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A Systematic Performance Evaluation of TCAS II and ACAS Xa

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Delft University of Technology

A Systematic Performance Evaluation of TCAS II and ACAS Xa

Volume I – Thesis Body

Summary

The goal of an Airborne Collision Avoidance System (ACAS) is to ensure separation between aircraft after air traffic control services failed to give an effective resolution [1]. An ACAS issues advisories to the pilots if aircraft come within a certain range of each other. Two ACAS are of interest, the Traffic Alert and Collision Avoidance System (TCAS) II and ACAS Xa. TCAS II is the only ACAS currently in use and the advisories that it issues are decided on by its logic, which is built relying on fixed rules [2]. ACAS Xa has been developed as a more flexible and robust successor to TCAS II, able to accommodate the evolution in airspace [3]. The collision avoidance logic in ACAS Xa operates significantly different from the TCAS II logic. ACAS Xa obtains the desired resolutions to issue from offline optimisation-based lookup tables. Surveillance information is used to determine where to look in the lookup table, which includes optimal policies based on a dynamic model of the aircraft in the encounter that provides a statistical representation of the future aircraft position.

Evaluation of an ACAS can only be as reliable as the models used to evaluate it. That is why modelling uncertainties to accurately portray a real life scenario is key to the reliability of the evaluation of TCAS II and ACAS Xa. Preceding evaluations of ACAS, and specifically ACAS Xa, mainly emphasised the effect of varying input parameters and geometries [4] [5] on the risk ratio, the number of alerts given to the pilot and the type of alerts. These are deterministic, hence no intrinsic uncertainties that occur during the encounter are taken into account, while these may have a considerable influence on the outcome of an encounter. For example, sensor errors can influence the Resolution Advisories (RAs) and pilot responses can influence the trajectories of the aircraft which in their turn can influence the RAs that are issued.

CAVEAT (Collision Avoidance Validation and Evaluation Tool) is a novel agent-based simulator developed by NLR together with EUROCONTROL and Everis. This simulator makes it possible to conduct a performance evaluation of TCAS II and ACAS Xa behaviour under various encounter geometries and uncertainties while computing relevant statistics for the user to analyse.

The main objective of this thesis was to develop a systematic performance evaluation of TCAS II and ACAS Xa in which responses to various encounter geometries are evaluated and compared. Additionally, the sensitivity of TCAS II and ACAS Xa to variability in encounter geometries and uncertainty in sensor errors and pilot response was to be investigated. This was to be done using CAVEAT 3.4.0, specifically its stochastic mode. CAVEAT uses two main inputs for a simulation of an encounter: the trajectories of all aircraft in the encounter and the settings of all agents in the Agent-Based Model (ABM).

The trajectories of the aircraft in the encounter were user-defined. Firstly, the parameters defining an encounter between two aircraft were identified. These were used to construct three encounter types, which each contained multiple encounter geometries based on the location of the aircraft in the encounter at the moment they were closest to each other, the Closest Point of Approach (CPA). Per type, one or more parameters that define the encounter geometry were systematically

varied for the two aircraft in the encounter. These included the altitude, relative course angle, the horizontal miss distance, the Vertical Miss Distance (VMD), the airspeed, and the vertical velocity.

The settings of the agents in the CAVEAT ABM are either deterministic or stochastic. Several parameter settings were created which each contained combinations of agent settings. The two main parameter settings were fully deterministic and fully stochastic, each using default values. These parameter settings were constructed such that both aircraft in an encounter were either equipped with TCAS II or ACAS Xa.

The performance evaluation was based on specific indicators. The main indicator was the Near Mid-Air Collision (NMAC) probability. An NMAC is an undesired event that occurs if aircraft are within 500 ft horizontally and 100 ft vertically of each other [3] [2]. The probability of the two aircraft crossing each other's paths, the VMD, the issued RAs and the timing of the RAs were also of interest. In case of stochastic simulations these indicators were given by probabilities and distributions while deterministic simulations resulted in binary and single values of the indicators. Deterministic results were compared to stochastic results to see the influence of the uncertainties on the TCAS II and ACAS Xa behaviour. TCAS II results were compared to ACAS Xa results to identify the differences in their behaviour.

ACAS policy plots were also suitable to use during analysis. These are 2D plots which show a section of the state space around one of the aircraft in an encounter, with timing to CPA in seconds on the x-axis and relative altitude in feet on the y-axis. They give insight in the state space around the aircraft in term of which RAs are issued where. Additionally, by evaluating both TCAS II and ACAS Xa using this same procedure the comparison between the behaviour of the two systems can contribute to the understanding of the black box ACAS Xa logic. To generate them, one deterministic simulation of the encounter in CAVEAT was used per combination of relative altitude and number of seconds before CPA. These encounters start at an increasing number of seconds before CPA to guide TCAS II and ACAS Xa in issuing RAs around these moments in time. The timing at which the RAs are issued cannot be specified by the user beforehand resulting in plots with an irregular grid.

Each stochastic CAVEAT simulation contained 10000 runs to ensure significance in the results. This number was based on a 95% confidence level and the rule of thumb of 100 occurrences of a rare event, such as an NMAC. Deterministic CAVEAT simulations naturally contained only 1 run.

A verification of the stochastic ABM in CAVEAT showed that all stochastic parameter settings resulted in stochastic results. Elements that on itself resulted in NMACs using default settings were identified to be the pilot response mode and the pressure altitude. During the use of CAVEAT several issues were identified and communicated to the developers. Most of them have been solved in newer versions of the ABM tool. Additionally, points of improvement not critical for operation of the tool include incorporating ACAS policy plots into the tool, improving the CPU usage to reduce runtime and allowing for results that are output automatically, instead of having to download the results manually.

To investigate the influence of encounter geometry on TCAS II and ACAS Xa behaviour, the altitude, relative course angle, the horizontal miss distance, the vertical miss distance, the airspeed and the vertical velocity were systematically varied for the two aircraft in the encounter. The two main ABM parameter settings were used: one fully deterministic and one fully stochastic. From the analysis several conclusions could be drawn:

- Uncertainties have a significant effect on the NMAC probability, the RAs that are issued as well as the timing with which they are issued.
- The altitude of CPA significantly influences the NMAC probability for both TCAS II and ACAS Xa.
- The relative course angle significantly influences the TCAS II NMAC probability while it has little to no effect on the ACAS Xa NMAC probability.
- The horizontal miss distance is only of influence to TCAS II and ACAS Xa behaviour when it is 500 ft or larger.
- The VMD in the original trajectories influences both ACASs in the same manner: the lower the VMD in the original trajectory, the larger the NMAC probability in the simulated trajectory.
- Stochastic simulation results in a mean VMD reached at CPA that is lower than the VMD reached in deterministic simulation for both TCAS II and ACAS Xa.
- ACAS Xa generally has lower NMAC probabilities than TCAS II while it reaches higher VMDs in both deterministic and stochastic settings.
- When one of the aircraft has a vertical velocity and performs a level-off manoeuvre before CPA, TCAS II shows higher NMAC probabilities when the vertical velocity is positive while ACAS Xa shows lower NMAC probabilities when the vertical velocity is positive.
- When one of the aircraft has a vertical velocity that remains constant during the complete encounter, TCAS II shows lower NMAC probabilities when the vertical velocity is positive while ACAS Xa shows higher NMAC probabilities when the vertical velocity is positive.

During the sensitivity analysis it was investigated how sensitive TCAS II and ACAS Xa are to uncertainties in sensor errors and pilot response. Since the number of possible ABM parameter settings is so vast, a selection was made to only investigate the effect of the most interesting and influential uncertainties on the TCAS II and ACAS Xa behaviour. These uncertainties were identified to be the pilot response mode, the pilot delay and the pressure altitude based on exploratory runs and information from the CAVEAT manual. Each of these three elements contained more detailed settings, which were worsened one by one (e.g. the pilot response probability was halved or the delay time was doubled) and simulated to see the resulting ACAS behaviour.

Both TCAS II and ACAS Xa turned out to be most sensitive to the same parameters:

- The initial RA response probability in the pilot response mode
- The mean of the action delay in the pilot delay
- The altitude-based standard deviation of the bias in the pressure altitude

Both TCAS II and ACAS Xa showed the highest sensitivities at 7500 and 15000 ft altitude. ACAS Xa indicated nearly linear sensitivity to parameter settings, meaning that doubling one of these three specific parameters results in double the NMAC probability. TCAS II generally showed less sensitivity to changes in these parameter settings than ACAS Xa did. Both TCAS II and ACAS Xa displayed lower sensitivity to parameter setting changes at 36000 ft altitude.

It was also investigated how the TCAS II and ACAS Xa behaviour changed when all settings that together made up each of the three elements of pilot response mode, pilot delay and pressure altitude were worsened simultaneously. For the pilot response mode and the pressure altitude the results were a logical combination of the separate results of each of the worsened settings combined. The pilot delay however gave less clear results. Here the NMAC probability reduced when all worsened settings of an element were combined while the separate worsened settings indicated larger NMAC probabilities. More elaborate analysis is required to find out where this result comes from.

Recommended follow-up research includes looking at the influence of the airspeed and acceleration of the aircraft. Encounters with more than two aircraft are also of interest. Additionally, once sufficient knowledge about TCAS II and ACAS Xa behaviour is obtained, the transition from user-defined encounters to encounters generated by dynamic Bayesian belief network encounter models could be made. This allows for encounter geometries tailored to a specific part of the airspace, based on radar data. This, for example, could be useful for the validation of ACAS Xa in Europe specifically. Another situation worth investigating is one where one aircraft is equipped with TCAS II and the other aircraft is equipped with ACAS Xa. Results of these simulations could demonstrate the co-operation between TCAS II and ACAS Xa, and if this co-operation influences the outcomes of the encounters differently than when the aircraft are equipped with identical ACAS.

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Preface

This report contains a research thesis, which is the last step to complete my masters in Aerospace Engineering at the Delft University of Technology (TU Delft). The research for this report was conducted from February 2021 to December 2021 at the Aerospace Operations Safety Institute of the Royal Netherlands Aerospace Centre (NLR). It builds on a priorly conducted literature study.

Guiding me during this task were prof.dr.ir. H.A.P. Blom from TU Delft and dr. S. Stroeve from NLR. They formulated the main objective of this thesis around the use of CAVEAT, a novel agent-based simulator developed by NLR together with EUROCONTROL and Everis. This novel simulator makes it possible to conduct a systematic performance evaluation of TCAS II and ACAS Xa under various encounter geometries and uncertainties. I would like to thank both Henk and Sybert for their guidance and suggestions and for answering the questions that arose along the way. In person meetings with them were not possible due to COVID-19 which did not make the process any easier. However, I am grateful that through online meetings they still provided me with the necessary support.

Furthermore, a word of appreciation to all my friends that were also conducting their master thesis at the faculty at the same time. Being able to meet in person and discuss certain aspects of the research helped me tremendously in the process. Additionally, I would like to thank my father Raymond for taking the time to proofread the majority of this report and providing me with feedback from an outsiders perspective. Lastly, I would like to thank Jan for listening to my many monologues about this report and for pointing me in the right direction.

I hope you enjoy reading this report.

Manouschka van Beek
Delft, 2021

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Glossary of Symbols

$\chi_{i,j}^{course}$	Relative course angle between aircraft i and aircraft j
χ_{i}^{course}	Course angle of aircraft i with respect to North
η	Angle of airspeed with respect to the horizontal at start of level-off manoeuvre
φ	latitude
$\varphi(z)$	Probability density function of standard normal distribution
λ	longitude
λ_{AFCS}^{pc}	Position feedback control parameter of AFCS of CAVEAT
μ	Expected value of random variable
ρ	Model-based accident risk
σ^2	Variance
τ	Time constant level-off manoeuvre
a_c	Acceleration
$d_{i,j}$	Absolute distance between aircraft i and aircraft j
$d_{i,j}^{h}$	Horizontal distance between aircraft i and aircraft j
$d_{i,j}^{v}$	Vertical distance between aircraft i and aircraft j
$d_{i,j}^{CPA}$	Distance between aircraft i and aircraft j at CPA
$d_{i,j}^{HMD}$	Horizontal miss distance between aircraft i and aircraft j at CPA
$d_{i,j}^{HMD,lat}$	Lateral horizontal miss distance between aircraft i and aircraft j at CPA
$d_{i,j}^{HMD,lon}$	Longitudinal horizontal miss distance between aircraft i and aircraft j at CPA
$d_{i,j}^{VMD}$	Vertical miss distance between aircraft i and aircraft j at CPA
F_N	Normal force
g	Gravitational acceleration
$h_{i,j}^{CPA}$	Altitude of CPA
$h_{level-off}$	Height of level-off manoeuvre
$\dot{h}$	Rate of climb/descent during level-off manoeuvre
$l_{level-off}$	Length of level-off manoeuvre
L	Lift
m	Mass
n_{MC}	Number of MC simulations
n_{run}	Number of runs per MC simulation
r	Radius of circle in flare manoeuvre approximation
s_i	Log-sensitivity or elasticity of model-based accident risk for i-th parameter variation
$\mathbf{s}_i$	Position vector of aircraft i

$\boldsymbol{s}_{t,AFCS,i}$	Situational awareness by the AFCS in CAVEAT of position information of the aircraft in the ENU frame
$\boldsymbol{s}_{t,AFCS,i}^{FP}$	Situational awareness by the AFCS in CAVEAT of position information of trajectory in the flight plan
$\left(s_{0,i}^{x}, s_{0,i}^{y}, s_{0,i}^{z}\right)$	Initial position coordinates of aircraft i
$\left(s_{i}^{x}, s_{i}^{y}, s_{i}^{z}\right)$	Position coordinates of aircraft i at time t
$\left(s_{i}^{x,CPA}, s_{i}^{y,CPA}, s_{i}^{z,CPA}\right)$	Position coordinates of aircraft i at CPA
t	Time
t_{end}	Time at end of encounter
t_{flare}	Duration of level-off manoeuvre
$t_{postCPA}$	Duration of encounter after CPA has occurred
t_{preCPA}	Duration of encounter before CPA occurs
t_{start}	Time at start of encounter
$t_{i,j}^{CPA}$	Time at which CPA occurs
v	Number of ABM parameters
$\overline{v}_{i}$	Airspeed of aircraft i
$\overline{\boldsymbol{v}}_{t,AFCS,i}^{a}$	Airspeed of aircraft i as calculated by AFCS of CAVEAT
$\boldsymbol{v}_{t,AFCS,i}^{FP,g}$	Ground speed of aircraft i in the flight plan
$\overline{v}_{i}^{right}$	New/right parameter value
$\overline{v}_{i}^{left}$	Baseline/left parameter value
v_{i}^{z}	Vertical velocity of aircraft i
$\boldsymbol{w}_{t,AFCS,i}$	Vertical wind velocity
W	Weight

Glossary of Terms

ABM	Agent-Based Model
AC	Aircraft
ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance-Broadcast
AFCS	Automatic flight control system
APFD	Autopilot/Flight Director
CAS	Collision avoidance system
CAVEAT	Collision Avoidance Validation and Evaluation Tool
CCL	Crossing Climb
CDE	Crossing Descent
CDF	Cumulative density function
CL	Climb
CNS	Communication, navigation, surveillance
COC	Clear of Conflict
CPA	Closest point of approach
CPU	Central Processing Unit
DCL	Do Not Climb
DDE	Do Not Descend
DE	Descend
ECEF	Earth-centered, Earth-fixed
ENU	East, North, Up
FAA	Federal Aviation Administration
FL	Flight Level
FMS	Flight Management System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GUI	Graphical User Interface
HMD	Horizontal miss distance
HMI	Human-Machine Interface
ICAO	International Civil Aviation Organization
LC05	Limit climb rate to a maximum of 500 fpm
LC10	Limit climb rate to a maximum of 1000 fpm
LC20	Limit climb rate to a maximum of 2000 fpm
LD05	Limit descent rate to a maximum of 500 fpm
LD10	Limit descent rate to a maximum of 1000 fpm
LD20	Limit descent rate to a maximum of 2000 fpm
LO	Level Off
MC	Monte Carlo
MCCL	Maintain Crossing Climb
MCL	Main Climb

MOPS	Minimum Operational Performance Standard
NACp	Navigational Accuracy Category for Position
NACv	Navigational Accuracy Category for Velocity
NIC	Navigation Integrity Category
NMAC	Near Mid-Air Collision
OAT	One-at-a-Time
PA	Parallel Approach
PDF	Probability density function
PF	Pilot Flying
PT	Proximate Traffic
RA	Resolution Advisory
RCL	Reversal to Climb
RDE	Reversal to Descend
RR	Rate Reversal
SA	Situational Awareness
SI	International System of Units
SIL	Surveillance Integrity Level
SL	Sensitivity Level
SSR	Secondary Surveillance Radar
STF	Statistics Transfer File
TA	Traffic Alert
TCAS	Traffic Alert and Collision Avoidance System
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
VMD	Vertical Miss Distance
WGS	World Geodetic System
ZTHR	Vertical distance threshold

1 Introduction

The goal of an Airborne Collision Avoidance System (ACAS) is to ensure separation after air traffic control services failed to give an effective resolution [1]. An ACAS issues advisories to the pilots if aircraft come within a certain range of each other. Two ACAS are of interest, the Traffic Alert and Collision Avoidance System (TCAS) II and ACAS Xa. TCAS II is the only ACAS currently in use and the advisories that it issues are decided on by its logic, which is built relying on fixed rules [2]. ACAS Xa has been developed as a more flexible and robust successor to TCAS II, able to accommodate the evolution in airspace [3]. The collision avoidance logic in ACAS Xa operates significantly different from the TCAS II logic. ACAS Xa obtains the desired resolutions to issue from offline optimisation-based lookup tables. Surveillance information is used to determine where to look in the lookup table, which includes optimal policies based on a dynamic model of the aircraft in the encounter that provides a statistical representation of the future aircraft position.

To establish the desired level of safety and effectiveness of ACAS, intensive performance evaluation and validation is required as instructed by multiple authorities such as EUROCAE [3]. Evaluation of an ACAS can only be as reliable as the models used to evaluate it. That is why modelling uncertainties to accurately portray a real life scenario is key to the reliability of the evaluation of TCAS II and ACAS Xa. A distinction can be made between intrinsic uncertainties, which include sensor errors and pilot response, and uncertainty with respect to the geometry of an encounter. The first two types can be seen as error inputs to the situation, while the uncertainty in the encounter geometries is a result of these intrinsic uncertainties.

Preceding evaluations of ACAS, and specifically ACAS Xa, mainly emphasised the effect of varying input parameters and geometries [4] [5] on the risk ratio, the number of alerts given to the pilot and the type of alerts. These are deterministic, hence no intrinsic uncertainties that occur during the encounter are taken into account, while these may have a considerable influence on the outcome of an encounter. For example, sensor errors can influence the Resolution Advisories (RAs) and pilot responses can influence the trajectories of the aircraft which in their turn can influence the RAs that are issued.

1.1 Research Objective

The research objective is to conduct an evaluation of TCAS II and ACAS Xa that includes the effect of various uncertainties. To accomplish this, use is made of CAVEAT (Collision Avoidance Validation and Evaluation Tool). CAVEAT is an agent-based simulator developed in collaboration by EUROCONTROL, NLR and Everis. This simulator is able to include uncertainties, such as sensor errors and pilot responses, while modelling the behaviour of TCAS II and ACAS Xa. CAVEAT can be used in the traditional deterministic mode as well as in the stochastic mode. In the latter mode, CAVEAT can conduct Monte Carlo (MC) simulations with a user selected number of random runs. In addition, an MC simulation can be repeated under different model parameter settings, which allows to conduct parameter sensitivity analysis.

In summary, the aim of this research is the following:

To develop a systematic performance evaluation of TCAS II and ACAS Xa in which responses to various encounter geometries are evaluated and compared by using CAVEAT, specifically its stochastic mode.

The additional aim is:

To investigate and compare the sensitivity of TCAS II and ACAS Xa to variability in encounter geometries and uncertainty in sensor errors and pilot response using CAVEAT, specifically its stochastic mode.

To reach these two goals, encounters are simulated in CAVEAT and its output metrics indicate the performance of TCAS II and ACAS Xa. Additionally, ACAS policy plots are developed to gain insight in the TCAS II and ACAS Xa behaviour.

The result of this thesis contributes to the understanding of the influence that uncertainties such as sensor error and pilot response behaviour can have on TCAS II and ACAS Xa and will allow for more accurate validation of ACAS Xa in Europe.

1.2 Outline of the Report

This report consists of two volumes. Volume I – Thesis Body and Volume II – Appendices.
This volume includes of the main body of the report that contains the research.

Firstly the background of TCAS II and ACAS Xa is discussed in Chapter 2 together with the methodology of the research. Chapter 3 explains how encounter geometries are defined and how they can be ordered into different types. Chapter 4 contains six sets of parameter settings, each with a different goal. Each set contains several parameter settings used during simulation. ACAS performance indicators are identified in Chapter 5. In Chapter 6 TCAS II and ACAS Xa policy plots are generated. Chapters 7 to 9 present simulation based performance results for TCAS II and ACAS Xa. The sensitivity of TCAS II and ACAS Xa behaviours against input changes is summarised in Chapter 10. Finally the report is concluded in Chapter 11, where follow-up research and possible CAVEAT improvements are presented as well.

In Volume II the appendices are included. Appendix A gives a description of the structure of encounter files used as input by CAVEAT. Appendix B includes all CAVEAT simulation parameters, organised in tables and presented in the order that they are defined in CAVEAT. 0 gives the agent-based model parameter settings. In Appendix D it is explained how the number of MC simulations is determined and which considerations are taken into account in deciding on this number. Appendix E gives an overview of improvements of CAVEAT that have been realised thanks to this MSc thesis research, as well as potential future improvements. Appendix E also explains how these improvement needs have been identified. In Appendix F it is explained how the verification of the self-developed code was performed.

2 ACAS Background

Before the set-up of the research can be understood, some background on the systems that are used for this research is required. In Section 2.1, TCAS II version 7.1 and ACAS Xa are explained in detail. The explanation on the Agent-Based Model (ABM) used for this thesis is included in Section 2.2. Section 2.3 provides information about the tool in which this ABM is implemented, called CAVEAT. Finally the methodology which is followed during the research is presented in Section 2.4.

2.1 Airborne Collision Avoidance Systems

The desire for a collision avoidance system on board of aircraft originated from a mid-air collision between two commercial aircraft above the Grand Canyon in 1956 [6]. This crash caused the establishment of the Federal Aviation Administration (FAA) in the United states, which improved the design and organisation of the airspace and air traffic control by a great deal. One of their improvements was the development of an Airborne Collision Avoidance System (ACAS). The goal of an ACAS was and still is to ensure the separation after air traffic control services failed to give an effective resolution [1].

TCAS II

The Traffic Alert and Collision Avoidance System (TCAS) II version 7.1 is the only ACAS currently in use. It is the successor of a system developed in the mid-1970s. This early system worked via radio beacons and simple transponders were used to indicate if aircraft were in each other's vicinity [1]. TCAS II has been developed from 1987 onwards and can give out Traffic Advisories (TAs) to help the pilot in visual search for the intruder aircraft as well as Resolution Advisories (RAs) which recommend certain manoeuvres for the pilot to follow [7]. These have the goal to prevent or avert a Near Mid-Air Collision (NMAC). EUROCAE, the European Organisation for Civil Aviation Equipment, defines an NMAC as a situation where two aircraft come within 500 feet horizontally and 100 feet vertically of each other [2] [3]. To observe the position, velocity and direction of the other aircraft TCAS II corresponds through mode C and mode S transponders on board of both aircraft. By obtaining multiple replies from the other aircraft, the time to Closest Point of Approach (CPA) can be obtained [8].

TCAS II works with a certain logic, which determines if an NMAC is going to happen based on the received transponder data. This depends on the sensitivity level that is selected, which is a measure of the volume around the aircraft that is protected by TCAS II and ACAS Xa [8]. This volume is directly linked to the altitude of the own aircraft. The higher the aircraft is flying, the higher the sensitivity level, the larger the distance threshold for an RA and thus the larger the protected volume around the aircraft. The time to CPA is a trigger for generating the advisories. The type of RA that is selected by TCAS II is based on its logic, which is built relying on fixed rules that are updated in some previous versions of the system. These are often specified in pseudo-code. This is a disadvantage of the system, making it a tedious task to write updates or validate additional rules [9].

ACAS Xa

Since 2008, the novel ACAS Xa is in development as part of ACAS X development. The aim of ACAS X development is to realize a more flexible and robust successor to TCAS II and is able to accommodate the evolution in airspace. To ease the transition from TCAS II to the novel system, ACAS X mostly uses the same sensors, same types of RAs that can be given as well as the same coordination between aircraft. The two main differences with TCAS II lie in the source of the surveillance information and the collision avoidance logic [10].

ACAS X can use inputs of several surveillance systems. It uses the mode C and mode S transponder, but can also use the more precise Automatic Dependent Surveillance-Broadcast (ADS-B) system, which uses GPS among other things. This on-board system sends its position and ground speed to other ADS-B equipped aircraft and ground stations every second. This results in a higher surveillance accuracy than the mode C and mode S transponders [11].

The output of the surveillance function forms the input for the Collision Avoidance System (CAS) logic. The CAS logic in ACAS X operates significantly different from the TCAS II logic. Both systems are deterministic, but where TCAS II has these rules separately implemented in pseudo-code, ACAS X obtains the desired resolution from offline generated lookup tables. The surveillance information is used to determine where to look in the lookup table, which includes the optimal policy to follow including issuing any advisories and if so, when they are issued and which one(s) is or are issued. Using such a lookup table makes it easier to implement updates, since the only part that needs to be updated are the values in the lookup table, which can be done offline. There is no need to alter the complete structure of the code of the system as there is with TCAS II.

The development and optimisation of the lookup tables is a complicated process, where a dynamic model of the aircraft in the encounter provides a statistical representation of the future aircraft position. Additionally, safety and operational considerations are taken into account. All this information is then implemented in an optimisation process. Here, a reward function determines which set of actions, called a policy, is optimal for the aircraft to follow, given the context of the encounter. The optimal policy for each specific situation is then stored in the lookup table, which is then consulted by ACAS X on board the aircraft.

The reward function of ACAS X can be optimised by altering the rewards, tied to the different advisories and closure rates. This is done during runs of simulation, where ACAS X is validated per separate run [4]. The validation of one run inputs the design and optimisation of the next run. Optimisation is done in three categories: safety, operational suitability and acceptability. Each of the categories have their own indicators that are typically used. The most widely used indicator is the risk ratio, which regards the safety of TCAS II and ACAS Xa. It is defined as the NMAC rate with ACAS divided by the NMAC rate without ACAS [10] [4].

ACAS X is a collective name for several versions of the system, each suitable for different types of aerial vehicles.

- ACAS Xa: the baseline system, meant for general use in commercial aviation. Approval for this version is currently pending.

- ACAS Xo: an extension of ACAS Xa which is meant for particular operations, like parallel approaches, where ACAS Xa might generate a large number of nuisance alerts. Approval for this version is currently pending.
- ACAS Xu: designed for use in unmanned aerial vehicle (UAV) and includes manoeuvres for horizontal resolutions. The MOPS were published in 2020, but this version is not ready for operation.
- ACAS Xp: future version of ACAS Xa that uses only ADS-B information for tracking aircraft and thus not actively interrogates. This version will be designed to be used by general aviation aircraft.

For this report ACAS Xa is of most interest, specifically ACAS Xa 15.4 CP 1, one of the versions of the system.

2.2 Agent-Based Model

An Agent-Based Model (ABM) of TCAS II and ACAS Xa operations that takes into account intrinsic uncertainties such as sensor errors and variability in pilot response, as well as variability in encounter geometry has been developed in collaboration of EUROCONTROL, NLR and Everis [12], [13]. This section provides a short overview of this ABM.

The agent entities of this ABM are shown in Figure 1. The right hand box in Figure 1 shows all agent entities that may play a role in an encounter scenario. These includes piloted aircraft i, for $i = 1, \ldots, N$. For the i-th piloted aircraft there are the following agents, which are within the left hand box in Figure 1:

- Flight Performance;
- Flight Management System (FMS);
- Ownship state estimation;
- Othership measurement and data communication;
- Pilot Flying;
- ACAS (TCAS II or ACAS Xa).

Each of these aircraft agents consists of one or more sub-systems, such as:

- Agent Flight performance captures the development of the position, speed and orientation of the aircraft. This can either be based on the control input by the automatic flight control system (AFCS) or by the pilot flying and might be influenced by the aircraft type.
- Agent FMS includes the original flight plan, the AFCS and the instrument system, which provides information about the state and the vertical speeds advised by ACAS to the pilot. For the scope of this research, the response to an advisory always goes via the pilot flying, not through the AFCS.
- Agent Ownship state estimation contains a set of four agents that together represent the estimation of the state of the own aircraft. These estimated states are then used as input for TCAS II and ACAS Xa and are also communicated to the other aircraft in the environment.

- Agent Othership measurement and interaction contains a set of four agents which represent the othership measurements and the coordination between the aircraft, which is transponder-based.
- Agent Pilot flying contains definitions of situational awareness (SA) and its actions, which includes agents that represent the response mode, delay, vertical rate and acceleration.
- Agent ACAS can be TCAS II or ACAS Xa. Within the scope of this research TCAS II version 7.1 and ACAS Xa 15.4 CP1 are used.

These aircraft related agents are subjected to agents in the environment, such as other aircraft, weather conditions and terrain and can interact with Global Navigation Satellite Systems (GNSSs), ground Communication, Navigation, Surveillance (CNS) systems and Unmanned Aircraft Control Systems (UACSs).

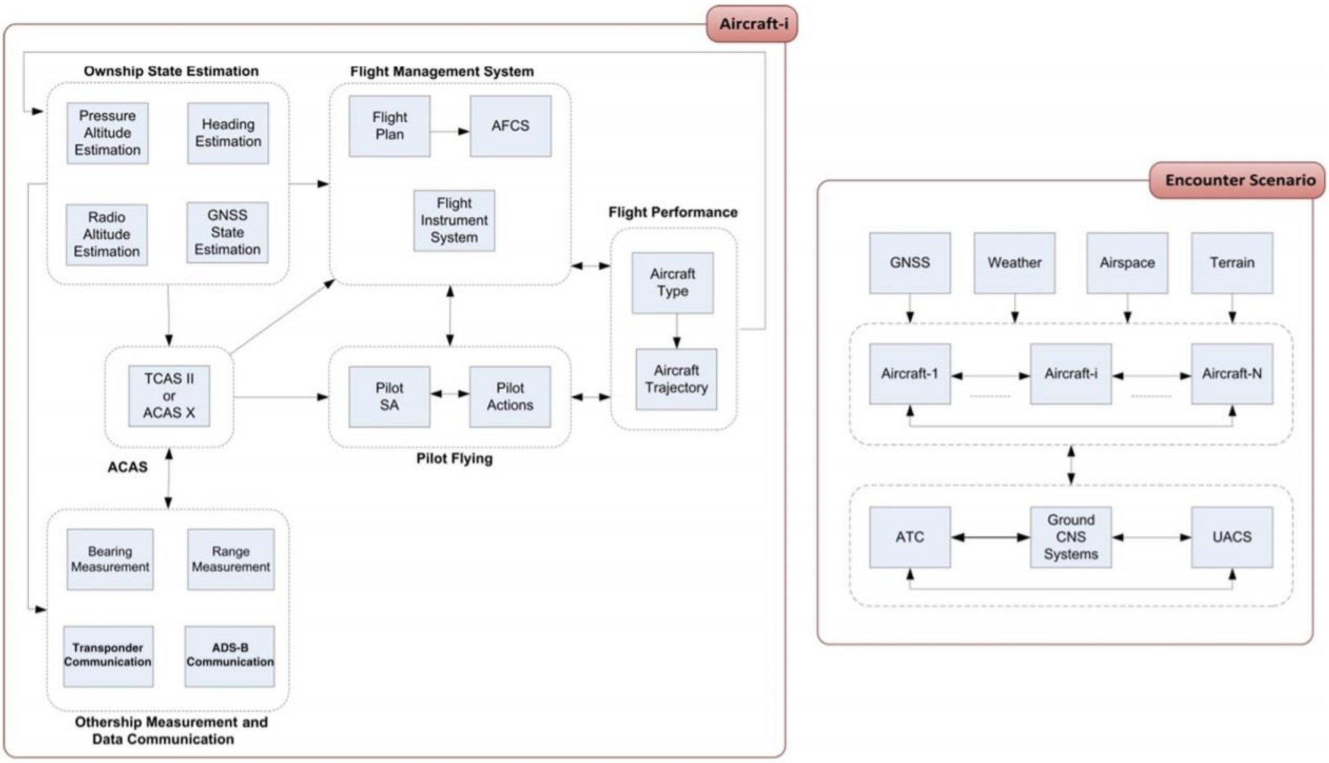


Figure 1. Agent-based model of encounter scenario with N aircraft (right), where each aircraft contains the elements shown to the left (SA = situational awareness) [3]

2.3 CAVEAT

The ABM presented in the previous section is implemented in the Collision Avoidance Validation and Evaluation Tool (CAVEAT), an agent-based tool. This section focuses on operating the tool. Figure 2 contains a high-level composition of CAVEAT which consists of four modules.

- M1, Encounter Determination. In this module the encounter trajectories that are to be simulated are generated. They can either be based on reconstructed encounters or synthetic encounters.
- M2, Simulation. In this module the performance of the complete system including the pilot is simulated. Per scenario, all the agents in the ABM of Figure 1 are specified. Monte Carlo (MC) simulation is used to evaluate the intrinsic uncertainty in the ABM.
- M3, Evaluation. This module determines the results of the simulation in terms of indicators.
- M4, Visualisation. The visualisation module can either visualise a single simulation run or it can list the statistics of a set of simulations runs.

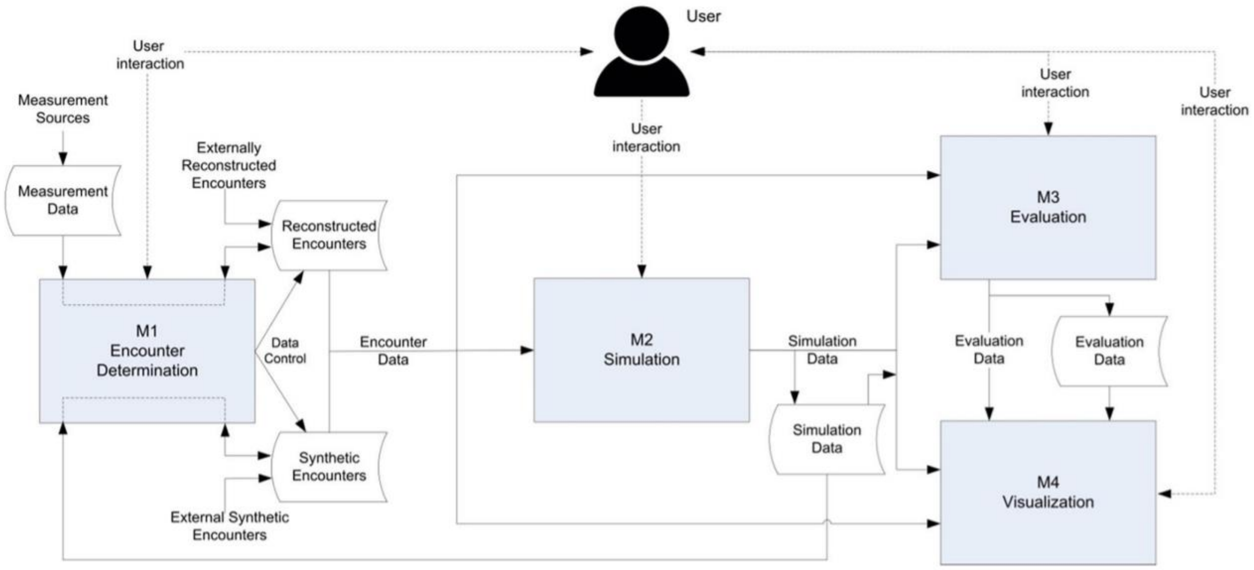


Figure 2. High level CAVEAT composition [3]

Input

CAVEAT requires two main inputs for a simulation: an encounter file and a scenario file. The encounter file contains the trajectories of all the aircraft in the encounter. For this research the trajectories are synthetically generated and stored in the CAVEAT-compatible .ftd format. Appendix A contains a detailed description of the contents of the encounter file. Since CAVEAT cannot generate the encounter .ftd files itself, a separate program is written, which is explained in Section 3.7. The second input file, the scenario file, specifies the environment in which the encounter takes place as well as the parameter settings of the aircraft, the models that are used in each aircraft and their equipment. This is why a scenario will from now on be called a parameter setting.

As was indicated in the previous section, a parameter setting file can be run in deterministic mode, where all parameters are simulated deterministically, or stochastic mode, where one or more parameters are simulated stochastically. The parameter setting file thus contains the settings of all agents introduced in the previous section and specifies the uncertainty in sensor error and pilot response variability. In the parameter setting file it is also indicated which types and versions of

ACAS are used by the aircraft in the simulation. This means the simulated aircraft can be equipped with TCAS II version 7.1, ACAS Xa 15.4 CP1, a combination of TCAS II and ACAS Xa or unequipped.

Simulation

Combinations of these encounter files and parameter setting files, so called encounter-scenarios in CAVEAT, can be simulated as often as the user would like by specifying the number of MC runs per simulation. CAVEAT can also run simulations by combining (multiple) folders, where at least one folder contains the encounter files and at least one folder contains the parameter setting files. Then, all encounters in the folder(s) are automatically combined with all the parameter settings in the folder(s).

Output

The output to a simulation is extensive, there are several data files and visualisations available from which information can be gathered about the simulation.

- The main file that is output by CAVEAT is the .sim file, which can be loaded in CAVEAT and used to visualise and further analyse the results via the user interface. The visualisation function can display vertical views, horizontal views and a timeline of events of the original and modified trajectories. It can also show vertical and horizontal velocities and additionally there is the option to see the cockpit view during the encounter. More interesting, however, is the statistics module, which shows statistics about the timing of events, about the CPA events and several advanced metrics. Each of these three pages contains the opportunity to download raw data and precalculated statistic files in .csv format by hand. The timing of events .csv contains precalculated statistics about all advisories that each aircraft received, which include the number of realisations, the probability with which the advisories occurred and information about the mean, standard deviation and spread of their timings. The CPA .csv contains raw data about the original and modified Vertical Miss Distance (VMD), Horizontal Miss Distance (HMD) and slant range per simulated run. The advanced metrics .csv contains precalculated statistics about the occurrence of specific RAs, the probability of NMACs and the probability of crossing encounters.
- Per simulation, CAVEAT automatically outputs a summary .csv. It combines information of advisories and CPA events from different encounter parameter settings. It also records the position and velocities of the aircraft at the time of occurrence of these events.
- The Statistic Transfer File (STF) stores all simulation results. Per simulation of an encounter parameter setting, one STF is generated. It contains blocks of bytes that represent information about crossing encounters, advisories that were given by TCAS II and ACAS Xa and CPA data.
- The last output file is the output .csv file, which is automatically generated per simulation. It contains the modified trajectories of the aircraft and their advisories and CPAs. Only a maximum of 100 realisations are saved in this file.

During this thesis several versions of CAVEAT were used, as new versions were often released. The final results all come from simulations with CAVEAT 3.4.0, the latest CAVEAT version at the moment this report was written.

2.4 Methodology

To achieve a systematic approach to the performance evaluation, the process that will be followed must be clear. This section provides the methodology that will be followed, based on the objective and the ABM that is implemented in CAVEAT.

To understand in what way the ABM will be used for this specific research, Figure 2, the high level composition of the use of CAVEAT is used again. The required steps for each module are included below.

- M1, Encounter Determination. For this research, the encounters that are used are all generated synthetically. These encounters can be generated by using an additional ABM which includes the estimations of the own state. This thesis, however, purposely does not include this agent-based approach since the encounter geometry is to be systematically varied. Firstly, all parameters necessary to define an encounter trajectory are listed and defined. Several encounter types are defined, which all contain multiple encounters that are similar to each other. Then, a Matlab program is written, which is able to generate a set of encounter files in the CAVEAT input format. This complete process is documented in Chapter 3.
- M2, Simulation. To add structure to the simulations and evaluation, the input of this module, the parameter settings, are defined in sets. Each parameter setting serves a specific research purpose, for example varying the sensor errors or varying the pilot response modes. The different parameter settings including the specifications of each agent in the model are included in Chapter 4. Then, certain encounter types are combined with certain parameter settings for simulation. In CAVEAT this can either be a combination of a single file with another single file, or a folder with another folder. For the latter, all possible combinations of file combinations in the folder will then be run. The simulation is either deterministic, in case of deterministic parameter settings, or it is stochastic, in case of stochastic parameter settings. A deterministic simulation is run just once, for a stochastic simulation multiple MC runs will be used and the intrinsic uncertainties introduced by the agents can be evaluated by comparing the different parameter settings. The number of required MC runs needs to be carefully considered to ensure that the uncertainty in the results is small enough to be able to draw conclusions. This process is included in Appendix D.
- M3, Evaluation. To compute the results, a set of indicators is formed. These are based on the extensive list of used indicators presented in [13] and on the availability of output data from CAVEAT. Some of the indicators are built into CAVEAT and are output in statistic files. These statistics are gathered by downloading statistics .csv files from the simulation in the CAVEAT interface. Additional indicators are obtained by manipulating the data in the statistics .csv files or by using the output files which contain the raw data of the modified trajectories of the aircraft in the encounter. The set of indicators is included in Chapter 5. Furthermore, it is investigated if .stf files, which are automatically output by CAVEAT, can provide more detailed numbers of the simulation runs. Ideally, these will be used to automate the process of obtaining data files from CAVEAT to compute results.

- M4, Visualisation. It is explored which types of graphs or figures are useful and effective for display of what indicator. Additionally, Matlab code is written to obtain the desired visualisation format of the values of the indicators.

Not all encounter types and parameter settings are going to be combined during the simulations, since they do not all result in useful and realistic situations. An iterative process, where smaller numbers of combinations of encounters and parameter settings will be simulated at a time, will provide results on which new selections are made. At the start of this iterative process are several exploratory simulations, which each contain a small number of runs. The results of these exploratory simulations are not definitive and cannot be used to draw conclusions, which is why they are also not reported. They do, however, give indication on how the different agents in the model behave. Once a basic understanding of the behaviour of the agents is formed, the first actual simulation is started. Based on the results of this simulation and the understanding of the agent behaviour, new combinations of encounters and parameter settings are simulated. In Chapter 3 and 4 the encounter geometries and parameter settings of interest for the performance evaluation are introduced.

3 Two Aircraft Encounter Trajectory Generation

This chapter presents how encounters between aircraft can be described in terms of parameters. Section 3.1 explains what type of encounter modelling is used for this research. To give structure to the analysis, the possible encounters are ordered into three types which are presented in Section 3.2. Sections 3.3 and 3.4 explain how a single trajectory of an aircraft can be defined and related to trajectories from other aircraft. The trajectory of a level-off manoeuvre is defined in Section 3.5. The propagation of the trajectories is included in Section 3.6. Section 3.7 contains the description of a Matlab program that is written to generate trajectories and to save them in the CAVEAT-specific .ftd format. Lastly, in Section 3.8 the encounter types presented in Section 3.2 are fully defined by using the definitions from the previous sections.

3.1 Encounter Data

When ACAS evaluations have to be conducted using actual aircraft in the air, they could take numerous years because of the select nature of close encounters during normal operation. Therefore, computer generated aircraft trajectories are often used because they allow developers of particular ACAS to test their system in a relatively short amount of time. As is visualized in Figure 2, the M1 block distinguishes two types of generated encounter data: Reconstructed encounters; and Synthetic encounters.

Reconstructed encounters are based on radar data from actual flights. This functionality is mainly used for analysis of incidents in specific encounters.

Synthetic encounters are computer simulated encounters that make use of an encounter simulation model. There are several types of encounter simulation models.

- User-defined encounter models [7] [14];
- Dynamic Bayesian belief network model [4] [15].

A well known user-defined encounter model has been specified by ICAO [7]. Various extensions of this user-defined model are feasible, e.g. [14]. These user-defined encounter models do not make use of live traffic data.

A dynamic Bayesian belief network model is an encounter simulation model that is explicitly trained on live traffic data. In [15] it is described how to train a dynamic Bayesian belief network on a large set of radar based aircraft trajectory data from USA airspace. In [4] use is made of a dynamic Bayesian belief network that has been trained on large set of data from European airspace.

Both user-defined encounter model and dynamic Bayesian belief network model allow to generate as many as desired random aircraft encounters. Simulated encounters generated by a dynamic

Bayesian belief network model capture real life like behaviour of aircraft in USA or European airspace. This advantage is missing in trajectory encounters generated by a user-defined encounter model. However a user-defined encounter model has the advantage that the user has control over the geometries and the parameters of the encounter.

