deg/s
	Typical SSR	3	Mode C	6s	Mode C	8s	Mode C	8s	6s	0.6 deg/s
	Typical SSR or Mode S	3	Mode S	6s	Mode S	8s	Mode C	8s	6s	0.6 deg/s
	Full Mode S	3	Mode S	6s	Mode S	6s	Mode S	8s	5s	0.6 deg/s
TMA	Perfect (*)	2	Mode S (no errors)	4s	Mode S (no errors)	4s	-	-	4s	0.6 deg/s
	Basic SSR	2	Mode C	6s	Mode C	4s	-	-	4s	0.6 deg/s
	Typical SSR	3	Mode C	6s	Mode C	4s	Mode C	4s	4s	0.6 deg/s
	Typical SSR or Mode S	3	Mode S	6s	Mode C	4s	Mode C	4s	4s	0.6 deg/s
	Full Mode S	3	Mode S	4s	Mode S	4s	Mode S	4s	4s	0.6 deg/s

Table 8: Surveillance model parameters

B.1.2. The typical transponder and TCAS equipage assumed for all simulations (apart from the specific sensitivity analysis on communication characteristics) is as follows.

class	engine	maximum take-off mass		Mode S	altitude reporting		TCAS equipped	Enhanced Mode S (with SFL)
		lower	upper		100ft	25ft		
A	piston	–	5,700kg	50%	80%	20%	0%	0%
B	turbo-prop	–	5,700kg	50%	80%	20%	0%	0%
C		5,700kg	15,000kg	100%	5%	95%	100%	95%
E		15,000kg	–	100%	5%	95%	100%	95%
G	jet	high performance (military) aircraft		20%	80%	20%	0%	0%
D		5,700kg	15,000kg	100%	5%	95%	100%	95%
F1		15,000kg	100,000kg	100%	5%	95%	100%	95%
F2		100,000kg	–	100%	5%	95%	100%	95%

Table 9: Aircraft system parameters per performance class

B.2. Set of simulated STCA configurations

B.2.1. For each STCA family identified for the TMA and en-route airspace, three different configurations were typically defined, i.e. 'basic', 'standard' and 'extended' configurations, which include an increasing number of optional features.

B.2.2. Table 10 details the optional features used by the STCA model in the different operational scenarios investigated for the TMA airspace. Twelve STCA configurations for TMA specific operations were defined and evaluated as follows. Cells shaded in green show, for a given STCA family, the additional features introduced in a configuration compared to the less advanced one. For e.g., the 'extended' configuration of the "nearby_last_mn" family introduces the use of the CFL over the 'standard' configuration.

scenarios			Coarse filter	Linear prediction filter			Current proximity filter	Turning prediction filter
airspace	family	version		Linear prediction	Use of CFL/SFL	Use of vertical uncertainty		
TMA	STCA nearby_last_mn	basic	Yes	Yes	No	No	No	No
		standard	Yes	Yes	No	Yes	No	Yes
		extended	Yes	Yes	Yes (CFL)	Yes	No	Yes
	STCA beyond_last_mn	basic	Yes	Yes	No	No	No	No
		standard	Yes	Yes	No	No	No	Yes
		extended	Yes	Yes	Yes (SFL)	No	No	Yes
	STCA about_very_last_mn	basic	Yes	Yes	No	No	No	No
		standard	Yes	Yes	No	No	Yes	Yes
		extended	Yes	Yes	Yes (SFL)	No	Yes	Yes
	STCA very_last_mn	basic	Yes	Yes	No	No	No	No
		standard	Yes	Yes	No	No	Yes	Yes
		advanced	Yes	Yes	Yes (CFL)	No	Yes	Yes

Table 10: STCA model configuration for TMA airspace

	TMA			
	STCA nearby_last_mn	STCA beyond_last_mn	STCA about_very_last_mn	STCA very_last_mn
Update rate	Cf. surveillance output rate (depending on surveillance scenario)			
CoarseFilterPredictionTime	80	60	80	60
CoarseFilterLateralSeparation	3	3	3	3
CoarseFilterVerticalSeparation[vsep]	1000	1000	1000	1000
LinearPredictionTime	80	60	80	60
LinearPredictionLateralSeparation	**3**	**2.9**	**2**	**1.5**
LinearPredictionLateralSeparationDiverging	**2**	**2**	**1.5**	**1**
LinearPredictionVerticalSeparation[vsep]	**740**	**725**	**500**	**500**
UseCFLFlag	0 / 1	0 / 1	0 / 1	0 / 1
LinearPredictionImminentTime	35	35	35	35
LinearPredictionConflictCount	2	2	2	2
LinearPredictionCycleCount	3	3	3	3
LinearPredictionWarningTime	**50**	**40**	**60**	**40**
UseVerticalUncertaintyRatio	0 /10	0	0	0
UseCurrentProximityFlag	0	0	0 / 1	0 / 1
CurrentProximityLateralSeparation	0	0	2.9	2
CurrentProximityVerticalSeparation[vsep]	0	0	750	700
CurrentProximityConflictCount	0	0	2	2
CurrentProximityCycleCount	0	0	2	2
UseTurnIndication	None / Value	None / Value	None / Value	None / Value
TurnRateStandard	0	0	0	0
TurningPredictionTime	60	60	60	60
TurningPredictionLateralSeparation	2.5	1.5	2.5	1.5
TurningPredictionImminentTime	30	30	30	30
TurningPredictionConflictCount	2	2	2	2
TurningPredictionCycleCount	4	4	4	4
TurningPredictionWarningTime	**50**	**40**	**50**	**40**

Table 11: STCA model parameters for TMA airspace

B.2.3. Table 12 details the optional features used by the STCA model in the different operational scenarios investigated for the en-route airspace. Fourteen STCA configurations for en-route operations thus defined and evaluated as follows. Cells shaded in green show, for a given STCA family, the additional features introduced in a configuration compared to the less advanced one. For e.g., the 'extended' configuration of the "before_last_mn" family introduces the use of the CFL over the 'standard' configuration.

Scenarios for STCA configuration			Coarse filter	Linear prediction filter			Current proximity filter	Turning prediction filter
airspace	family	version		Linear prediction	Use of CFL/SFL	Use of vertical uncertainty		
En-route	STCA last_two_mns	basic	Yes	Yes	No	No	No	No
		standard	Yes	Yes	Yes (CFL)	Yes	No	No
	STCA before_last_mn	basic	Yes	Yes	No	No	No	No
		standard	Yes	Yes	No	Yes	Yes	No
		extended	Yes	Yes	Yes (CFL)	Yes	Yes	No
	STCA almost_last_mn	basic	Yes	Yes	No	No	No	No
		standard	Yes	Yes	No	No	Yes	Yes
		extended	Yes	Yes	Yes (CFL)	Yes	Yes	Yes
	STCA beyond_last_mn	basic	Yes	Yes	No	No	No	No
		standard	Yes	Yes	No	No	Yes	Yes
		extended	Yes	Yes	Yes (CFL)	No	Yes	Yes
	STCA very_last_mn	basic	Yes	Yes	No	No	No	No
		standard	Yes	Yes	No	No	Yes	Yes
		extended	Yes	Yes	Yes (SFL)	No	Yes	Yes

Table 12: STCA model configuration for en-route airspace

	En-route				
	STCA last_two_mns	STCA before_last_mn	STCA almost_last_mn	STCA beyond_last_mn	STCA very_last_mn
Update rate	Cf. surveillance output rate (depending on surveillance scenario)				
CoarseFilterPredictionTime	120	120	90	90	90
CoarseFilterLateralSeparation	8	8	8	5	5
CoarseFilterVerticalSeparation[vsep]	1000 / 2000	1000 / 2000	1000 / 2000	1000 / 2000	1000 / 2000
LinearPredictionTime	120	120	90	90	90
LinearPredictionLateralSeparation	**5**	**4.9**	**4.9**	**3.7**	**2.5**
LinearPredictionLateralSeparationDiverging	**3**	**3**	**3**	**2.7**	**1.9**
LinearPredictionVerticalSeparation[vsep]	**800 / 1800**	**800 / 1800**	**750 / 1750**	**700/1700**	**500/ 1500**
UseCFLFlag	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1
LinearPredictionImminentTime	60	60	40	40	40
LinearPredictionConflictCount	2	2	2	2	2
LinearPredictionCycleCount	3	3	3	3	3
LinearPredictionWarningTime	**120**	**90**	**70**	**55**	**55**
UseVerticalUncertaintyRatio	0 / 10	0 / 10	0 / 10	0	0
UseCurrentProximityFlag	0	0 / 1	0 / 1	0 / 1	0 / 1
CurrentProximityLateralSeparation	0	5.1	5.1	4	3
CurrentProximityVerticalSeparation[vsep]	0	800 / 1800	750 / 1750	750 / 1750	700 / 1700
CurrentProximityConflictCount	0	2	2	2	2
CurrentProximityCycleCount	0	2	2	2	2
UseTurnIndication	None	None	None / Std	None / Std	None / Std
TurnRateStandard	0	0	1.2	1.2	1.2
TurningPredictionTime	0	0	80	60	60
TurningPredictionLateralSeparation	0	0	4.9	3.5	3.5
TurningPredictionImminentTime	0	0	30	30	30
TurningPredictionConflictCount	0	0	2	2	2
TurningPredictionCycleCount	0	0	4	4	4
TurningPredictionWarningTime	0	0	60	50	50