In the current research the aim is to evaluate TCAS II and ACAS Xa on well controlled encounters. Hence the preferred approach is to make use of a user-defined encounter model. Section 3.2 explains the selected encounter types to be modelled. In subsequent Sections 3.3 to 3.7 the mathematical framework of the user-defined encounter model is given. Finally, Section 3.8 explains how the encounter types are captured in this mathematical framework.

3.2 Selection of Encounter Types to be Simulated

Since the number of ways aircraft can encounter each other in the air is vast, the encounter geometries used for simulation are ordered into encounter types. Using these types makes it easier to maintain structure during the analysis and when using types of increasing complexity it becomes more clear which parameters influence the outcome of the encounter in what way. This section presents three encounter types. Each encounter type holds a specific goal, which is explicitly mentioned.

Several assumptions are taken, which are valid for all encounter types.

- There are two aircraft in the encounter, aircraft 1 and aircraft 2.
- The aircraft both fly at the same airspeed.
- The aircraft both fly straight.
- Aircraft 1 always flies Northerly.

Type 1

This type contains encounters where both aircraft fly at the same level. There is variety in the angle under which they encounter each other at CPA or in the HMD between the aircraft at CPA. This is schematically visualised by two top views and one side view in Figure 3.

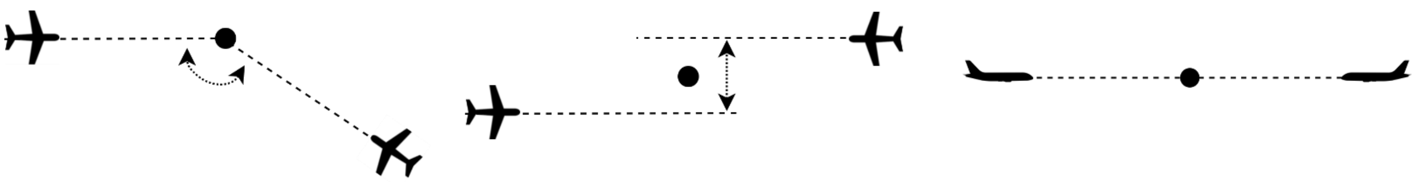


Figure 3. Schematic overview of type 1 encounter, with variation in course angle and HMD

Type 2

This type concerns encounter geometries where both aircraft fly at different attitudes towards each other. There is variety in the VMD between the aircraft at CPA. This is schematically visualised by one top view and one side view in Figure 4.

Figure 4. Schematic overview of type 2 encounter, with variation VMD

Type 3

These are encounters where aircraft 1 flies level and aircraft 2 climbs or descends to fly at that same level. This is visualised by one top view and two possible side views in Figure 5.

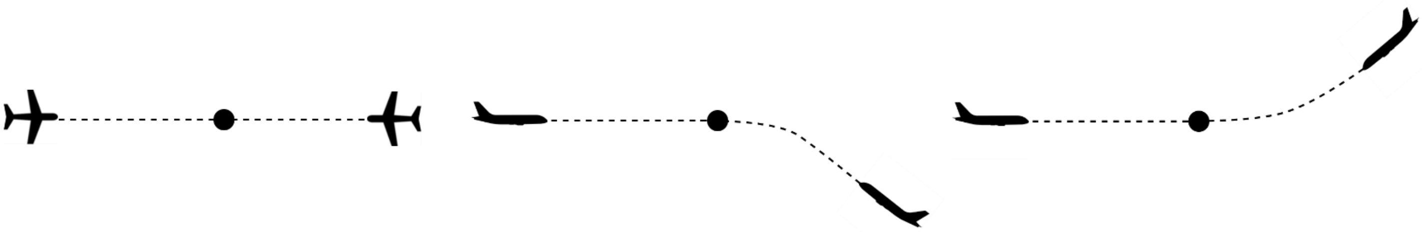


Figure 5. Schematic overview of type 3 encounter, with level-off manoeuvres

The encounters used in this report all belong to one of the three encounter types. The following sections explain how an encounter between two aircraft can be mathematically defined. Once these definitions are clear, the encounters that belong to each of the encounter types are defined mathematically as well.

3.3 Trajectory Definition

To fully define the encounter types presented in the previous section several definitions need to be established. This section includes all parameters that together define a trajectory of a single aircraft in space. Additionally it also states how propagation of this aircraft can be calculated. The definitions adhere to the definition used in CAVEAT.

The trajectories are defined in the East-North-Up (ENU) reference frame, as visualised in Figure 6. The x-axis points East, the y-axis points North and the z-axis points up. The geodetic altitude is measured along the z-axis and is defined as zero at mean sea level. Angles in the xy-plane are taken with respect to the y-axis (North) and clockwise direction is defined to be positive. The ENU frame is placed with its origin at the intersection of the Equator and the Prime Meridian, unless alternative longitude (λ) and latitude (φ) are specified.

The position vector s_i of an aircraft i at a certain time t in the ENU frame can be defined by three coordinates (s_i^x, s_i^y, s_i^z). The trajectory of an aircraft consists of a series of these coordinates over time. Several assumptions have been made with respect to the trajectories of the aircraft.

- The aircraft flies straight. This means there are no horizontal turns, such that the direction of travel that is given as input is the direction that is maintained by the aircraft during the complete original trajectory.
- The aircraft do not experience any acceleration.
- There is no wind.

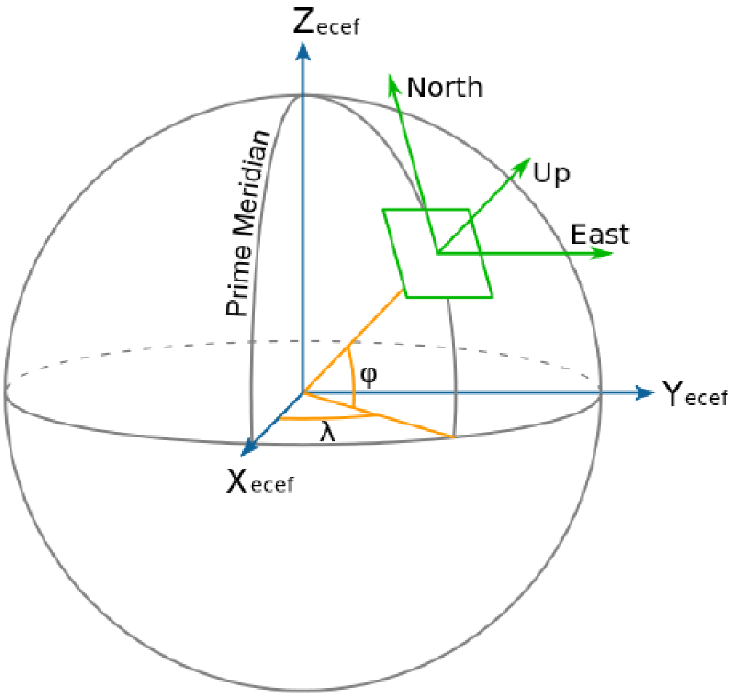


Figure 6. ENU frame in relation to the world geodetic (WGS84) and ECEF frames [3]

These assumptions make it possible to define the trajectory by using initial position, direction, velocity and time. Since there is zero wind, the course angle χ_i^{course} indicates in which direction the aircraft is headed in the horizontal plane and it is measured in degrees with respect to the North. Each aircraft i has a total velocity, or airspeed, of $\overline{v}_i$ in meters per second, which is constant over time. The vertical velocity v_i^z is used to indicate the inclination of the aircraft and states how much the aircraft climbs or descends in meters per second.

Table 1. Parameters to define a trajectory of aircraft i

Parameter	Symbol	Unit
Altitude	s_i^z	Meters (m)
X-coordinate	s_i^x	Meters (m)

Y-coordinate	s_i^y	Meters (m)
Course	χ_i^{course}	Degrees (°)
Velocity vertical	v_i^z	Meters per second (m/s)
Velocity total	$\overline{v}_i$	Meters per second (m/s)
Time	t	Seconds (s)

From these seven parameters, summarised in Table 1, the trajectory of an aircraft i can be obtained by using the continuous definitions in Eq. (3.1). This can only be done if the initial position ($s_{0,i}^x, s_{0,i}^y, s_{0,i}^z$) is known.

$$\begin{pmatrix} s_i^x \\ s_i^y \\ s_i^z \end{pmatrix} = \begin{pmatrix} s_{0,i}^x \\ s_{0,i}^y \\ s_{0,i}^z \end{pmatrix} + \begin{pmatrix} \sqrt{\overline{v}_i^2 - v_i^{z^2}} \sin \chi_i^{course} \\ \sqrt{\overline{v}_i^2 - v_i^{z^2}} \cos \chi_i^{course} \\ v_i^z \end{pmatrix} t \tag{3.1}$$

The x- and y-position of aircraft i can be calculated by its initial position plus the horizontal velocity times the sine and cosine of the course angle multiplied by the time. Since the horizontal velocity of aircraft i is not known beforehand, it can be calculated by using the Pythagorean Theorem with as input the vertical and total velocities. The z-position is calculated by simply taking the initial z-position and adding the vertical velocity multiplied by the time. The time goes from zero for the initial conditions to time t in steps of 1 second. The side and top view of two aircraft trajectories, including the position, velocities and course angle, are included in Figure 7 and Figure 8.

3.4 Encounter Geometry and Propagation

Encounters between multiple aircraft can be obtained by relating the parameters that describe the trajectories of each aircraft to each other. For the following section, there are two aircraft in the encounter, aircraft i and aircraft j, both with their own trajectory. Since there are now two trajectories defined in the same space, some of the parameters can be related to each other. The absolute distance between aircraft i and j at a certain time t can be obtained by Eq. (3.2).

$$d_{i,j} = \left\| \mathbf{s}_i - \mathbf{s}_j \right\| = \sqrt{(s_i^x - s_j^x)^2 + (s_i^y - s_j^y)^2 + (s_i^z - s_j^z)^2} \tag{3.2}$$

This distance can be split in an horizontal distance and a vertical distance, as demonstrated in Eq. (3.3) and (3.4).

$$d_{i,j}^h = \sqrt{(s_i^x - s_j^x)^2 + (s_i^y - s_j^y)^2} \tag{3.3}$$

$$d_{i,j}^v = \left| s_i^z - s_j^z \right| \tag{3.4}$$

When the distance between the two aircraft is minimised, the Closest Point of Approach (CPA) is reached, as defined in Eq. (3.5). The two distances, called the Vertical Miss Distance (VMD) and Horizontal Miss Distance (HMD), are thus defined by Eq. (3.6) and (3.7).

$$d_{i,j}^{CPA} = \min_t d_{t,i,j} \text{ attained at time } t_{i,j}^{CPA} \quad (3.5)$$

$$d_{i,j}^{HMD} = d_{i,j}^{h,CPA} \quad (3.6)$$

$$d_{i,j}^{VMD} = d_{i,j}^{v,CPA} \quad (3.7)$$

The VMD and HMD are also indicated in Figure 7 and Figure 8. To fully constraint the encounter, the HMD is split into the longitudinal and the lateral distance. This is necessary as otherwise the direction of the HMD with respect to one of the aircrafts locations is not defined. The longitudinal HMD is measured along the y-axis, lateral HMD is measured along the x-axis as also indicated in Figure 7 and Figure 8. These can be calculated by using Eq. (3.8) and (3.9).

$$d_{i,j}^{HMD,lon} = \left| s_i^{y,CPA} - s_j^{y,CPA} \right| \quad (3.8)$$

$$d_{i,j}^{HMD,lat} = \left| s_i^{x,CPA} - s_j^{x,CPA} \right| \quad (3.9)$$

The altitude of the CPA is defined to be the altitude of aircraft i as in Eq. (3.10).

$$h_{i,j}^{CPA} = s_i^{z,CPA} \quad (3.10)$$

The relative course between the two aircraft can be defined as in Eq. (3.11).

$$\chi_{i,j}^{course} = \left| \chi_j^{course} - \chi_i^{course} \right| \quad (3.11)$$

For this thesis, it is assumed that aircraft i always flies in Northerly direction, such that $\chi_{i,j}^{course}$ is always equal to the course angle of aircraft j. From this definition follows that the relative course angle and course angle are in this case one and the same. Therefore, from now on, the relative course angle is called the course angle χ^{course} for the rest of this report. The starting time of the encounter and the end time of the encounter together define how long the encounter will last. Finally, the speed of the aircraft is defined by the total airspeed $\overline{v}_i$ and the vertical velocity v_i^z. Using the Pythagorean theorem, the horizontal velocity v_i^{xy} can be obtained. Note that this last velocity is not required as input to define the encounter if the total airspeed and vertical velocity are already given.

In Table 2 the parameters that together fully define an encounter between two aircraft are listed, including their symbols and units. Note that these are not the SI units as used in the definition of the trajectories in the previous section. The parameters in Table 2 adhere to the format that is used by CAVEAT, which uses imperial units.

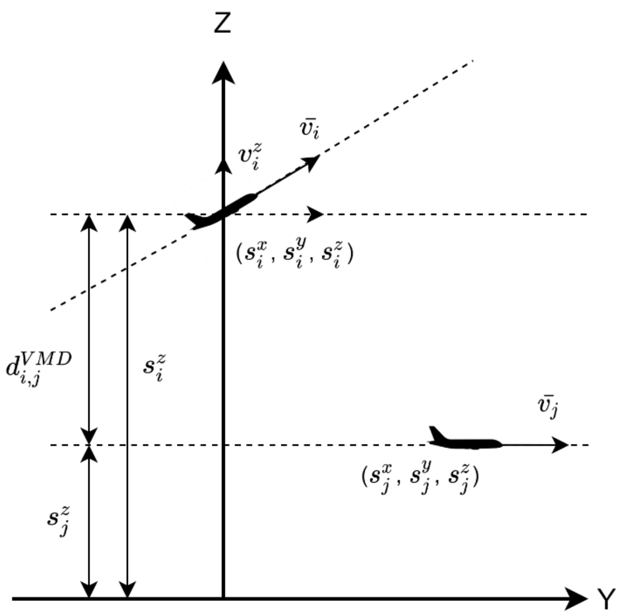


Figure 7. Side view of encounter geometry

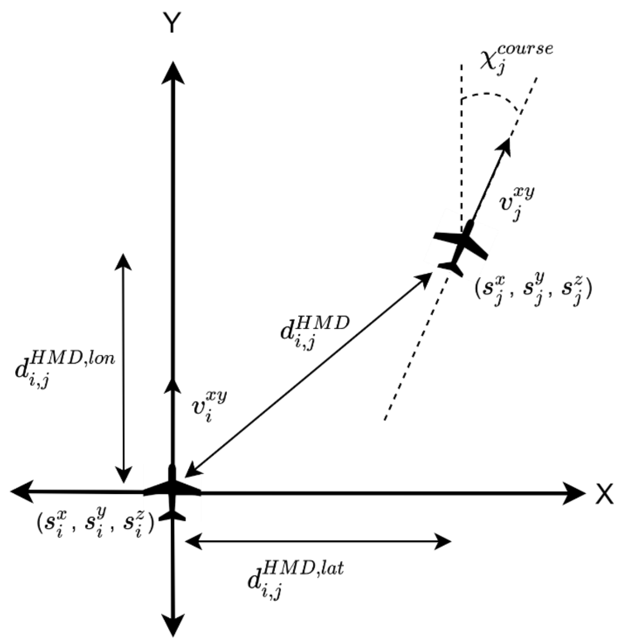


Figure 8. Top view of encounter geometry

Table 2. Parameters that define the encounter geometry between aircraft i and aircraft j

Parameter	Symbol	Unit
Altitude of CPA	$h_{i,j}^{CPA}$	Feet (ft)
VMD	$d_{i,j}^{VMD}$	Feet (ft)
Longitudinal HMD	$d_{i,j}^{HMD,lon}$	Feet (ft)
Lateral HMD	$d_{i,j}^{HMD,lat}$	Feet (ft)
Course angle	χ^{course}	Degrees (°)
Vertical velocity aircraft 1	v_i^z	Feet per minute (ft/min)
Vertical velocity aircraft 2	v_j^z	Feet per minute (ft/min)
Airspeed aircraft 1	$\bar{v}_i$	Knots (KTS)
Airspeed aircraft 2	$\bar{v}_j$	Knots (KTS)
Start of encounter	t_{start}	Seconds (s)
End of encounter	t_{end}	Seconds (s)

There are several limitations to the parameters in Table 2, which mainly have to do with the operation of commercial airliners. First of all, the altitude of the aircraft is technically limited to the specified ceiling of the aircraft type. Commercial aircraft do normally not fly at this ceiling altitude, but fly at cruise altitude, where the travel is as fast as possible with as little fuel burned as possible. This cruise altitude depends on the type of aircraft, the weight of the aircraft and the atmospheric conditions.

Next to that, the airspeed and vertical velocity depend on the altitude of the aircraft. In Table 3, a brief overview of typical altitudes and speeds for commercial airliners is included, which can be used as a guideline for the selection of the altitudes and velocities. These numbers are based on the performance data of five popular commercial airliners: B737-800 [16], B747-400 [17], B777-300 [18], A320 [19] and A340-500 [20]. It can be seen that generally, the higher the aircraft flies, the higher its airspeed is. The vertical velocity does not follow this pattern. For this thesis, this gives an accurate enough window of operation for commercial airliners.

Table 3. Typical airspeeds and vertical velocities for commercial airliners

Altitude (ft)	$\bar{v}$ (KTS)	v^z Climb (ft/min)	v^z Descend (ft/min)
0-5000	165-215	1500-3000	900-1100
5000-10000	290-300	1200-2500	
10000-15000	290-300	1200-2500	2000-3500
15000-24000	290-300	1000-2000	2000-3500
24000-ceiling	450-510	1000-2000	800-1000

3.5 Level-off Manoeuvre

Next to the straight flight introduced in the previous section, there is one manoeuvre that is added to the trajectories of the aircraft in this research. This manoeuvre, which occurs between a climb or descent and level flight is called a level-off.

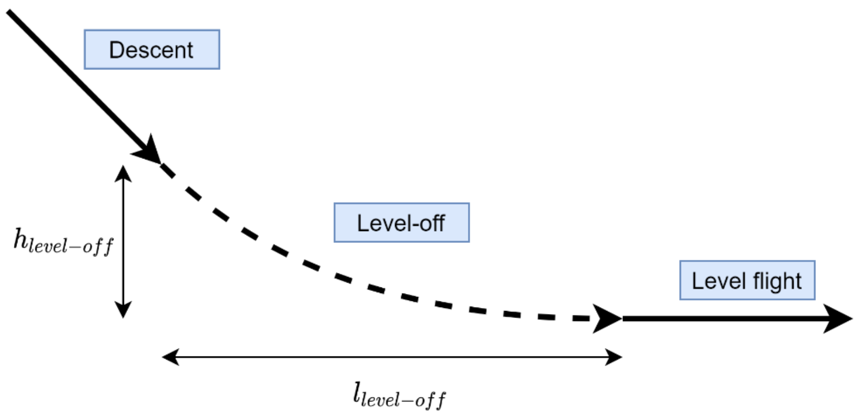


Figure 9. Flight profile of the descent, the level-off and level flight

In Figure 9 the flight profile of a descending aircraft that performs such a level-off is seen. For the rest of this section the situation of a descent, level-off and level flight is used, however, the reasoning and set of equations presented can also be used to obtain the characteristics of a level-off manoeuvre to transition to level flight after a climb.

It is assumed that the level-off starts at the unspecified altitude above the level flight $h_{level-off}$.

To smoothly model the level-off part of the trajectory, an exponential approximation of the level-off path is used, as in Eq. (3.12) [21].This equation approximates the altitude of the aircraft in the level-off manoeuvre in feet and uses the start altitude of the level-off $h_{level-off}$, a time constant τ and the time since the start of the level-off in seconds.

$$h = h_{level-off} \cdot e^{-t/\tau} \tag{3.12}$$

The value of $h_{level-off}$ can be obtained by using the geometry of the situation as illustrated in Figure 9. This process is started by drafting the force equilibrium of the situation, as displayed in Figure 10. At the start of the level-off, the aircraft is still flying at airspeed $\overline{v}$ and with the vertical velocity v^z that is used during the descent. These can be used to calculate η, the angle at which the aircraft is descending. The height and length of the level-off can then be calculated by assuming the start of the level-off path is part of a circle. This circle is displayed in Figure 11, it has large radius r which is not displayed completely in the figure due to size limitations. Using Newton's Second Law, the forces that act in the direction of the centre of the circle can be equalled to the mass of the aircraft times its centripetal acceleration, as in Eq. (3.13).

$$\sum F_N = m \cdot a_c = m \cdot \frac{\overline{v}^2}{r} \tag{3.13}$$

The centripetal acceleration is expressed by the squared airspeed over the radius. This radius can be used to calculate the approximate height and length of the level-off. Substituting the lift and the component of the weight into Eq. (3.13) gives the following equilibrium.

$$L - W \cos\eta = m \cdot \frac{\overline{v}^2}{r} \tag{3.14}$$

To ensure that the g forces on the aircraft remain within reasonable limits and passengers remain comfortable, the limits are often taken to be 0.75 and 1.25gs. To ensure these limits are not exceeded, minimum and maximum values of 0.9 and 1.1 g's are used. The minimum value is reached when the aircraft starts to level off from a climb and the maximum g force value is reached when the aircraft starts to level off from a descent. These indicate a reduction and increase of 0.1 g with respect to the nominal value of 1 g felt at Earth, respectively.

Hence, the lift is assumed to be equal to 1.1 times the weight at the end of the descent, which is the start of the level-off. If this is substituted into Eq. (3.8), the mass of the aircraft cancels out, as in Eq. (3.9).

$$W \cdot 1.1 - W \cdot \cos\eta = m \cdot \frac{\overline{v}^2}{r} \tag{3.15}$$

$$m \cdot g \cdot 1.1 - m \cdot g \cdot \cos\eta = m \cdot \frac{\overline{v}^2}{r} \tag{3.16}$$

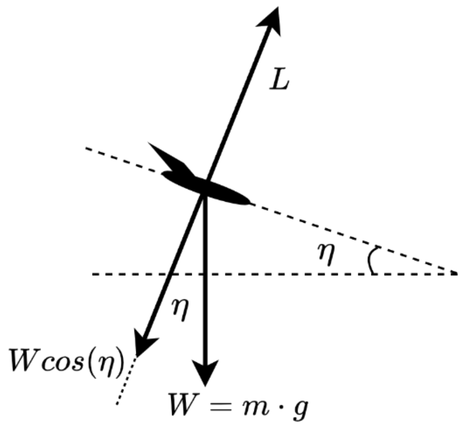


Figure 10. Free body diagram of aircraft at the moment before the start of the level-off, as seen from the side.

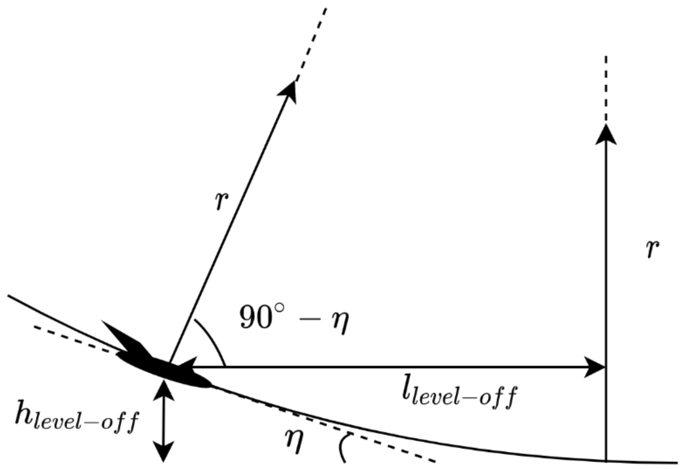


Figure 11. Overview of aircraft flying in circle as seen from the side

Rearranging this equation results in Eq. (3.17), where the radius of the approximate level-off path is expressed by the airspeed v_t, gravitational acceleration g and the airspeed angle η.

$$r = \frac{\bar{v}^2}{g \cdot (1.1 - \cos\eta)} \tag{3.17}$$

Now that the radius of the circle that approximates the level-off path is known, the horizontal and vertical distances of the level-off, as displayed in Figure 9, can be calculated using the trigonometry in Eq. (3.18) and (3.19).

$$l_{level-off} = \cos(90-\eta) \cdot r \tag{3.18}$$

$$h_{level-off} = -\tan(90-\eta) \cdot l_{level-off} + r \tag{3.19}$$

Now that the geometry of the level-off is known, τ can be obtained by setting the derivative of the level-off approximation in Eq. (3.20) equal to the rate of descend at the start of the level-off. This rate of descent is equal to the rate of descent that is used for the linear part of the descent path, which is stated in Eq. (3.21).

$$\dot{h} = \frac{-h_{level-off}}{\tau} \cdot e^{-t/\tau} \tag{3.20}$$

$$\dot{h}(0) = \frac{-h_{level-off}}{\tau} = v^z \tag{3.21}$$

The expression for τ then becomes as in Eq. (3.22).

$$\tau = \frac{-h_{level-off}}{v^z} \tag{3.22}$$

At this point the height at which the level-off starts and the constant τ are known, which allows for the use of Eq. (3.12). For the propagation of the total trajectory, it is necessary to know the duration of the level-off $t_{level-off}$. This can be calculated using Eq. (3.23) which is a combination of Eq. (3.20) and (3.22). The level-off is executed in the moments before CPA and is assumed to last till the rate of descend or the rate of climb is below -0.01 or 0.01 ft/min. At this point, the level-off ends and the aircraft continuous its trajectory with level flight.

$$t_{flare} = -\tau \cdot \ln\left(\frac{1}{v^z} \cdot \dot{h}\right) \quad (3.23)$$

The altitude at which the level-off starts and the duration of the level-off are thus specified by the horizontal and total velocity v^z and $\bar{v}$ of the aircraft. Level-off heights and durations for typical values of the airspeed and vertical velocity are listed in Table 4.

Table 4. Level-off heights and durations for typical values of horizontal and vertical velocities

Altitude (ft)	Airspeed $\bar{v}$ (KTS)	Vertical velocity v^z (ft/min)	Level-off height (ft)	Level-off duration (s)
7500, 15000	295	2000	170	41
36000	480	1500	97	30

3.6 Propagation of Two Aircraft Trajectories

In the previous section the parameters that define an encounter were presented. This section explains how the trajectories of the two aircraft are obtained from these parameters in combination with the propagation formulas presented in Section 3.4 and 3.5. To obtain the trajectories, code was written in Matlab.

The input of the Matlab program is a .txt file where each new line represents a new encounter. On each line, nine variables are used to fully define the encounter at CPA and one is used for bookkeeping, they are separated by commas.

- The altitude of the CPA ($h_{i,j}^{CPA}$) in feet.
- The VMD ($d_{i,j}^{VMD}$) in feet.
- The longitudinal HMD ($d_{i,j}^{HMD,lon}$) in feet.
- The lateral HMD ($d_{i,j}^{HMD,lat}$) in feet.
- The relative course angle between the aircraft in degrees (χ^{course}).
- The airspeed ($\bar{v}_i$) of aircraft i in KTS.
- The vertical velocity (v_i^z) of aircraft i in feet per minute. Climb is positive, descend is negative.
- The airspeed ($\bar{v}_j$) of aircraft j in KTS.
- The vertical velocity (v_j^z) of aircraft j in feet per minute. Climb is positive, descend is negative.

- The encounter geometry type this particular encounter belongs to, as will be introduced in Section 3.8. This parameter is solely used for bookkeeping.

The freedom of this input format allows for flexibility in the definition of the CPA geometry. It also makes it easy to add additional variables, in case more details to the trajectory are needed. Next to the txt file, some standard parameters are defined in the Matlab program itself, such as the duration of the trajectory that is to be generated.

Since the parameters define the position of the aircraft at CPA, the CPA position serves as initial position for aircraft i in the encounter. This aircraft will always be located at the x-,y-, and z-coordinates calculated by Eq. (3.24) to (3.26).This means that the location of aircraft i at CPA is independent of the indicated VMD and HMDs.

$$s_i^{z,CPA} = h_{i,j}^{CPA} \quad (3.24)$$

$$s_i^{x,CPA} = 0 \quad (3.25)$$

$$s_i^{y,CPA} = 0 \quad (3.26)$$

The coordinates of the second aircraft j are calculated by taking the VMD, longitudinal and lateral HMD at CPA in mind according to Eq. (3.27) to (3.29).

$$s_j^{z,CPA} = h_{i,j}^{CPA} - d_{i,j}^{VMD,CPA} \quad (3.27)$$

$$s_j^{x,CPA} = d_{i,j}^{HMD,lat,CPA} \quad (3.28)$$

$$s_j^{y,CPA} = d_{i,j}^{HMD,lon,CPA} \quad (3.29)$$

Now the initial positions of the two aircraft at CPA are known. It is assumed that aircraft i always flies in Northerly direction, so its course angle χ_i^{course} is always zero. This means that automatically that the course angle of the second aircraft χ_j^{course} is equal to the relative course angle χ^{course}. It is assumed that CPA occurs at 12:02:00.0 and the trajectories of the aircraft in the encounter are propagated two minutes before CPA and one minute after CPA. In total, a standard encounter thus takes 3 minutes, from 12:02:00.0 till 12:03:59.0.

Depending on whether the aircraft is currently in a level-off, two sets of propagation equations are used. The position of an aircraft not in a level-off at any time t can be calculated by the regular propagation in Eq. (3.30).

$$\begin{pmatrix} s_{t,i}^x \\ s_{t,i}^y \\ s_{t,i}^z \end{pmatrix} = \begin{pmatrix} s_{0,i}^x \\ s_{0,i}^y \\ s_{0,i}^z \end{pmatrix} + \begin{pmatrix} \sqrt{\bar{v}_i^2 - v_i^{z^2}} \cdot \sin\left(\chi^{course}\right) \\ \sqrt{\bar{v}_i^2 - v_i^{z^2}} \cdot \cos\left(\chi^{course}\right) \\ v_i^z \end{pmatrix} \cdot t \quad (3.30)$$

If the aircraft is currently in a level-off manoeuvre, the position of the aircraft at time t is calculated according to Eq. (3.31). The x- and y-coordinates of the aircraft are computed in the exact same manner as in Eq. (3.30), since these are not influences by a level-off manoeuvre. However, the altitude of the aircraft is now modelled according to the method explained in Section 3.5.

$$\begin{pmatrix} s_{t,i}^x \\ s_{t,i}^y \\ s_{t,i}^z \end{pmatrix} = \begin{pmatrix} s_{0,i}^x \\ s_{0,i}^y \\ s_{0,i}^z \end{pmatrix} + \begin{pmatrix} \sqrt{\bar{v}_i^2 - v_i^{z^2}} \cdot \sin\left(\chi^{course}\right) \cdot t \\ \sqrt{\bar{v}_i^2 - v_i^{z^2}} \cdot \cos\left(\chi^{course}\right) \cdot t \\ h_{level-off} \cdot e^{-t/\tau} \end{pmatrix} \tag{3.31}$$

The level-off only occurs during the moments before CPA, its length is defined by the calculated level-off duration time. After CPA, both aircraft fly level, unless otherwise specified.

The encounters are defined by the position of both aircraft at CPA, which is different to the position of the aircraft at the beginning of the encounter. Hence, the propagation is split into two parts: forward propagation for the part after CPA and backwards propagation for the part before CPA. Both have their own durations, defined by $t_{postCPA}$ and t_{preCPA}. The forward propagation, from CPA to the end of the encounter, is then a straightforward process using Eq. (3.30). The pseudo code in Eq. (3.32) defines how the forwards propagation is done. In Table 5 the input parameters to the algorithm are stated as well as typical ranges used during the research presented in this report. The forward propagation goes from a lower limit of 0 seconds to an upper limit of 60 seconds, meaning that the part of the trajectory after CPA takes 60 seconds in total.

$$\begin{aligned} &\text{FOR } t = t_{postCPA,lower} \text{ TO } t = t_{postCPA,upper} \\ &\quad s_{t+1,i}^x = s_{t,i}^x + \sqrt{\bar{v}_i^2 - v_i^{z^2}} \cdot \sin\left(\chi^{course}\right) \cdot \Delta t \\ &\quad s_{t+1,i}^y = s_{t,i}^y + \sqrt{\bar{v}_i^2 - v_i^{z^2}} \cdot \cos\left(\chi^{course}\right) \cdot \Delta t \\ &\quad s_{t+1,i}^z = s_{t,i}^z + v_i^z \cdot \Delta t \\ &\text{NEXT} \end{aligned} \tag{3.32}$$

Table 5. Input parameters forward propagation

Input parameters	Description	Unit	Typical value or range
$h_{i,j}^{CPA}$	Altitude of CPA	ft	7500 - 36000
$d_{i,j}^{VMD}$	VMD at CPA	ft	0 - 1000
$d_{i,j}^{HMD,lon}$	Longitudinal HMD at CPA	ft	0
$d_{i,j}^{HMD,lat}$	Lateral HMD at CPA	ft	0 - 1000
χ^{course}	Relative course angle	degrees	0 - 180
$\bar{v}_i$	Airspeed aircraft i	kts	295 - 480
v_i^z	Vertical velocity aircraft i	ft/min	0

$\bar{v}_j$	Airspeed aircraft *j*	kts	295 - 480
v_j^z	Vertical velocity aircraft *j*	ft/min	0 - 2000
$t_{postCPA,lower}$	Time after CPA, lower limit	s	0
$t_{postCPA,upper}$	Time after CPA, upper limit	s	60
Δt	Time step	s	1

For the backward propagation, from CPA to the start of the encounter where $t = t_{preCPA}$, the plus sign in Eq. (3.30) is adjusted to a minus sign. This way the time can still run from 0 to positive and the next position of the aircraft is calculated at $t+1$, while calculating the positions in backwards order. The pseudocode in Eq. (3.33) represents the backwards propagation that is used to calculate the trajectory of the aircraft during the moments before CPA.

The part of the trajectory before CPA takes 120 seconds per default for this thesis, ranging from the lower limit 0 seconds to the upper limit 120 seconds. By checking if the duration of the level-off $t_{level-off}$ is positive, it is checked if a level-off manoeuvre should be included. If the level-off duration is zero, the z-coordinates are calculated by regular propagation. If the level-off duration is positive, the z-coordinates are calculated using the exponential level-off approximation for the complete duration of the level-off. The direction of the level-off depends on the vertical velocity of the aircraft v_i^z. The height of the level-off $h_{level-off}$ and τ are calculated according to the equations stated in Section 3.5.

The series of positions found during the backwards propagation are flipped, such that this part of the trajectory starts at t_{preCPA} and ends at CPA. Finally, the series of positions from the forward propagation from CPA to $t_{postCPA}$ are added, such that the complete, three minute trajectory is complete and saved.

$$
\begin{array}{l}
\text{FOR } t = t_{preCPA,lower} \text{ TO } t = t_{preCPA,upper} \\
\quad s^x_{t+1,i} = s^x_{t,i} - \sqrt{\overline{v}_i^{\,2} - v_i^{z^2}} \cdot \sin\left(\chi^{course}\right) \cdot \Delta t \\
\quad s^y_{t+1,i} = s^y_{t,i} - \sqrt{\overline{v}_i^{\,2} - v_i^{z^2}} \cdot \cos\left(\chi^{course}\right) \cdot \Delta t \\
\quad \text{IF } t_{level-off} > 0 \text{ AND } t \leq t_{level-off} \\
\quad\quad \text{IF } v^z_i = 0 \text{ THEN} \\
\quad\quad\quad s^z_{t+1,i} = s^z_{t,i} - v^z_i \cdot \Delta t \\
\quad\quad \text{ELSEIF } v^z_i > 0 \text{ THEN} \\
\quad\quad\quad s^z_{t+1,i} = s^z_{0,i} - h_{level-off} \cdot e^{-t/\tau} \\
\quad\quad \text{ELSEIF} \\
\quad\quad\quad s^z_{t+1,i} = s^z_{0,i} + h_{level-off} \cdot e^{-t/\tau} \\
\quad\quad \text{ENDIF} \\
\quad \text{ELSEIF} \\
\quad\quad s^z_{t+1,i} = s^z_{t,i} - v^z_i \cdot \Delta t \\
\quad \text{ENDIF} \\
\text{NEXT}
\end{array}
\tag{3.33}
$$

Table 6. Input parameters backward propagation

Input parameters	Description	Unit	Typical value or range
$h^{CPA}_{i,j}$	Altitude of CPA	ft	7500 - 36000
$d^{VMD}_{i,j}$	VMD at CPA	ft	0 - 1000
$d^{HMD,lon}_{i,j}$	Longitudinal HMD at CPA	ft	0
$d^{HMD,lat}_{i,j}$	Lateral HMD at CPA	ft	0 - 2000
χ^{course}	Relative course angle	degrees	0 - 180
$\overline{v}_i$	Airspeed aircraft i	kts	295 - 480
v^z_i	Vertical velocity aircraft i	ft/min	0
$\overline{v}_j$	Airspeed aircraft j	kts	295 - 480
v^z_j	Vertical velocity aircraft j	ft/min	0 - 2000
$t_{preCPA,lower}$	Time before CPA, lower limit	s	0
$t_{preCPA,upper}$	Time before CPA, upper limit	s	120
$t_{level-off}$	Duration of level-off	s	30 - 45
Δt	Time step	s	1
-	Maximum number of g forces		0.9 – 1.1
-	Maximum vertical velocity at end of level-off	ft/min	-0.01 – 0.01

CAVEAT does not have a default encounter duration. As a standard, two minutes before and one minute after CPA are taken. In total, an encounter thus takes 3 minutes. A default time step Δt of one second is used.

Together, these computations can result in an encounter between two aircraft such as included in Figure 12 and Figure 13. The trajectory of aircraft 1 is visualised by the blue line and the red line indicates the path of aircraft 2. This encounter has a 14 ft VMD, 5000 ft lateral HMD, course angle of 180° at 36000 ft altitude. Both aircraft travel at an airspeed of 480 kts and aircraft 2 has a vertical velocity of 2000 ft/min.

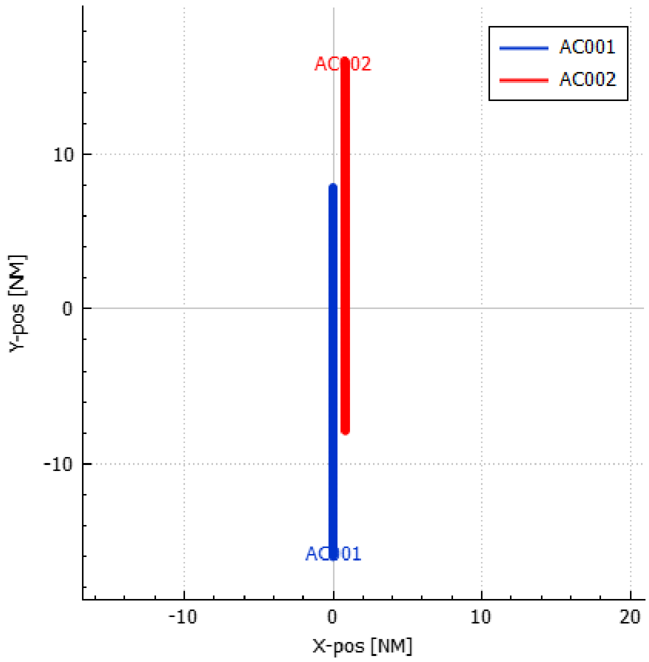


Figure 12. Top view of encounter with 14 ft VMD, 5000 ft lateral HMD, course angle of 180° at 36000 ft altitude. Airspeed of 480 kts and aircraft 2 has a vertical velocity of 2000 ft/min before the level-off.

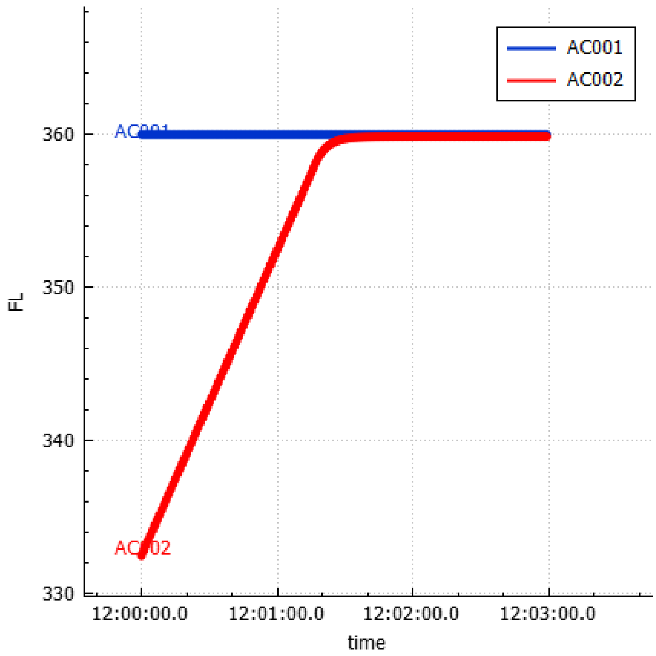


Figure 13. Side view of encounter with 14 ft VMD, 5000 ft lateral HMD, course angle of 180° at 36000 ft altitude. Airspeed of 480 kts and aircraft 2 has a vertical velocity of 2000 ft/min before the level-off.

3.7 Encounter File Generation

This section describes how the encounter files, which contain the trajectories of the aircraft in the encounter, are generated.

File Format

CAVEAT uses .ftd files as input, which consists of two parts. The first part is the header, which includes general encounter parameters and aircraft static parameters, displayed in Table 7 and Table 8. During this thesis only artificial data will be used, which is why the category will always be 'synthetic'. For the initial simulation runs, 2 aircraft are used in the encounter.

Table 7. General encounter parameters in .ftd file

Parameter	Definition	Value
Category	This parameter indicates what type of data is included in the file • Synthetic: complete, second-by-second data generated by a model. • Radar: radar tracking data, needs to be reconstructed before the simulation. Reconstructed: complete, second-by-second reconstructed encounters based on radar tracking data.	Synthetic
Number_AC	The number of aircraft in the encounter, with an absolute maximum of 10.	2

Table 8. Aircraft static parameters in .ftd file

Parameter	Definition	Value
AC_tracknumber	A unique integer to identify aircraft in the encounter	1, 2
Mode_S_address	The Mode S address of the aircraft, 6-digit hexadecimal number	000001, 000002
Mode_A_code	The Mode A code of the aircraft, 4-digit octal number	1100, 2200
AC_callsign	The aircraft callsign, used for result visualisation	AC001, AC002
ACAS_version	The ACAS version with which the aircraft is equipped. • Unequipped • TCAS II 7.0 • TCAS II 7.1 • TCAS II 7.2 • ACAS Xa 15.2 • ACAS Xa 15.4 • ACAS Xa 15.4 CP1	Unknown, will be overwritten by CAVEAT scenarios
Manual_SL	The setting of the sensitivity level. • 0: automatic, TAs and RAs are provided • 1: standby, no TAs or RAs are provided • 2: TA only, only TAs are provided	0

The track numbers of the aircraft, the Mode S address, Mode A code and callsign can be chosen arbitrarily and are mainly used to be able to identify the aircraft during analysis. The ACAS version is left to be unknown, so a zero is written in the .ftd file. This is done so that the specification of the ACAS version will be overwritten by the ACAS version specification in the scenario file, such that one .ftd file can be used for TCAS II equipped aircraft, ACAS Xa equipped aircraft and nonequipped aircraft. The sensitivity setting is always set to be automatic, such that both TAs and RAs are provided.

The second part of the .ftd file consists of the aircraft dynamic parameters, displayed in Table 9. These five parameters are defined each time step, with every time step on a new line of the .ftd file. The time should always starts from 12:00:00.0 in CAVEAT and increases with a time step of 1 second, as also used during the trajectory propagation in the previous section. The track number of the aircraft should match the track number that is in the aircraft static parameters in the header. The x, and y values reflect the position of the aircraft in the horizontal plane, the z value is used as the altitude of the aircraft, all are calculated using the process in Section 3.6.

Table 9. Aircraft dynamic parameters in .ftd file

Parameter	Unit	Definition
Time	-	A time stamp in the format hh:mm:ss.c, starting at 12:00:00.0.
AC_tracknumber	-	A unique integer to identify aircraft in the encounter
X-position	nm	X-position of the aircraft in ENU coordinate system
Y-position	nm	Y-position of the aircraft in ENU coordinate system
Altitude	ft	Geodetic altitude of the aircraft, with zero altitude at mean sea level in standard atmospheric conditions

To combine the general encounter, aircraft static and aircraft dynamic parameters into one .ftd file, Matlab R2018b is used to integrate the trajectory propagation with the generation of the .ftd files. This program generates the header and prints the trajectory in the desired format, after which the file is automatically saved in .ftd format with an according name. Multiple trajectories, and thus multiple .ftd files, can be generated at the same time using the .txt file referred to in Section 3.6.

Now that it is clear how trajectories are defined and how the encounter files are generated, the structure that is added to the vast number of possible encounters is presented in the next section.

3.8 User-defined Encounter Model

Now that all parameters are introduced, the three encounter types introduced in Section 3.2 can be captured in the user-defined encounter model. For this the nine parameters presented in Table 2 are used. Specific values are given for these parameters, as well as the maximum total number of different encounter geometries that is possible per encounter type.

To reduce the number of encounter geometries, all three encounter types contain encounters at the same three altitudes and only one airspeed is chosen per altitude. Both the altitudes and the airspeeds are chosen based on the typical values in Table 3.

Type 1

This type contains encounters where both aircraft fly with zero relative altitude. There is variety in the altitude and velocity of the complete encounter and the course angle. In one special cases there is another variable to keep in mind, which occurs when the aircraft fly with a course angle of 180 degrees. In that case, the horizontal distance between the aircraft can also be varied.

- The vertical velocity of both aircraft is zero.
- The VMD is zero, as the aircraft fly at the same level.
- For the special case, the lateral HMD can either be 500 or 1000 ft. These values are based on experimental simulations.
- The course angle is varied from 45 to 180 degrees, as the situation is symmetrical around the flight path trajectory of the main aircraft. This is done in steps of 45 degrees. The course angle of 0 degrees will not be used as this situation is physically not possible.

Table 10. Type 1 encounter parameters

AC	Symbol	Unit	Values		
	$h_{i,j}^{CPA}$	Ft	7500	15000	36000
i	$\bar{v}_i$	KTS	295	295	480
	v_i^z	Ft/min	0	0	0
j	$\bar{v}_j$	KTS	295	295	480
	v_j^z	Ft/min	0	0	0
	$d_{i,j}^{VMD}$	Ft	0		
	$d_{i,j}^{HMD,lon}$	Ft	0		
	$d_{i,j}^{HMD,lat}$	Ft	0, 500, 1000		
	χ^{course}	Deg. (°)	45, 90, 135, 180		

In Table 10 the values for the geometries of type 1 encounters are listed. Together, these parameters result in a maximum of 18 unique trajectories:

- 3 different altitudes times 4 different positive course angles with zero HMD (12 unique trajectories)
- 3 different altitudes times 2 180-degree course angles with positive HMD (6 unique trajectories)

Type 2

This type concerns encounter geometries where both aircraft fly level with non-zero relative vertical distance. There is variety in the altitude and velocity of the complete encounter and the VMD between the aircraft at CPA.

- The vertical velocity of both aircraft is zero.

- The VMDs of the encounter geometries are based on experimental simulations and cover altitudes at which the ACAS are triggered. This ensures that behaviour of TCAS II and ACAS Xa is completely captured without running useless simulations.
- The course angle is always 180 degrees, this is done such that the number of encounters remains workable.

Table 11. Type 2 encounter parameters

AC	Symbol	Unit	Values		
	$h_{i,j}^{CPA}$	Ft	7500	15000	36000
i	$\bar{v}_i$	KTS	295	295	480
	v_i^z	Ft/min	0	0	0
j	$\bar{v}_j$	KTS	295	295	480
	v_j^z	Ft/min	0	0	0
	$d_{i,j}^{VMD}$	Ft	100, 200, 300, 400, 500, 600, 700, 800, 900	100, 200, 300, 400, 500, 600, 700, 800, 900	100, 200, 300, 400, 500, 600, 700, 800, 900
	$d_{i,j}^{HMD,lon}$	Ft	0		
	$d_{i,j}^{HMD,lat}$	Ft	0		
	χ^{course}	Deg. (°)	180		

In Table 11 the values for the geometries of type 2 encounters are listed. Together, these parameters result in a maximum of 27 unique trajectories, which come from encounters at 3 different altitudes times 9 different VMDs times 1 positive course angles.

Type 3

These are encounters where aircraft 1 flies level and aircraft 2 climbs or descends from a different altitude and levels-off before CPA at the same altitude as aircraft 1 is flying. Encounters of this type can have variety in the altitude of CPA, the course angle and the vertical velocity of aircraft. In Figure 5 a schematic visualisation of the type 3 encounters is included.

- The vertical velocity is zero. Only the second aircraft has a non-zero vertical velocity which is chosen based on the typical values stated in Table 3.
- The course angle can either be 90 or 180 degrees, this is done such that the number of encounters does not grow too much.

In Table 12 the values for the geometries of type 3 encounters are listed. Together, these parameters result in a maximum of 12 unique trajectories. These originate from the 3 different altitudes times 2 different vertical velocities per altitude times 2 different positive course angles with zero HMD.

Table 12. Type 3 encounter parameters

AC	Symbol	Unit	Values		
	$h_{i,j}^{CPA}$	Ft	7500	15000	36000
i	$\bar{v}_i$	KTS	295	295	480
	v_i^z	Ft/min	0	0	0
j	$\bar{v}_j$	KTS	295	295	480
	v_j^z	Ft/min	2000, -2000	2000, -2000	1500, -1000
	$d_{i,j}^{VMD}$	Ft	0		
	$d_{i,j}^{HMD,lon}$	Ft	0		
	$d_{i,j}^{HMD,lat}$	Ft	0		
	χ^{course}	Deg. (°)	90, 180		

The three types of encounters presented in this section do not capture all possible encounter geometries, but serve as a basis for the performance evaluation. The choices for the specific encounter geometries are based on preliminary results and are chosen keeping in mind simulation time and the amount of work that is required to obtain results. As the thesis work progresses, modifications or additions may be done to these three encounter types. These include encounters with different total and/or vertical velocities, with different HMDs or VMDs, without level-offs or encounters that have a different duration. If this is the case, it is explicitly indicated. However, it is important to realise that the three encounter types presented in this section together already contain 57 unique encounter geometries, a number that is doubled when looking at both TCAS II and ACAS Xa results.

4 Agent-Based Model Parameter Settings

This chapter introduces the different agent-based parameter settings that are used in running CAVEAT to analyse TCAS II and ACAS Xa. Section 4.1 introduces all relevant parameters. Sections 4.2 to 4.7 specify the parameter sets that are used for simulation.

4.1 Relevant Parameters

The different parameters correspond to the agents in Figure 1. All parameters settings that can be defined in CAVEAT are included in Table 13 with references to the tables in Appendix B, where all default values and settings are stated. The main elements are the airspace environment parameters and the aircraft parameters, which can be selected for each aircraft in the encounter separately. The aircraft parameters consist of a set equipment and operation settings, settings of the pilot response model, settings of the ownship estimation and settings of the othership estimation.

The agent-based parameter settings that are going to be used for the simulation can also be indicated, the models can either be deterministic or stochastic. Deterministic settings can reflect a simple model, which will be easier to understand and is currently used as a standard in encounter evaluation. The stochastic settings can provide a more true representation of the situation, by introducing uncertainties. If it is possible to model an element both deterministically and stochastically, it is indicated in the second column in Table 13, including the respective tables with the specific parameter settings in the third column. If a parameter setting contains one or more stochastic element settings, it is called stochastic. If no stochastic settings are included, it means it the parameter setting deterministic.

Table 13. CAVEAT default parameter settings table references

CAVEAT Element	Comment	Table Reference
Environment Parameters		
Reference's Frame Origin		Table 55
Wind		Table 55
Terrain		Table 55
Aircraft Parameters – Equipment & Operation		
Unmanned Aircraft System		Table 56
ACAS Equipment		Table 57
Onboard Equipment		Table 58
Parallel Approach Operation		Table 59
Aircraft Attitude		Table 60
APFD ACAS RA Mode	If selected	Table 61
Advanced Options	If APFD ACAS RA Mode is selected	Table 62

Encounter File Override		Table 63
Aircraft Parameters – Pilot Model		
Pilot Response Mode	Deterministic	Table 64
	Stochastic, 80% response	Table 65
Vertical Rate Error	Deterministic	Table 70
	Stochastic	Table 71
Delay	Deterministic	Table 72
	Stochastic	Table 73
Vertical Acceleration	Deterministic, ICAO model	Table 78
	Deterministic, speed dependent	Table 79
	Stochastic, ICAO defaults	Table 80
Aircraft Parameters – Ownship State Estimation		
GNSS-based Position Error Model	Deterministic	Table 81
	Stochastic	Table 82
GNSS-based Velocity Error Model	Deterministic	Table 83
	Stochastic	Table 84
Pressure Altitude	Deterministic	Table 85
	Stochastic, MOPS model	Table 86
	Stochastic, ICAO Annex 10 model	Table 87
Radio Altitude	Deterministic	Table 90
	Stochastic	Table 91
Heading	Deterministic	Table 92
	Stochastic	Table 93
Aircraft Parameters – Othership State Estimation		
Transponder-based Slant Range	Deterministic	Table 94
	Stochastic, MOPS model	Table 95
	Stochastic, ICAO Annex 10 model	Table *96*
Transponder-based Bearing	Deterministic	Table 97
	Stochastic, MOPS model	Table 98
	Stochastic, ICAO Annex 10 model	Table *99*

Airspace environment parameters, as listed in Table 13, will not be deviated from their default settings in any of the parameter settings. The equipment and operations parameters will also not be varied between the different settings, with the exception of TCAS II and ACAS Xa Equipment. Each encounter can be run equipped with TCAS II version 7.1, ACAS Xa 15.4 CP1, a combination of TCAS II and ACAS Xa or unequipped. During this thesis, only encounters where both aircraft are equipped with TCAS II and encounters where both aircraft are equipped with ACAS Xa are simulated and analysed. APFD (Autopilot/Flight Director) ACAS RA Mode will not be selected in CAVEAT. The airspace environment parameters and equipment and operations parameters are therefore not displayed in the tables for the parameter settings.

Due to the vast amount of simulation parameters in CAVEAT, the different parameter settings are also divided into sets. The following sections present the different sets of parameter settings. The parameter settings in the sets are varied in such a way that influences of specific settings can be deducted from the analysis. They all have a different purpose:

- Parameter Sets 1 and 2 are used for the verification of the ABM in CAVEAT
- Parameter Set 3 is used to analyse the influence of the encounter geometry parameters on TCAS II and ACAS Xa behaviour.
- Parameter Sets 4, 5 and 6 are used to perform a sensitivity analysis of the different ABM settings. The choices that have been made to construct these parameter settings are covered in the sensitivity analysis in Chapter 10.

For the first set of parameter settings, all tables have been added to the main body of the report, to demonstrate how the sets can be used to systematically investigate the influence of certain parameters on the performance of TCAS II and ACAS Xa. The other sets of parameter settings follow this same method, but their tables are included in 0 to maintain the readability of this report. A parameter setting can belong to multiple sets, if it is used as a default setting to compare to for example.

4.2 Parameter Set 1

This set contains four stochastic parameter settings, where the separate elements of the pilot model are modelled stochastically one by one. This allows for the verification of the stochastic behaviour of each of the four stochastic elements in the pilot model. The tables referenced in this section are included in Appendix C.1.

Stochastic Setting – S1.1

This setting contains all default deterministic parameters, except for the standard altitude-dependent stochastic setting of the pilot response mode, as indicated in Table 14. When comparing this setting to the completely deterministic setting D1.1, it can be seen what the influence of a standard altitude dependent pilot response mode is on the trajectories modified by TCAS II and ACAS Xa.

Table 14. Agent-based model parameter settings, stochastic setting – S1.1

CAVEAT Element		Table Reference
Pilot Response Mode	Stochastic, 80% response	Table 65
Vertical Rate Error	Deterministic	Table 70
Delay	Deterministic	Table 72
Vertical Acceleration	Deterministic, ICAO model	Table 78

GNSS-based Position Error Model	Deterministic	Table 81
GNSS-based Velocity Error Model	Deterministic	Table 83
Pressure Altitude	Deterministic	Table 85
Radio Altitude	Deterministic	Table 90
Heading	Deterministic	Table 92
Transponder-based Slant Range	Deterministic	Table 94
Transponder-based Bearing	Deterministic	Table 97

Stochastic Setting – S1.2

This parameter setting contains all the default deterministic settings, except for the stochastic setting of the vertical rate error, as indicated in Table 15. When comparing this to the fully deterministic setting D1.1, it can be seen what the influence of the variability in pilot response mode is on the trajectories modified by TCAS II and ACAS Xa.

Table 15. Agent-based model parameter settings, stochastic setting – S1.2

CAVEAT Element		Table Reference
Pilot Response Mode	Deterministic	Table 64
Vertical Rate Error	Stochastic	Table 71
Delay	Deterministic	Table 72
Vertical Acceleration	Deterministic, ICAO model	Table 78
GNSS-based Position Error Model	Deterministic	Table 81
GNSS-based Velocity Error Model	Deterministic	Table 83
Pressure Altitude	Deterministic	Table 85
Radio Altitude	Deterministic	Table 90
Heading	Deterministic	Table 92
Transponder-based Slant Range	Deterministic	Table 94
Transponder-based Bearing	Deterministic	Table 97

Stochastic Setting – S1.3

This parameter setting contains all default deterministic settings, except for the stochastic setting of the delay in pilot response, as indicated in Table 16. When comparing this to the fully deterministic setting D1.1, it can be seen what the influence of the variability in delay in pilot response is on the trajectories modified by TCAS II and ACAS Xa.

Table 16. Agent-based model parameter settings, stochastic setting – S1.3

CAVEAT Element		Table Reference

Pilot Response Mode	Deterministic	Table 64
Vertical Rate Error	Deterministic	Table 70
Delay	Stochastic	Table 73
Vertical Acceleration	Deterministic, ICAO model	Table 78
GNSS-based Position Error Model	Deterministic	Table 81
GNSS-based Velocity Error Model	Deterministic	Table 83
Pressure Altitude	Deterministic	Table 85
Radio Altitude	Deterministic	Table 90
Heading	Deterministic	Table 92
Transponder-based Slant Range	Deterministic	Table 94
Transponder-based Bearing	Deterministic	Table 97

Stochastic Setting – S1.4

This parameter setting contains all default deterministic settings, except for the stochastic setting of the vertical acceleration, as indicated in Table 17. When comparing this to the fully deterministic setting D1.1, it can be seen what the influence of the variability in vertical acceleration is on the trajectories modified by TCAS II and ACAS Xa.

Table 17. Agent-based model parameter settings, stochastic setting – S1.4

CAVEAT Element		Table Reference
Pilot Response Mode	Deterministic	Table 64
Vertical Rate Error	Deterministic	Table 70
Delay	Deterministic	Table 72
Vertical Acceleration	Stochastic, ICAO defaults	Table 80
GNSS-based Position Error Model	Deterministic	Table 81
GNSS-based Velocity Error Model	Deterministic	Table 83
Pressure Altitude	Deterministic	Table 85
Radio Altitude	Deterministic	Table 90
Heading	Deterministic	Table 92
Transponder-based Slant Range	Deterministic	Table 94
Transponder-based Bearing	Deterministic	Table 97

4.3 Parameter Set 2

This set contains parameter settings which are used for the verification of the state estimation errors in the ABM. They can be compared to the baseline deterministic setting D1.1 to see the influence of the uncertainties in state estimation. All tables are located in Appendix C.1.

Stochastic Setting – S2.1
This parameter setting contains all default deterministic setting, except for the position error model, as indicated in Table 100. When comparing this set of parameter settings to the completely deterministic setting D1.1, it can be seen what the influence of the position error model is on the performance of and the trajectories modified by TCAS II and ACAS Xa.

Stochastic Setting – S2.2
This parameter setting contains all default deterministic setting, except for the velocity error model, as indicated in Table 101. When comparing this set to the completely deterministic setting D1.1, it can be seen what the influence of the velocity error model is on the performance of and the trajectories modified by TCAS II and ACAS Xa.

Stochastic Setting – S2.3
This parameter setting contains all default deterministic setting, except for the pressure altitude, as indicated in Table 102. The stochastic setting of the pressure altitude is according to the ACAS MOPS [3]. When comparing this parameter setting to the fully deterministic setting D1.1, it can be seen what the influence of the pressure altitude according to the ACAS MOPS is on the performance of and the trajectories modified by TCAS II and ACAS Xa.

Stochastic Setting – S2.4
This parameter setting contains all default deterministic setting, except for the radio altitude, as indicated in Table 103. When comparing this parameter setting to the completely deterministic setting D1.1, it can be how the radio altitude influences the performance of and the trajectories modified by TCAS II and ACAS Xa.

Stochastic Setting – S2.5
This parameter setting contains all default deterministic setting, except for the heading, as indicated in Table 104. When comparing this parameter setting to the completely deterministic setting D1.1, it can be how the heading influences the performance of and the trajectories modified by TCAS II and ACAS Xa.

Stochastic Setting – S2.6
This parameter setting contains all default deterministic setting, except for the slant range estimation, as indicated in Table 105. When comparing this parameter setting to the completely deterministic setting D1.1, it can be how the slant range estimation influences the performance of and the trajectories modified by TCAS II and ACAS Xa.

Stochastic Setting – S2.7
This parameter setting contains all default deterministic setting, except for the bearing estimation, as indicated in Table 106. When comparing this parameter setting to the completely deterministic setting D1.1, it can be how the bearing estimation influences the performance of and the trajectories modified by TCAS II and ACAS Xa.

4.4 Parameter Set 3

This set contains a baseline parameter setting that only contains deterministic settings and a full-stochastic parameter setting. This way the difference between deterministic and fully-stochastic settings can be analysed, which is one of the main goals of this research. The tables referenced in this section are included in Appendix C.2.

Deterministic Setting – D1.1

For this settings, all parameters are in the default deterministic setting in CAVEAT. This means the equipment and operation settings are default, no variability in pilot response is present, the pilot responds to advisories 100% of the time and no sensor errors are taken into account. The references to the tables with the default deterministic setting are added in Table 18. This deterministic setting is added to test how TCAS II and ACAS Xa perform without any intrinsic uncertainty and will be used to compare to parameter settings with one single source of uncertainty, to see the influence of that single source of uncertainty.

Table 18. Agent-based model parameter settings, Deterministic Settings – D1.1

CAVEAT Element		Table Reference
Pilot Model		
Pilot Response Mode	Deterministic	Table 64
Vertical Rate Error	Deterministic	Table 70
Delay	Deterministic	Table 72
Vertical Acceleration	Deterministic, ICAO model	Table 78
Ownship State Estimation		
GNSS-based Position Error Model	Deterministic	Table 81
GNSS-based Velocity Error Model	Deterministic	Table 83
Pressure Altitude	Deterministic	Table 85
Radio Altitude	Deterministic	Table 90
Heading	Deterministic	Table 92
Othership State Estimation		
Transponder-based Slant Range	Deterministic	Table 94
Transponder-based Bearing	Deterministic	Table 97

Stochastic Setting – S3.1

Stochastic Setting S3.1 contains the default full-stochastic settings for both the pilot model and the state estimation. This means variability in pilot response is present, the pilot responds to all advisories with a 80% probability and all sensor errors are taken into account. The stochastic setting of the vertical acceleration is speed dependent and the pressure altitude is according to the ACAS MOPS. The references to the tables with the settings are added in Table 19. This parameter setting will be used as a default for this set, to compare all other parameter settings to.

Table 19. Agent-based model parameter settings, stochastic setting – S3.1

CAVEAT Element		Table Reference
Pilot Response Mode	Stochastic, 80% response	Table 65
Vertical Rate Error	Stochastic	Table 71
Delay	Stochastic	Table 73
Vertical Acceleration	Stochastic, ICAO defaults	Table 80
GNSS-based Position Error Model	Stochastic	Table 82
GNSS-based Velocity Error Model	Stochastic	Table 84
Pressure Altitude	Stochastic, MOPS model	Table 86
Radio Altitude	Stochastic	Table 91
Heading	Stochastic	Table 93
Transponder-based Slant Range	Stochastic, MOPS model	Table 95
Transponder-based Bearing	Stochastic, MOPS model	Table 98

4.5 Parameter Set 4

This set contains parameter settings that can be used to analyse the sensitivity of the pilot response mode settings on the results. Together, they give a good overview of the effect of the different pilot response mode settings. The tables referenced in this section are included in Appendix C.3.

Stochastic Setting – S4.1

This set contains all stochastic parameter settings. The pilot response is modelled with a probability of 0.6 of a response to an initial RA and 0.8 for modified RAs. In Table 109 the references to the detailed parameters setting are included.

Stochastic Setting – S4.2

This set contains all stochastic parameter settings. The pilot response is modelled with a probability of 0.8 of a response to an initial RA, 0.6 for a modified RA if the previous RA is responded to and 0.8 for modified RAs that are not responded to. The references to all detailed settings are included in Table 110.

Stochastic Setting – S4.3

This set contains all stochastic parameter settings. The pilot response is modelled with a probability of 0.8 of a response to an initial RA, 0.8 for a modified RA if the previous RA is responded to and 0.6 for modified RAs that are not responded to. The references to all detailed settings are included in Table 111.

Stochastic Setting – S4.4

This set contains all stochastic parameter settings. The pilot response is modelled with a probability of 0.6 of a response to any RAs that are issued. The references to all detailed settings are included in Table 112.

To systematically investigate the influence of the uncertainty in the pilot response mode, the results of simulations with each of these settings are compared to results of the fully stochastic parameter settings S3.1. In these settings the probability of a pilot responding to any RA during the encounter is 80%. Its detailed parameter settings are stated in Table 19.

4.6 Parameter Set 5

This set contains parameter settings that can be used to analyse the influence of the pilot delay settings on the results. By comparing the results of each of the four alternative stochastic pilot delay with the default results, the effect of each of the settings can be deducted. The tables referenced in this section are included in Appendix C.4.

Stochastic Setting – S5.1

These parameter settings are all stochastic and the pilot response delay is altered by doubling the default preparation delay. In Table 113 all references to the detailed parameters setting are included.

Stochastic Setting – S5.2

These parameter settings are all stochastic and the pilot response delay is modelled with double the default mean action delay value. In Table 114 all references to the detailed parameters setting are included.

Stochastic Setting – S5.3

These parameter settings are all stochastic and the pilot response delay is modelled with double the default standard deviation of the action delay. In Table 115 all references to the detailed parameters setting are included.

Stochastic Setting – S5.4

These parameter settings are all stochastic and the pilot response delay is modelled by doubling the values of the preparation delay, the mean action delay and the standard deviation of the action delay with respect to their default values. In Table 116 all references to the detailed parameters setting are included.

To systematically investigate the influence of the uncertainty in the pilot delay, the results of simulations with each of these settings are compared to results of the fully stochastic parameter settings S3.1. Its detailed parameter settings are stated in Table 19.

4.7 Parameter Set 6

This set contains parameter settings that can be used to analyse the influence of the pressure altitude settings on the results. The tables referenced in this section are included in Appendix C.5.

Stochastic Setting – S6.1

This set contains all stochastic parameter settings. The pressure altitude is modelled according to ACAS MOPS and the values of the altitude-based standard deviation of the bias are double their default values. In Table 117 the references to the detailed parameters setting are included.

Stochastic Setting – S6.2

This set contains all stochastic parameter settings. The pressure altitude is modelled according to ACAS MOPS and the values of the standard deviation of jitter are double their default values. In Table 118 the references to the detailed parameters setting are included.

Stochastic Setting – S6.3

This set contains all stochastic parameter settings. The pressure altitude is modelled according to ACAS MOPS and the values of the altitude-based standard deviation of the bias and the standard deviation of jitter are double their default values. In Table 119 the references to the detailed parameters setting are included.

To systematically investigate the influence of the pressure altitude, the results of simulations with each of these settings are compared to results of the fully stochastic parameter settings S3.1. Its detailed parameter settings are stated in Table 19.

Together, the number of unique parameter settings amounts to 24. In combination with the 57 encounter geometries presented in Section 3.8, the total number of unique combinations of encounters and parameter settings is 2736 when looking at both TCAS II and ACAS Xa. It is too time consuming and beyond the scope of this research to individually analyse all these encounter-scenarios individually. The challenge lies in narrowing down this group to a lower number that is more workable. This can be done by looking at the combinations of encounters and parameter settings that give similar results and trying to gain a rough understanding of the relations between the encounter geometry, parameter setting settings and results. This is done by looking at several indicators.

5 ACAS performance indicators

This chapter introduces the indicators that are used for the analysis. A clear division can be made between general performance indicators and advisory indicators. The former regard the modified trajectory while the latter inform about the type of advisories that the ACAS equipment gave as part of the solution. In Section 5.1 the general indicators are stated, these are useful to obtain for each encounter geometry and parameter settings. Section 5.2 includes indicators that are specific to the advisories that are given and are useful to generate for encounter geometries of specific interest. These data expressed by these indicators is obtained from the CAVEAT Statistics module.

5.1 General Performance Indicators

This section includes the general indicators that are used during the analysis. The general indicators give information about the modified trajectory and do not indicate the details of the solutions that TCAS II and ACAS Xa gave for the encounters. Instead, they indicate the statistics about the resulting trajectory. The general indicators that are used in the analysis are displayed in Table 20, together with the information they contain when parameter settings are run in deterministic or stochastic setting.

Table 20. General Performance Indicators and how they are expressed for deterministic and stochastic simulations

Indicator	Definition	
	Deterministic	Stochastic
P(NMAC)	Encounter contains NMAC or does not contain NMAC	Probability of an encounter containing an NMAC
VMD	Vertical distance between the aircraft at CPA	Distribution of vertical distances between the aircraft at CPA
HMD	Horizontal distance between the aircraft at CPA	Distribution of horizontal distances between the aircraft at CPA
P(Crossing Encounter)	Encounter is crossing or not	Probability of an encounter containing a crossing trajectory

The most important general indicator that is used is the probability that an NMAC occurs. It gives an indication on how effective the end solution of ACAS is, without going into detail about how good the actual effective solutions are. When this indicator is computed for each separate type of encounter geometry, it can also give an indication about the effectiveness of ACAS with respect to specific types of geometries. This can help to identify possible sets of similar geometries where ACAS is less able to provide solutions to the situation. Ideally, the probability on an NMAC is as low as possible at all times, as the number of NMACs should be minimised at all times. For deterministic settings, the outcome of this indicator indicates directly if the simulated encounter contains an NMAC or not. For stochastic settings, the outcome of the indicator tells the user what the probability is of an encounter containing an NMAC in the simulated set of encounters.

The VMD is an indicator that goes into more detail regarding the geometry of the corrected trajectory, after TCAS II and ACAS Xa have issued advisories. It is interesting to compare the VMD in the original encounter to the VMD in the modified encounter, to test how much impact TCAS II and ACAS Xa solutions have on the trajectory. The modified HMD is slightly less interesting to compare to the original HMD, as there will be little change since encounters are solved with vertical solutions most of the time. However, the HMD can be used to indicate the severity of the solution and to gain insight in the types of RAs that are issued. When looking at minimum separation distances, both HMD and VMD should at least reach above the 100 ft vertically and 500 ft horizontally to not classify the encounter as an NMAC [2] [3]**.** Ideally, the separation margins are larger than that. For deterministic parameter settings, both VMD and HMD are given by a single distance in feet. When stochastic parameter settings are used, the indicators contain more information, in the form of a distribution.

The crossing encounters indicator indicates the probability that an encounter contains a trajectory where the two aircraft cross each other's trajectory. An encounter is said to be crossing if the sign of altitude difference between aircraft at CPA is opposite to the sign of altitude difference between aircraft at the time of the first TA (traffic alert, as issued by any of the two aircraft) or at the start of the encounter (if there is no first TA issued) [22]. This situation is undesirable as crossing encounters that originate from the interference of ACAS are counter-intuitive to pilots. For deterministic parameter settings, the indicator simply specifies if the simulated encounter contains a crossing or not. For stochastic parameter settings, the indicator gives the probability that an encounter in the simulated set contains a crossing trajectory.

5.2 Advisory Indicators

More specific indicators which relate to the type of solutions are included in Table 21. The most obvious indicators in this case are TAs and the types of RAs. They can give insight in the difference and probability of occurrence of the solutions used by TCAS II and ACAS Xa and how much impact TCAS II and ACAS Xa solutions have on the trajectory. When using these indicators for each of the encounter types, it can be seen in which encounter geometries ACAS opts for a solution with more impact on the trajectory (the RAs) rather than a milder solution (a TA), or both.

Several indicators are related to the desirability of the type of RA, which can be used to investigate how intuitive or invasive TCAS II and ACAS Xa RAs are to pilots. RAs can either be corrective or preventive. Corrective RAs are '*resolution advisories that instruct the pilot to deviate from current vertical rate*', and thus require an action from the pilot [2]. Preventive RAs are '*resolution advisories that instruct the pilot to avoid certain deviations from current vertical rate'* and thus do not require an action from the pilot [2]. Three types of Corrective RAs are of special interest:

- Increase Rate RAs advise the pilot to increase the altitude rate to a value exceeding that of a previous RA [2]. This can be done in both the positive (climb) or negative (descend) direction.
- A Reversal RA changes the sense to the opposite of the original RA [2]. The number of reversal RAs is ideally as low as possible as they are extremely confusing for pilots. This can result in a distrust in TCAS II and ACAS Xa solutions. Naturally, if there is no other option, a reversal RA should be chosen. If a certain encounter geometry generates numerous reversal RAs, it should be investigated why these are issued.
- The number of crossing RAs is investigated as crossing RAs are counterintuitive to pilots and their numbers should be monitored. An RA given by TCAS II is found to be crossing if '*own TCAS II aircraft is currently more than 100 ft below or above the threat aircraft for upward or downward sense advisories, respectively'* [2]. ICAO uses a slightly different definition of RAs that are issued by ACAS Xa, which are crossing if '*an advisory is based on the intention to resolve the risk of collision by crossing in altitude prior to reaching closest point of approach'* [3]. For this report, the ACAS Xa definition is used. This indicator should not be confused with the crossing encounter probability in Table 20.

Note that the Increase Rate, Reversal and Crossing RAs are all Corrective RAs, but a Corrective RA does not have to be an Increase Rate, Reversal or Crossing RA.

Table 21. Performance Indicators Related to Advisories

Indicator	Definition	
	Deterministic	Stochastic
TAs	TA is received or not	The probability of receiving a TA
RAs	Certain RA is received or not	The probability of receiving a certain RA
Corrective RAs	The mean number of corrective RAs per aircraft per encounter.	The mean number of corrective RAs per aircraft per encounter.
Increase Rate RAs	The mean number of increase rate RAs per aircraft per encounter.	The mean number of increase rate RAs per aircraft per encounter.
Reversal RAs	The mean number of reversal RAs per aircraft per encounter.	The mean number of reversal RAs per aircraft per encounter.
Crossing RAs	The mean number of crossing RAs per aircraft per encounter.	The mean number of crossing RAs per aircraft per encounter.
Timing of RAs	The time with respect to the start of the encounter it takes to issue a certain RA.	Distribution of time with respect to CPA it takes to issue a certain RA.
Timing of COC	The with respect to the start of the encounter it takes to issue the COC.	Distribution of time with respect to CPA it takes to issue the COC.

The timing of advisories is important to keep in mind and should always be related to a threshold timing. On itself, the number of seconds between the start of an encounter and the issue of an advisory does not indicate anything, but relating it to the time of CPA indicates how much time there is for the pilot to resolve the encounter by following the advisory. It should be more than five seconds as that is the average time it takes for a pilot to respond [7]. Apart from single RAs, RAs can also occur in sequences and when this is the case, the timing of the consecutive RAs is also of interest. It can indicate how much time it takes for ACAS to increase or reverse an advisory. Naturally, the type of RA issued to the own aircraft and the intruding aircraft at that time are needed to be able to interpret these timings.

The indicators mentioned in the previous section and this section will be used to generate percentages, timing and boxplots which present the results. This is done by using the data from the three .csv files introduced in Section 2.3.

6 Visualisation of TCAS II and ACAS Xa Policies

Because both TCAS II and ACAS Xa are black boxes, in this chapter the policies of TCAS II and ACAS Xa are visualised by making use of ACAS policy plots for specific encounter geometries. Section 6.1 describes how ACAS policy plots should be generated. Section 6.2 presents an algorithm that is developed to obtain the necessary information from CAVEAT output data. Visualisation techniques of this data are discussed in Section 6.3. Finally, the influences of the parameters used to define an encounter on the policy plot are included in Section 6.4.

6.1 Introduction to ACAS Policy Plots

As indicated in Section 1.1, one of the additional goals of this thesis is to understand how ACAS policy plots can be obtained. Understanding and constructing ACAS policy plots is a useful process to gain more insight in the ACAS Xa decision logic, among other things, as the complicated ACAS Xa decision logic is often considered to be a black box process. TCAS II on the other hand uses clear rules in pseudocode. By evaluating both TCAS II and ACAS Xa using the same procedure the comparison between the behaviour of the two systems can contribute to the understanding of the black box ACAS Xa logic. Additionally, TCAS II and ACAS Xa policy plots give a clear overview of TCAS II and ACAS Xa intentions over a wide range in altitudes and timings. Before this goal can be achieved, it is crucial to know exactly what TCAS II and ACAS Xa policy plots look like and how they should be interpreted.

From the literature study conducted in [13] it was found that ACAS policy plots illustrate the effect of different relative altitudes and timings to CPA on the RAs that are issued by ACAS in an encounter between a pair of aircraft. Currently, ACAS policy plots are mostly used for deterministic encounters, which have a 100% probability of issuing a certain advisory at a certain altitude and time. They are 2D, with timing to CPA in seconds on the x-axis and relative altitude in feet on the y-axis.

Figure 14 shows an example of an ACAS Xa policy plot which was derived in the development phase of ACAS Xa [23]. In the encounter that is shown, both aircraft fly level and the own aircraft is equipped with ACAS Xa. The intruding aircraft is pictured at zero time to CPA. As in a typical ACAS policy plot, the time to CPA is represented in seconds on the x-axis and the relative altitude between the two aircraft is represented in feet on the y-axis. Each coloured pixel represents the advisory that ACAS Xa of the own aircraft would give, if the own aircraft was at that position in the air. If the aircraft is in the white region, ACAS Xa would not alert. It can be seen that, for example, when the own aircraft is flying 300 feet below the intruder, an advisory at 15 seconds before CPA will indicate the own aircraft should descend. Since the two aircraft are flying level and no uncertainties are included, this policy plot is symmetric around the zero relative altitude line.

Two regions of interest are indicated by red areas. The first one is the triangle. When the own aircraft is located in that region, the CPA is still at least 20 seconds away and the uncertainty that comes with this makes it hard to decide on an RA to give. This uncertainty is not uncertainty in the pilot response or sensor errors, since there is a deterministic encounter. Rather it concerns the uncertainty of making a decision at a moment which is still far from CPA when there is a rather small relative distance between the aircraft. That is why ACAS Xa delays giving out an RA to a later point in time where this uncertainty is less and unnecessary or incorrect RAs are prevented. The other region of interest is the vertical region, from 5 seconds to CPA till CPA. Here, no RAs are given as, according to the standard pilot response model [7], the pilot will be too late with responding before CPA is reached. It can be argued if this really is the case, since this pilot response model takes large assumptions with respect to the reaction time. If the response model is altered, this orange region changes accordingly.

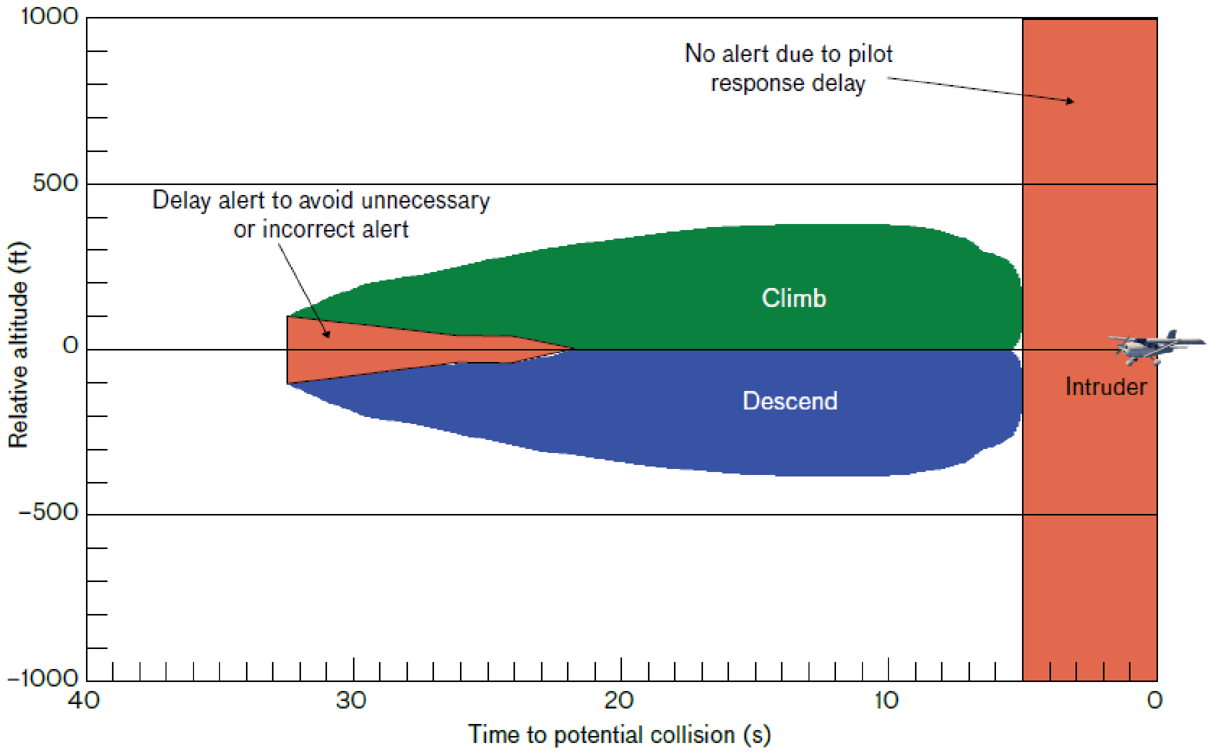


Figure 14. ACAS Xa policy plot where both aircraft fly level [14]

In literature no explanation is given on how to generate these plots, however, several conclusions can be drawn by inspecting the ACAS Xa policy plot in Figure 14 more closely. Figure 14 only displays one RA per combination of relative altitude and time to CPA, it does not display consecutive RAs. In real life, the simple visualisation in the ACAS Xa policy plot would have looked different. If an aircraft received a climb RA at 25 seconds before CPA and it would not have acted on this RA at 10 seconds before CPA, an additional climb now RA would most likely have been issued pressing the urgency of the initial RA. It seems as if the ACAS Xa policy plot in Figure 14 only displays initial RAs, specific to one altitude and moment in time. The issuing of a single RA at, for example, 8 seconds before CPA is not realistic, since ACAS Xa would have noticed the intruder and alerted before that time.

And thus it can be concluded that Figure 14 was most likely not obtained by running simulations with encounters at several altitudes and visualising all RAs that are issued, but was artificially generated looking directly at TCAS II and ACAS Xa logic assuming a certain state for the aircraft.

6.2 ACAS Policy Plots Data for Deterministic Settings

As indicated in Section 6.1, it is most likely that typical ACAS policy plots are obtained directly from an ACAS logic. The reasoning from previous section indicates that for the generation of typical ACAS policy plots, at every point in time an ACAS logic indicates what advisory would be given if the aircraft would instantaneously be located at the specified altitude. This approach will not be used for this thesis because the TCAS II and ACAS Xa logics are not available for public use. Instead, CAVEAT will be used to generate the initial RAs. This section presents the steps that were taken to generate ACAS policy plots from the output provided by CAVEAT.

Since ACAS policy plots only indicate the RA cloud of one of the aircraft in the encounter, it is decided that only aircraft 1 follows the trajectory for which an ACAS policy plot is generated. Aircraft 2 flies level in Northerly direction with the same airspeed as aircraft 1 for the complete duration of the encounter. It does so at the main altitude around which an ACAS policy plot is centered.

For the generation of ACAS policy plots using CAVEAT data, only the initial RA of the encounter is of interest, as was concluded in Section 6.1. The three pieces of information about aircraft 1 that are required to generate an ACAS policy plot are the specific initial RA, the relative altitude at which it is given and the time at which it is given with respect to CPA. This RA information can all be found in the summary.csv file from CAVEAT. This file contains all advisories that the TCAS II or ACAS Xa issues to the pilot, their timing since the beginning of the encounter and the altitude of both AC in the encounter at that time for the first 100 runs of a simulation. Since ACAS policy plots in this report all concern deterministic simulations, only one run per simulated encounter is included in this summary.csv file. The three pieces of information are filtered from the summary.csv file as follows.

- The specific initial RA issued for aircraft 1 is directly given by the summary.csv file. If no initial RA is issued for aircraft 1 for a certain altitude, this encounter does not contribute to the RA cloud in an ACAS policy plot.
- Time to CPA is the amount of seconds before CPA that the RA is issued to aircraft 1. In the summary.csv file, this time is not directly given. Instead, the time at which the RA was issued to the pilot since the beginning of the encounter is given, as well as the time of CPA also since the beginning of the encounter. By subtracting these two timings, the time from the issuing of the RA to CPA remains.
- Relative altitude between the two aircraft at which the RA is issued is also not directly given by the summary.csv file, only the absolute altitudes of both aircraft are supplied. Subtracting the altitude of aircraft 2 from the altitude of aircraft 1 results in the desired relative altitude.

These three required pieces of information are displayed inside of the plot by a specific colour, on the x-axis and on the y-axis, respectively. They need to be obtained for the complete state space that the user is interested in.

The difficulty of generating an ACAS policy plot with CAVEAT data lies in obtaining the RAs at desired points in time. Ideally, when generating such a plot, the timing on the x-axis is linear and is taken at a predefined, constant interval, set by the user. This is also seen in the examples in literature. However, it is not possible for a CAVEAT user to indicate at exactly what time they would like to know what the initial RA will be. The fact that the exact timing of the RA cannot be set by the user of CAVEAT is thus something that has to be accepted and taken in mind when generating the policy plots.

A viable option to work around part of this problem is to manipulate the input data such that the generated encounters start at a certain time before CPA. This way the timing of the RAs can still not be completely defined by the user, but it can be guided by the start time of the encounter to include only a certain range. For example, if the encounter is generated such that it starts only five seconds before CPA, the user knows that if an RA is generated, this RA will either be between 5 and 0 seconds before CPA or it will be after CPA. The latter can easily be filtered from the data, leaving relevant RAs from 5 to 0 seconds before CPA in the data. This way of working does not directly entail that ACAS will then also immediately give an RA at the start of the encounter. From exploratory runs it is seen that ACAS will, if the aircraft are in close proximity of each other, often first issue a TA before issuing its first RA. Naturally, it is possible to filter only the useful data from CAVEAT output, the RA in this case. However, this also means that the RA is issued at a later moment in time than the start of the encounter, namely after the first TA is issued. In conclusion: the timing of the RAs is not constant, cannot be predicted by the CAVEAT user and can only be influenced to a certain extent by the CAVEAT input.

Nonetheless, keeping this in mind it is still possible to generate ACAS policy plots using CAVEAT. In Figure 15 to Figure 18 it is visualised how one CAVEAT encounter is used to generate one data point of the RA cloud in an ACAS policy plot. Figure 15 displays the start of an encounter between two aircraft. This encounter is visualised in the state space of an ACAS policy plot. The aircraft have a relative altitude of 400 ft between them and aircraft 1 is approximately 35 seconds away from CPA, which is located at aircraft 2. Note: aircraft 2 is only visualised to mark CPA. Since this is the start of the encounter, aircraft 1 does not immediately issue RAs, it first starts to move. After approximately five seconds the initial RA is issued, a ‘Climb’ RA. The situation at this point in time is displayed in Figure 16. In the code to generate an ACAS policy plot, this RA at the specific relative altitude and time to CPA is given a colour, which is aqua in the case of a ‘Climb’ RA. It is then included in an ACAS policy plot, as displayed in Figure 17. If this process is then repeated for encounters of the same encounter geometry where aircraft 1 is located at all the desired relative altitudes and the encounters start at the desired timings to CPA, the complete RA cloud can be generated. The final product is included in Figure 18, where the highlighted data point of the example encounter then becomes part of a larger RA cloud.