Table 13: STCA model parameters for en-route airspace

B.3. Set of simulated human (ATCO and pilot) behaviours

B.3.1. The different simulated human behaviours were as follows. Default assumption for all simulations apart from the sensitivity analysis on human behaviour was "standard" ATCO and pilot response to STCA alert and avoiding instruction respectively.

Scenario for Human Performance	controller's input of CFL	controller's response to STCA			pilot response to AIs
		delay reaction time	type of AI	use of avoiding phraseology	
standard (*)	100%	average (6s)	H or V	sometimes (+)	standard
standard with nominal phraseology	100%	average (6s)	H or V	never	standard
optimal	100%	prompt (4s)	H or V	always	standard
relaxed	100%	slow (10s)	H or V	never	standard
typical	100%	typical	H or V	sometimes (+)	typical

Table 14: Simulated scenarios for ATCO and pilot behaviour

Appendix C. Key elements of the STCA performance evaluation

C.1. Encounter severity

C.1.1. For a given encounter, the 'Closest Point of Propinquity' (CPP) is defined as the point of minimum 'propinquity' between the aircraft in the encounter time window. The term 'elliptic distance' is sometimes used since surfaces of constant 'propinquity' are oblate ellipsoids. To reduce the uncertainty linked to the 'elliptic' nature of the 'propinquity', more accurate separation metric can be defined by increasing the scale factor as follows (with n > 2):

$$Rho_n = \sqrt[n]{(Hsep/Hmin)^{**}n + (Vsep/Vmin)^{**}n}$$

C.1.2. When the scale factor is infinite, this gives the 'separation factor' (Mu), which is the maximum scale factor of the horizontal and vertical distances (Hsep and Vsep) between the aircraft according to the respective separation minima (Hmin and Vmin) applicable by ATC:

$$Mu = LIMIT_{n \to \infty} (Rho_n) = MAX (Hsep/Hmin, Vsep/Vmin)$$

C.1.3. For $Mu < 1$ there is an infringement of separation, for $Mu \geq 1$ the aircraft are separated.

C.1.4. For a given encounter, the 'Point of Minimum Separation' (POMS) is defined as the point of minimum 'separation factor' between the aircraft in the encounter time window.

C.1.5. Distinction is then made between five classes of encounter severity depending on the extent of the separation infringement that exists between the aircraft (as indicated by the 'separation factor' measured at the POMS).

(*) Assuming realistic altitude keeping capabilities, aircraft are considered "level" when flying with a vertical rate of less than 200 fpm.

Severity	Definition
Severity 1 (SC1)	Encounters with "serious" separation infringement, i.e. 'separation factor' lower than 20% (Mu< 0.2) at the 'Point of Minimum Separation'
Severity 2 (SC2)	Encounters with "major" separation infringement, i.e. 'separation factor' lower than 50% but greater than 20% (0.2 ≤ Mu< 0.5) at the 'Point of Minimum Separation'
Severity 3 (SC3)	Encounters with "significant" separation infringement, i.e. 'separation factor' lower than 80% but greater than 50% (0.5 ≤ Mu< 0.8) at the 'Point of Minimum Separation'

Severity	Definition
Severity 4 (SC4)	Encounters with "minor" separation infringement, i.e. 'separation factor' lower than 1 but greater than 80% (0.8 ≤ Mu< 1) at the 'Point of Minimum Separation', unless both aircraft are flying "level" (*) with a 'separation factor' of more than 90% (Mu ≥ 0.9)
Severity 5 (SC5)	Encounters with "safe" encounters with no separation infringement, i.e. 'separation factor' greater than 1 (Mu ≥ 1) at the 'Point of Minimum Separation' or greater than 90% (Mu ≥ 0.9) with both aircraft "level" (*) at the 'Point of Minimum Separation'