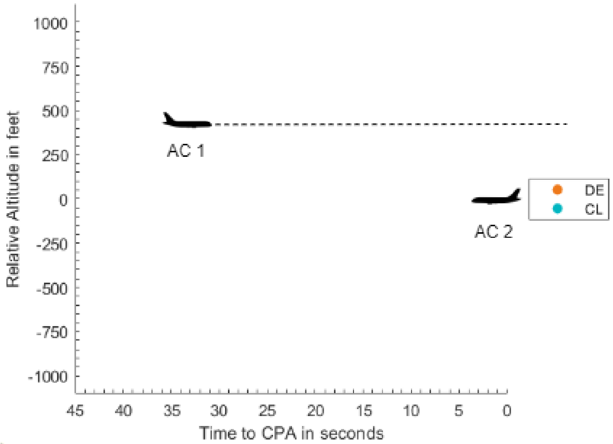


Figure 15. Situation at start of a single encounter used to generate one data point in an ACAS policy plot. Aircraft 1 flies level along the dotted trajectory and aircraft 2 flies level at the main altitude for the complete duration of the encounter.

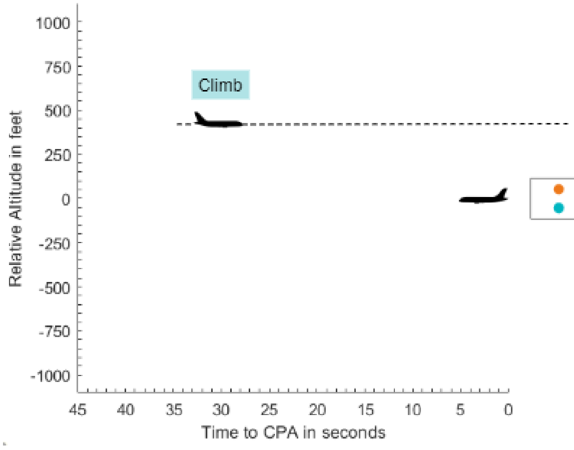


Figure 16. After aircraft 1 started propagating forward, the initial RA is issued to aircraft 1 by an ACAS on board.

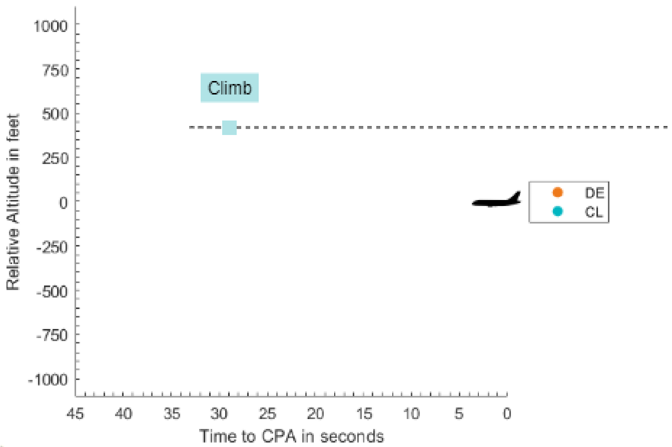


Figure 17. The RA is given a colour and visualised at the correct location in an ACAS policy plot of the encounter.

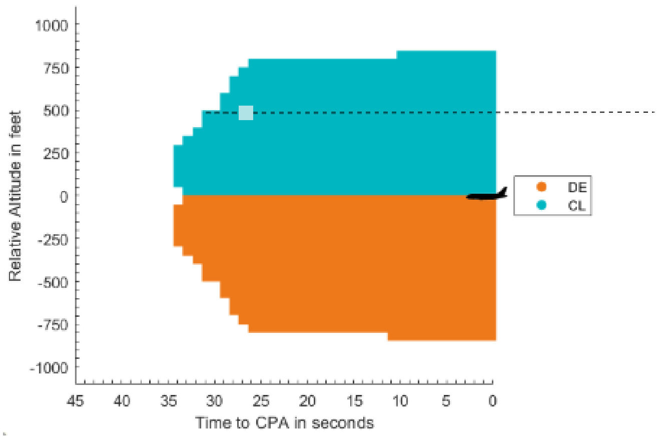


Figure 18. This process is repeated for the entire state space which results in the finished ACAS policy plot. The RA in the figure has a different shade of aqua for demonstrational purposes.

Generating an ACAS policy plot in such a way generates a grid of given initial RAs. As indicated before, exact x-position of the grid points, and the horizontal distance between these grid points, however, cannot be set beforehand.

In principle, the amount of encounter files that is needed to generate an ACAS policy plot is thus equal to the number of points inside the grid of an ACAS policy plot. For example, if an ACAS policy plot is to have 6 points in time before CPA and 8 altitudes, the grid contains 48 points, which all contain one RA or no RA. Therefore, in this example 48 encounter files are required, where each set of 8 encounters starts at the same time before CPA.

To build an understanding of the timings of the initial RAs, several exploratory ACAS policy plots were generated. During the encounters that were used for the exploratory ACAS policy plots, the trajectory of aircraft 1 followed the trajectory for which an ACAS policy plot was generated.

In the exploratory runs, several plots were generated by using encounters starting from 1 second to CPA to encounters starting from 60 seconds to CPA. It was observed that during the encounters that started in the two seconds before CPA, no RAs were issued at all. During the encounter that starts at 3 seconds to CPA, there are RAs given, but they are only issued 3.5 seconds into the encounter, making them have negative time to CPA. These encounters are not useful for the generation of an ACAS policy plot and are therefore not used. Encounters that start 4 seconds before CPA are the first encounters where initial RAs are issued before CPA.

It is important to think about the boundaries of the plot. At altitudes far from CPA or at moments far before CPA, there will be no RA given by TCAS II or ACAS Xa, simply because they are not triggered (yet). It is also of interest when TCAS II or ACAS Xa stop issuing RAs, albeit due to altitude difference or due to time before CPA. That is why an ACAS policy plot should not only include the altitudes and timings where RAs are issued, but also the first several altitudes and timings outside of the RA cloud. These altitude and timing thresholds are be obtained by trial and error. For the use of this thesis the relative altitude ranges from 1000 ft below to 1000 ft above the main altitude of aircraft 2 in steps of 50 ft.

The relative altitude between the aircraft is calculated by subtracting the altitudes of the two aircraft from each other as in (3.4 in Section 3.4. The altitude of aircraft 2 s_2^z remains the altitude of CPA $h_{t_{CPA},i,j}$ for the complete duration of all encounters that are used to generate an ACAS policy plot. The altitude of aircraft 1 at CPA $s_{t_{CPA},1}^z$ varies as an ACAS policy plot is generated for aircraft 1. The altitude of aircraft 1 at CPA is calculated by subtracting the VMD $d_{i,j}^{VMD}$ from the altitude of CPA, as was described in (3.27 in Section 3.6. The input altitude of the encounters thus is defined by the altitude of CPA and the VMD $d_{i,j}^{VMD}$.

The duration of the encounter files ranges from 4 seconds to CPA to 60 seconds to CPA, in steps of 1 second. Of course, these typical relative altitude and duration ranges can be easily altered if necessary.

Table 22. Input ranges of VMD and timing before CPA for TCAS II and ACAS Xa policy plots

Input parameters	Description	Unit	Range
$d_{1,2,lower}^{VMD}$	VMD at CPA, lower limit	ft	-1000
$d_{1,2,upper}^{VMD}$	VMD at CPA, upper limit	ft	1000
$d_{1,2,step}^{VMD}$	VMD steps	ft	50
$t_{preCPA,lower}$	Time before CPA, lower limit	s	4
$t_{preCPA,upper}$	Time before CPA, upper limit	s	60

Keeping all this in mind, the same ten parameters as introduced Section 3.4 and equations introduced in Section 3.6 are used to propagate the trajectories and generate the encounter files as input for CAVEAT. The propagation is done according to the backwards propagation in Eq. (3.33), since an ACAS policy plots only use data from the moments before CPA. The trajectories are then generated for the ranges of VMDs and time before CPA displayed in Table 22. The pseudocode for the process explained in this section is included in Eq. (6.1).

$$\begin{aligned}
&\text{FOR } i = 0 \text{ TO } i = d_{1,2,step}^{VMD} \\
&\quad d_{1,2}^{VMD} = d_{1,2,lower}^{VMD} + d_{1,2,step}^{VMD} \cdot i \\
&\quad \text{FOR } t = t_{preCPA,lower} \text{ TO } t = t_{preCPA,upper} \\
&\qquad \text{Backward Trajectory Propagation} \\
&\quad \text{NEXT} \\
&\text{NEXT}
\end{aligned} \tag{6.1}$$

The combination of the lower and upper VMD limits and the VMD step size $d_{1,2,step}^{VMD}$ of 50 ft for this thesis results in a loop that is repeated forty times. Each time the upper for-to-next loop is started, the VMD $d_{1,2}^{VMD}$ is calculated again such that the VMD starts at -1000 and then takes altitude steps of 50 ft which result in consecutive VMDs of -950, -900 etc. ft with respect to CPA.

After the generated encounter files are used to simulate the RAs, the output data needs to be filtered to contain only the altitude, initial RA and time to CPA of the first aircraft. This is done according to the pseudo-code included in Eq. (6.2).

$$\begin{aligned}
&\text{FOR each row in summary.csv} \\
&\quad \text{IF row contains initial RA of aircraft 1 THEN} \\
&\qquad \text{Save initial RA} \\
&\qquad \text{Save altitude} \\
&\qquad \text{COMPUTE time to CPA} \\
&\qquad \text{Save time to CPA} \\
&\quad \text{END} \\
&\text{END}
\end{aligned} \tag{6.2}$$

If all information is saved, each RA type is given a specific colour and a plot can be generated.

6.3 ACAS Policy Plot Visualisation Techniques for Deterministic Settings

Now that it is clear how the data used in an ACAS policy plot is gathered and filtered, the visualisation of the data is discussed in this section.

Several different plots are made with one set of data, used to show the difference between the plots and to point out the difficulties in generating the policy plot. The data comes from a simulation of the deterministic parameter setting D1.1 and the type 1 encounter with a course angle of 180 degrees and 0 lateral HMD. The main altitudes at which this encounter is simulated is 36000 ft, with upper and lower vertical distances of 35000 to 37000 feet, simulated in intervals of 50 feet. The aircraft fly with an airspeed of 480 kts. The time before CPA is varied from 0 seconds to CPA to 60 seconds to CPA and after CPA five seconds are simulated, with the regular time steps of one second.

How the data is displayed influences an ACAS policy plot by a great deal. An initial ACAS policy plot that was generated consisted of only the grid points, that were plotted using the Scatter function in Matlab R2018b, as displayed in Figure 19. CPA is located at the far right of the plot, at zero seconds to CPA and zero relative altitude. It can be observed that in this encounter geometry the timing of the RA per altitude happens at the exact same intervals, resulting in the vertical lines of data points.

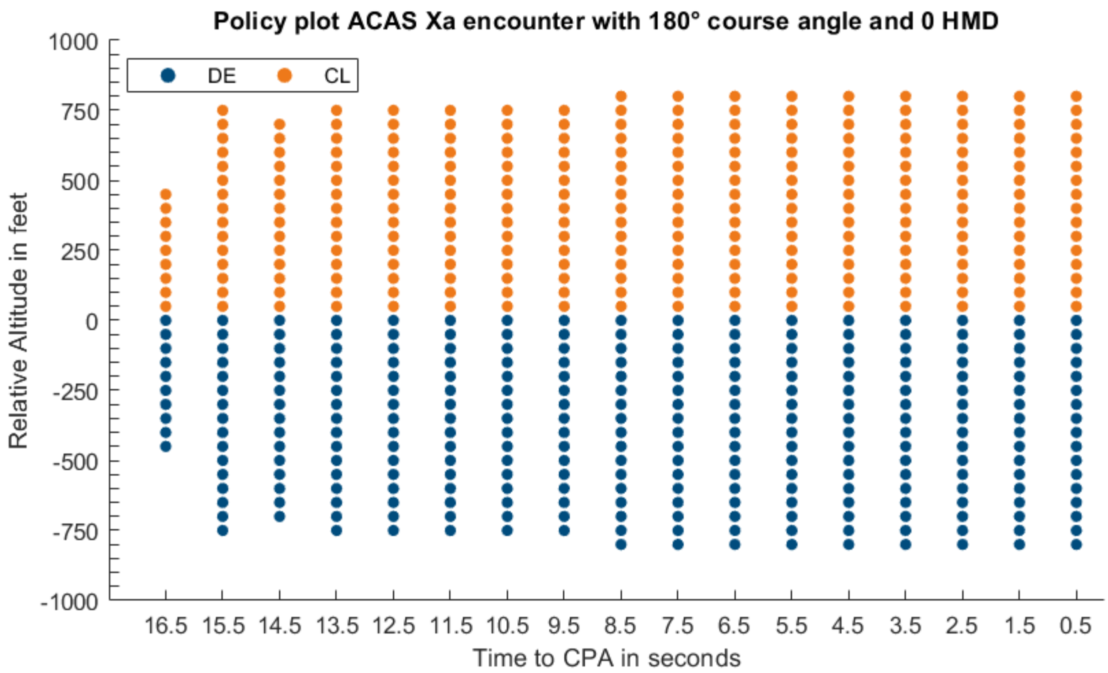


Figure 19. Example of ACAS Policy Plot - Matlab Scatterplot

Since it is desired to have a sort of cloud with the RA types as in Figure 14, instead of the separate points as in Figure 19, other display methods are also investigated. There are several standard functions in Matlab to fill a state space with colours according to values given to grid points. They all use a grid with points along horizontal and vertical lines. One example of such a plot is included in Figure 20. The RAs given at each point in the grid are now connected to each other and form one solid RA cloud without empty grid points. The colour of each face depends on the value of the top-left vertex. Of the four vertices, the one that comes first in the x-y grid determines the colour of the face.

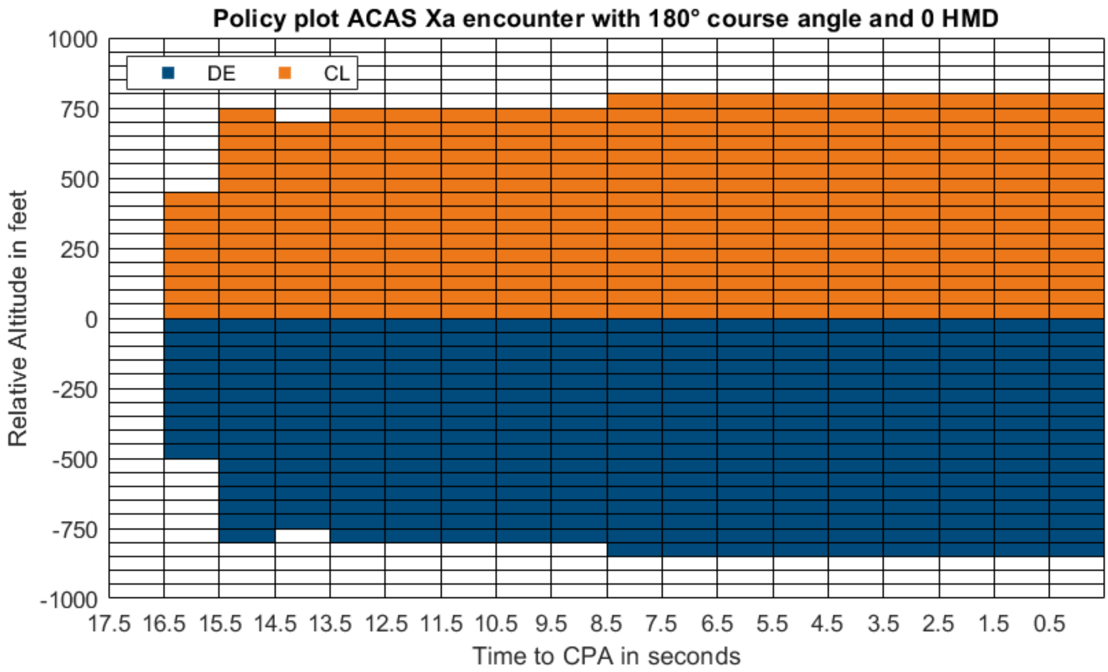


Figure 20. Example of ACAS policy plot with solid RA cloud using grid along horizontal and vertical lines

Practically, this means that for this ACAS policy plot the grid in Figure 21 is used. In this grid, the type of RA that is gathered at point B is displayed in the square that is below B vertically and next to be B horizontally, namely the square that is indicated by RA_1.

At the borders of each RA cloud, interpolation needs to be used with care. In the previous two generated policy plots, in Figure 19 and Figure 20, the grid consisted of horizontal and vertical direction and the division between the two RAs was quite clear. This, however, will not always be the case. More intricate encounter geometries result in more intricate policy plots, where the division between two RAs can vary per relative altitude. Interpolating is not straightforward in that case. Especially the borders of the RA cloud are difficult to interpolate without taking large assumptions.

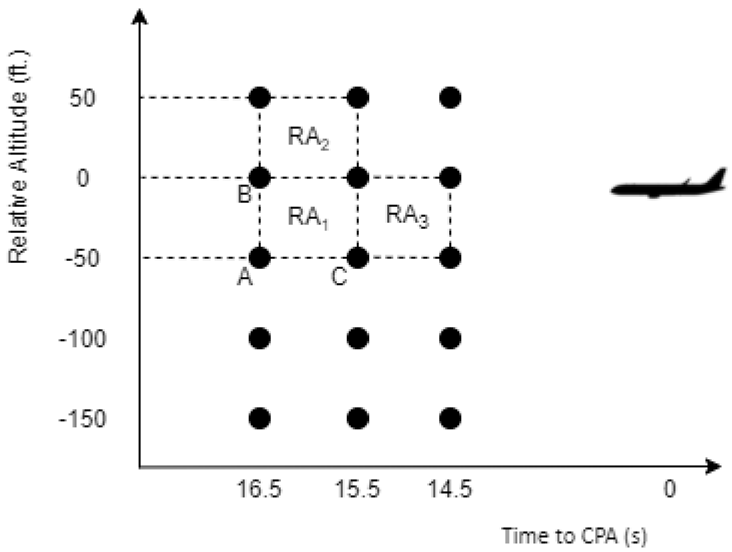


Figure 21. Grid along horizontal and vertical lines used to compute ACAS policy plot in Figure 20.

It was found that this phenomenon occurs in encounters with a climbing or descending aircraft 1 that are used to generate an ACAS policy plot. The grid points are then not ordered in horizontal and vertical lines, but in lines that go diagonally. An example of an ACAS policy plot where aircraft 1 has a positive vertical velocity is added in Figure 22. If the grid with horizontal and vertical lines as in Figure 20 is now used, there will be gaps in the RA cloud as not every timing contains an RA at each relative altitude, which is not desirable. That is why this grid plot can only be used for ACAS policy plots if there are no gaps in the data.

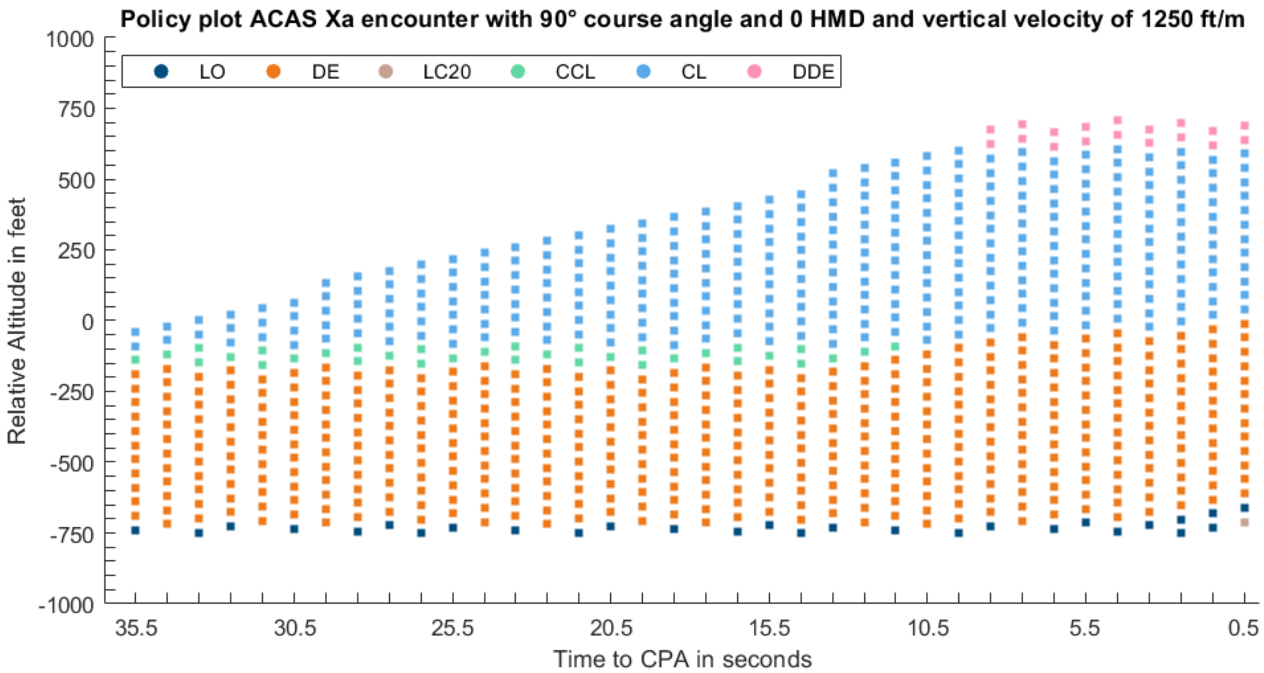


Figure 22. ACAS Policy plot for encounter with climbing aircraft with single grid points

Since a more robust way of generating ACAS policy plots is desired, another technique is explored. One relatively easy way to fill up the space surrounding the grid points is to simply increase the size of the bullets in the scatterplot. This way the grid points inside the RA cloud are merged such that no gaps are left and at the borders, no extreme assumptions have to be taken. These bullets are located on top of the data point.

The size of the bullets that is required to reach the full RA cloud depends on the location of the datapoints. If they are located in percent horizontal and vertical lines as was the case in the example of Figure 19, a full RA cloud can be reached if the width bullet represents one second of time and the height of the bullet represents 50 ft. These are the intervals with which the encounter files are generated. However, if the grid points have less structure, the size of the bullets can only be determined by trial and error, as the location of the grid points is not known in advance.

As a consequence, the bullets used to display the RA at the grid points can overlap, meaning that the borders of the different RA clouds might not lie exactly at the location that they truly lie at. At most, the borders are located half a second or 25 feet from their actual location. However, ACAS policy plots are used to obtain a general understanding of the behaviour of an ACAS so this relatively small offset is acceptable.

An example of what an ACAS Xa policy plot with the climbing aircraft then looks like is included in Figure 23. This figure starts to look similar to ACAS policy plots in literature, but it still has a rough grid.

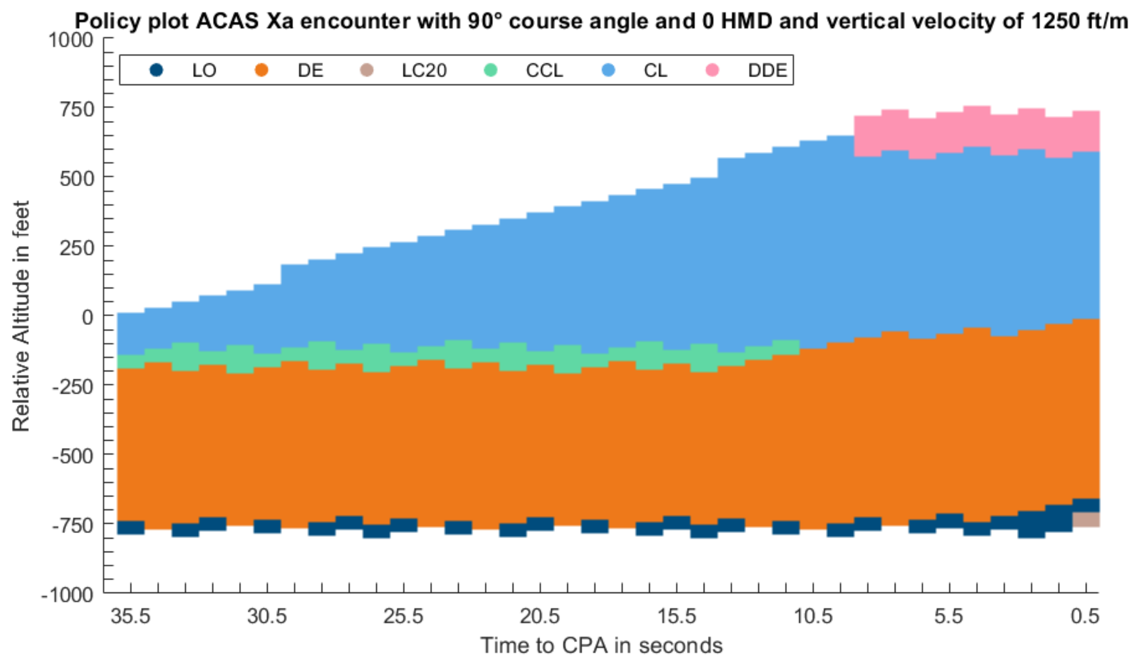


Figure 23. ACAS Xa Policy plot for encounter with climbing aircraft with merged grid points

Naturally, a finer grid increases the accuracy of and details in the policy plot. The timing of an RA can be specified in 1 second intervals in CAVEAT, which is then the smallest possible dimension of the grid on the x-axis. The altitude of an encounter can be specified as accurate as the CAVEAT user desires, however in raw CAVEAT data the altitude is expressed to the tenth of a foot, so the smallest dimension of the grid possible on the y-axis is a tenth of a foot. Increasing the grid accuracy significantly increases the amount of encounters and computations that are required to cover the complete state space. This results in a longer computation time. That is why it is decided to use a step size of 50 ft relative altitude and the default step size of one second for the timing. This way one ACAS policy plot can be generated within a reasonable time, roughly an hour in this case, while it remains accurate enough to clearly display the RA cloud in the state space.

6.4 Comparison of TCAS II and ACAS Xa Policy Plots

This chapter demonstrates the influences of the different parameters that define the encounters on the shape of the RA cloud and its contents by using TCAS II and ACAS Xa policy plots. To demonstrate these influences, one standard encounter geometry is used. Unless otherwise specified, this encounter geometry occurs at 36000 ft altitude, where both aircraft fly level and the relative course angle is 180°. The airspeed at this altitude is the default 480 kts. For the generation of the TCAS II and ACAS Xa policy plots, the altitude of aircraft 1 is varied, such that positive and negative vertical relative distances occur, as explained in Section 6.2. Aircraft 2 is fixed at CPA for the complete duration of the encounter. The encounter trajectories all have a duration of 5 seconds after CPA and vary from 0 to 70 seconds before CPA. This is enough to capture the complete RA cloud. Each ACAS policy plot is generated separately for TCAS II and ACAS Xa, such that the comparison between the two systems can be made. In Table 23 all RAs that were issued by TCAS II and ACAS Xa are included, as well as their CAVEAT code, which is used in the legend of the figures. Since TCAS II has a wider range of RAs available to issue, the last column of the table indicates for which ACAS the RA is available.

Table 23. TCAS II and ACAS Xa advisories and CAVEAT codes

CAVEAT Code	RA	Available for
LO	Level Off	TCAS II & ACAS Xa
DE	Descend	TCAS II & ACAS Xa
CL	Climb	TCAS II & ACAS Xa
DDE	Do Not Descend	TCAS II & ACAS Xa
DCL	Do Not Climb	TCAS II & ACAS Xa
MCL	Maintain Climb	TCAS II & ACAS Xa
CDE	Crossing Descent	TCAS II & ACAS Xa
CCL	Crossing Climb	TCAS II & ACAS Xa
MCCL	Maintain Crossing Climb	TCAS II & ACAS Xa
LD05	Limit descent rate to a maximum of 500 fpm	TCAS II
LD10	Limit descent rate to a maximum of 1000 fpm	TCAS II
LD20	Limit descent rate to a maximum of 2000 fpm	TCAS II

LC05	Limit climb rate to a maximum of 500 fpm	TCAS II
LC10	Limit climb rate to a maximum of 1000 fpm	TCAS II
LC20	Limit descent rate to a maximum of 2000 fpm	TCAS II

Level Flight

In Figure 24 and Figure 25 ACAS policy plots for the standard geometry are displayed, for TCAS II and ACAS Xa, respectively. Three important notes can be made. Firstly, the shape of the TCAS II policy plot is rectangular, this means that regardless of the altitude, TCAS II issues its initial advisories at around 36 seconds before CPA and till an altitude of 700 ft. In [13] it was described how the alerting volume around an aircraft is defined according to TCAS II logic. It can be described by the horizontal range tau in seconds, which expresses the amount of time to CPA at which an RA is first issued, and the vertical distance threshold ZTHR in ft. At altitudes between 20000 and 420000 ft the alarm thresholds are 35 seconds and 700 ft respectively, which is in line with the findings in the TCAS II policy plot in Figure 24 [8].

The ACAS Xa policy plot does not show this clear 'time threshold' at which at all altitudes RAs are issued. For example, at a relative altitude of 600 ft ACAS Xa is only triggered from 27 seconds onwards, while TCAS II is triggered from 36 seconds onwards. ACAS Xa also issues RA at larger relative altitudes than TCAS II does. There is a small cove at the division between the 'Climb' and 'Descend' RA at around 35 seconds to CPA.

Also of interest are the contents of the RA cloud. The contents of both RA clouds are mostly similar, the division between the 'Climb' and 'Descend' RA lies exactly at the zero relative altitude line, as is expected without the influence of uncertainties. Additionally, TCAS II issues the 'Do Not Climb' and 'Do Not Descent' RAs to the aircraft at altitudes around 550 to the ZTHR 700 feet above and below the intruder. When equipped with ACAS Xa the own aircraft receives a 'Climb' RA if it flies above the intruder and a 'Descend' RA if the own aircraft flies below the intruder. The 'Do Not Descend' and 'Do Not Climb' RAs are not used in this case.

Thirdly, the ACAS Xa policy plot does not match the explanation presented in [23]. There it was described that a few seconds before CPA, ACAS Xa would stop issuing RAs, as the pilot could not respond before CPA, as seen in Figure 14. In Figure 25 this behaviour is not seen, ACAS Xa keeps issuing RAs to the aircraft till the moment of CPA.

Varying the relative course angle, or even adding level turns to the standard encounter resulted in identical ACAS policy plots. This indicates that the course angle has no influence on the initial RAs issued by TCAS II and ACAS Xa.

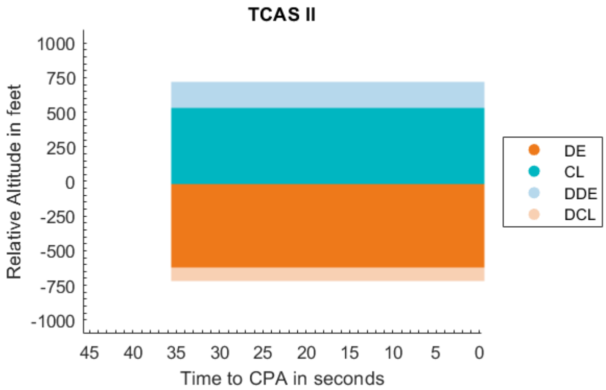


Figure 24. TCAS II policy plot of level encounter with course angle of 180° at 36000 ft.

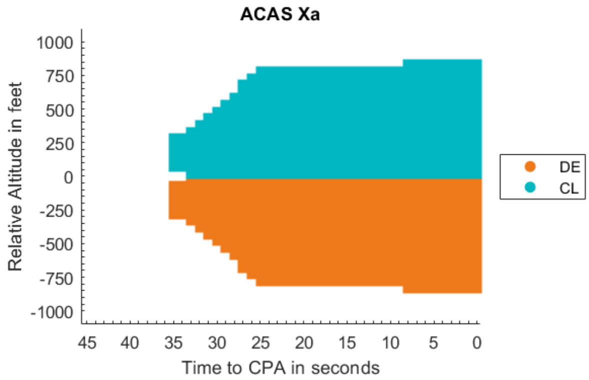


Figure 25. ACAS Xa policy plot of level encounter with course angle of 180° at 36000 ft.

Influence of altitude

In Figure 27 to Figure 28 the TCAS II and ACAS Xa policy plots of the standard encounter are shown, but now at the lower altitudes of 15000 and 7500 ft. At these altitudes, both aircraft in the encounter fly at 295 kts.

In the TCAS II policy plots it can be seen that the typical rectangular shape of the RA cloud remains. At lower altitudes, the RA cloud starts at a time closer to CPA. TCAS II logic thus indicates that it is only necessary to issue RAs closer to CPA. This is in line with the alarm thresholds presented in [13], where it was seen that at the altitudes from 1000 to 20000 ft the ZTHR is located at 600 ft. Tau is 30 seconds at 15000 ft altitude and 25 seconds at 7500 ft altitude. Figure 27 and Figure 26 show the exact same RA thresholds.

Additionally, TCAS II issues various types of RA at these two lower altitudes that were not seen at the original altitude of 36000 ft. These are only issued at relative distances far away from CPA and at moments just before CPA. The RAs are all preventive and indicate a maximum descent or climb rate from that moment forward. They are only available for TCAS II, as indicated in Table 23. Slight differences are seen in the relative altitudes that the 'Climb' and 'Descend' RAs are issued at. In the original ACAS Xa policy plot at 36000 ft these were issued to relative altitudes of 550 ft above and below the main altitude. At 15000 and 7500 ft altitude, they are only issued to 350 ft above and below the main altitude. The 'Do Not Descend' and 'Do Not Climb' RAs are issued over a slightly wider range of relative altitudes as the altitude decreases.

The ACAS Xa policy plot only retains part of its characteristic shape found in the original ACAS policy plot at 36000 ft. In contrary to the TCAS II policy plot, the ACAS Xa RA cloud does not start at timings closer to CPA, it remains to start at 35 seconds to CPA, regardless of the altitude of the encounter. The main difference in the shape is concerning the large relative altitudes, far away from the main altitude. At 36000 ft altitude, ACAS Xa was triggered when aircraft 1 was roughly 800 ft from the intruding aircraft. At an altitude of 15000 ft ACAS Xa is only triggered if the relative altitude is below 500 ft. This trigger altitude decreases to 400 ft if the altitude is decreased to 7500 ft ACAS Xa also does not use any other RAs than the 'Climb' and 'Descend' RAs.

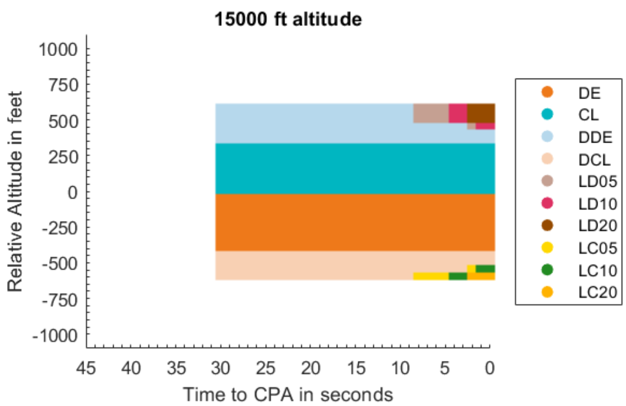


Figure 27. TCAS II policy plot of level encounter with course angle of 180° at 15000 ft.

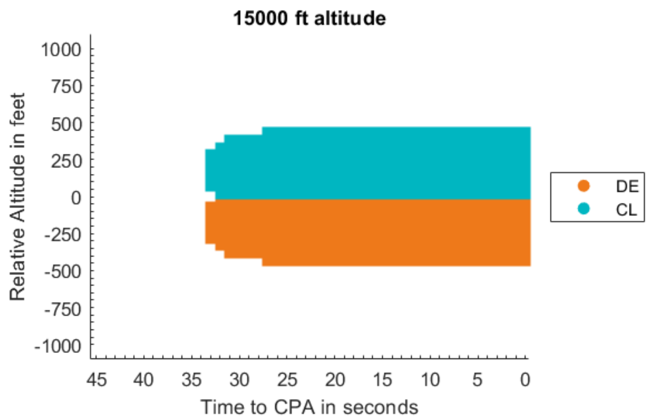


Figure 29. ACAS Xa policy plot of level encounter with relative course angle of 180° at 15000 ft.

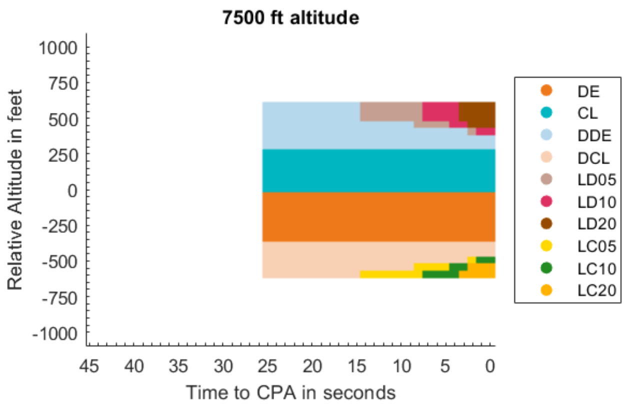


Figure 26. TCAS II policy plot of level encounter with relative course angle of 180° at 7500 ft.

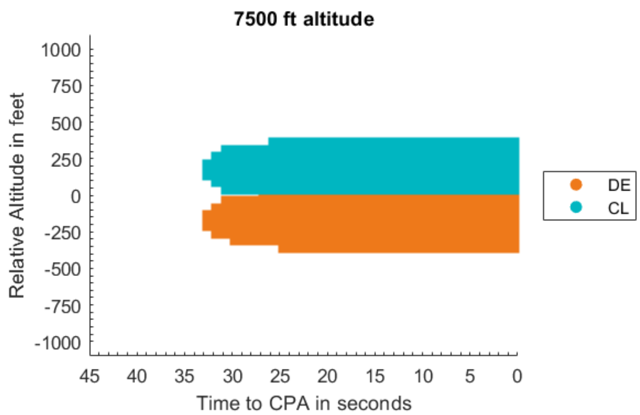


Figure 28. ACAS Xa policy plot of level encounter with relative course angle of 180° at 7500 ft.

Influence of vertical velocity

To test how the vertical velocity in an encounter influences TCAS II and ACAS Xa policy plots, three policy plots with vertical velocities of aircraft 1 between 500 ft/min and 1500 ft/min are generated. An example of such an encounter is shown in Figure 30.

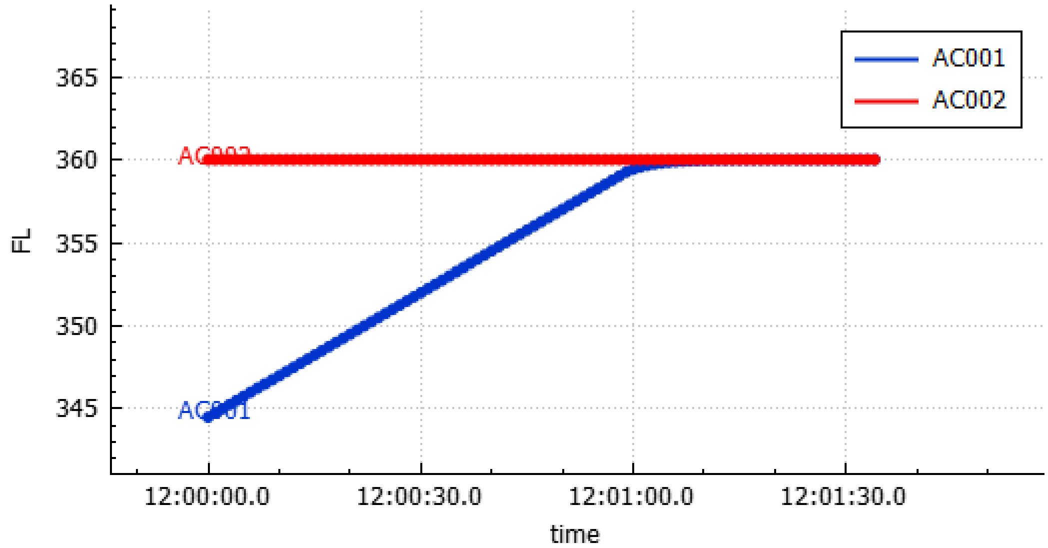


Figure 30. Example of encounter where aircraft 2 flies level and aircraft 1 climbs and levels off at the same altitude.

Aircraft 1 is seen climbing with a positive vertical velocity and level-offs to fly level just before CPA. In Figure 31 and Figure 32 TCAS II and ACAS Xa policy plots for an encounter where the own aircraft has a vertical velocity of 500 ft/min are added. It can be seen that especially TCAS II issues a wider range of RAs just seconds before CPA than in the encounter where both aircraft fly level. It must be said that these RAs cannot be issued by ACAS Xa, such as the climb and descent rate limitations, as indicated in Table 23.

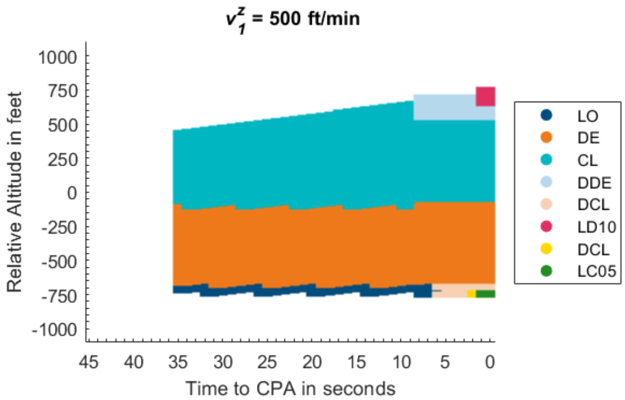


Figure 31. TCAS II policy plot of encounter with vertical velocity of 500 ft/min at 36000 ft.

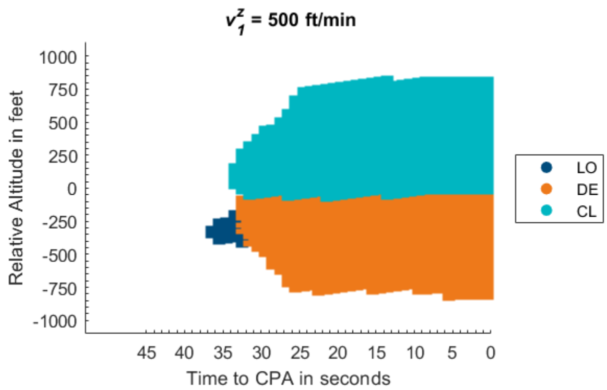


Figure 32. ACAS Xa policy plot of encounter with vertical velocity of 500 ft/min at 36000 ft.

From around 7 seconds to CPA till CPA, both systems again exhibit the clear horizontal division between the ‘Climb’ related RAs and the ‘Descend’ related RAs. At altitudes just below the zero relative altitude line, the aircraft are given a type of ‘Climb’ RA by both TCAS II and ACAS Xa. Since aircraft 1 already has a positive vertical velocity, it cannot reverse this positive velocity to a negative vertical velocity so soon before CPA, which is why both ACAS choose to issue a climb RA to the aircraft. The clouds of the respective RAs have a straight, horizontal top and bottom.

Moving to moments further away from CPA, sawtooth patterns can be observed at the borders of the different RA clouds. These are the result of the grid that is used to generate an ACAS policy plot, hence why both TCAS II and ACAS Xa policy plots exhibit this behaviour. Since it is impossible for CAVEAT users to specify exactly at what altitude and time before CPA an RA is desired, the grid in the plot follows the trajectories used to generate the plot. As long as the aircraft flies level, the grid points remain in vertical and horizontal lines. As soon as the own aircraft climbs or descends, the vertical and horizontal position of the grid points starts to shift along with the trajectory of the own aircraft, which causes these sawtooth patterns. In Figure 32 another grid effect is visible as well which is shown in more detail in Figure 33. At 33 seconds to CPA, the two small coves in the orange 'Descend' RA cloud are also the result of how the grid points overlap if there is a climbing or descending aircraft in the encounter.

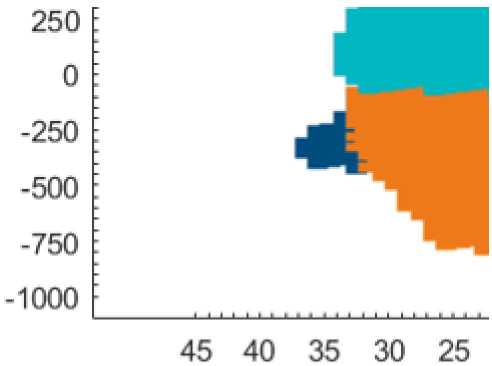


Figure 33. Detail of grid effects - sawtooths and coves

Due to the grid points that are following the trajectory of the own aircraft, the markers that are used on grid points can partly overlap each other and they do not always do so with the same amount. When analysing an ACAS policy plots it is important to understand that these two behaviours originate from grid and plotting effects and not from the systems itself. Since ACAS policy plots are primarily meant to gain understanding about the initial intentions of TCAS II and ACAS Xa and to provide the user with a broad view of the RA cloud, these relatively small grid effects do not significantly influence the results. They are therefore accepted as a limitation.