Table 15: Definitions of encounter severity classes used in the PASS study

C.2. Operational relevance of STCA alerts

C.2.1. In the prospect of defining quantified performance requirements for STCA, the following definitions of "genuine", "missed", "nuisance" and "false" alerts have been used, together with other definitions relating to the quality of the alerts:

(*) Potentially all separation infringements (SC1 to SC4), or only substantial separation infringements (SC1 to SC3), or only the most severe separation infringements (SC1 to SC2), depending on the safety contribution expected from STCA, i.e. primarily "collision prevention" or also "separation protection"

Notion	Definition
Missed alert	Encounter that does not generate an alert despite the occurrence of a separation infringement (*).
Genuine alert	Alert that occurs during an encounter that would result in a separation infringement (*) in the absence of a prompt and appropriate controller's reaction to the alert.
Nuisance alert	Alert that occurs during an encounter that would not result in a separation infringement (*) even in the absence of a controller's reaction to the alert.
False alert	Alert that occurs during an encounter where errors elsewhere in the ATM system produced an apparent hazardous situation which did not in fact exist.
Early ended alert	Alert that ends while the alert conditions still exist.
Short duration alert	Alert that ends less than 20 seconds after having been generated.
Split alert	Alert that is temporarily switched-off (at least once) during the alert time window

Table 16: Definitions of warning time and late alert used in the PASS study

C.2.2. These performance-oriented definitions are consistent with those defined in the existing EUROCONTROL documentation ([ES11], [GM20], [Guide]), yet simpler and less subjective to allow for their implementation and use in the PASS WA2 study.

C.2.3. The definition of "short-duration" alert is derived from an FAA Human Factor study ([HFFAA]), which suggested that "alerts lasting less than 20 seconds that do not result in operation errors can be considered nuisances because they deactivated before a response by the controller could have taken effect".

C.3. Warning time of STCA alerts

C.3.1. In the prospect of defining quantified performance requirements for STCA, the following performance-oriented definitions related to the notion of "warning time" of alerts have been used:

(*) Relative to the separation minima applicable by ATC (assuming the operational use of STCA is not limited to "collision prevention", but also include "separation protection")

Notion	Definition
Warning time before LOS	The amount of time between the first indication of an alert to the controller and the loss of separation (*) between the aircraft involved.
Initial warning time before LOS	The amount of time between the first indication of an alert to the controller and the loss of separation (*) that would happen in the absence of a controller's reaction to the alert.
Final (or achieved) warning time before LOS	The amount of time between the first indication of an alert to the controller and the loss of separation (*) that would happen despite a prompt and appropriate controller's reaction to the alert and the time at which the alert is first generated.
Sufficient warning time	A warning time that would not result in a separation infringement (*) assuming a prompt and appropriate controller's reaction to the alert.
Late alert	Alert that occurs during an encounter that would likely result in a separation infringement (*) despite a prompt and appropriate controller's reaction to the alert.

Table 17: Definitions of warning time and late alert used in the PASS study

C.3.2. These definitions are consistent with those defined in the existing EUROCONTROL documentation ([ES11], [GM20], [Guide]), yet more limited in scope and less subjective to allow for their implementation and use in the PASS WA2 study.

C.3.3. Since the focus is on the scenarios where ATC is aiming at preserving or restoring separation between the aircraft, the event of 'Loss of Separation' (LOS) is used in place of the hazardous situation referred to in the EUROCONTROL definition of warning time.

C.3.4. To a certain extent the "initial warning time" can be considered as a "predicted" warning time, as it corresponds to the warning time measured without the effect of the controller's reaction to the alert. However, it needs to be clearly distinguished from the warning time "predicted" by STCA. Indeed, the "initial" encounter (used to compute the "initial" warning time) reflects what would have happened in the absence of the alert, including both planned and unplanned aircraft manoeuvres. The STCA prediction filters might have a rather different view of the encounter situation at the time at which the alert is first generated.

C.3.5. It is worthwhile noting that the definition of "late" alerts depends on the assumptions taken with regard to the possible controller's instruction following the alert, and to a lesser extent the probable pilot's response to any controller's instruction.

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