While the TCAS II policy plot shows a banner of 'Level Off' RAs along almost the complete duration of the plot if the own aircraft flies 600 to 700 ft lower than the intruder, the ACAS Xa policy plot does not show this behaviour. Instead, ACAS Xa issues a small cloud of 'Level Off' RAs between 32 and 36 seconds before CPA when the own aircraft flies 200 to 450 ft below the intruder.

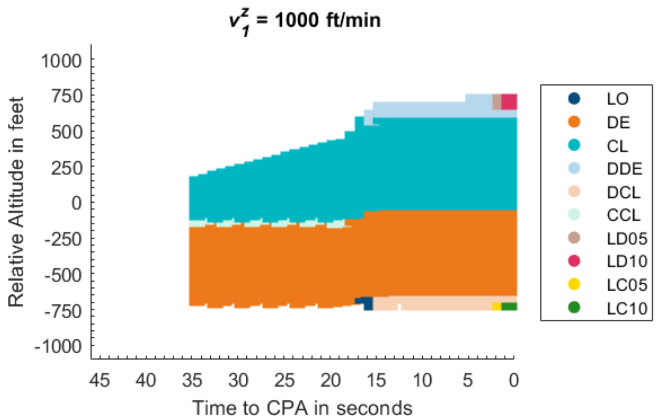


Figure 34. TCAS II policy plot of encounter with vertical velocity of 1000 ft/min at 36000 ft.

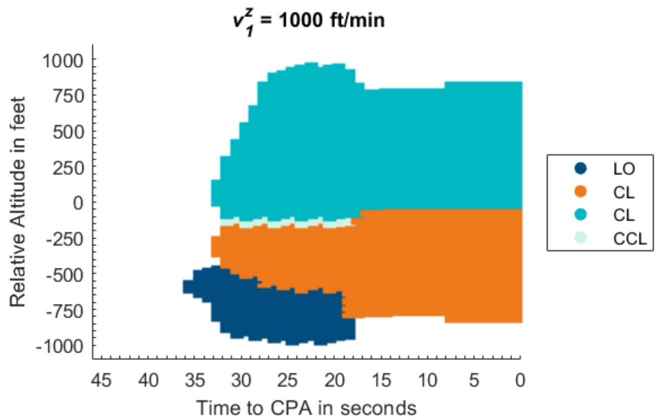


Figure 35. ACAS Xa policy plot of encounter with vertical velocity of 1000 ft/min at 36000 ft

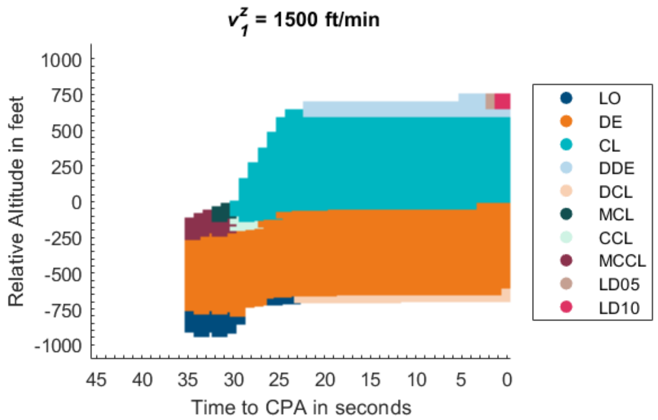


Figure 36. TCAS II policy plot of encounter with vertical velocity of 1500 ft/min. at 36000 ft.

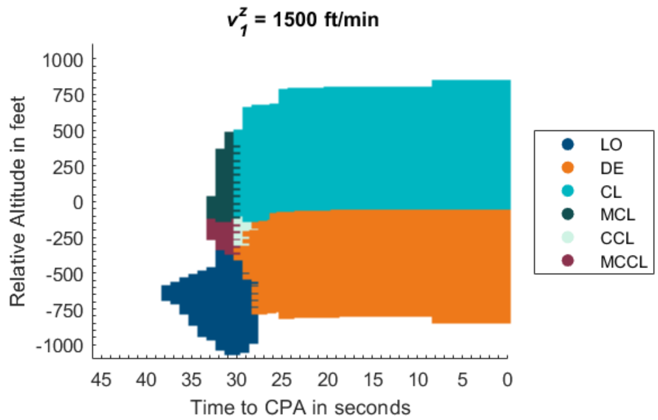


Figure 37. ACAS Xa policy plot of encounter with vertical velocity of 1500 ft/min at 36000 ft.

This ‘Level Off’ cloud then increases in size and moves to the lower regions of the ACAS Xa policy plot when the vertical velocity is increased, as can be seen in Figure 35 and Figure 37. TCAS II also issues some ‘Level Off’ RAs but does so in significantly less instances, as can be seen in Figure 34 and Figure 36. This indicates that ACAS Xa prefers more passive solutions than TCAS II if possible. The ‘Level Off’ RA is a less invasive solution that minimizes the deviation from the original flight plan.

Next to the RAs that limit the climb and descent rate and the ‘Level Off’ RAs, in the encounters with vertical velocities of 1000 ft/min both TCAS II and ACAS Xa issue the ‘Crossing Climb’ RA to the own aircraft when it is situated just below the intruder and between 36 and roughly 18 seconds before CPA. In the encounters with the vertical velocity of 1500 ft/min ‘Maintain Climb’ and ‘Maintain Crossing Climb’ RAs are issued as well.

The effect of the sawtooths lessens as the vertical velocity increases, since the level-off takes longer as the vertical velocity increases.

Just as in the level encounter, the RA cloud of TCAS II starts at 36, where at the majority of the relative altitudes the first initial RAs are issued. As the vertical velocity increases, this 'wall' of initial RAs continues to exist but focuses more on negative relative altitudes. These are the encounters where the own aircraft flies below the intruder.

It was expected that the lower part of the cloud with 'Climb' RAs moved further down as the vertical velocity increased, as a larger vertical velocity means it takes more time for the aircraft to reverse its direction. This, however is not the case.

So in conclusion, increasing the positive vertical velocity results in a larger number of different RAs in the RA cloud for both TCAS II and ACAS Xa. ACAS Xa prefers the 'Level Off' RA while TCAS II prefers the 'Descend RA'. The latter is more invasive. Additionally, ACAS Xa waits with issuing its RAs until there is less uncertainty about the encounter while TCAS II anticipates.

Difference between climbing and descending flight

ACAS policy plots of climbing and descending aircraft show similar behaviour at opposite sides of the plot. In Figure 38 and Figure 39 TCAS II and ACAS Xa policy plots of an encounter with a descending aircraft are shown. The vertical velocity of aircraft 1 is now -1000 ft/min. If these two ACAS policy plots are compared to Figure 34 and Figure 35 it is seen that the situation is partially mirrored around the zero relative altitude line. The RAs indicating 'Crossing Climb' in Figure 34 and Figure 35 are now located on the other side of the zero relative altitude line and indicate a 'Crossing Descend'. The large cloud of 'Level Off' RAs in the ACAS Xa policy plot is also located at exactly the same position on the other side of the zero relative altitude line. There are additional minimal differences which are not of interest for this research.

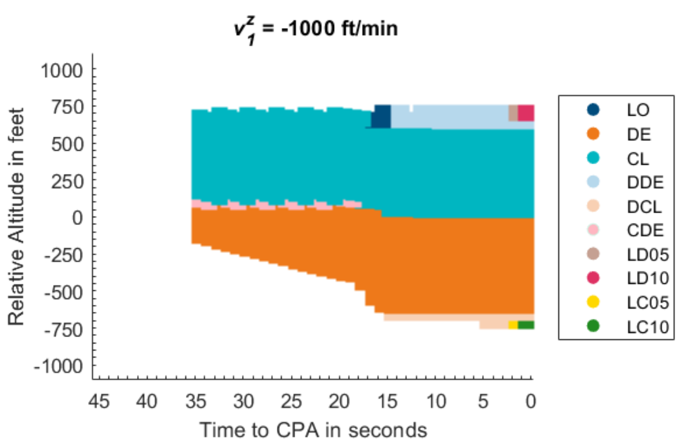


Figure 38. TCAS II policy plot of encounter with vertical velocity of -1000 ft/min at 36000 ft.

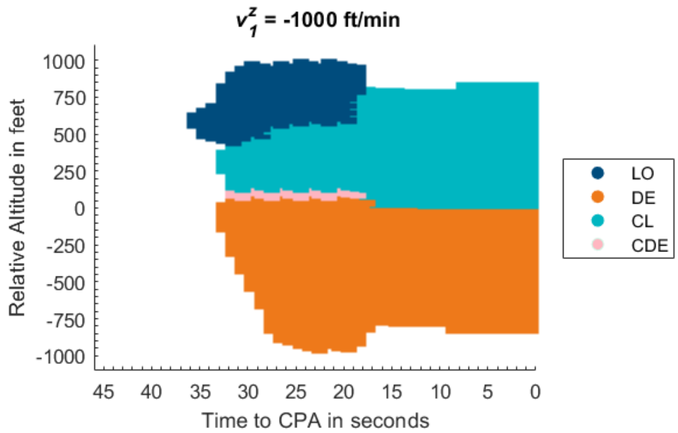


Figure 39. ACAS Xa policy plot of encounter with vertical velocity of -1000 ft/min at 36000 ft.

This mirroring behaviour changes at altitudes that are lower than 1850 ft. Around this altitude both TCAS II and ACAS Xa start to favour climbing advisories over descending advisories because of the close proximity to the ground. However, the ACAS do not do this in the same manner. Figure 40 and Figure 41 display TCAS II and ACAS Xa policy plots for an encounter at an airspeed of 185 ft/min and with vertical velocity of -500 ft/min at an altitude of 1200 ft. It can be seen that there is a clear band of ‘Climb’ advisory along all timings. The orange ‘Descend’ advisory cloud however, as seen in all ACAS policy plots before, has a completely different shape. Instead of mostly mirroring the ‘Climb’ advisory RA cloud as in most of the encounters so far, it is now only issued in a small band very close to relative altitude zero. Most of the relative altitudes below zero are now given a ‘Do Not Climb’ RA, which is especially apparent in the TCAS II policy plot. The ACAS Xa policy plot only gives this ‘Do Not Climb’ RA in the last seconds before CPA.

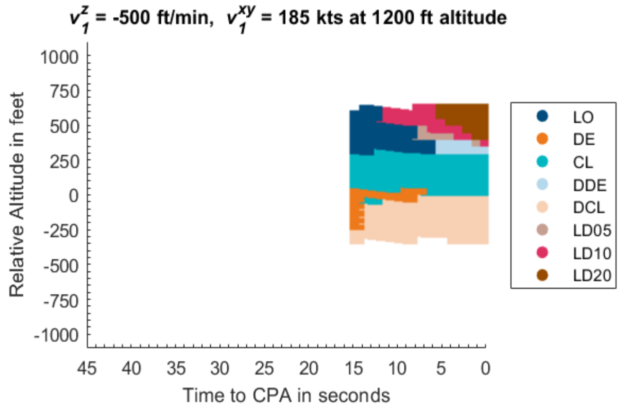


Figure 40. TCAS II policy plot of encounter with vertical velocity of -500 ft/min at 1200 ft.

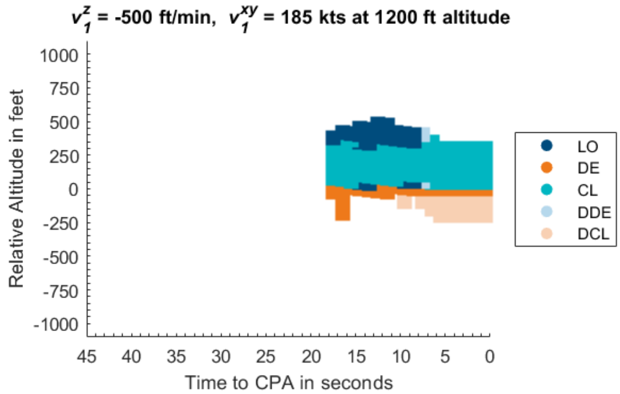


Figure 41. ACAS Xa policy plot of encounter with vertical velocity of -500 ft/min at 1200 ft.

Influence of total airspeed

The own aircraft in the standard encounter at 36000 ft altitude flew with a total velocity of 480 kts. In Figure 42 and Figure 43 TCAS II and ACAS Xa policy plots of an encounter at the lower total velocity of 420 kts are displayed. The aircraft climbs with a vertical velocity of 1500 ft/min and these figures can thus be compared to Figure 36 and Figure 37. Although the majority of the RA cloud and its timing is identical to that of the encounter at 480 kts for both TCAS II and ACAS Xa, minimal differences can be found at the left side of the RA cloud. TCAS II changes some of the RAs it is giving. It now issues ‘Maintain Crossing Climb’ at around 35 seconds to CPA at -200 ft relative altitude, instead of the ‘Climb’ and ‘Crossing Climb’ RAs that are issues in the encounter with a total velocity of 480 kts. ACAS Xa does not change any of the RAs it is giving but instead adds RAs to the left side of the ‘Level Off’ RA cloud at -600 ft relative altitude. Decreasing the total velocity in an ACAS Xa equipped encounter thus results in RAs that are issued at more seconds before CPA.

Although multiple differences between TCAS II and ACAS Xa are presented in this section, these only regard the initial RAs. For more in depth differences between TCAS II and ACAS Xa, such as the sequence and timing of RAs in an encounter, specific encounter geometries need to be analysed in more detail.

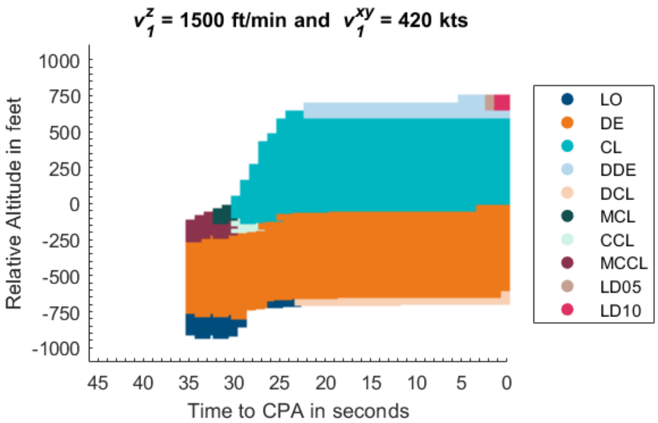


Figure 42. TCAS II policy plot of encounter with vertical velocity of 420 kts at 36000 ft.

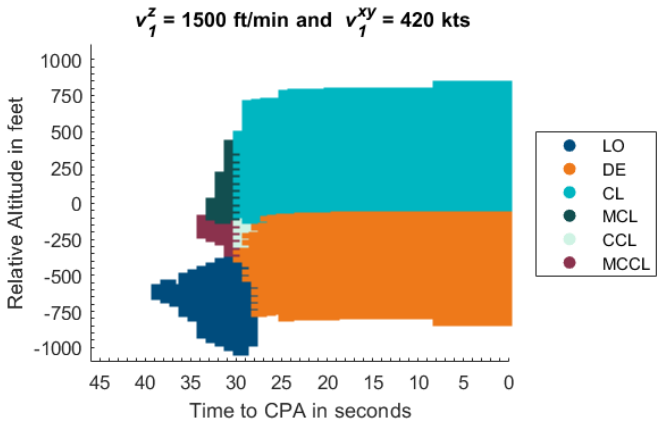


Figure 43. ACAS Xa policy plot of encounter with vertical velocity of 420 kts at 36000 ft.

7 Performance of TCAS II and ACAS Xa on Type 1 Encounters

This chapter presents the performance and analysis results of the simulation of all type 1 encounters. Section 7.1 summarises the specifics of the type 1 encounters. Subsequent subsections provide the results.

7.1 Type 1 Encounter

As explained in Appendix E.4, all original type 1 encounters are altered to contain a VMD of 14 ft to ensure correct results. The parameters of type 1 encounters are included in Table 24.

Table 24. Parameters of modified type 1 encounters, including 14 ft original VMD

AC	Symbol	Unit	Values		
	$h_{i,j}^{CPA}$	ft	7500	15000	36000
i	$\bar{v}_i$	KTS	295	295	480
	v_i^z	ft/min	0	0	0
j	$\bar{v}_j$	KTS	295	295	480
	v_j^z	ft/min	0	0	0
	$d_{i,j}^{VMD}$	ft	14		
	$d_{i,j}^{HMD,lon}$	ft	0		
	$d_{i,j}^{HMD,lat}$	ft	0, 500, 1000		
	χ^{course}	deg (°)	45, 90, 135, 180		

Together, these parameters result in a maximum of 18 unique trajectories:

- 3 different altitudes times 4 different positive course angles with zero HMD (12 unique trajectories)
- 3 different altitudes times 2 180-degree course angles with positive HMD (6 unique trajectories)

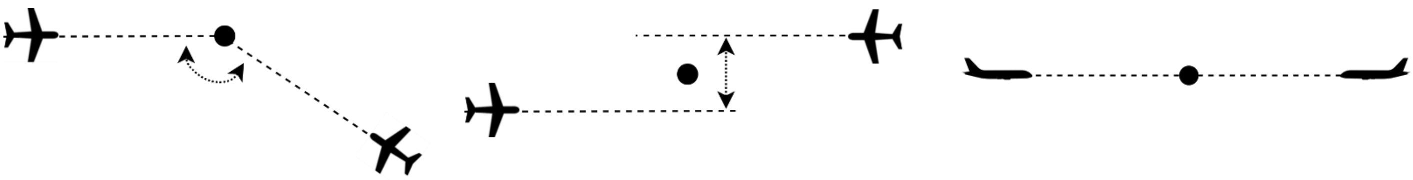


Figure 44. Schematic overview of type 1 encounter, with variation in course angle and HMD

They are simulated with the deterministic setting D1.1 and the stochastic setting S3.1. Additionally, at the end of this section the results of original deterministic setting D1.1 are compared with a deterministic setting without its time shift, to see the influence of this parameter on the timing of the RAs. All encounters in this section are run for 180 seconds, of which 120 seconds occur before CPA.

7.2 Analysis of Vertical Miss Distance

This section present the VMDs of both TCAS II and ACAS Xa in deterministic and stochastic simulations. When simulated with deterministic settings D1.1, each encounter reaches one single VMD. At the lowest altitude of 7500 ft, there is barely any difference between the VMDs from TCAS II or ACAS Xa encounters, with very few exceptions. Most VMDs are at 625 ft. At the two higher altitudes, the VMDs reached with both TCAS II and ACAS Xa are much larger than that. The aircraft equipped with TCAS II reach VMDs of 670 ft at 15000 ft altitude and 875 ft at 36000 ft altitude. VMDs reached by ACAS Xa equipped aircraft are even larger with 1000 ft at 15000 ft altitude and 1225 ft at 36000 ft altitude. This also means that the difference between the TCAS II and ACAS Xa VMDs increases with altitude and ACAS Xa continuously reaches higher VMDs than TCAS II does. These results are summarised in Table 25.

Table 25. Typical VMDs reached by TCAS II and ACAS Xa equipped aircraft in a type 1 encounter in deterministic setting D1.1

Altitude (ft)	TCAS II VMDs (ft)	ACAS II VMDs (ft)
7500	625	625
15000	670	1000
36000	875	1225

The VMDs reached by ACAS Xa at the two higher altitudes sometimes drop slightly when the encounter geometry contains large HMDs. It can be reasoned that the higher the HMD, the lower the VMD has to be to still have a safe encounter. The VMDs reached by TCAS II do not change with increasing HMD.

The difference between VMDs at a lower altitude and a higher altitude is illustrated in Figure 45 where the VMDs of several encounter geometries at 7500 and 36000 feet altitude are displayed for both TCAS II and ACAS Xa with dots and diamond shapes respectively. The results from TCAS II are blue, ACAS Xa results are marked orange.

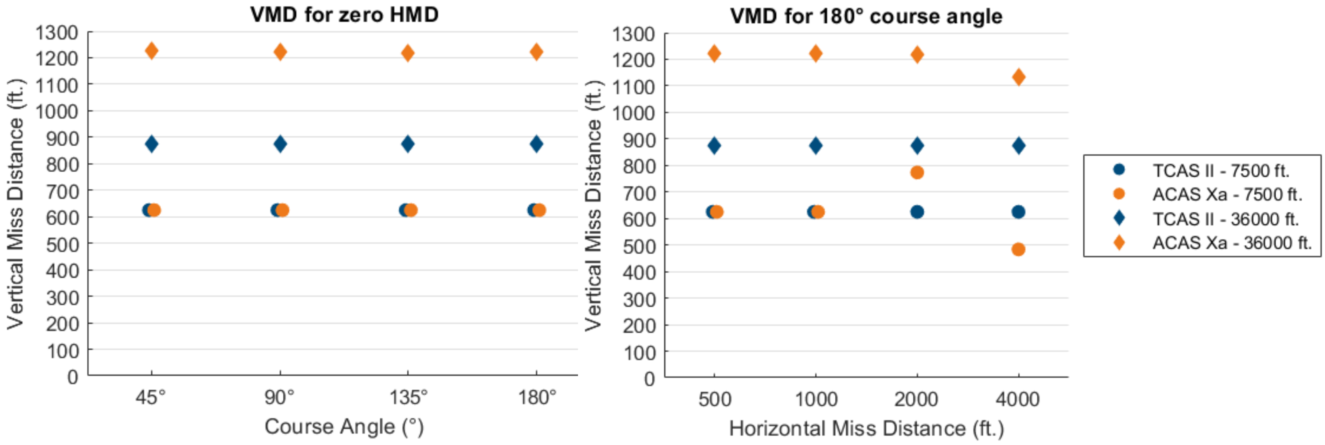


Figure 45. VMDs for type 1 encounters at 7500 and 36000 ft. altitude

TCAS II reached the same VMDs of 625 ft and 875 ft for all the encounter geometries at 7500 ft and 36000 ft altitude. ACAS Xa reaches VMDs of 625 ft and around 1220 ft for all the encounter geometries with zero HMD at 7500 ft and 36000 ft altitude. The difference between the VMDs of the two ACAS at 7500 ft altitude is thus non-existent and is around 350 ft at 36000 ft altitude for the encounters with zero HMD. When the HMD is positive, it can be seen that this does not influence the VMDs reached by TCAS II, which are the same value as without the positive HMD. The VMDs reached by ACAS Xa, however, vary at larger HMDs. The trend that is seen at the higher altitude of 36000 ft is the larger the HMD, the lower the VMD has to be to still have a safe encounter, which is a probable relationship. What happens at 7500 ft is less straightforward to explain. Here, a sudden increase in VMD is seen in the encounter with 2000 ft HMD, while the HMD increases. If the HMD is then increased to 4000 ft, the VMD value reached by ACAS Xa is 150 ft lower than the VMD reached by TCAS II. This lower VMD can be explained by reasoning that at this relatively large HMD ACAS Xa does not think it is necessary to reach VMDs as high as with lower HMDs. The horizontal distance in this situation might already be more sufficient to ensure safe separation between the aircraft than when it was with lower HMDs. This is supported by looking at the datapoints at 36000 ft altitude, where the VMD reached in the encounter with 4000 ft HMD is also lower than the VMDs reached in encounters with less HMD.

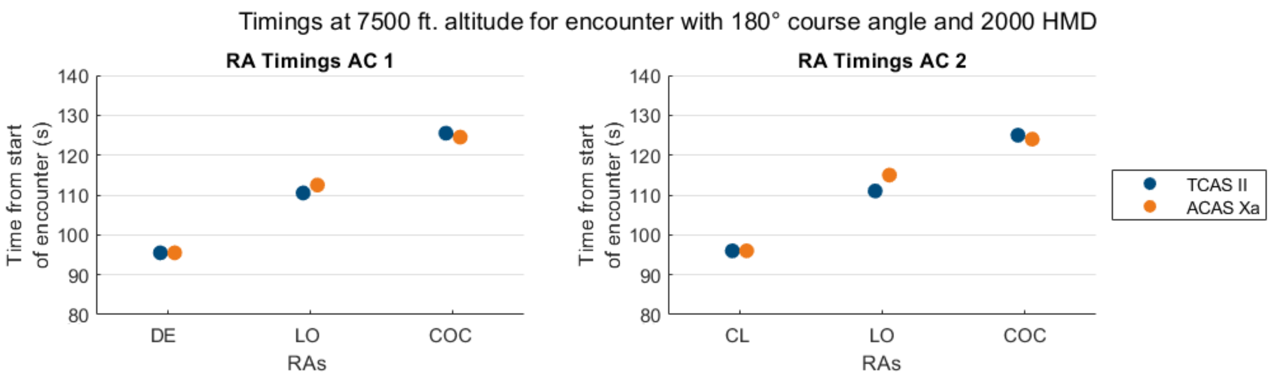


Figure 46. Timing of RAs in encounter with 180 degree course angle and 2000 ft. HMD at 7500 ft. altitude. Timings of aircraft 1 left and timings of aircraft 2 right.

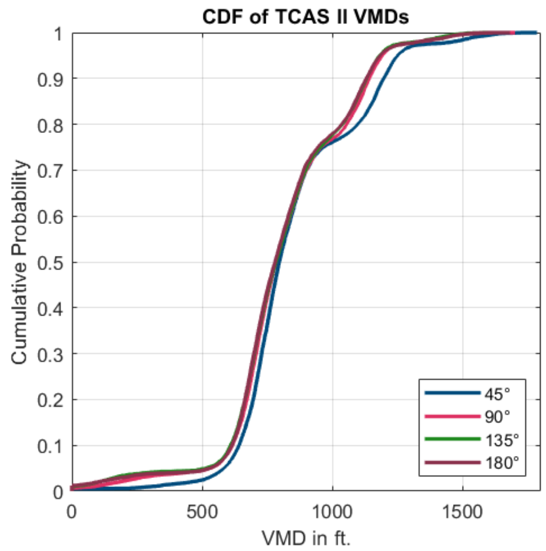
To see what is the cause of the unexpectedly large VMD in the encounter with 2000 ft HMD at 7500 ft altitude, the timings and specific RAs of the encounter are analysed in more detail. From the datapoints in the trajectory it was deducted that during the encounter, both the aircraft equipped with TCAS II and ACAS Xa had the identical vertical velocity of 25 ft/s upwards or downwards. This vertical velocity is the typical velocity with which the aircraft climb or descend after an RA. In Figure 46 the timing of the RAs can be seen. On the x-axis the RAs that are issued are given and on the y-axis the time that has passed since the beginning of the encounter is stated. Note that CPA in the input trajectory occurred after 120 seconds.

The aircraft in the TCAS II encounter holds its climb and descend for a total of 30 seconds, from 95 to 125 seconds. The aircraft in the ACAS Xa encounter takes 6 seconds more than that to climb and descend. In these 6 seconds, 150 ft is travelled, the exact difference between the two VMDs that are reached by TCAS II and ACAS Xa. The difference between the TCAS II and ACAS Xa VMDs thus purely originates from the timing of the RAs. ACAS Xa deliberately instructs the pilot to hold the climb or descent longer than TCAS II does, such that larger VMDs are reached. Although this data does not explain why in the encounter with 2000 ft HMD at 7500 ft altitude there is an unexpectedly large VMD for ACAS Xa, it does explain why ACAS Xa generally reaches higher VMDs than TCAS II does. The origin of the large VMD in the encounter with 2000 ft HMD at 7500 remains unknown.

Now that the VMDs reached in the deterministic encounters are analysed, the stochastically reached VMDs are analysed based on their distributions. They all show a wide range of VMDs as a direct result of taking into account the intrinsic uncertainties. This demonstrates that not taking the uncertainties into account only presents a very limited view of the VMD situation.

The first thing that can be noted is that per altitude and per ACAS, the shape of the VMD distributions and the VMD values are largely similar. This is an indication that the course angle barely influences the VMDs that are reached by the aircraft in the encounters. This is demonstrated by the Cumulative Density Function (CDF) in Figure 47. On the x-axis, the VMD that is reached is displayed, on the y-axis the cumulative probability that this VMD is reached is indicated. The larger the vertical distance between the distributions at a certain VMD, the larger the difference between the distributions. For both ACAS the VMD distributions from simulations with the four course angles are visualised. These lines mostly overlap, especially for the ACAS Xa results. Hence, the course angle has very limited influence on the VMDs.

The CDFs in Figure 47 do not resemble a symmetrical distribution as there are regions that have a slight plateau. For example the region around 1000 ft VMD for TCAS II and the region from 750 to 1000 ft VMD for ACAS Xa. This is confirmed when looking at the Probability Density Functions (PDF) of the data. An example of typical VMD pdfs is included in Figure 48. These result from simulations with the S3.1 settings. Additionally, deterministic results from the D1.1 settings are included as well, displayed by the vertical lines. They all belong to the encounter with 135° course angle and zero HMD and the results for all three altitudes are displayed. Although this is just one course angle, the other type 1 encounters showed similar results. The pdfs show a wide range of VMD values that is reached when running the simulation 10000 times.



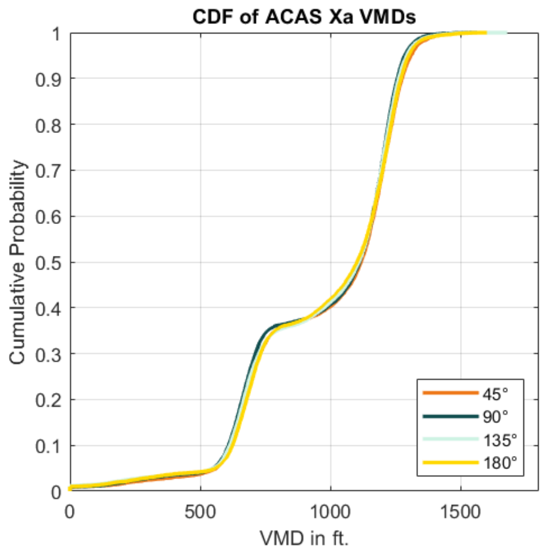


Figure 47. Cumulative Density Function of VMD distribution of encounters with zero HMD at 36000 ft. altitude

The VMDs in the D1.1 setting at different altitudes are larger at higher altitudes, as discussed previously. The VMD distributions also indicate this behaviour, although it might be less clear due to the distributions being multimodal. Each pdf has at least one clear peak, which indicates that there is a clear VMD which is reached the most by the aircraft in the encounter.

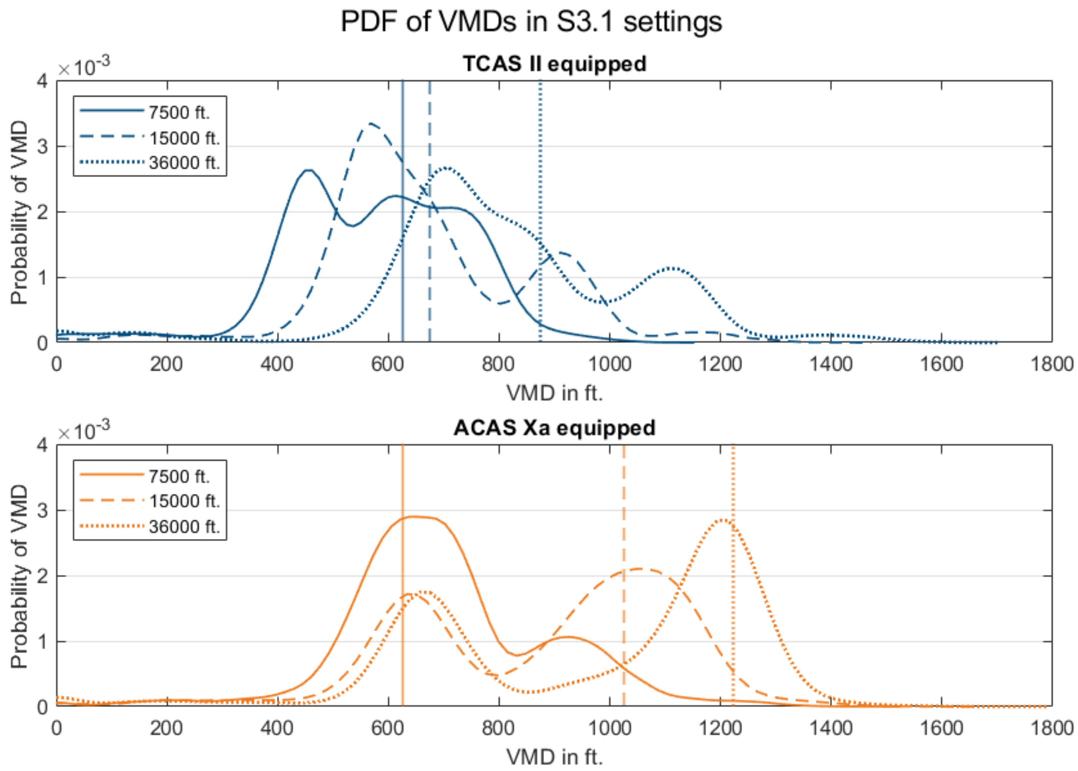


Figure 48. VMDs from D1.1 settings (vertical lines) and PDFs of VMDs from S3.1 settings for encounter with 135° course angle and zero HMD equipped with TCAS II (top) and ACAS Xa (bottom)

For TCAS II in the upper plot, the highest peak for the 7500 ft altitude is located at the VMD of around 470 ft with the majority of the distribution falling between 400 and 800 ft. At 15000 ft, the highest peak of VMDs occurs at around 570 ft and another small peak is seen at 900 ft VMD. At 36000 ft altitude the highest peak of VMDs is found to be at 700 ft and a smaller peak at 1100 ft. An interesting result is that the deterministic VMDs seem to lie close to the mean of the VMD distribution of the stochastic simulation.

In Table 26 both the deterministic VMDs and the mean of the stochastic VMD distributions are given for all three altitudes. It can be seen that at 15000 ft altitude the deterministic VMD and the mean VMD lie extremely close together. However, at the other two altitudes the mean of the stochastic VMDs is lower than the deterministic VMD. Thus, the majority of the time the TCAS II equipped aircraft in a stochastically modelled encounter thus do not reach the VMD that is reached in a deterministically modelled encounter.

Table 26. Deterministic VMDs and mean of stochastic VMDs of type 1 encounter with 135° course angle and zero HMD at all three altitudes equipped with TCAS II

Altitude (ft)	Deterministic VMD (ft)	Mean of stochastic VMDs (ft)
7500	625	583
15000	675	669
36000	875	817

When looking at the bottom graph of Figure 48, the ACAS Xa VMD distributions in the S3.1 settings at all three altitudes have a peak at around 630 ft. For the lowest altitude, this peak is the highest peak of the pdf, while for the two highest altitudes the highest peaks are located at around 1050 and 1200 ft VMD. Here it is observed that the deterministic VMDs and the highest peaks of the stochastic VMD distribution are located at the same values at each altitude. Thus, the VMD that is reached most in the stochastically modelled encounter corresponds to the deterministic VMD for ACAS Xa. This differs from the TCAS II behaviour described above.

The probability of the VMD with the highest peak in the ACAS Xa VMD pdf is lower than in the TCAS II VMD pdf, which indicates that there is more variety in the VMDs reached in ACAS Xa equipped encounters. The different shapes of the two ACAS indicate that although both solve the vast majority of the encounters, they use different tactics or logics to so, which result in the different shapes of the VMD distributions.

The ACAS Xa pdfs at 15000 and 36000 ft altitude are also negatively skewed with respect to the TCAS II pdfs, which means that more values are concentrated on the right side of the distribution. This finding confirms results presented in [12]. The influence of the inclusion of the intrinsic uncertainties is comparable for both TCAS II and ACAS Xa. In Table 27 the medians for the TCAS II and ACAS Xa distributions for the encounter are included for all three altitudes. For TCAS II these median of the stochastic VMDs are always lower than the single VMD from the deterministic setting. For ACAS Xa this is the case at 15000 and 36000 ft altitude as well.

Table 27. Median of VMD distribution in feet of type 1 encounter with 135° course angle and zero HMD at all three altitudes

Altitude (ft)	Median of TCAS II VMD distribution (ft)	Median of ACAS Xa VMD distribution (ft)
7500	591	683
15000	633	951
36000	782	1108

This indicates that at these altitudes in more than half the times that TCAS II and ACAS Xa solve an encounter in the S3.1 setting, the VMD deemed necessary to do so is smaller than the one that is reached in the D1.1 setting. At 7500 ft altitude, the median of ACAS Xa is slightly higher than the deterministic VMD, so this reasoning does not hold.

To investigate if the origin of the multimodal behaviour of the ACAS Xa VMD results can be attributed to the timing of specific RAs as can be done with the deterministic results, additional metrics are used. This can be done by visualising the pdf of the timing of each specific RA in CAVEAT. All initial RAs are given at similar moments in time for both aircraft 1 and aircraft 2. For the RAs that are given second it is interesting to look at the timing distribution of the LO RA. This RA has a direct influence on the VMD distribution by ending the climb or descend of an aircraft, resulting in a smaller or larger VMD. In Figure 49 the pdf of the timing of an LO RA issued to the second aircraft in a type 1 encounter at 36000 ft altitude is included. This LO RA was issued following the initial 'Climb' or 'Descend' RAs in an ACAS Xa equipped encounter with 135° course angle and zero HMD.

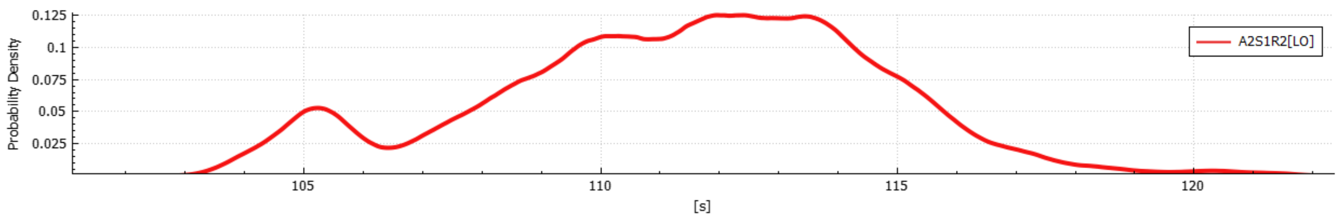


Figure 49. Pdf of timing of LO RA to second aircraft in ACAS Xa type 1 encounter with 135° course angle and zero HMD at 36000 ft altitude

There are two peaks in the pdf. One around 105 seconds after the start of the encounter and a wider peak between 110 and 115 seconds since the start of the encounter. Hence, there is a small amount of simulations runs where the aircraft receive the LO RA relatively soon after the issuing of the initial RA. These runs result in a smaller VMD. In a larger amount of simulation runs the aircraft receive the LO RA at a later moment in time and these thus result in larger VMDs. This behaviour matches the multimodal behaviour in the VMD distribution visualised for the ACAS Xa equipped encounter at 36000 ft altitude in Figure 48.

Based on this behaviour one would expect that for the same encounter at 7500 ft altitude, the largest peak in the timing of this LO Ra is located around 105 seconds, since the VMD distribution has the largest peak at a lower VMD at this altitude. As observed from Figure 50 this is indeed the case. The tail of the timing distribution is relatively long and has a plateau that stretches from around 113 til 122 seconds. This behaviour is different from the timing distribution at 36000 ft altitude, where a clear smaller peak was seen. In the VMD distribution, this plateau in timing also results in different behaviour. The smaller peak in the VMD distribution at 7500 ft altitude, around 900 ft VMD, is more moderate than the smaller peak at 36000 ft.

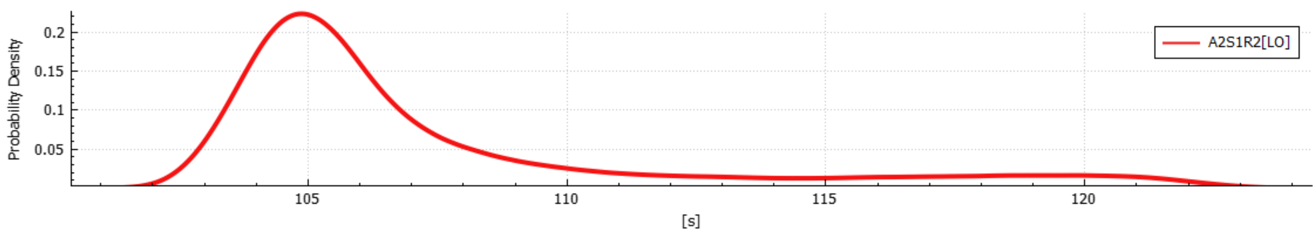


Figure 50. Pdf of timing of LO RA to second aircraft in ACAS Xa type 1 encounter with 135° course angle and zero HMD at 7500 ft altitude

These observations confirm that the timing of the LO RAs is thus a cause for the multimodal behaviour in the VMD distribution.

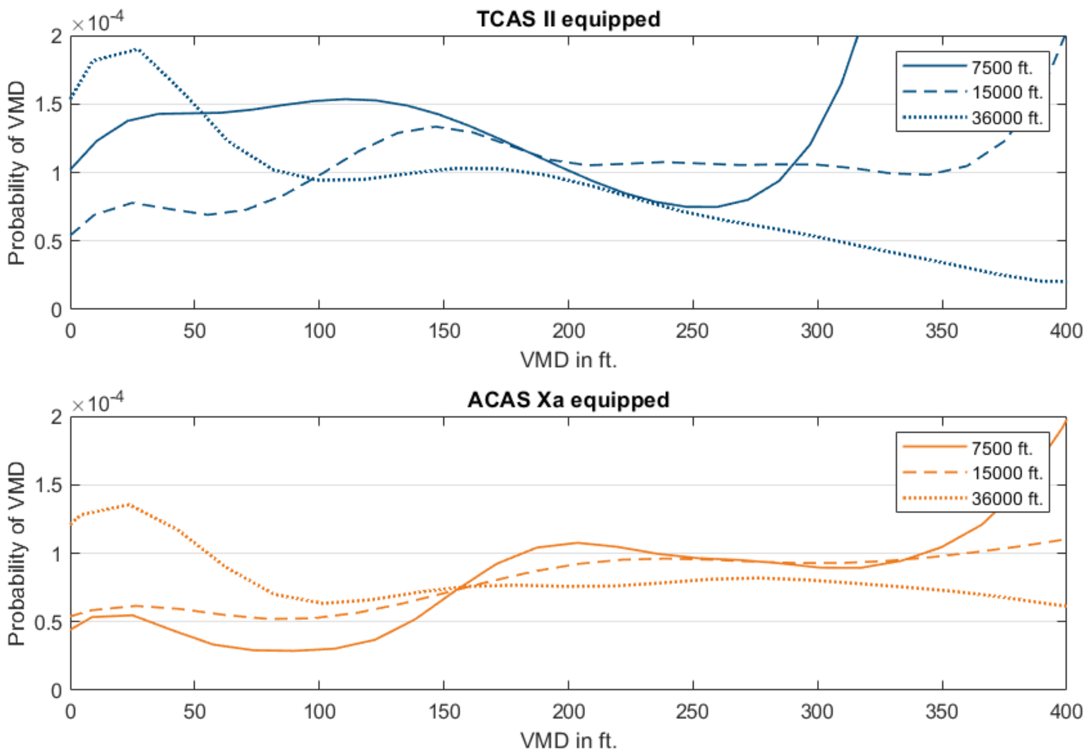


Figure 51. Pdfs of VMDs from S3.1 settings for encounter with 135° course angle and zero HMD equipped with TCAS II (top) and ACAS Xa (bottom), zoomed in to only contain the VMD distribution below 400 ft.

An important observation is the range of VMDs lower than 300 ft for both TCAS II and ACAS Xa. In [12] this range was also found for ACAS Xa equipped encounters, while TCAS II only showed few VMD values close to zero. Yet the CAVEAT simulation results show differently. In Figure 51 a small section of the VMD distributions of the type 1 encounter with 135° course angle is enlarged to only contain modified VMDs from 0 to 400 ft. It can be seen that both TCAS II and ACAS Xa have a positive probability to generate modified VMDs of between 0 and 400 ft. The difference between TCAS II and ACAS Xa results is most apparent in the VMD distribution at 7500 ft altitude. Between 0 and 200 ft modified VMD, aircraft equipped with TCAS II even have a larger probability to reach those VMDs than ACAS Xa has, which is in contrary to the findings reported in [12].

Besides the specific differences between the VMDs of TCAS II and ACAS Xa, several general trends were observed in the VMD distributions of the type 1 encounters:

- The higher the altitude, the higher the VMDs for both TCAS II and ACAS Xa
- The higher the altitude, the larger the difference between TCAS II and ACAS Xa, where the latter indicates the highest VMDs.
- The higher the altitude, the more the TCAS II distribution is skewed to the left and the more the ACAS Xa distribution is skewed towards the right.
- Course angle and HMD have little to no influence on the VMDs that are reached.
- The multimodal behaviour in the VMD distributions is cause by the timing of the LO RAs.
- All VMD distributions contain a small number of encounters where 0 VMD is reached.

The encounters that reach a VMD that remains below 100 ft are counted as an NMAC, according to the definition of an NMAC [2], [3]. In the following section NMACs are discussed in more detail.

7.3 NMAC Probability of Modified Trajectories

From CAVEAT data it was found that in the deterministic setting D1.1 none of the modified trajectories, over all the three altitudes and all encounter geometries, contained an NMAC. This indicates that whenever ACAS is triggered, it was successful in its goal to safely resolve the encounter and prevent NMACs. The fully stochastic setting S3.1 results in small, but significant percentages of NMACs at all three altitudes. These percentage vary between the altitudes, the encounter geometries and TCAS II and ACAS Xa.

Figure 52 includes the NMAC probabilities in geometries with 0 HMD, where the altitudes in feet are displayed on the x-axis and the relative course angles in degrees are displayed on the y-axis. The probabilities for TCAS II are displayed in blue and the probabilities for ACAS Xa are displayed in orange.

When looking at the TCAS II data, it can be seen that at all three altitudes, the higher the course angle, the higher the NMAC probability. This trend is most clearly seen at the altitudes of 7500 and 36000 ft. At 15000 ft the NMAC probabilities in the TCAS II equipped encounters also increase with course angle, but they are significantly lower than the other two altitudes.

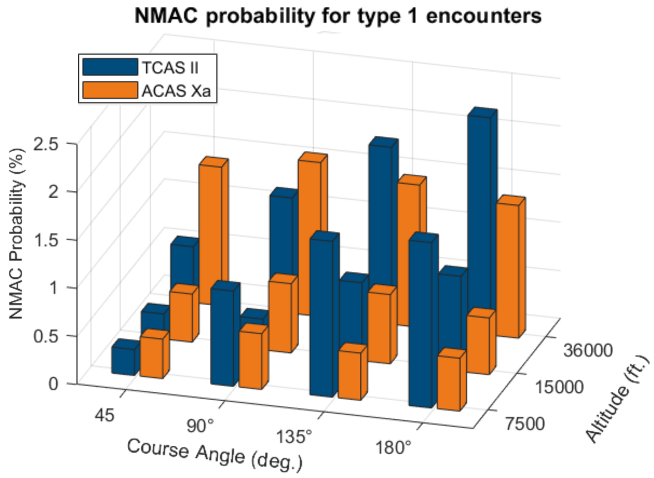


Figure 52. NMAC probability for type 1 encounters with 0 HMD with setting S3.1

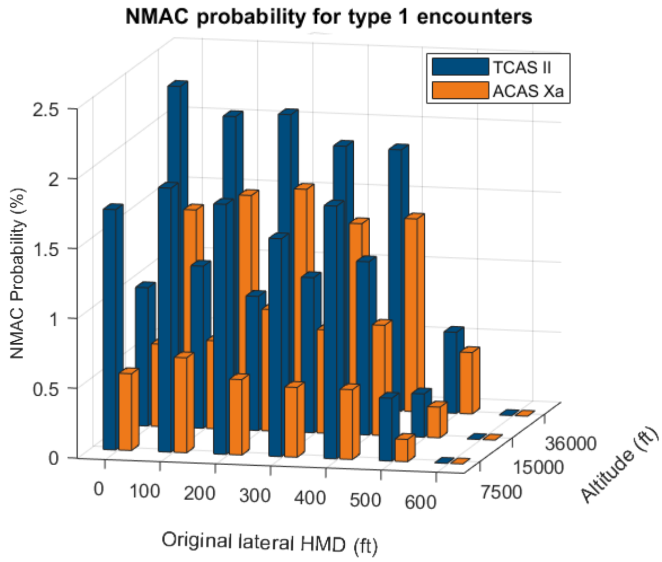


Figure 53. NMAC probability for type 1 encounters with 180° course angle with setting S3.1

ACAS Xa does not follows the trend of increasing NMAC probability with increasing course angle. More obvious in ACAS Xa equipped encounters is the trend that the higher the altitude, the higher the NMAC probability. The two lowest altitudes show similar NMAC probabilities between 0.3% and 0.65%, while at 36000 ft the probabilities are more than twice as high and reach between 1% and 1.3%. This trend is not seen in the TCAS II data. For example, with a course angle of 90°, the NMAC probability in the ACAS Xa equipped encounters increases from just over 0.5% to around 0.6% from 7500 to 15000 ft, after which it reaches 1% at 36000 ft. When the aircraft in this same encounter are equipped with TCAS II, the NMAC probability is around 0.7% at 7500 ft, while it decreases to 0.3% at 15000 ft and increases again to 1% at the higher altitude of 36000 ft.

When comparing the TCAS II NMAC probabilities to the ACAS Xa NMAC probabilities, the latter is sometimes higher in the encounters with the lowest two course angles and the former is always higher when the course angle is larger than 45°. The difference between the two is quite significant, especially in encounters with higher course angles at 7500 ft. For example, in the encounter with 180° course angle the TCAS II NMAC probability is nearly 3 times higher than the ACAS Xa NMAC probability.

Figure 53 includes the NMAC probabilities in geometries with positive HMDs. To clearly visualise trends, several additional encounters with increasing HMD in steps of 100 ft are simulated at all three altitudes. At every HMD that is simulated, TCAS II reaches higher NMAC probabilities than ACAS Xa does. The same trends as in the encounters with varying course angle can be seen. TCAS II has relatively high probabilities at 7500 and 36000 ft altitude, while the NMAC probabilities at 15000 ft altitude are lower. ACAS Xa has comparable NMAC probabilities at 7500 and 15000 ft which increase at the altitude of 36000 ft. Both TCAS II and ACAS Xa show similar NMAC probabilities in encounters with HMDs between 0 and 400 ft. Encounters with an HMD of 500 ft clearly have a lower NMAC probability for both TCAS II and ACAS Xa, around 1/5th of the NMAC probability with a lower HMD. When the HMD is larger than 500 ft no modified NMACs are reported. This is in line with the definition of an NMAC, which is an encounter where aircraft are closer than 100 ft vertically and 500 ft horizontally.

7.4 Probability of Modified Crossing Encounters

The type 1 encounters as presented in the introduction of this chapter, did not contain any crossings encounters. The modified trajectories in the D1.1 setting did also not contain any modified crossings, as was expected after changing the VMD from zero to 14 ft as discussed in Appendix E.4.

In Figure 54 and Figure 55 the probability of modified crossing encounters with S3.1 settings is included for encounters with zero HMD and encounters with a course angle of 180°, respectively. Note that the z-axis is zoomed in to only include probabilities from 40 to 46%, as that is the range that the modified crossing probabilities lie in for the type 1 encounters.
A few notes can be made. First of all, it is immediately clear that the probability of modified crossing encounters is barely influenced by the course angle or the HMD for either of TCAS II and

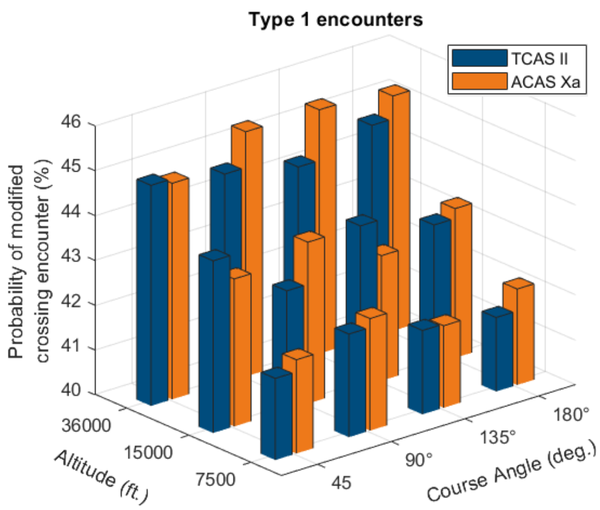


Figure 54. Probability of modified crossing encounter for type 1 encounters with 0 HMD with setting S3.1

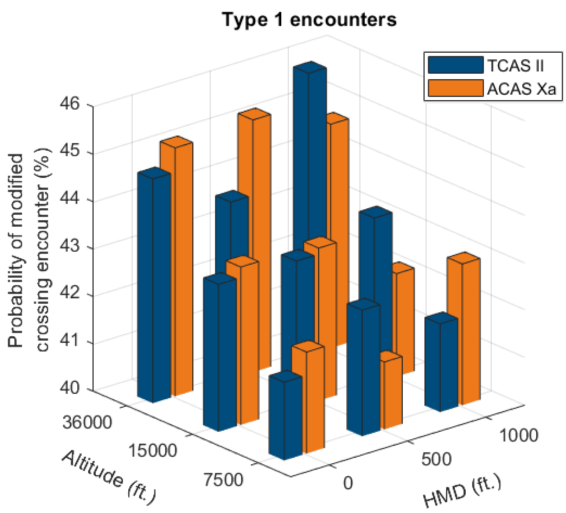


Figure 55. Probability of modified crossing encounter for type 1 encounters with 180° course angle with setting S3.1

ACAS Xa. The differences between the different encounter geometries remain within a few percent, which, with respect to the absolute percentage of around 45% is not significant. No trend in the slight differences in probabilities between the course angles and the HMDs can be obtained. The altitude has a larger influence on the modified crossing probability. At 7500 ft altitude the probabilities roughly lie between 41 and 42% for all encounter geometries, at 15000 ft altitude the probabilities have increased and roughly lie between 42 and 43.5%. The highest probabilities are seen at 36000 ft, where they lie between 44 and 45%.

TCAS II and ACAS Xa give comparable modified crossing probabilities. The difference between the two is within 1% for most of the type 1 encounters. In comparison to the total probability, which lies between 40 and 46%, this difference is deemed small.

It is clear that these modified crossing probabilities found in simulations with stochastic parameter setting S3.1 are significantly larger than the zero modified crossing probability found in simulations with the deterministic parameter setting. The increase in modified crossings is thus due to the inclusion of uncertainties in the S3.1 setting.

7.5 Advisories and Their Timings

To analyse the advisories, the average number of advisory types issued per encounter per aircraft is used. The advisory types are split into four groups, corrective RAs, reversal RA, increase Rate RAs and crossing RAs, using the definitions in Section 5.2. Note that the Increase Rate, Reversal and Crossing RAs are all Corrective RAs, but a Corrective RA does not have to be an Increase Rate, Reversal or Crossing RA. In case of the latter, the Corrective RA will be called 'Other' from this point forward. These can include 'Climb' and 'Descend' RAs, for example.

The first thing that was noted during the analysis of the results, is that with the D1.1 setting there are no major differences between the RA types that aircraft 1 receives and the RA types that aircraft 2 receives. There are some small differences at the lower altitudes, but in general both aircraft receive nearly the same advisory types, namely other RAs. Next, it was seen that all altitudes TCAS II consistently only issues 2 other RAs per aircraft per encounter, regardless of encounter geometry. ACAS Xa follows this statement.

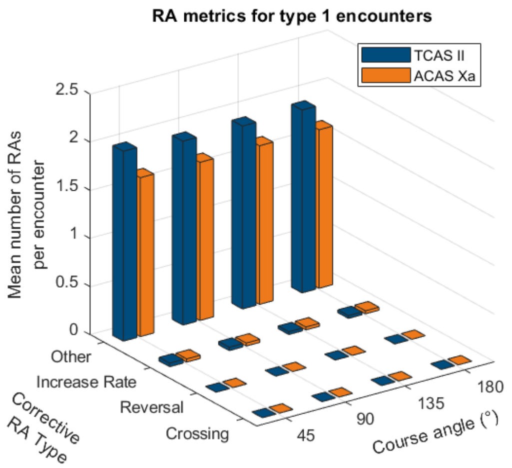


Figure 56. RA metrics for type 1 encounter at 36000 ft. altitude with S3.1 settings

In simulations runs with the stochastic S3.1 settings, there was slightly more variation in RA numbers and types. In Figure 56 the mean number of RAs per aircraft per encounter are included for type 1 encounters equipped with TCAS II and ACAS Xa at 36000 ft altitude. Just like the simulations with the D1.1 setting, the majority of the RAs given are of the Other type. The amount with which they are given is slightly lower than in the D1. Settings. TCAS II equipped aircraft receive almost 2 of these RAs per encounter, ACAS Xa equipped aircraft receive just 1.5 of these per encounter. There is also a slight possibility that aircraft equipped with either TCAS II or ACAS Xa receive an increase rate RA. At other altitudes, these number remain similar, indicating that the altitude does not influence the RA types to a great extent.

A typical encounter is analysed in further detail for both the deterministic D1.1 setting and the stochastic S3.1 setting. Since the aircraft in the type 1 encounters all fly level, it is most interesting to investigate an encounter geometry and altitude combination that has a relatively big chance of occurrence in real life. For example, at lower altitudes two aircraft in an encounter generally do not fly level, they descend or climb. Although it is interesting to see how TCAS II and ACAS Xa behave in this situation, it is more useful to investigate a more realistic encounter geometry. Hence, a higher altitude, such as 36000 ft is more suitable. At this altitude, not all encounter geometries are as realistic. For example, at cruise altitude, the aircraft rarely fly parallel. More realistically would be an encounter with a relative course angle of 180° and zero HMD. The next part of the analysis is applicable to this situation.

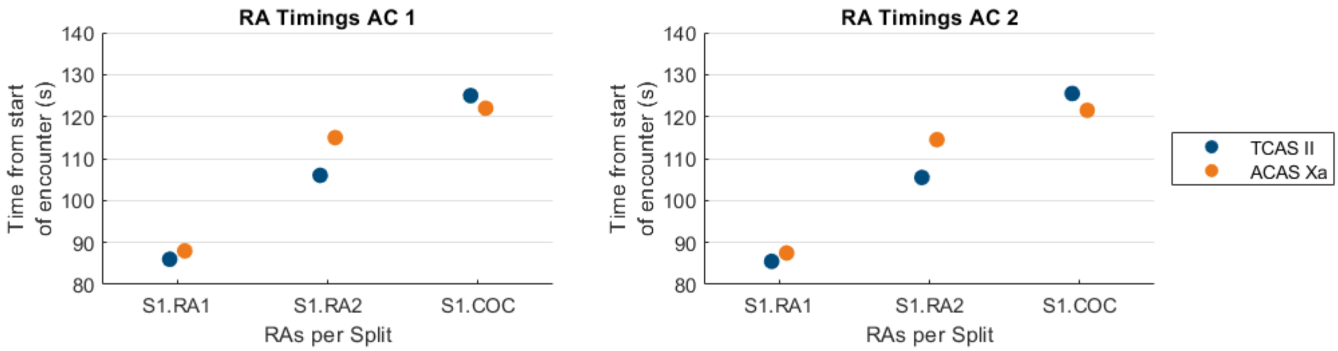


Figure 57. Timings for TCAS II and ACAS Xa encounters with 180° course angle and 0 HMD at 36000 ft. altitude, with D1.1 settings

Figure 57 shows per aircraft and per ACAS equipage the timings of the RAs in the encounter. The left graphs displays the timings of the RAs that were received by aircraft 1 and the right graphs contains the timings of the RAs that were received by aircraft 2. On the x-axis of each graph are codes indicating the RA number. The marker S1.RA1 refers to the first RA during the first split of the encounter. A split is a name for the sequence of advisories from the first TA till the first COC. There can be multiple splits during one encounter, if the aircraft trigger each other's ACAS multiple times. However, in this encounter all aircraft experience just one split. This graph can only fully be interpreted if together with Table 28, which includes the specific RA that each RA marker indicates along with the exact timing. For now, that specific RA that is given is not yet of interest. First the timing of the RAs is analysed.

Table 28. RA markers, RA codes and timings for TCAS II and ACAS Xa encounters with 180° course angle and 0 HMD at 36000 ft altitude, with D1.1 settings

Scenario	AC	RA Marker	RA	Time (s)
D1.1 TCAS II	1	S1.RA1	CL	86
		S1.RA2	LO	106
		S1.COC	COC	126
	2	S1.RA1	DE	85.5
		S1.RA2	LO	105.5
		S1.COC	COC	125.5
D1.1 ACAS Xa	1	S1.RA1	CL	88
		S1.RA2	LO	115
		S1.COC	COC	122
	2	S1.RA1	DE	87.5
		S1.RA2	LO	114.5
		S1.COC	COC	121.5

In Figure 57 it can be seen that both TCAS II and ACAS Xa issue S1.RA1 to the two aircraft in the encounter around roughly the same time, between 85.5 and 88 seconds after the start of the encounter. S1.COC, the COC advisory, is issued around 125 and 122 seconds by TCAS II and ACAS Xa, respectively. These timings are still relatively close together. The timing of S1.RA2, however, differs significantly between the two ACAS. TCAS II issues its second RA around 105 seconds after the start of the encounter, while ACAS Xa takes ten seconds longer and issues its second advisory 115 seconds after the start of the encounter. This indicates that ACAS Xa allows the aircraft to hold the advisory for a longer time, which could potentially be an explanation for the larger VMDs in encounters with aircraft equipped with ACAS Xa.

When looking at the side profiles of the modified trajectories in Figure 58 and Figure 59 the timing and altitude of the three different RAs can be seen. Note that the scale on the y-axis differs in the two figures. The blue line represents the modified trajectory of aircraft 1 while the red line represents the modified trajectory of aircraft 2. Both receive certain TAs, RAs and the COC indication. These are represented by the yellow dot, the red squares and the green dot on both of the trajectory lines. The code of the advisory is also indicated. Additionally, the final VMD is also indicated in the figure. The RAs in the figures naturally match the RAs that are indicated in Table 28. In both modified trajectories, one aircraft climbs while the other aircraft descends. A difference in slope, and thus aircraft speed, could also be part of the explanation of the VMD difference between ACAS Xa and TCAS II. Keeping in mind the different scaling in the figures, it can be calculated that both side profiles have identical slopes, indicating that they have similar speeds, both horizontally and vertically. Thus it can be concluded that the aircraft equipped with ACAS Xa reach higher VMDs then TCAS II equipped aircraft, solely because they receive their LO advisory at a later moment in time. This allows them to climb or descend longer than the TCAS II equipped aircraft can. As indicated before, the difference in VMD only occurs at higher altitude, at lower altitude both ACAS reach similar VMDs.

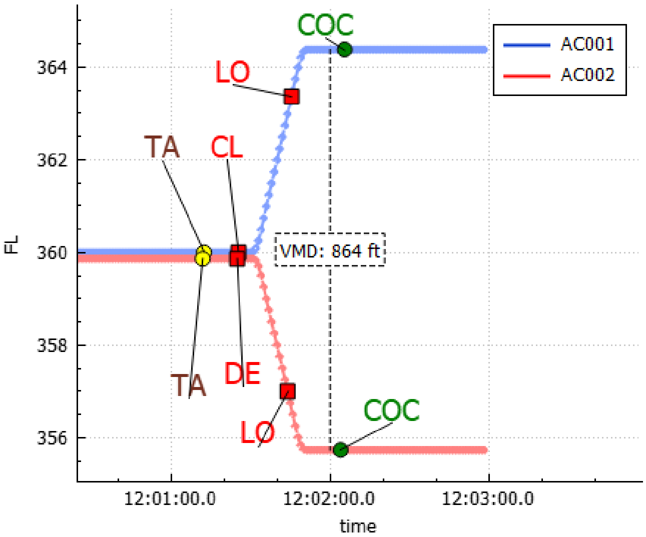


Figure 58. Side view of trajectory D1.1 encounter at 36000 ft. with 180° course angle and 0 HMD, aircraft equipped with TCAS II

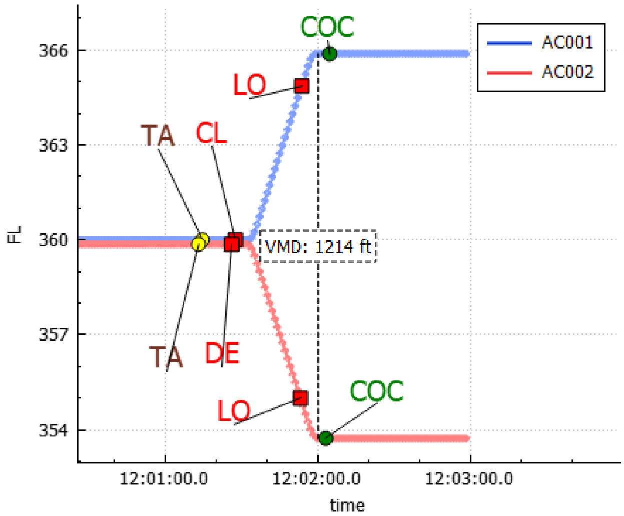


Figure 59. Side view of trajectory D1.1 encounter at 36000 ft. with 180° course angle and 0 HMD, aircraft equipped with ACAS Xa

The timings for the same encounter geometry with 180° course angle and zero HMD at 36000 ft altitude, simulated with S3.1 settings, are included in Figure 60. On the x-axis the RAs per split are given. Each sequence of RAs, from the first RA till the last COC RA is called a split. During an encounter, one single or multiple splits of RAs can occur. This particular encounter had only one split. The code on the x-axis indicates the number of the split and the number of the RA. For example, S1.RA1 is the first RA in split number 1 of the encounter. It is also possible for TCAS II and ACAS Xa to not have the same number of RAs during a split, as is the case in this encounter. This is why in the left graph ACAS Xa does not have a boxplot for the timing of the fourth RA, while TCAS II does.

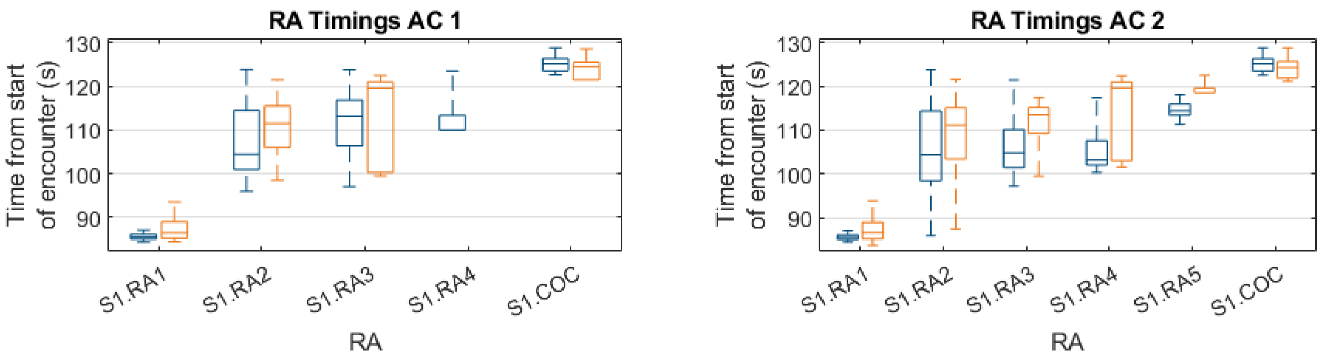


Figure 60. Timings for TCAS II (blue) and ACAS Xa (orange) encounters with 180° course angle and 0 HMD at 36000 ft. altitude, with S3.1 settings

The boxplots indicate the distributions of timings of the issuing of the RAs, measured from the start of the encounter. CPA is located at 120 seconds from the start of the encounter. TCAS II timings are indicated in blue, ACAS Xa timings are indicated in orange.

One clear phenomenon that can be seen is that for both TCAS II and ACAS Xa both the first RA and the COC have narrow timing distributions that centre around roughly the same time from start of the encounter. This indicates that in nearly every encounter, they have very similar timings of the first RA and the COC RA. Except for the first and last RA, it can be seen that ACAS Xa RAs are generally issued at a later moment in time than the TCAS II RAs. A clear exception to this statement is the third RA that is issued to AC 1. Although the median of the RA timing is significantly higher in ACAS Xa encounters, the interquartile range of ACAS Xa covers almost the complete timing distribution of TCAS II.

Advisory trees are used to see which specific RAs are issued in what sequence. In Figure 62 and Figure 61 the advisory trees for the RAs issued to aircraft 1 by TCAS II and ACAS Xa are displayed, respectively. Advisory trees are used to clearly display the sequence of RAs. Each RA is located at a node and the probability of each RA in the sequence is included as well. In each encounter the aircraft all first receive a TA, which was not included in the boxplots in Figure 60. From then on, each row in the advisory tree corresponds to a new consecutive RA given to the aircraft. The addition of the probabilities of all children of a given parent node is always equal to 100%.

The first RA has a 50% chance to be a 'Descend' advisory and a 50% chance to be a 'Climb' advisory for both TCAS II and ACAS Xa. This can be attributed to the errors in the pressure altitude. These can trigger the upward and downward RAs that are issued. Although these errors are slightly biased due to the 14 ft offset included in the type 1 encounters, the RAs are distributed about equally. Starting from this first advisory, the differences between TCAS II and ACAS Xa start to increase. TCAS II has a clear preference for a second RA that is a 'Level Off', which is issued in 90% of the cases, after which the COC is given. The preference of ACAS Xa is less clear, in 64% of the encounters, the same 'Level Off' and COC are given as second RA, but in 32% of the encounters a direct COC is given. It could be that these RAs cause the multimodal behaviour seen in Figure 48. These RA indicate that, if possible, ACAS Xa presents simpler solutions with less RAs than TCAS II does. This is also seen when looking at the other RAs that are issued after the initial RA. Both TCAS II and ACAS Xa issue an 'Increase Climb' or 'Increase Descent' roughly 3% of the time as a second RA, after which 99.4% of the time a COC is issued. The other 0.6% of the time, ACAS Xa issues a 'Level Off' and then a COC. According to TCAS II however, it is necessary to issue a 'Reversal to Climb' or 'Reversal to Descent' as a consecutive RA, after which the 'Level Off' and COC are issued as well. Adding an additional RA to an already quite long split of RAs increases the complexity of the situation and the chance that the pilot will not follow the RAs.

As indicated in Appendix E.4, the advisory tree of aircraft 2 is not displayed correctly in CAVEAT and can therefore not be used for analysis. However, given the symmetry that is seen in the advisory trees of aircraft 1 and given the encounter geometry, the advisory tree of aircraft 2 will look quite straightforward in this situation.

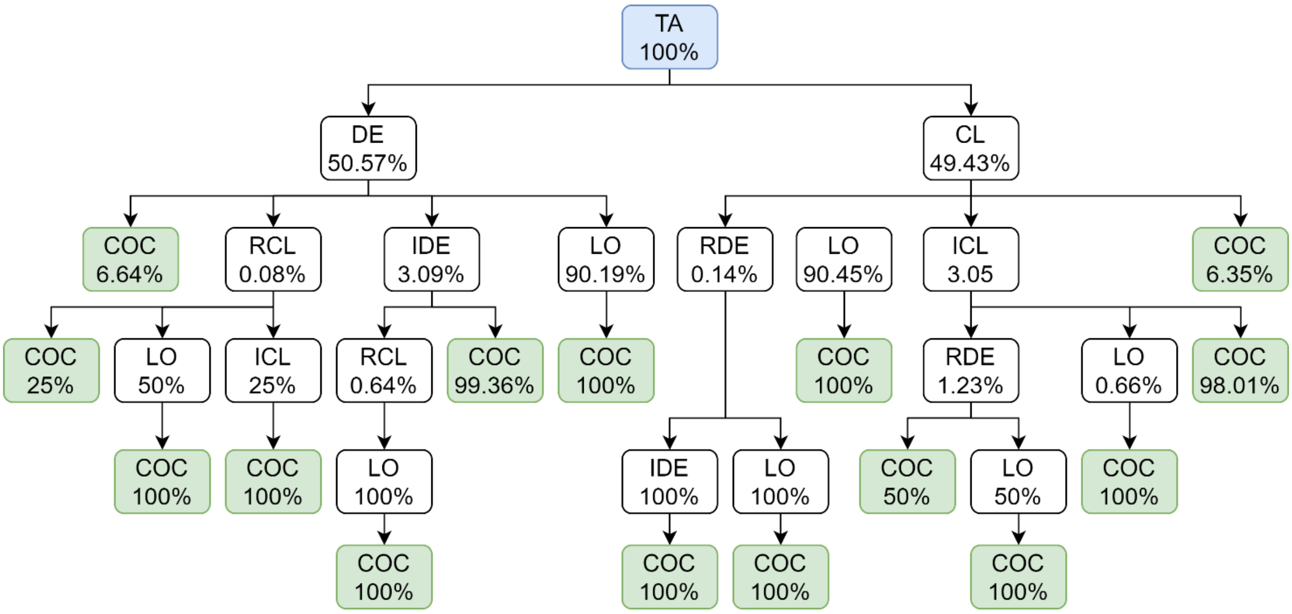


Figure 62. Advisory tree of RAs issued to aircraft 1 by TCAS II in encounter with 180° course angle and zero HMD at 36000 ft altitude, with S3.1 settings

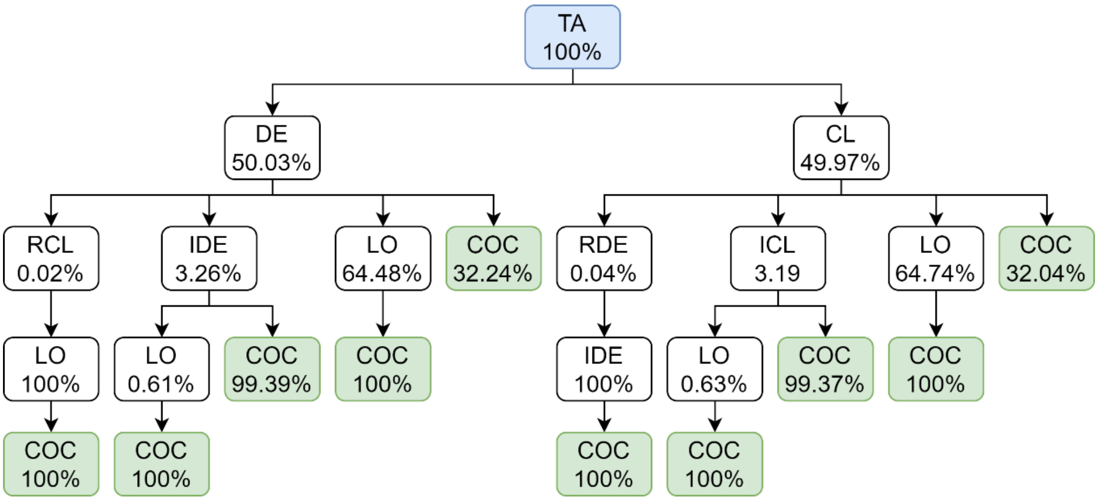


Figure 61. Advisory tree of RAs issued to aircraft 1 by ACAS Xa in encounter with 180° course angle and zero HMD at 36000 ft altitude, with S3.1 settings

7.6 Effect of Time Shift

This section describes the effect of the inclusion of a time shift in the deterministic D1.1 parameter settings. When looking at Table 28 a recurring phenomenon can be noticed. For both ACAS types, the RAs of each aircraft have a time difference of exactly 0.5 seconds. This time difference originates from the aircraft time shift, of which the settings are included in Table 57 in Appendix B.3. In CAVEAT the input signals of the ACAS are updated at 1 second intervals and the time shift indicates the offset of this interval, which can indicated per aircraft. In the deterministic D1.1

scenario, aircraft 2 has zero time shift and aircraft 1 has 0.5 seconds time shift. A time shift of 0.5 seconds thus means that the systems modelling aircraft 2 are update at 0.5, 1.5, 2.5, etc. seconds into the encounter. From this, the observed difference in the timing of the RAs can be explained.

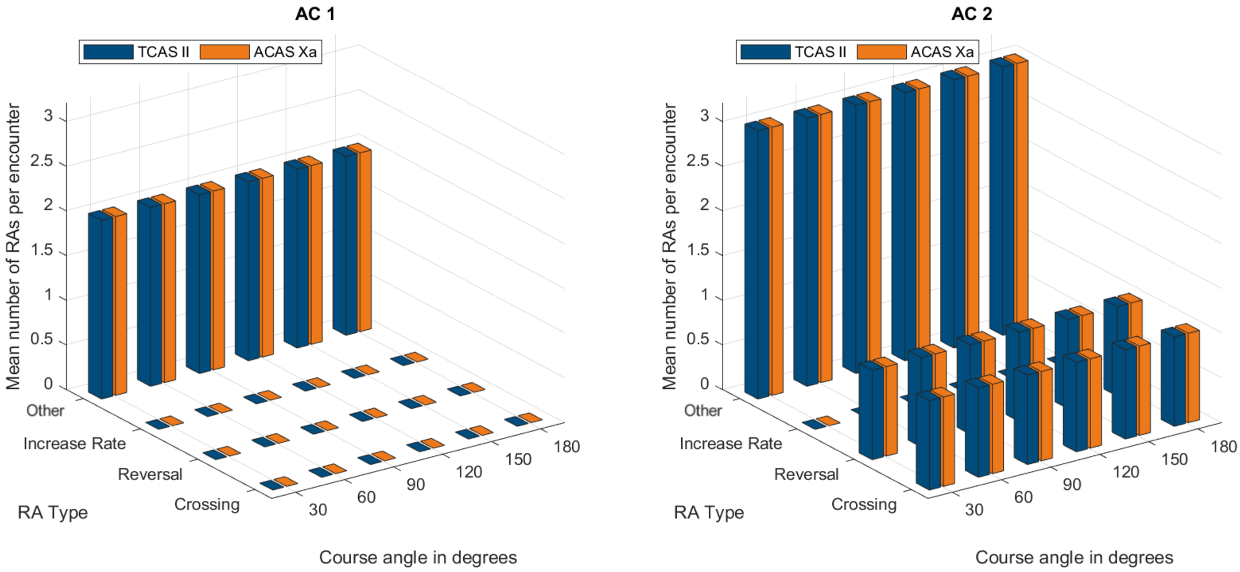


Figure 63. RA metrics for part of Class 1 encounters at 30000 ft. in the D1.1 scenario without time shift

When the simulation is run again without this time shift of 0.5 seconds, so with deterministic scenario D1.1 without time shift, with both aircraft updating simultaneously, several results change. First, the encounter of interest, at 30000 ft altitude with 180° course angle and zero HMD, is analysed. The VMDs of this encounter were slightly lower, 861 ft for the TCAS encounter and 1200 ft for the ACAS Xa encounter. The type of advisories also differed from the results of original scenario D1.1, which indicated two corrective RAs per encounter for both aircraft in the encounter.

In Figure 63, it can be seen that an encounter with a course angle of 180° in the D1.1 scenario without time shift gives the exact same results for aircraft 1 as it did in the original D1.1 scenario. Aircraft 2 however, shows additional corrective, reversal and crossing RAs for both ACAS types. The exact advisories, including their timing, are displayed in Table 29. There it can be seen for both ACAS types, aircraft 1 receives 3 RAs while aircraft 2 now receives 4 RAs. The first RA that is issued is identical for both aircraft, and is issued at exactly the same moment in time. This results in a reversal RA for aircraft 2, which changes its initial descend RA into a reversal climb RA. After that, the encounter is similar to the original D1.1 encounter. The short amount of time it took for ACAS to issue the reversal RA explains why the VMDs are slightly smaller, as the aircraft had less time to climb or descend.

Table 29. Timing of RAs for D1.1 encounter without time shift at 30000 ft with 180° course angle and zero HMD, for both TCAS II and ACAS Xa

Scenario	AC	RA Marker	RA	Time (s)

D1.1 TCAS II	1	S1.RA1	DE	86.0
		S1.RA2	LO	106.0
		S1.COC	COC	125.0
	2	S1.RA1	DE	86.0
		S1.RA2	RCL	87.0
		S1.RA3	LO	105.0
		S1.COC	COC	125.0
D1.1 ACAS Xa	1	S1.RA1	CL	87.5
		S1.RA2	LO	114.5
		S1.COC	COC	121.5
	2	S1.RA1	DE	87.5
		S1.RA2	RCL	88.5
		S1.RA3	LO	114.5
		S1.COC	COC	121.5

For the rest of the type 1 encounters in the D1.1 scenario without time shift, it can be seen that in general, the VMDs are similar or just slightly lower than in the D1.1 scenario. The advisories types showed that aircraft 1 in the D1.2 scenario receives similar advisories as in the D1.1 scenario, regardless of altitude, encounter geometry or ACAS equipage. Aircraft 2 in the D1.2 scenario, however, receives an extra corrective, reversal and crossing RA on top of the two corrective RAs it received in the D1.1 scenario per encounter.

8 Performance of TCAS II and ACAS Xa on Type 2 Encounters

Now that it is clear how TCAS II and ACAS Xa behave when aircraft fly level at the same altitude, VMDs are introduced to the original encounters. Section 8.1 includes the type 2 encounter geometries. The results of these encounter types in simulation are presented in the subsequent sections.

8.1 Type 2 Encounters

In Table 30 the values for the geometries of type 2 encounters are listed. Together, these parameters result in a maximum of 27 unique trajectories, which come from encounters at 3 different altitudes times 9 different VMDs times 1 positive course angles.

Table 30. Type 2 encounter parameters

AC	Symbol	Unit	Values		
	$h_{i,j}^{CPA}$	Ft	7500	15000	36000
i	$\bar{v}_i$	KTS	295	295	480
	v_i^z	Ft/min	0	0	0
j	$\bar{v}_j$	KTS	295	295	480
	v_j^z	Ft/min	0	0	0
	$d_{i,j}^{VMD}$	Ft	100, 200, 300, 400, 500, 600, 700, 800, 900	100, 200, 300, 400, 500, 600, 700, 800, 900	100, 200, 300, 400, 500, 600, 700, 800, 900
	$d_{i,j}^{HMD,lon}$	Ft	0		
	$d_{i,j}^{HMD,lat}$	Ft	0		
	χ^{course}	deg (°)	180		

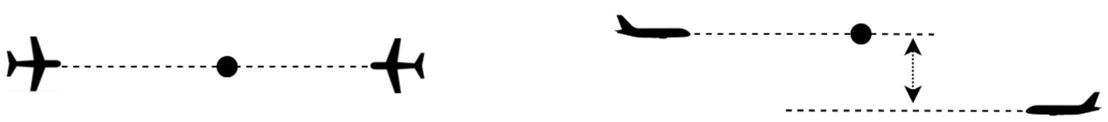


Figure 64. Schematic overview of type 2 encounter, with variation VMD

This chapter contains the results of these type 2 encounters that are simulated with the D1.1 and S3.1 settings. All encounters in this section are run for 180 seconds, of which 120 seconds occur before CPA. The focus lies on finding the influence the original VMDs have on the indicators.

8.2 Analysis of Vertical Miss Distance

Not all type 2 encounters resulted in larger VMDs after deterministic simulation. In Table 31 it is stated which original type 2 trajectories did not result in larger VMDs in simulated trajectories based on the VMD in the original trajectories. At 7500 ft the range is equal for both ACAS Xa and TCAS II. At this altitude, a VMD of 500 ft in the original trajectory resulted in the exact same VMD in the simulated trajectory. At 15000 and 36000 ft altitude, this changes. TCAS II uses the same threshold for the VMD but ACAS Xa increases the threshold with altitude. This results in a larger range of VMDs where RAs are issued by ACAS Xa to increase the VMD. A type 2 encounter with 700 ft VMD at 36000 ft altitude, for example, will not be altered by TCAS II. However, ACAS Xa will issue RAs to increase the VMD in this same encounter.

Table 31. Range of VMD in original trajectories that did not result in larger VMDs in simulated encounters

Altitude (ft)	TCAS II	ACAS Xa
7500	≥400 ft	≥400 ft
15000	≥400 ft	≥500 ft
36000	≥500 ft	≥800 ft

The simulations with the deterministic parameter settings D1.1 where the VMDs were increased, so with VMDs lower than the numbers mentioned in Table 31, showed VMDs that were similar to the VMDs found for the type 1 at 15000 and 36000 ft altitude. However, at 7500 ft the VMDs in the simulated trajectories were slightly higher than the typical 625 ft VMD.

In Figure 65 the VMD distributions for type 2 encounters with stochastic parameter settings S3.1 at 7500 ft altitude are displayed in violin plots for both TCAS II and ACAS Xa. Violin plots indicate the kernel density of the distribution rotated on its side. By plotting the violins for both TCAS II and ACAS Xa on top of each other, the difference in the pdfs can clearly be seen. Additionally, the medians of the distributions are highlighted by the blue line and red line, for TCAS II and ACAS Xa respectively.

In the figure it can be seen that the original VMDs of 100, 200 and 300 ft a result in a broad VMD distribution for both TCAS II and ACAS Xa, with medians that increase with increasing original VMD. ACAS Xa reaches higher VMDs, which is in line with the behaviour that was seen in Section 7.2. In the encounters with original VMDs of 400 ft and higher, the distributions look rather different. The majority of the VMD values reached are identical, or nearly identical, to the original VMDs. This indicates that only at original VMDs below the 300 ft the systems find it necessary to intervene the encounter to enlarge the VMD. The division in reached VMD distributions between the lower three altitudes and the higher altitudes is most clear for TCAS II, of which the distribution abruptly changes from a broad distribution at 300 ft original VMD to an extremely narrow distribution at 400 ft original VMD. ACAS Xa is more gradual in this behaviour, at 400 ft original VMD, the tail of the distribution is still visible and even at 500 ft original VMD slight occurrences of VMDs that reach around 800 and 900 ft can be seen.

This behaviour is not only seen at 7500 ft, the encounters at 15000 ft experience similar behaviour. At 36000 ft both TCAS II and ACAS Xa intervene till larger VMDs. This is the case in the TCAS II equipped encounters with original VMD up to and including 600 ft and the ACAS Xa equipped encounters up to and including 800 ft.

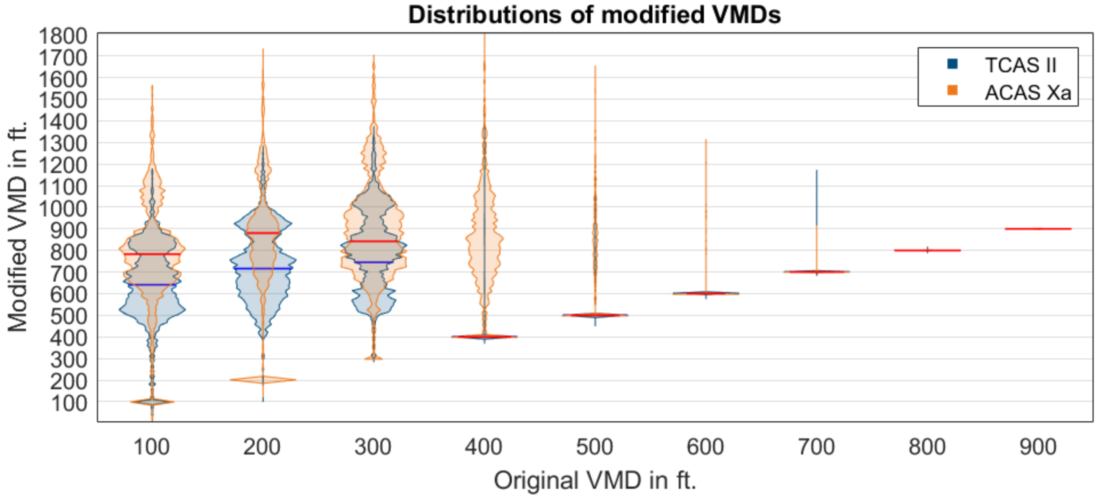


Figure 65. Distributions of TCAS II and ACAS Xa VMDs reached for the type 2 encounters at 7500 ft.

Interesting are the encounters where the reached VMDs are lower than the original VMDs. These represent the encounters that, due to intervention of TCAS II and ACAS Xa, result in a situation that is 'worse' than the original. This is especially the case if the original VMD is larger than, but relatively close to 100 ft. The percentages of these encounters are included per altitude and ACAS equipage in Figure 66. It is seen that ACAS Xa, in orange, has percentages all below the 0.4% with a VMD of 100 ft which quickly decrease to zero percent from 400 ft VMD onwards. This decrease of the ACAS Xa percentages at the higher original VMDs can be attributed to the fact that at these altitudes the modified encounters are often very similar to the modified encounter trajectories. And thus, ACAS Xa does not issue any RAs because the separation is found to be sufficient. TCAS II shows very different results. At the lower original VMDs, the percentages of encounters where the modified VMD is lower than the original VMD seem to be kept below 1%. With an original VMD of 500 ft or higher, the percentage increases to a maximum for all three altitudes after which it decreases again. However, this graph does not tell what the VMDs were after simulation. When looking at the TCAS II encounter with 500 ft VMD in the original trajectory at 7500 ft altitude, a clear peak is seen. 3.8% of these simulated encounters resulted in a VMD lower than 500 ft. When combining this information with the information from Figure 65, it can be concluded that all encounters that fall within this 3.8% have VMDs that lie only just below the 500 ft. Only 0.66% of the encounters have a VMD lower than 495 ft and the minimum VMD at this altitude is found to be 452 ft.

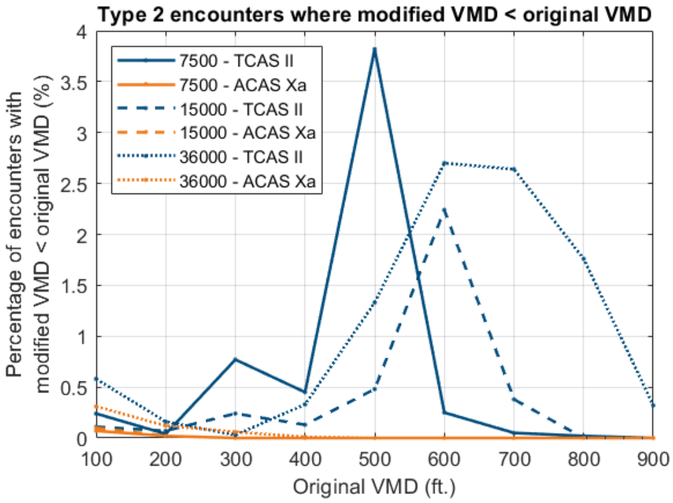


Figure 66. The percentage of type 2 encounters where the modified VMD is lower than the original VMD

So although it seems as if the ACAS Xa logic focusses more on limiting the modified VMD to be equal or larger than the original VMD, while TCAS II only sees the need to do so in encounters with low original VMDs, this is not the case. Both TCAS II and ACAS Xa ensure that the modified VMDs are close to or larger than the VMDs in the original trajectory.

An interesting indicator to investigate at this point would be the VMDs in encounters with unresolved risk versus VMDs in encounters with induced risk. This terminology can be explained using Table 32. A distinction is made between the encounter that is used as input to a situation and the encounter that results after the situation has occurred. Ideally, there is no NMAC present in both the input encounter and the resulting output encounter, since TCAS II and ACAS Xa then do not need to act. When the input encounter does contain an NMAC and the output encounter does not, this NMAC is called *resolved*, it is eliminated by the use of an ACAS. *Unresolved* risk occurs in a situation where TCAS II and ACAS Xa do not remove an NMAC that was originally present in an encounter. *Induced* risk is where ACAS creates an NMAC that was originally not there. Induced risk is thus found to be even less desirable than unresolved risk. This terminology is in line with industry standard. It is possible to calculate the NMAC probabilities of these four situations, since it is known which encounters, before and after simulation, contained NMACs or did not contain NMACs. However, the current output data format does not allow for a comparison between VMD distributions or RA types of the four situations.

Table 32. Typical terminology regarding NMACs in encounters

Input Encounter / Output Encounter	Contains NMAC	Does not contain NMAC
Contains NMAC	Unresolved NMAC	Induced NMAC
Does not contain NMAC	Resolved NMAC	No NMAC

8.3 NMAC Probability of Modified Trajectories

In the original type 2 encounters there were three original encounters that contained an NMAC. These were the encounters with 100 ft VMD at each of the three altitudes, as these just fall within the definition of an NMAC, as defined by EUROCAE [24]. In the data of the simulation with deterministic settings D1.1, no modified NMACs were found for both TCAS II and ACAS Xa.

The stochastic simulations with settings S3.1 did show several positive modified NMAC probabilities, which are included in Figure 67. Note that not all type 2 encounter geometries are represented in this graph. This is done on purpose, as the encounter geometries with an original VMD larger than 300 did not contain any positive NMAC probabilities.
The probability of a modified NMAC is clearly the highest for encounters with 100 ft original VMD at all three altitudes. With this VMD, this probability thus consists of encounters where no change in altitude was made and encounters where the VMD was decreased in the modified encounter. Originally, the encounter with 100 ft VMD had an NMAC probability of 100%. One could say that an NMAC reduction of for example 99.6%, which is the case in the ACAS Xa encounter with 100 ft VMD at 36000 ft, is a good result. However, for every 10000 simulated encounters there are thus still 40 which result in an NMAC. At 7500 and 36000 ft altitude there is quite a difference between TCAS II and ACAS Xa NMAC probabilities, although no definitive trend can be seen. For encounters with 100 ft VMD at 7500 ft the ACAS Xa modified NMAC probability is only one third of that of TCAS II. At 15000 ft, the ACAS Xa modified NMAC probability is slightly higher than that of TCAS II, while at 36000 ft the TCAS II probability is twice as high.

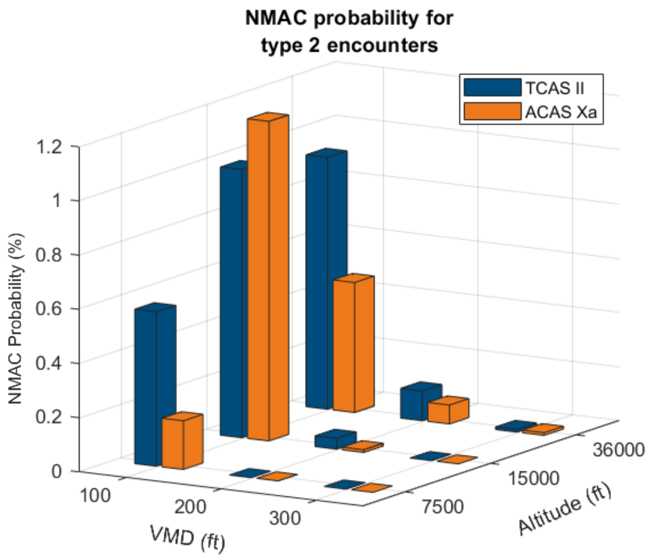


Figure 67. NMAC probability in type 2 encounters with stochastic parameter settings S3.1

The NMAC percentages for encounters with original VMDs higher than 100 ft are significantly lower, albeit still positive, which at first sight seems to be acceptable. However, these percentages of modified NMACs represent the group of encounters that originally were not NMACs, but resulted in NMACs after intervention of TCAS II and ACAS Xa. These are defined as induced risk. It means that the intervention of TCAS II and ACAS Xa caused the NMAC, which is the exact opposite of the goal of the systems. It is observed that this behaviour is most seen in encounters that have original VMDs that are close to 100 ft which is the threshold of the NMAC definition, such as 200 or 300 ft original VMD. The induced risk is more prevalent if the altitude of the encounter is increased and is higher when both aircraft are equipped with TCAS II.

To investigate this further, additional simulations are run with VMDs between 25 and 300 ft in steps of 25 ft. The deterministic settings D1.1 did not cause any NMACs in these encounters. In Figure 68 the NMAC probabilities of the additional type 2 encounters are included. When the VMD is below 100 ft, the encounters originally contain an NMAC. Both TCAS II and ACAS Xa show similar behaviour at all altitudes as when no VMD is present, as seen in the results of the type 1 encounters in Section 7.3. When the VMD is 100 ft the NMAC percentages at 7500 and 36000 ft altitude decrease significantly for both TCAS II and ACAS Xa while the NMAC percentages at 15000 ft remain similar as with lower VMDs.

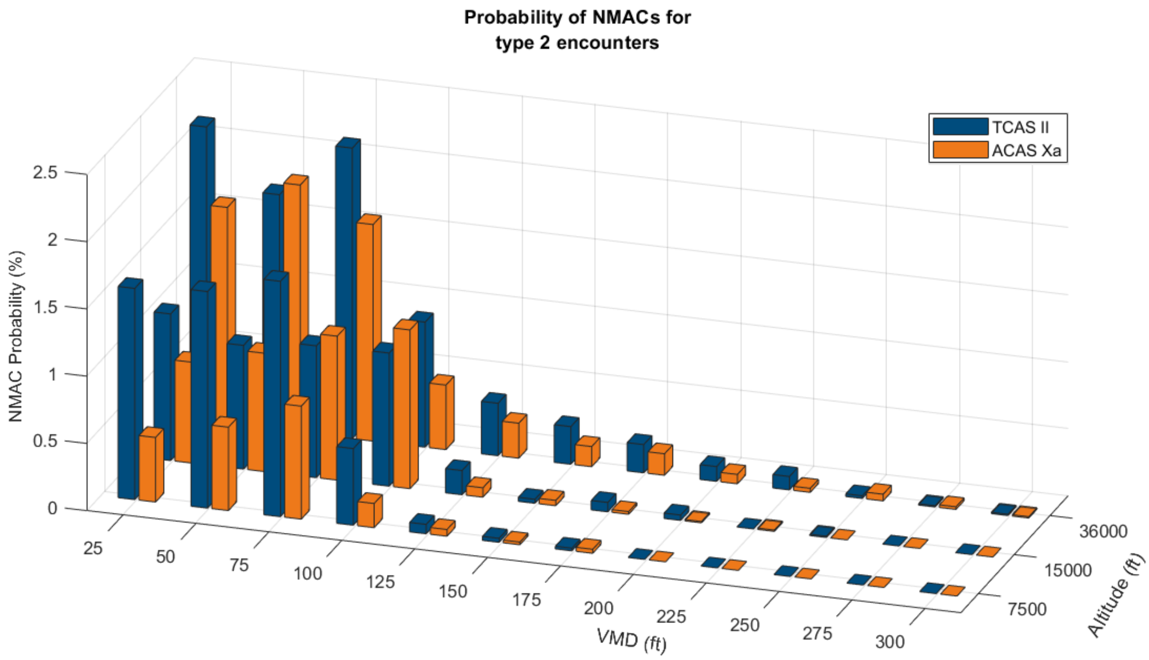


Figure 68. NMAC probability in additional type 2 encounters with stochastic parameter settings S3.1

When the VMDs is larger than 100 ft, the TCAS II NMAC probabilities gradually decrease till they are zero when the original VMD is increased from 100 to 300 ft. At lower altitudes this process is fairly quick, at the original VMD of 200 there are already no NMACs in the simulated encounters. At higher altitudes, this process takes longer, as there is still a slight positive NMAC probability visible in the encounter with original VMD of 300 ft. In the encounters with 100 ft original VMD at 7500 and 15000 ft altitude, ACAS Xa has lower NMAC probabilities than TCAS II does. It also gradually induces less NMACs as the original VMD is increased. However, the NMAC probabilities do not reduce to zero as fast as the TCAS II NMAC probabilities go to zero. At larger original VMDs ACAS Xa sometimes even has a larger NMAC probability than TCAS II has.

It should be noted that the NMAC probabilities at higher VMD distances in Figure 68 are relatively small, which means that only a small number of NMACs was found in the simulated trajectories. As explained in Chapter Appendix D.1, this might not be enough to draw conclusions from.

8.4 Probability of Modified Crossing Encounters

The original type 2 encounters did not contain any crossings and the encounters modelled with the D1.1 settings did contain any either. The modified crossing probabilities for the encounters that were modelled with the S3.1 settings are included in Figure 69 and show several trends. First of all it can be seen that TCAS II and ACAS Xa perform very similar with nearly identical modified crossing probabilities. Second, the higher the altitude of the encounter, the higher the modified crossing probability. Additionally, a higher VMD has a positive influence on the modified crossing probability, since it decreases with increasing VMD. This is in line with expectations, as the further the aircraft are originally apart, the less they need to climb or descend to reach safe separation distances and thus the less likely it is to cross the other aircraft during this manoeuvre.

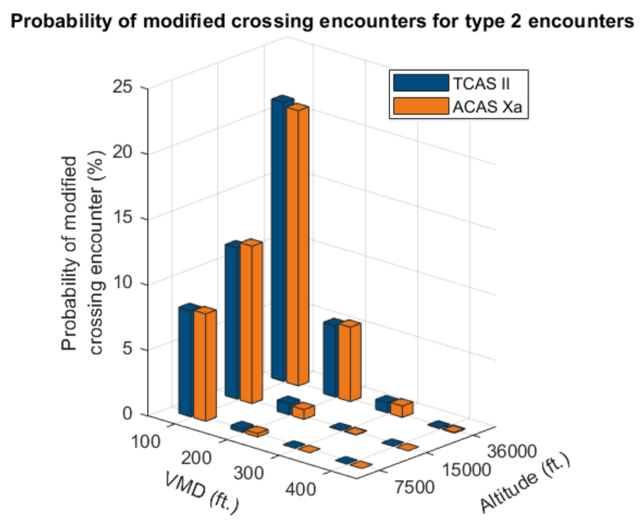


Figure 69. Probability of crossing encounters for the type 2 encounters. TCAS II in blue, ACAS Xa in orange.

8.5 Advisories and Their Timings

The specific RAs that are given when deterministic D1.1 settings are used at certain VMDs with respect to a centre altitude in a specific encounter can be obtained by generating ACAS policy plots. The process of generating such a plot was explained in Chapter 6.

Information about the exact RAs that are given is interesting to investigate to obtain knowledge about when ACAS is triggered and how severe the TCAS II and ACAS Xa solutions are. In Table 33 it is displayed at which of the type 2 encounter geometries the TAs, preventive RAs and corrective RAs are issued, these can either be issued to both the aircraft or to one of the aircraft. The TAs and RAs issued by TCAS II are marked by a blue cell and the orange cells mark the advisories issued by ACAS Xa.

It can be seen that at 7500 and 15000 ft TCAS II issues the exact same types of advisories at the same original VMDs. The TAs are issued in the large VMD range from 100 to 800 ft. Preventive RAs are issued at 400 and 500 ft VMD and corrective RAs are issued from 100 to 300 ft VMD. It makes sense that the preventive RAs and to a stronger extent corrective RAs are only issued when the VMD is decreased, as this is when the encounter geometry could potentially result in an NMAC. ACAS Xa issues TAs from 100 to only 500 ft and corrective RAs till 300 and 400 ft at 7500 and 15000 ft altitude respectively. Preventive RAs are not issued by ACAS Xa, while these do belong to the advisory data base of ACAS Xa. This behaviour was also seen during the analysis of TCAS II and ACAS Xa policy plots in Section 6.4. It thus seems that with deterministic setting D1.1 ACAS Xa waits till there is a definitive need for an advisory, rather than warning the pilot of potential danger that is unharmful when the current flight plan is followed. TCAS II on the other hand seems to prefer to warn its pilot of potential danger that occurs if there is any deviation from the flight plan.

Table 33. TAs, preventive RAs and corrective RAs that are issued per original VMD in type 2 encounters per altitude

Altitude of encounter	ACAS Type	Type of Advisory	Original VMD								
			100	200	300	400	500	600	700	800	900
7500 ft	TCAS II	TA									
		Preventive RA									
		Corrective RA									
	ACAS Xa	TA									
		Preventive RA									
		Corrective RA									
15000 ft	TCAS II	TA									
		Preventive RA									
		Corrective RA									
	ACAS Xa	TA									
		Preventive RA									
		Corrective RA									
36000 ft	TCAS II	TA									
		Preventive RA									
		Corrective RA									
	ACAS Xa	TA									
		Preventive RA									
		Corrective RA									

The behaviour of the preventive and corrective RAs can be verified using ACAS policy plots, which indicate the exact RAs that are given. The TCAS II and ACAS Xa policy plots for the altitude of 15000 ft are displayed in Figure 70 and Figure 71 as an example. Since the advisories in Table 33 are from an encounter with 120 seconds before CPA, it is safe to say that the advisories are given around 32 seconds before CPA. This is the longest time from CPA when there are RAs issued. At this point in the TCAS II policy plot can be seen that TCAS II issues the preventive 'Do Not Descend' and 'Do Not Climb' RAs when the VMD is between 400 and 600 ft. Corrective RAs are given at VMDs between zero and 400 ft. In the ACAS Xa policy plot it is seen that ACAS Xa does not start with issuing RAs at one moment in time before CPA, but rather 'waits' till the aircraft is close enough both horizontally and vertically such that an RA needs to be issued to solve the encounter. Only corrective RAs are issued. This is all in line with the preventive and corrective RAs in Table 33. At the moments just before CPA, the TCAS II policy plot displays additional preventive RAs that limit the descend and climb rates. These are not seen in the ACAS Xa policy plot, as these do not belong to the possible RAs that can be issued by ACAS Xa.

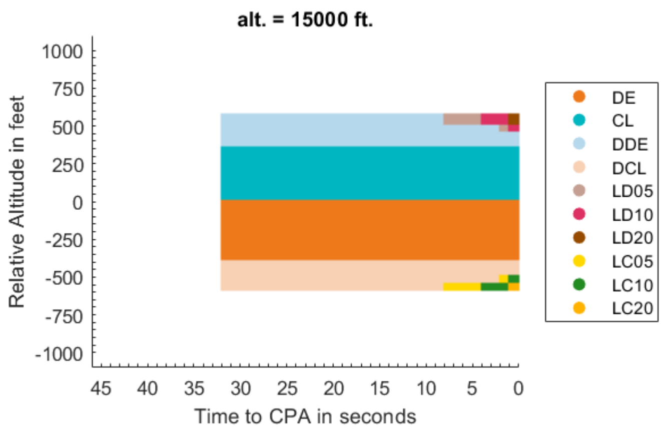


Figure 70. TCAS II policy plot of type 1 encounter with relative course angle of 180° at 15000 ft.

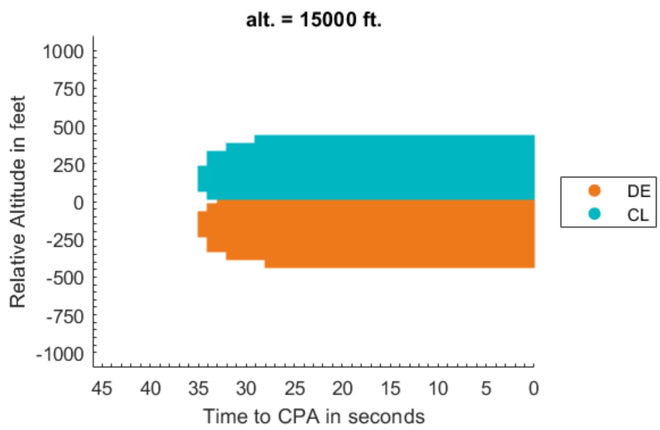


Figure 71. ACAS Xa policy plot of type 1 encounter with relative course angle of 180° at 15000 ft.

Since stochastic ACAS policy plots are not developed yet, the RA types that are issued per aircraft in an encounter are discussed using bar charts instead. In Figure 72 the RA metrics for type 2 encounters at 15000 ft are displayed, valid for simulation with the S3.1 settings. Both aircraft in the encounter receive extremely similar mean number of RAs at all altitudes, which is why only the RA metrics for aircraft 1 are shown, these are thus also valid for aircraft 2. The similarity indicates that neither TCAS II and ACAS Xa have preferences for one of the aircraft and intent to solve the encounters by diverging both of the aircraft instead of just one. Just like with the type 1 encounters, the majority of the corrective RAs that are issued are neither an increase rate, reversal or crossing RAs.

The RAs are issued during encounters with low original VMDs and the mean number of RAs that are issued per encounter decreases with increasing original VMD. In the encounters with 100 ft VMD at all altitudes TCAS II a mean around 1.8 RAs per encounter.

It is seen that the mean number of Other RAs issued starts to decrease from 200 ft original VMD onwards, till it reaches zero at 700 ft original VMD, for TCAS II. ACAS Xa issues a slightly lower mean of around 1.6 RAs per aircraft per encounter, but the decrease from 300 ft VMD onwards is less quick. This is seen when looking at the encounters with 400 and 500 ft original VMDs.

This behaviour is not only seen at 15000 ft altitude, but also at 7500 and 36000 ft altitude. However, at lower altitudes both ACAS start to decrease their mean number of RAs that are issued at lower original VMDs. Additionally, at higher altitudes the decrease of the mean number of RAs is less quick.

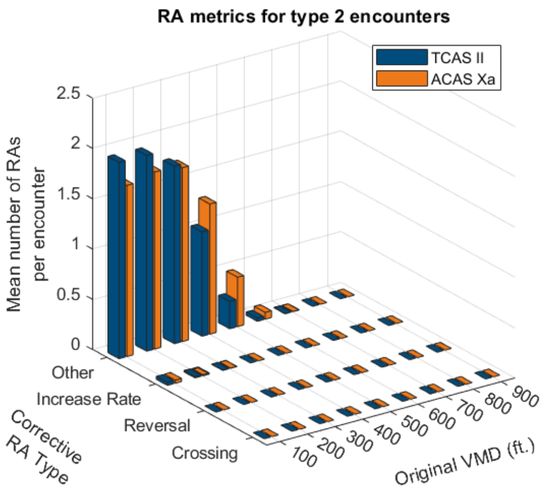


Figure 72. RA metrics for type 2 encounters with S3.1 settings at 15000 ft. altitude

This could be due to the lower velocity of the aircraft. For example, at 36000 ft altitude both TCAS II and ACAS Xa start decreasing their mean number of RAs per aircraft from encounters with VMDs of 400 ft onwards. And although TCAS II has decreased its mean number of RA issued per encounter to zero in the encounter with 900 ft original VMD, ACAS Xa still issues a small number of RAs in this type 2 encounter with the largest original VMD. There are also some extremely low mean numbers of increase rate RAs that are issued by both ACAS mainly during encounters with 100 ft VMD.

To better understand the difference between TCAS II and ACAS Xa in terms of specific RAs, an encounter with an original VMD of 400 ft at 15000 ft is analysed in more detail. At this VMD the difference between the mean number of RAs that TCAs II and ACAS Xa issued was relatively large. In Figure 73 and Figure 74 the TCAS II and ACAS Xa advisory trees of the encounter are displayed. Immediately it can be seen that TCAS II uses many different RAs and ACAS Xa issues just a few. TCAS II issues a ‘Climb’ RA as a first RA in roughly 51% of the simulated runs, while the other 49% of the runs receive one of the preventive RAs that dictate not to descent or limit the descent rate or a TA. The three preventive RAs that limit the descent rate, LD05, LD10 and LD20, are not available for ACAS Xa to issue. The preventive RA that is issued most is the ‘Do Not Descend’ RA, issued in 49% of the simulated runs. After this ‘Do Not Descend’ RA, the COC is in the majority of the cases, in just 6% of the cases a ‘Climb’ RA is given. ACAS Xa issues a ‘Climb’ RA in nearly all simulated runs after which in three quarters of the simulated runs a 'Level Off' RA is given. In 23% of the runs, a COC is given as second RA. This indicates that ACAS Xa logic fully decides on a corrective RA as a first RA, while the TCAS II logic divides the initial RA between corrective and preventive RAs.

In bold, the sequences of RAs given in the simulation with the deterministic D1.1 settings are marked in the two advisory trees. In the case of ACAS Xa, this deterministic sequence has a nearly 100% probability to occur in the stochastic S3.1 settings as well. In the case of TCAS II, however, only half of the time this sequence is followed. This indicates that including intrinsic uncertainties influences the specific RAs greatly.

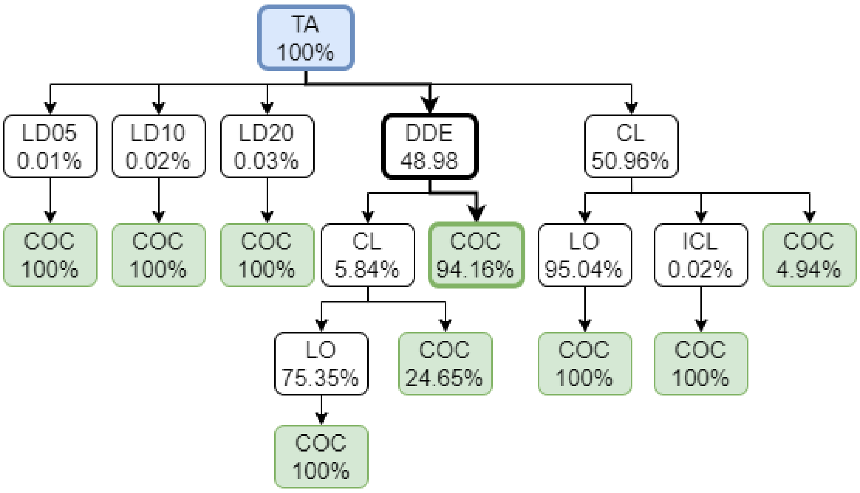


Figure 73. TCAS II advisory tree of type 1 encounter with 400 ft. VMD at 15000 ft. altitude with S3.1 settings. RAs issued in same encounter with D1.1 settings are marked bold.

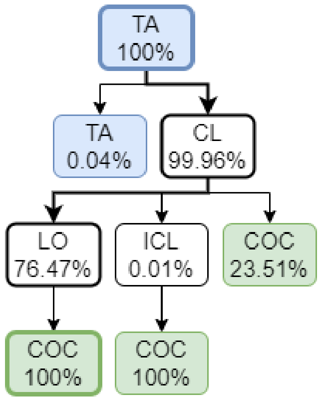


Figure 74. ACAS Xa advisory tree of type 1 encounter with 400 ft. VMD at 15000 ft. altitude with S3.1 settings. RAs issued in same encounter with D1.1 settings are marked bold.

In Figure 75 the timings of the different RAs issued by TCAS II and ACAS Xa are displayed. As was seen in the advisory trees, TCAS II can issue a sequence of a maximum of four RAs while ACAS Xa can issue a sequence of a maximum of three RAs, which is why the third RA can only be issued by TCAS II. The timings of the RAs look very similar, the only real differences are the maximum timings of the first and second RA. The first RA that is issued by ACAS Xa is most of the time already issued at a later time than the initial RA issued by TCAS II. This difference increases with the second RA. The second RA issued by ACAS Xa is most of the time even issued later in time than the third RA issued by TCAS II. The COC is then issued around the same time, with a narrow distribution. This behaviour again indicates the 'waiting' behaviour that the ACAS Xa logic has with respect to the TCAS II logic.

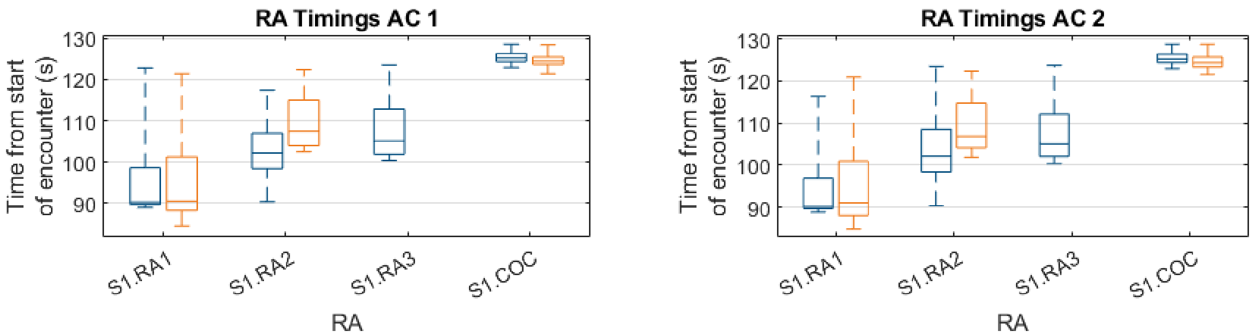


Figure 75. RA timings of type 2 encounter with 400 VMD at 15000 ft. altitude. TCAS II in blue, ACAS Xa in orange

9 Performance of TCAS II and ACAS Xa on Type 3 Encounters

The third type of encounters include one aircraft that flies level and one aircraft that climbs or descends, as described in Section 9.1. The successive sections discuss the results from simulation.

9.1 Type 3 Encounters

Moments before CPA, the second aircraft levels off and flies exactly 14 ft above or below the first aircraft, without crossing its trajectory. A sideview over time of a typical type 3 encounter is included in Figure 76. The moment at which the level-off manoeuvre starts depends on the total and vertical velocity $\overline{v}_j$ and v_j^z of the aircraft, as was explained in Section 3.5.

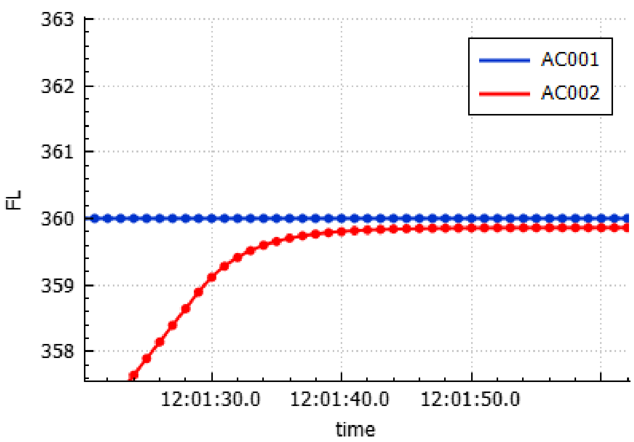


Figure 76. Typical sideview of type 3 encounter

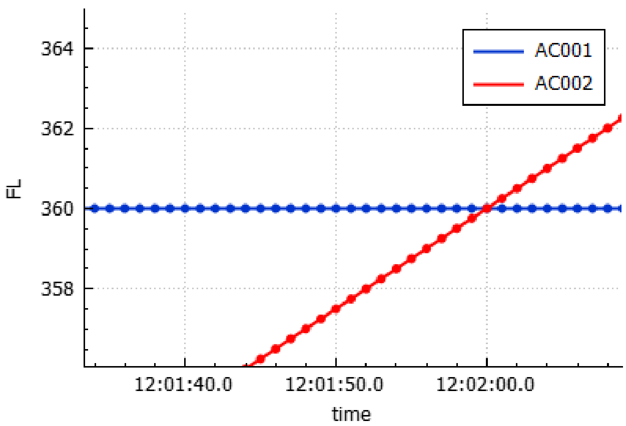


Figure 77. Typical sideview of altered type 3 encounter, without level-off

In Figure 78 a typical vertical acceleration profile of the aircraft performing the level-off manoeuvre following a climb is included. It can be seen that before the start of the level-off there is no vertical acceleration, as the vertical velocity is constant. At the start of the level-off the vertical acceleration peaks at -0.2g and within three seconds the vertical acceleration is below 0.1g. After 30 seconds the acceleration is reduced back to zero and the aircraft flies level. The maximum vertical acceleration and the duration of the flare are dependent on the exact encounter geometry, as explained in Section 3.5.

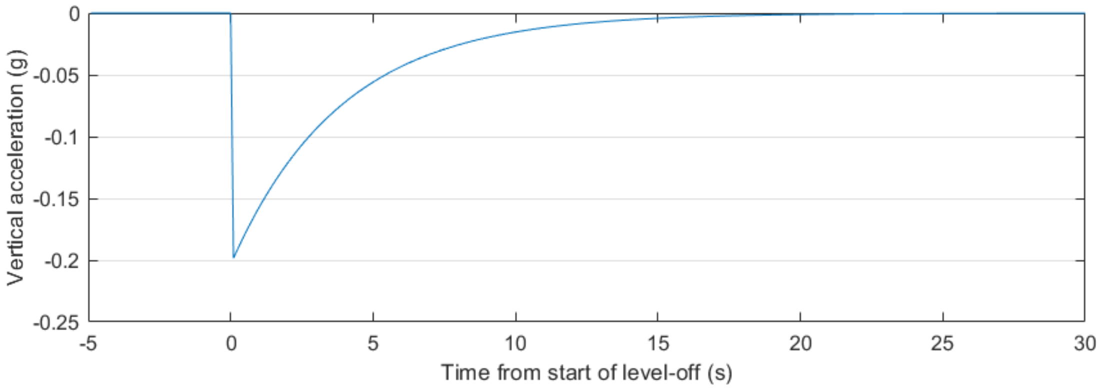


Figure 78. Typical vertical acceleration profile of aircraft in level-off manoeuvre

The parameters that together describe the set of type 3 encounters are stated in Table 34. The range of the vertical acceleration peaks for these encounters lies between -0.19g and -0.21g.

Table 34. Type 3 encounters parameters

AC	Symbol	Unit	Values		
	$h_{i,j}^{CPA}$	ft	7500	15000	36000
i	$\overline{v}_i$	KTS	295	295	480
	v_i^z	ft/min	0	0	0
j	$\overline{v}_j$	KTS	295	295	480
	v_j^z	ft/min	2000, -2000	2000, -2000	1500, -1000
	$d_{i,j}^{VMD}$	ft	14		
	$d_{i,j}^{HMD,lon}$	ft	0		
	$d_{i,j}^{HMD,lat}$	ft	0		
	χ^{course}	deg (°)	90, 180		

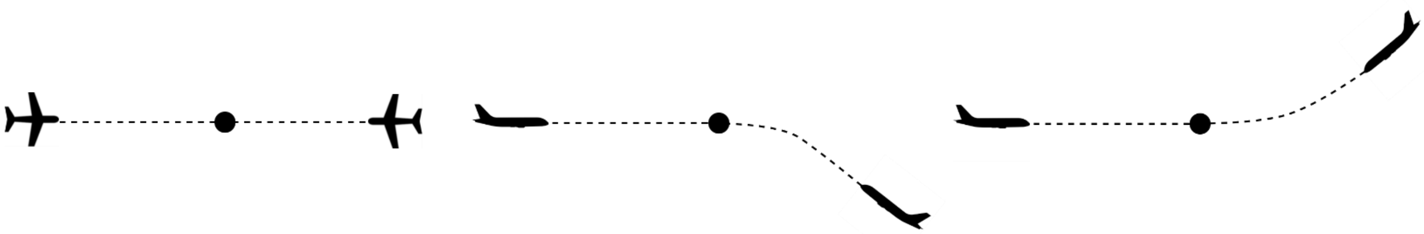


Figure 79. Schematic overview of type 3 encounter, with level-off manoeuvres

Figure 79 includes a schematic overview of the type 3 encounters. At the end of the chapter, the results of the type 3 encounters are compared to the results of a set of altered type 3 encounters. In these new type 3 encounters the second aircraft does not perform the level-off manoeuvre, but instead it holds its initial vertical velocity for the complete duration of the encounter. This means that there is no acceleration present and that the example manoeuvre in Figure 76 is modified to the altered manoeuvre in Figure 77. By comparing the two sets of encounters, the influence of the level-off manoeuvre on the TCAS II and ACAS Xa solutions can be analysed, as well as the influence of a constant vertical velocity. In the two figures the slope of the climb before CPA seems to be different, but this is due to the different scales on the y-axis.

All encounters in this section are run for 180 seconds, of which 120 seconds occur before CPA. The simulations are done with deterministic parameter settings D1.1 and stochastic parameters S3.1.

9.2 Analysis of Vertical Miss Distance

The simulations with the deterministic parameter settings D1.1 showed VMDs that were extremely similar to the VMDs found for the type 1 encounters. In Table 35 to

Table 37 these results are included. At 7500 ft both ACAS result in similar VMD values around 620 ft. For TCAS II the VMD increases to around 670 ft and 870 ft when the altitude is increased to 15000 and 36000 ft. ACAS Xa equipped aircraft reach VMDs of around 1010 and 1200 ft at these altitudes. Thus, at 15000 and 36000 ft. altitude ACAS Xa always reaches higher VMDs and the difference between TCAS II and ACAS Xa increases with altitude.

Note that there is no significant difference between the VMDs reached in the encounters with a positive vertical velocity or the VMDs reached in the encounters with a negative velocity in the deterministic parameter settings. The sign of the vertical velocity does not influence the VMDs in that case. The course angle also does not have any effect on the results, an effect that was also seen in the type 1 encounter results.

Table 35. VMDs from type 3 encounters at 7500 ft altitude, obtained from deterministic simulation

	Course angle of 90°		Course angle of 180°	
	TCAS II	**ACAS Xa**	**TCAS II**	**ACAS Xa**
Vertical velocity of 2000 ft/min	615	610	635	610
Vertical velocity of -2000 ft/min	638	612	637	662

Table 36. VMDs from type 3 encounters at 15000 ft altitude, obtained from deterministic simulation

	Course angle of 90°		Course angle of 180°	
	TCAS II	**ACAS Xa**	**TCAS II**	**ACAS Xa**
Vertical velocity of 2000 ft/min	658	1008	659	1008
Vertical velocity of -2000 ft/min	686	1010	687	1011

Table 37. VMDs from type 3 encounters at 36000 ft altitude, obtained from deterministic simulation

	Course angle of 90°		Course angle of 180°	
	TCAS II	ACAS Xa	TCAS II	ACAS Xa
Vertical velocity of 1500 ft/min	852	1182	874	1182
Vertical velocity of -1000 ft/min	852	1137	885	1227

The VMD distributions of the type 3 encounters in simulations with stochastic parameters S3.1 also show similar behaviour that was observed during the analysis of the type 1 and 2 encounters.

- TCAS II often reaches lower VMDs than ACAS Xa.
- The higher the altitude, the higher the VMDs that are reached by both TCAS II and ACAS Xa and the difference between TCAS II and ACAS Xa increases with altitude as well.
- The higher the altitude, the more the ACAS Xa VMD distribution is skewed to the right.
- The course angle has no influence on the VMDs that are reached.

To see the influence of the vertical velocity on the VMD distribution, as an example a plot including type 3 encounters with several vertical velocities at 15000 ft altitude is displayed in Figure 80. The vertical velocity is varied within typical values, from 1000 ft/min to 2000 ft/min in steps of 200 ft/min. The VMDs reached at 7500 and 36000 ft altitude show similar distributions. It is observed that for both ACAS, the general shape of the pdf remains similar with increasing vertical velocity.

For TCAS II, the pdfs of the VMD distributions all show a large peak around 550 ft VMD and a smaller peak around 900 ft. The encounter with 1000 and 1400 ft/min vertical velocity do not show the large peak at 550 ft VMD as clearly, but do follow the general shape of the rest of the distributions.

The ACAS Xa encounters show a bimodal distribution with two peaks, one at 600 ft and one at 1100 ft VMD. These two peaks were also seen for the type 1 results. Different from the type 1 results is the height of these peaks. From Figure 80 it is seen that ACAS Xa tends to give more aircraft a higher VMD than it did in the type 1 results presented in Section 7.2.

Next to that the peaks thus lie at higher VMDs than the TCAS II peaks. The distribution with a vertical velocity of 1000 ft/min again is less clear in indicating the peaks but does follow the general shape of the rest of the distributions. This indicates that although there is a difference in VMD distribution when the vertical velocity is varied within a typical range, this difference in vertical velocity has limited influence on the VMDs that are reached. Only lower values of vertical velocity show a slightly different VMD distribution.

In the VMD range between 0 and 300 ft both ACAS show small probabilities. In the VMD range from 0 to 100 ft, which result in NMACs, TCAS II shows higher probabilities than ACAS Xa at all different vertical velocities. A detailed look at the NMAC probabilities is taken in the next section.

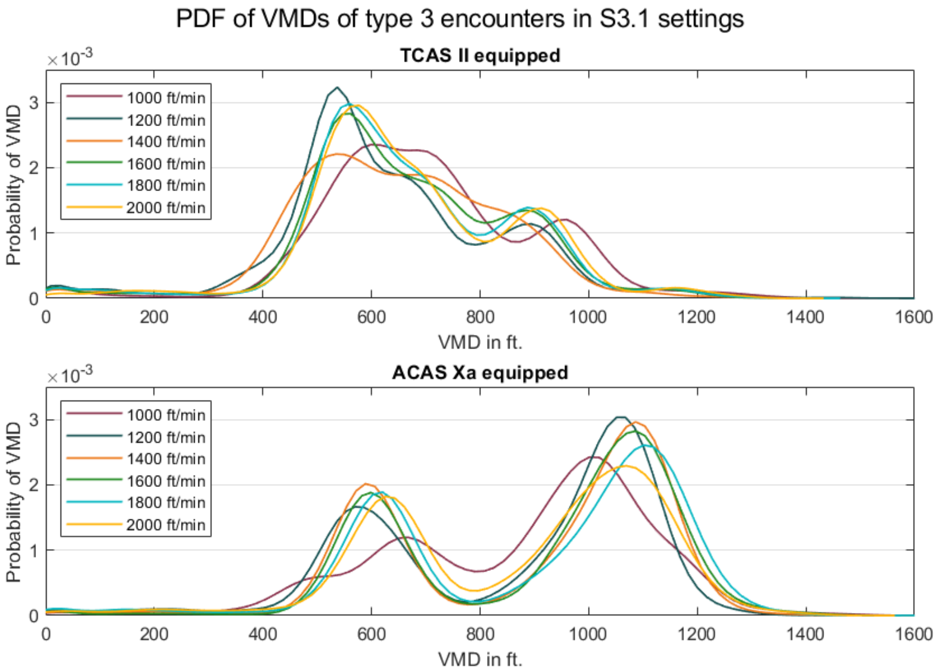


Figure 80. PDFs of the VMD distribution of type 3 encounters with varying vertical velocity in S3.1 settings at 15000 ft. Top graph: TCAS II and bottom graph: ACAS Xa.

9.3 NMAC Probability of Modified Trajectories

The original encounters all contained NMACs, as the aircraft come within 100 ft vertically of each other. With the deterministic D1.1 settings, none of the modified encounters contained an NMAC, indicating that both TCAS II and ACAS Xa were successful in resolving the NMACs.

In Table 38 the NMAC probabilities for encounters simulated with the stochastic S3.1 settings are presented for all three altitudes.

Table 38. NMAC probabilities in percentages for type 3 encounters at all three altitudes

Altitude (ft)	Vertical velocity (ft/min)	Course angle of 90°		Course angle of 180°	
		TCAS II	ACAS Xa	TCAS II	ACAS Xa
7500	2000	0.94	0.59	1.79	0.65
	-2000	0.88	0.48	1.62	0.72
15000	2000	0.37	0.57	0.83	0.85
	-2000	0.29	0.68	0.93	0.78
36000	1500	1.19	0.76	1.86	0.80
	-1000	0.91	1.11	1.54	0.95

TCAS II shows NMAC probabilities in a relatively large range, from 0.29% to 1.86% over the different encounter geometries and altitudes. There is a clear difference between the altitudes, at 7500 and 36000 ft the NMAC probabilities are similar, but at 15000 ft the NMAC probabilities are significantly lower. There is also a difference between the encounters with 90° course angle and 180° course angle. The dependency on the course angle was also seen in the type 1 encounters. The encounters with 180° course angle have a probability to end in an NMAC of roughly twice that of the encounters with a 90° course angle. This indicates that when a vertical velocity is included, the course angle still has an effect on the NMAC probability.

ACAS Xa has NMAC probabilities between that all lie between 0.5% and 0.9% NMAC probability, which is a significantly smaller range than TCAS II. There is no clear difference between the altitudes or encounter geometries.

When comparing these NMAC percentages to the NMAC percentages of the type 1 encounters with 90 and 180° course angles, the effect of the vertical velocity of aircraft 2 can be seen. TCAS II indicates similar percentages at all altitudes, regardless of the inclusion of the vertical velocity. ACAS Xa indicates slightly higher NMAC probabilities than it did in the type 1 encounters which is now independent of the altitude.

Finally, the vertical direction of the second aircraft does not seem to influence the NMAC probability to a great extent at 7500 and 15000 ft altitude for both TCAS II and ACAS Xa. However, at 36000 ft altitude, there are some differences between the NMAC probabilities of the encounters with a climbing or descending aircraft. For TCAS II the NMAC probability is slightly higher if the vertical velocity is positive while for ACAS Xa the NMAC probability is higher when the vertical velocity is negative. Again, TCAS II results are influenced by the course angle while those of ACAS Xa are not.

Since TCAS II shows a dependency on the course angle, the type 3 encounter with CPA at 15000 ft altitude is simulated with course angles ranging from 0 to 180 degrees. In Figure 81 the NMAC probabilities for these encounters are displayed. For TCAS II a clear trend is observed, the larger the course angle, the higher the NMAC probability. For ACAS Xa, this trend is not observed. This corresponds to the findings documented in Section 7.3.

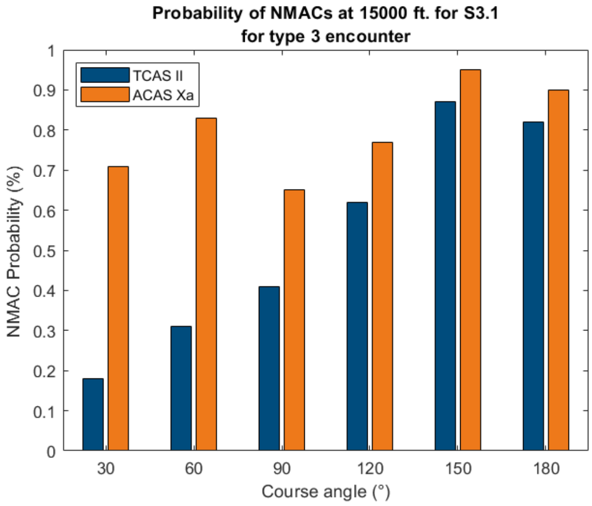


Figure 81. Probabilities of NMACs in percent for type 3 encounters with varying course angle at 15000 ft altitude

9.4 Probability of Modified Crossing Encounters

Table 39 presents the modified crossing encounter probabilities for the type 3 encounters at 7500 and 15000 ft altitude and at 36000 ft altitude. The majority of the percentages is rather high.

This could be caused by the relatively short duration of the level-off manoeuvre. As stated in Section 3.5, the manoeuvre takes between 30 and 41 seconds, depending on vertical velocity of the aircraft. It is plausible that TCAS II and ACAS Xa are alerted before the level-off manoeuvre is started or when the vertical velocity has not been reduced significantly. At this point it might not be possible to reverse the vertical velocity while ensuring safe vertical separation of 100 ft. TCAS II and ACAS Xa can then prefer to let the two aircraft cross each other trajectory if that does ensure a safe VMD.

At 7500 and 15000 ft altitude the modified crossing probability is not dependent on the course angle and similar for both TCAS II and ACAS Xa, around 60%. It is dependent on the vertical velocity. Negative vertical velocities give around 10% larger crossing encounter probabilities. TCAS II equipped encounters always have a higher crossing encounter probability, although the difference with ACAS Xa is small and remains within a few percent.

Table 39. Probabilities of Crossing Encounters in percentages for type 3 encounters at all three altitudes in stochastic parameter settings

Altitude (ft)	Vertical velocity (ft/min)	Course angle of 90°	Course angle of 180°

		TCAS II	ACAS Xa	TCAS II	ACAS Xa
7500	2000	58.52	52.00	55.35	49.68
	-2000	70.50	65.20	69.34	64.09
15000	2000	71.68	70.61	71.94	64.98
	-2000	79.96	77.78	80.37	74.46
36000	1500	45.27	93.81	48.72	92.43
	-1000	12.74	52.50	14.51	50.07

At 36000 ft altitude, this dependency on the vertical velocity is more prevalent in both TCAS II and ACAS Xa. To visualise this behaviour, Figure 82 is included.

TCAS II indicates a crossing encounter probability of 40% when the vertical velocity is positive while it is only around 10% when the vertical velocity is negative. This is a factor of four difference. The difference between the crossing encounter probability for ACAS Xa is a factor two smaller between a positive and negative vertical velocity, from around 90% to around 50%. The difference between TCAS II and ACAS Xa at 36000 ft altitude is larger than at the lower two altitudes and at 36000 ft altitude, ACAS Xa always results in significantly larger crossing encounter probabilities than TCAS II does. When aircraft 2 climbs the ACAS Xa results indicate more than twice the crossing encounter probability of TCAS II. When aircraft 2 descends, the TCAS II crossing encounter probability is a factor of four lower than the ACAS Xa probability.

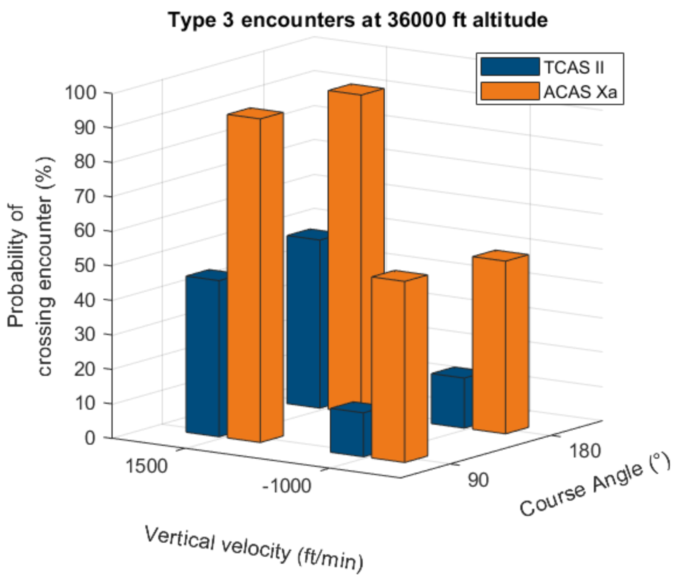


Figure 82. Probability of crossing encounter for type 3 encounters at 36000 ft altitude

This difference in TCAS II and ACAS Xa behaviour originates from the advisories that are issued during the encounter, which are included in the following section.

9.5 Advisories and Their Timings

The mean number of advisories per advisory type that is issued in an encounter does not vary per altitude. In Table 40 the mean number of RAs that are issued per encounter is included, for Other RAs and Increase Rate RAs. It can be observed that each aircraft in a type 3 encounter receives around 1.8 RAs that are not increase rate, reversal or crossing if the aircraft is equipped with TCAS II. When equipped with ACAS Xa this number is slightly lower around 1.6 other RAs. Additionally, there is also a very small possibility that an increase rate RA is issued. The course angle and the vertical velocity of the second aircraft do not influence these RA metrics.

Table 40. Mean number of indicated RA types for type 3 encounter at 36000 ft altitude

Type of RA	Vertical velocity (ft/min)	Course angle of 90°		Course angle of 180°	
		TCAS II	ACAS Xa	TCAS II	ACAS Xa
Other	1500	1.78	1.69	1.76	1.69
	-1000	1.87	1.65	1.86	1.66
Increase Rate	1500	0.035	0.053	0.041	0.055
	-1000	0.031	0.052	0.036	0.056

When a specific encounter is analysed in more detail, the difference between the two ACAS becomes more visible. The encounter for this detailed analysis has a course angle of 180° and occurs at 36000 ft altitude. In this encounter the vertical velocity of aircraft 2 before the level-off manoeuvre is 1500 ft/min. Aircraft 1 always flies above aircraft 2 in the original flight plan of the encounter. In Figure 83 and Figure 84 the modified trajectories of this encounter as flown with deterministic settings D1.1 for TCAS II and ACAS Xa are displayed. Although the shape of the modified trajectories is alike, the advisories that were issued during the encounter are not.

TCAS II starts with issuing a 'Crossing Climb' RA to aircraft 2, after which the first aircraft receives the preventive RA 'Do Not Climb' which is then changed to the corrective 'Descend' RA. This 'Descend' RA is issued at the moment the first aircraft is at the point where the second aircraft will later cross its trajectory. This is a possible reason why the RA is not a 'Crossing Descend' RA, since the action of descending is not the main cause of the crossing of trajectories. When a sufficient VMD is reached, the aircraft are issued a 'Level Off' and finally the COC is issued.

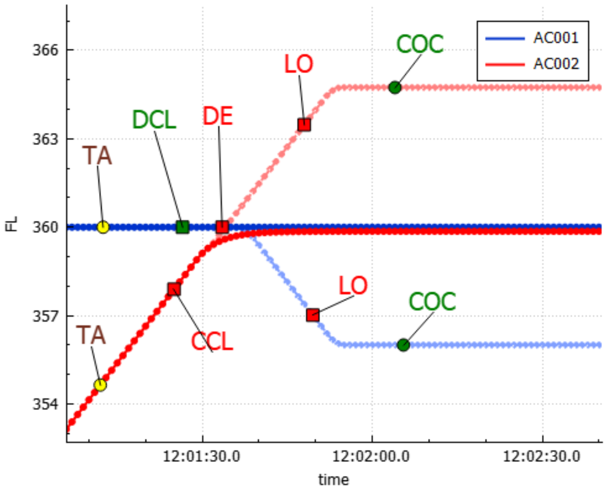


Figure 83. Type 3 encounter with a course angle of 180° where aircraft 2 is equipped with TCAS II and has a vertical velocity of 1500 ft/min before a level-off manoeuvre is performed, all at 36000 ft altitude

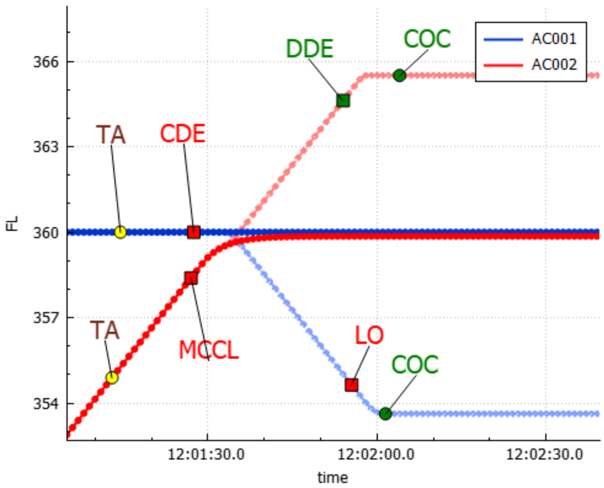


Figure 84. Type 3 encounter with a course angle of 180° where aircraft 2 is equipped with ACAS Xa and has a vertical velocity of 1500 ft/min before a level-off manoeuvre is performed, all at 36000 ft altitude

ACAS Xa starts with issuing the 'Maintain Crossing Climb' to the second aircraft, acknowledging that the current trajectory is already a crossing climb. Then, the first aircraft receives the 'Crossing Descend' RA, sending it downwards. After sufficient VMD is reached the first aircraft receives the 'Level Off' and COC RAs, just like TCAS II issued. The second aircraft however, receives a preventive 'Do Not Descend' RA during its climb, levels off and receives the COC.

With stochastic settings, the variety of the RAs used increases significantly. Note that only the most likely possible sequences are discussed, and thus the probabilities do not always add up to 100%.

In Figure 85 the advisory tree of aircraft 1 in a stochastic TCAS II equipped type 3 encounter where aircraft 1 flies at 36000 ft altitude is displayed, the deterministic RAs are included in bold. TCAS II issues a 'Climb' RA as an initial RA to aircraft 1 half of the time. 31% of the initial RAs are 'Do Not Climb' RAs and 16% a 'Descent' RA. In the majority of the encounters, roughly 90%, aircraft 1 also receives a second RA. In 5853 of the 10000 simulation runs, this second RA was a 'Level Off' and in 2745 of the runs the second RA was a 'Descent'. After all runs, a COC was issued. The probability of aircraft 1 receiving the exact same RAs in the stochastic settings as it did in the deterministic settings is only 2%, as is calculated using conditional probabilities.

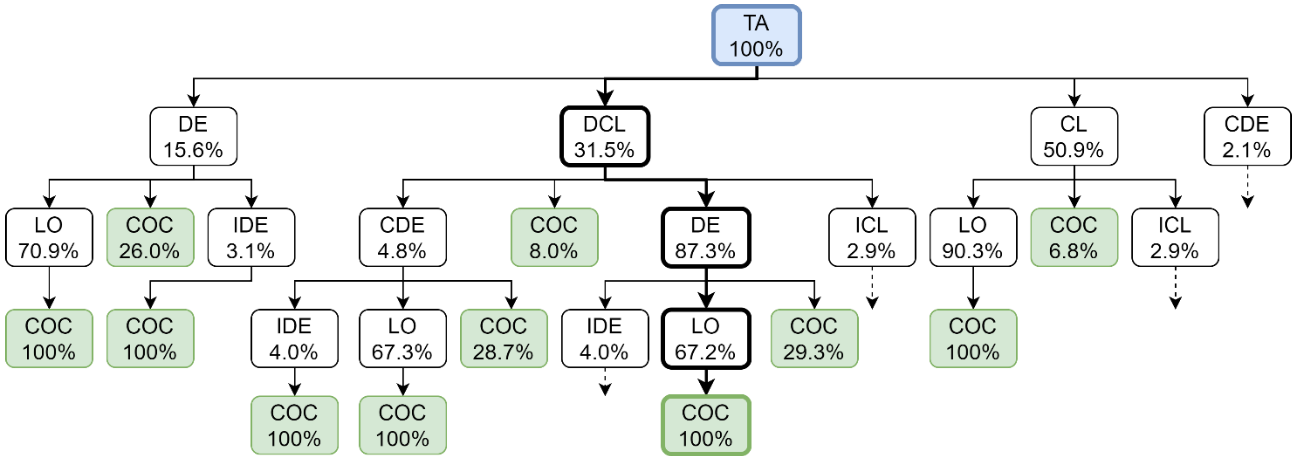


Figure 85. Advisory Tree of aircraft 1 in a TCAS II equipped type 3 encounter where aircraft 2 has a vertical velocity of 1500 ft/min at 36000 ft altitude

Aircraft 2 receives a 'Descent' RA 50% of the time, 31% of the time a 'Climb' is issued and in 11% of the simulations the first RA is a 'Crossing Climb'. In 80% of the simulations, the second RA is a 'Level Off'. The probabilities of the RAs indicate that although the deterministic settings result in a crossing encounter, the TCAS II intention in the stochastic settings is to avoid a crossing at least 50% of the time, by issuing a 'Climb' RA to the upper aircraft and a 'Descent' RA to the lower aircraft.

ACAS Xa approaches the encounter differently, as its solutions result in a crossing encounter the majority of the time, on contrary to TCAS II. The advisory tree for aircraft 1 equipped with ACAS Xa in the same stochastic encounter is included in Figure 86, the RAs from the deterministic encounter are included in bold.

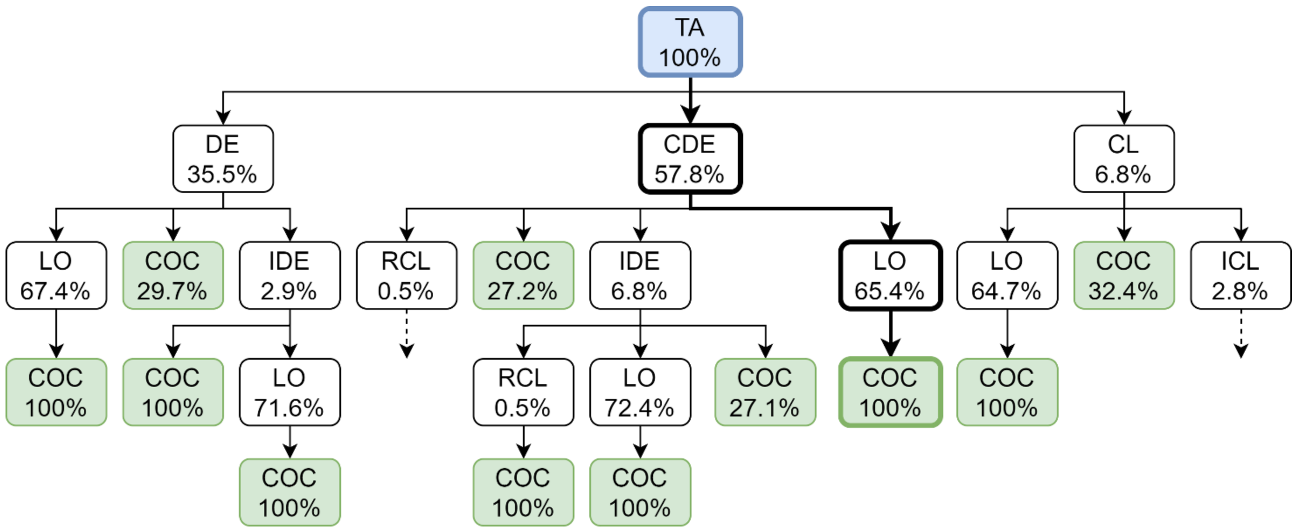


Figure 86. Advisory Tree of aircraft 1 in an ACAS Xa equipped type 3 encounter where aircraft 2 has a vertical velocity of 1500 ft/min at 36000 ft altitude

AC 1 receives a 'Crossing Descend' roughly 60% of the time and a 'Descent' 35% of the time. The rest of the time the aircraft is given a 'Climb' RA, which avoids a crossing. This is an important difference with TCAS II which sends aircraft 1 to climb more than 50% of the time.

A second RA is 66% of the time a 'Level Off'. This means that AC 1 receives similar RAs in the deterministic and stochastic settings almost 40% of the time. AC 2 receives a 'Maintain Crossing Climb' as an initial RA 44% of the time, while 'Maintain Climb' or 'Crossing Climb' RAs are issued 25% and 14% of the time, respectively. Looking at just the initial RAs, it is thus the clear intention of ACAS Xa to solve this encounter with a crossing. In 75% of the encounters there is a second advisory to aircraft 2, 4433 encounters receive a 'Do Not Descent' RA, indicating that the second aircraft is now above the first aircraft. A 'Level Off' as second RA is issued in 1730 runs.

The timing of all the RAs, ordered per number of RA that is issued is included in Figure 87. Since aircraft 1 and aircraft 2 do not receive the exact same RAs, their timings are displayed separately in the left and right plot. CPA occurs at 120 seconds. To both aircraft, ACAS Xa starts issuing its RAs slightly later than TCAS II. It then issues the subsequent RAs significantly later before it issues the COC at almost the exact same moment that TCAS II does. This behaviour was already seen before and was found to be the cause of the larger VMDs that are reached by ACAS Xa.

Additionally, it is seen that TCAS II issues the largest sequence of RAs to aircraft 1 while ACAS Xa does so to aircraft 2.

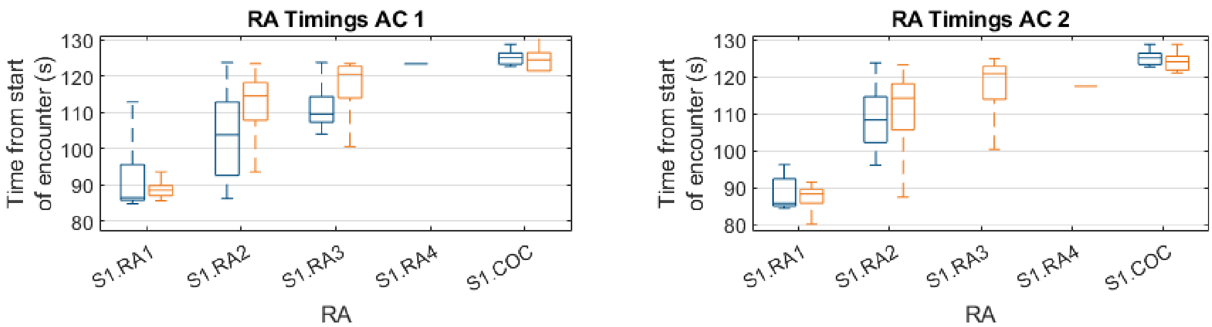


Figure 87. Timings of RAs for both aircraft in encounter with course angle of 180° and a vertical velocity of 1500 ft/min at 36000 ft. altitude. Blue is TCAS II timings, orange is ACAS Xa timings.

9.6 Type 3 Encounters without Level-off

The original type 3 encounters contained an aircraft that started with a vertical velocity and performed a level-off before CPA was reached. After CPA both aircraft in the encounter fly level. To see the effect of this level-off on TCAS II and ACAS Xa solutions, the original type 3 encounter results are compared to a set of modified type 3 encounter results, where the trajectory of the second aircraft does not contain the level-off. The second aircraft in both the original and the modified type 3 encounters have the same airspeed, but where the vertical velocity of this aircraft decreases to zero in the original type 3 encounter, it remains constant for the complete duration of the modified type 3 encounter.

In Table 41 the NMAC probability for the type 3 encounters without level-off are stated. Compared to the original type 3 encounters, these modified type 3 encounters show very different results. TCAS II shows significantly higher NMAC probabilities at 7500 and 15000 ft altitude. Originally the NMAC probabilities for the type 3 encounters were all below 1% for TCAS II at 15000 ft. The type 3 encounters at this altitude show NMAC probabilities that are all larger than 1.5%. On the other hand, the ACAS Xa equipped encounters have a lower NMAC probability in the type 3 encounters without a level-off than in the original type 3 encounters, they are below the 0.5%. Hence, the difference between TCAS II and ACAS Xa is significantly larger than it was for the original type 3 encounters and in these modified type 3 encounters TCAS II always has the largest NMAC probability.

Table 41. NMAC probabilities in percentages for type 3 encounters without level-off at all three altitudes

Altitude (ft)	Vertical velocity (ft/min)	Course angle of 90°		Course angle of 180°	
		TCAS II	ACAS Xa	TCAS II	ACAS Xa
7500	2000	2.30	0.36	2.35	0.24
	-2000	2.39	0.55	2.31	0.26
15000	2000	1.67	0.48	1.90	0.43
	-2000	1.90	0.56	1.76	0.59
36000	1500	0.52	0.31	0.52	0.29
	-1000	1.66	0.31	1.69	0.37

The vertical velocity only influences TCAS II equipped encounters at 36000 ft altitude. The NMAC probabilities at this altitude are included in Figure 88. A positive vertical velocity results in a lower NMAC probability for TCAS II. This behaviour is opposite to the behaviour seen in the original type 3 encounters. ACAS Xa NMAC probabilities are not clearly influenced by the vertical velocity and are significantly lower than the NMAC probabilities for type 3 encounters that did include the level-off. Additionally, the course angle has limited influence on the NMAC probability for both TCAS II and ACAS Xa.

The probability of a modified crossing encounter is almost zero for the type 3 encounters without a level-off while it was often higher than 50% in the original type 3 encounters. To see why, the modified trajectories of the one typical modified type 3 encounter are inspected. This is still the encounter with a 180° course angle and 1500 ft/min vertical velocity with CPA at 36000 ft altitude.

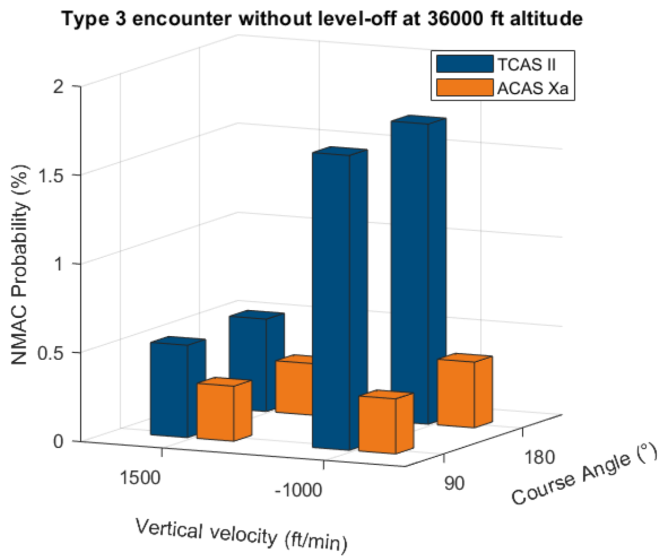


Figure 88. NMAC probability for type 3 encounters without level-off at 36000 ft altitude

The VMDs in the original type 3 encounter and the modified type 3 encounter were nearly identical, so these are not influenced by the level-off manoeuvre. However, the RAs issued did show a significant difference. In Table 42 the initial RAs and their probabilities issued by both TCAS II and ACAS Xa during the modified encounter without the level-off are stated.

Table 42. Initial RAs and their probabilities issued to aircraft in the modified type 3 encounter without level-off, 180° course angle and 1500 ft/min vertical velocity at 36000 ft altitude

AC	TCAS II		ACAS Xa	
	Initial RA	Probability (%)	Initial RA	Probability (%)
1	CL	72.99	CL	59.91
	DDE	10.39		
2	LO	97.49	LO	100
	DE	2.51		

For the original type 3 encounter, TCAS II had several different RAs that were issued with a relatively low probability, as stated in the previous section. For the modified type 3 encounter without the level-off manoeuvre, there are only two initial RAs issued to both aircraft. The ‘Climb’ RA is issued with 73% probability to aircraft one and the ‘Level Off’ RA is issued with nearly 100% probability. These RAs result in an encounter where the aircraft do not cross each other. TCAS II thus has a high probability to propose this same solution when the level-off is omitted from the trajectory, which does not result in a crossing encounter.

ACAS Xa only issues one initial RA to each aircraft in the encounter. 60% of the time, aircraft 1 receives a ‘Climb’ RA and aircraft 2 always receives a ‘Level Off’ RA. Again, these RAs do not result in a crossing encounter. This in contrary to the RAs issued in the original type 3 encounter, where often a crossing encounter was proposed by ACAS Xa. The exclusion of the level-off thus results in ACAS Xa solutions that are more unanimous.

If the initial TCAS II and ACAS Xa RAs for the modified type 3 encounter without level-off are followed exactly, no crossing counters will occur.

The level-off generates a wider set of RAs that sometimes indicate actions that are the complete opposite of each other. This could be caused by the change in vertical velocity that occurs during the level-off manoeuvre.

10 Sensitivity Analysis

For type 1 encounters, a sensitivity analysis is performed to investigate the effect of the intrinsic uncertainties on the behaviour of TCAS II and ACAS Xa. Remind that under a type 1 encounter the aircraft have a course angle of 180° and zero HMD. This encounter is modelled at each of the three altitudes used during this research. It is selected based on its relatively high NMAC probability for both TCAS II and ACAS Xa as presented in Section 7.3.

Ideally a sensitivity analysis assesses the influence of all the elements in the complete ABM. However, since the number of possible ABM parameter settings is so vast, a selection is made to only investigate the effect of the most interesting and influential uncertainties on TCAS II and ACAS Xa behaviour. In Appendix E.2 and Appendix E.3 the separate stochastic ABM elements in CAVEAT were verified and a quick look on their influence on the NMAC probability was taken. The default settings of two elements were identified to singlehandedly generate positive NMAC probabilities. These were the pilot response mode and the pressure altitude. Additionally, based on the ABM characteristics defined in [25] the influence of the pilot delay is also investigated.

All three elements are defined by multiple settings and the sensitivity of TCAS II and ACAS Xa behaviour to each of these settings is investigated and presented in this chapter. The outcome can help understand which uncertainties have the largest influence on TCAS II and ACAS Xa. The main indicator used for this analysis is the NMAC probability. If the sources of the high NMAC probabilities are known in more detail, these can be targeted more directly.

In contrary to the work presented so far, the results of the sensitivity analysis are compared for only one encounter geometry, to reduce simulation time. This is the type 1 encounter geometry with a course angle of 180° and zero HMD. This encounter is modelled at each of the three altitudes used during this research. It is selected based on its relatively high NMAC probability for both TCAS II and ACAS Xa as presented in Section 7.3.

In Section 10.1 it is defined how the sensitivity can be calculated. Then, the settings of the three elements of interest are presented and their results are discussed one by one. For the pilot response mode this is done in Section 10.2 and 10.3. Sections 10.4 and 10.5 include the settings and results for the pilot delay. Lastly, the pressure altitude settings and results are stated in Section 10.6 and 10.7, respectively.

10.1 Sensitivity and Normalised Sensitivity or Elasticity

Sensitivity captures the effect of a change in input parameter on the results. For this we define the model-based accident risk ρ which is a function of all ABM parameters v. The sensitivity of the model-based accident risk with respect to a certain parameter value v_i can then be defined by Eq. (10.1).

$$\frac{\partial \rho(v)}{\partial v_i} \tag{10.1}$$

Because safety risk assessment typically covers very small values, a common approach is to make use of logarithm. This leads to log-sensitivity (also referred to as normalised sensitivity or elasticity) [26]: the log-sensitivity or elasticity of the model-based accident risk is defined for the i-th parameter variation as follows:

$$s_i(v) \triangleq \frac{\partial \ln \rho(v)}{\partial \ln v_i} \tag{10.2}$$

For this research the normalised sensitivity is estimated using One-at-a-Time (OAT) change of parameters. This entails that changes are made relative to baseline parameter values. These baseline parameters are included in stochastic parameter settings S3.1. The normalised sensitivity s_i of the risk to changes of the i-th parameter are then obtained by using the approximation stated in Eq. (10.3).

$$s_i \simeq \frac{\ln\left(\dfrac{\rho\left(\overline{v}_1,..,\overline{v}_i^{right},..,\overline{v}_n\right)}{\rho\left(\overline{v}_1,..,\overline{v}_i^{left},..,\overline{v}_n\right)}\right)}{\ln\left(\dfrac{\overline{v}_i^{right}}{\overline{v}_i^{left}}\right)} \tag{10.3}$$

$\rho\left(\overline{v}_1,..,\overline{v}_i^{right},..,\overline{v}_n\right)$ and $\rho\left(\overline{v}_1,..,\overline{v}_i^{left},..,\overline{v}_n\right)$ are obtained by running the OAT MC simulations for the parameter values $\overline{v}_i^{right}$ and $\overline{v}_i^{left}$. In this research $\overline{v}_i^{left}$ is defined as the baseline setting used in the default fully stochastic parameter setting S3.1 while $\overline{v}_i^{right}$ is the setting that is altered to include worse circumstances. The normalised sensitivity can thus be obtained by dividing the natural logarithm of the factor by which the risk changes by the natural logarithm of the factor by which the parameter changes. Practically, this can be understood as follows: if a parameter changes with factor $\frac{\overline{v}_i^{right}}{\overline{v}_i^{left}}$ then the risk changes by factor $\left(\frac{\overline{v}_i^{right}}{\overline{v}_i^{left}}\right)^{s_i}$ due to this parameter change.

If the change in risk is small, the normalised sensitivity will be close to zero. When the newly obtained risk is smaller than the baseline risk, the normalised sensitivity will be negative. In this research, the factor by which the parameter changes has been set to be 2 at all times. This results in Eq. (10.4).

$$s_i \simeq \frac{\ln\left(\dfrac{\rho\left(\overline{v}_1,..,\overline{v}_i^{right},..,\overline{v}_n\right)}{\rho\left(\overline{v}_1,..,\overline{v}_i^{left},..,\overline{v}_n\right)}\right)}{\ln(2)} \tag{10.4}$$

Since there is uncertainty in the outcome of a MC simulation, the normalised sensitivities will also contain uncertainty. In Appendix D it is explained that the number of runs in the MC simulation is based on a default of 100 NMACs that should be included in the simulation, among other reasons. This indicates that small changes in number of NMACs, for example an extra 10 NMACs, could be attributed to the uncertainty in the MC simulation. In Eq. (10.5) the sensitivity corresponding to a change of 10 NMACs is computed.

$$s_i \simeq \frac{\ln\left(\frac{110}{100}\right)}{\ln(2)} = 0.1375 \tag{10.5}$$

This indicates that if the normalised sensitivity is lower than 0.1375, it could be due to noise in the MC simulation. Since the sensitivity can be both positive and negative depending on the sign of the numerator, the range of uncertainty exist on both sides of zero, as visualised in Figure 89. When the sensitivity lies inside this range, no definitive conclusions can be drawn about the origin of the sensitivity.

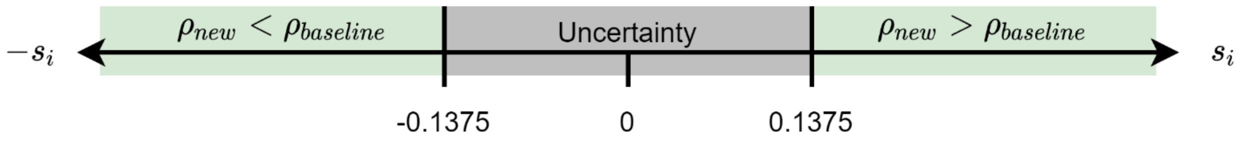


Figure 89. Uncertainty in range of normalised sensitivity

10.2 Pilot Response Mode Parameter Settings

The stochastic pilot response mode in CAVEAT consists of multiple settings which are all presented in Appendix B.4. For the sensitivity analysis only the response probabilities are varied. These response probabilities depend on multiple factors.

- If the encounter is a parallel approach or not,
- if the issued RA is a rate reversal or not,
- at what altitude the aircraft is flying,
- if the response to an initial RA is positive and
- if there was a positive response to a previous RA or not.

For this investigation the first three points are not taken into account as these describe specific encounters, which leaves the last two points. In Section 4.5 the exact parameter settings were discussed. Each of the parameter settings is fully stochastic and the settings of the pilot response mode vary per setting. A summary of the exact pilot response mode settings per parameter setting used for the sensitivity analysis is included in Table 43. These are the probability of a positive response. A positive pilot response is defined as a response from the pilot. It does no entail that this response is as desired.

Table 43. Probabilities of positive pilot response of parameter settings used for sensitivity analysis

Parameter Setting	Probability of response to initial RA	Probability of response to modified RA given a response to previous RA	Probability of response to modified RA given no response to previous RA

S3.1	0.8	0.8	0.8
S4.1	0.6	0.8	0.8
S4.2	0.8	0.6	0.8
S4.3	0.8	0.8	0.6
S4.4	0.6	0.6	0.6

For the sensitivity analysis the probability of a non-response is used. A positive response probability of 0.8 directly implies that the probability of the complement, a non-response is 0.2. This is the default non-response probability which is thus included in parameter settings S3.1. In Table 44 the non-response probabilities of the five parameter sets are included:

- S3.1 - the baseline stochastic parameter set
- S4.1 - fully stochastic and the probability of no response to initial RA is doubled
- S4.2 - fully stochastic and the probability of no response to modified RA given no response to previous RA is doubled
- S4.3 - fully stochastic and the probability of no response to modified RA given a response to previous RA is doubled
- S4.4 – fully stochastic and all three abovementioned no response probabilities are doubled simultaneously

Table 44. Probability of no pilot response of parameter settings used for sensitivity analysis

Parameter Setting	Probability of no response to initial RA	Probability of no response to modified RA given no response to previous RA	Probability of no response to modified RA given a response to previous RA
S3.1	0.2	0.2	0.2
S4.1	0.4	0.2	0.2
S4.2	0.2	0.4	0.2
S4.3	0.2	0.2	0.4
S4.4	0.4	0.4	0.4

In parameter settings S4.1, S4.2 and S4.3 the different non-response probabilities are increased by factor 2 one by one, as was explained in section 10.1. The non-response probability thus results in 0.4. If for these parameter settings the NMAC probability increases with the same factor as the non-response probability is increased, then the relation between the respective response probability and the NMAC probability is linear. If the NMAC probability increases by less than factor 2, the relation is less than linear.

In parameter setting S4.4 all three response probabilities are lowered simultaneously. This means that each of the non-responses is multiplied by a factor 2 at the same time. For this parameter setting the normalised sensitivity cannot be calculated as multiple parameter values are altered at once.

10.3 Sensitivity of TCAS II and ACAS Xa to Pilot Response Mode

The normalised sensitivities to changes in the three pilot response model parameters are included in Table 45. Several trends can be seen for these sensitivities.

Table 45. Normalised sensitivity to changes in the three pilot response model parameters for both TCAS II and ACAS as the three altitudes

s_i	TCAS II			ACAS Xa		
	7500	15000	36000	7500	15000	36000
Initial RA no response probability	1.93	1.95	1.81	2.05	2.33	2.07
Probability of no response to modified RA given no response to previous RA	-0.07	-0.03	-0.13	-0.08	0.25	-0.17
Probability of no response to modified RA given a response to previous RA	0.50	0.61	0.24	0.76	1.13	0.27

Both aircraft are most sensitive for the initial RA no response probability. For TCAS II these sensitivities are relatively close together, between 1.81 and 1.95. ACAS Xa shows a wider range of sensitivities from 2.05 to 2.33, which are thus also higher than for TCAS II. The relationship between the initial RA no response probability and the NMAC probability is thus more than proportional for both TCAS II and ACAS Xa.

The sensitivities to the probability of no response to modified RA given no response to previous RA are extremely small for both TCAS II and ACAS Xa. For TCAS II this means that they all lie within the uncertainty range of the sensitivity. Hence, the influence of this probability is so small that it is probable this is due to the uncertainty in the MC simulation. For ACAS Xa this is only the case at 7500 ft altitude. At 15000 and 36000 ft altitude the sensitivity of this probability is large enough to fall outside of the uncertainty interval. However, in general it can be said that the influence of the probability of no response to modified RA given no response to previous RA is so small that its effects are negligible.

The sensitivity to the probability of no response to modified RA given a response to previous RAs varies per ACAS equipage and altitude. Both TCAS II and ACAS Xa have higher sensitivities at the two lowest altitude, where ACAS Xa has the absolute highest sensitivities of both TCAS II and ACAS Xa. At the 36000 ft altitude the sensitivity of both TCAS II and ACAS Xa drops significantly to around 0.25.
These normalised sensitivities thus indicate that the initial RA no response probability is the most influential of the three.

The effect of combining the three worsened probabilities can be seen when looking at results from the simulation with parameter setting S4.4. In Figure 90 the NMAC probabilities of all five parameter settings at three altitudes are included. NMAC probabilities for type 1 encounter with course angle of 180° in the baseline S3.1 parameter settings were already discussed in Section 7.3. A few trends were recognised:

- TCAS II always has a larger NMAC probability.
- The TCAS II NMAC probability at 36000 ft altitude is highest followed by the NMAC probabilities at 7500 and 15000 ft altitude, respectively.
- For ACAS Xa the NMAC probabilities at 7500 and 15000 ft altitude are similar and the NMAC probability at 36000 ft altitude is roughly double that.

When looking at Figure 90 it is observed that although the NMAC probabilities differ greatly per parameter setting in set 4, these general conclusions also hold for the other four parameter settings used for the sensitivity analysis. This is why a detailed look is taken at the NMAC probability at one altitude. In Figure 91 the NMAC probabilities at 7500 ft altitude are included.

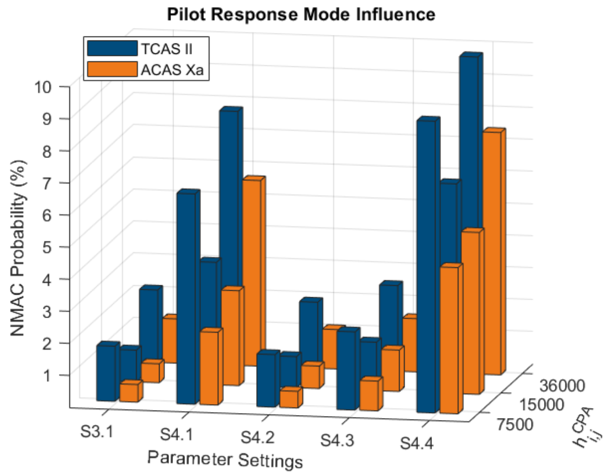


Figure 90. NMAC probability per pilot response mode parameter setting for all three altitudes

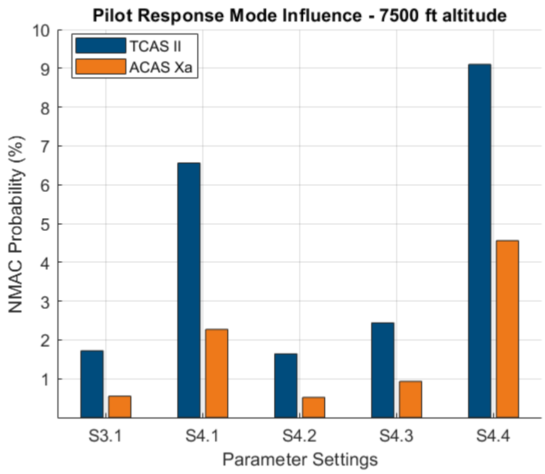


Figure 91. NMAC probability per pilot response mode parameter setting at 7500 ft altitude

As was concluded from the normalised sensitivity analysis, the initial RA no response probability increases the NMAC probability the most. This result corresponds to the S4.1 parameter setting. In parameter setting S4.2 the probability of no response to modified RA given no response to previous RA is increased which does not affect the NMAC probability, it remains nearly identical to the S3.1 NMAC probability. Parameter settings S4.3, with double the probability of no response to modified RA given a response to previous RAs, slightly increases the NMAC probability. These results naturally match the findings from Table 45.

Combining these parameter settings results in parameter setting S4.4, where all three no response probabilities are doubled. This setting results in an NMAC probability that is five times as high for TCAS II and 9 times as high for ACAS Xa. This increase in NMAC probability was expected, it can be reasoned that worsening the response probability of the pilot increases the NMAC probability.
The NMAC probability in the S4.4 parameter setting are higher than when each of the no response probabilities are doubled individually. It seems as though the no response probabilities influence each other for the worse. The difference between the S3.1 and S4.4 NMAC probability is larger than the addition of the S4.1, S4.2 and S4.3 NMAC probabilities.

The factor with which the NMAC probability of the S4.4 parameter setting is increased with respect to the baseline S3.1 parameter setting differs per altitude and ACAS equipage. In Table 46 these factors are listed. It is clear that ACAS Xa NMAC probabilities increase with a larger factor than TCAS II probabilities do at each altitude. This implies that ACAS Xa is more sensitive to the uncertainties in the pilot response than TCAS II is. The factor does decrease at higher altitudes.

Table 46. Factors with which the NMAC probability is increased for simulations with baseline parameter setting S3.1 and parameter setting S4.4, per altitude and ACAS equipage

	TCAS II	ACAS Xa
7500	5.29	8.29
15000	6.61	8.56
36000	4.38	5.48

10.4 Pilot Delay Parameter Settings

The pilot delay is defined as the time between the annunciation of an ACAS RA and the time that the pilot starts manoeuvring the aircraft in response to the RA [22]. A small delay is natural, as the pilot always has some sort of reaction time to advisories. Larger delays however, can have a disruptive effect on the solution proposed by TCAS II and ACAS Xa. In stochastic mode the pilot delay is comprised of the preparation delay and the action delay. This is modelled by a lognormal distribution based on the mean action delay and the standard deviation of the action delay. The following parameter sets are used for the sensitivity analysis of the pilot delay parameters:

- S3.1 - the baseline stochastic parameter set
- S5.1 - fully stochastic and the preparation delay is doubled
- S5.2 - fully stochastic and the mean of the action delay is doubled
- S5.3 - fully stochastic and the standard deviation of the action delay is doubled
- S5.4 – fully stochastic and all three abovementioned factors are doubled

In Table 47 the exact values of the delays are stated for each of the parameter settings used in the sensitivity analysis. The full parameter settings are described in Section 4.6.

Table 47. Pilot delay parameter settings used for sensitivity analysis

Setting	Preparation delay (s)	Action delay mean (s)	Action delay SD (s)
S3.1	1.5	3.3	1.5
S5.1	3	3.3	1.5
S5.2	1.5	6.6	1.5
S5.3	1.5	3.3	3
S5.4	3	6.6	3

Note that a change in preparation delay only influences the response time for the initial RA in a sequence while a change in the mean or standard deviation of the action delay influences the response time to each and every RA in a sequence.

10.5 Sensitivity of TCAS II and ACAS Xa to Pilot Delay

In Table 48 the normalised sensitivities of the TCAS II and ACAS Xa to the three settings of the pilot delay are included for the three altitudes.

Table 48. Normalised sensitivity of both TCAS II and ACAS Xa for settings of pilot delay, at all three altitudes

s_i	TCAS II			ACAS Xa		
	7500	15000	36000	7500	15000	36000
Preparation Delay	-0.09	0.14	-0.06	0.03	0.16	0.15
Action Delay Mean	1.26	1.89	0.71	2.10	2.05	1.38
Action Delay Standard Deviation	-0.20	0.13	-0.26	0.39	0.51	0.07

The sensitivities to the preparation delay for both TCAS II and ACAS Xa lie inside or extremely close to the uncertainty range of the normalised sensitivity. This indicates that the preparation delay barely influences the NMAC percentages for both TCAS II and ACAS Xa. This was expected since the preparation delay only effects the response time to the initial RA in a sequence, while sequences often contain more than one RA.

The sensitivities to the increase of the mean action delay are significant for both TCAS II and ACAS Xa. ACAS Xa shows higher sensitivities than TCAS II at each altitude. Both TCAS II and ACAS Xa are most sensitive at 7500 and 15000 ft altitude and significantly less sensitive at 36000 ft altitude. At the two lower altitudes, TCAS II gives NMAC probabilities that are around 1.3 to 1.9 times higher with double the action delay, than they are with the default action delay. ACAS Xa NMAC probability results are more than doubled with the increased action delay.

The standard deviation of the action delay has a small influence on the TCAS II and ACAS Xa results. For TCAS II the sensitivity is extremely close to the uncertainty range. This means it is not possible to identify if the sensitivity is due to the parameter change or due to noise in the MC simulation. ACAS Xa, on the other hand, shows moderate sensitivity at 7500 and 15000 ft altitude. At 36000 ft altitude the sensitivity also falls inside the uncertainty range of the sensitivity.

It was expected that the mean of the action delay influences the TCAS II and ACAS Xa results the most, as this directly influences the duration of the action delay. If the mean of the action delay distribution is shifted by a certain value, each and every action delay picked from the distribution is also shifted with this certain value. The standard deviation is an indicator for the spread of a distribution, it thus indicates how close the values picked from the distribution are from its mean. This has less influence on the picked action delay values than the mean of the distribution has.

Hence, the low sensitivities for this standard deviation of the action delay do not come as a surprise.

Combining the three increased pilot delay settings into one parameter setting results in S5.4. In Figure 92 the NMAC probabilities of both TCAS II and ACAS Xa in the baseline parameter setting S3.1, the sensitivity parameter settings S5.1, S5.2 and S5.3 and the combined parameter setting S5.4 are included for each altitude. The NMAC trends for TCAS II and ACAS Xa are still present. TCAS II has higher NMAC probabilities at 7500 and 36000 ft altitude while the NMAC probability at 15000 ft altitude is lower. ACAS Xa has lower NMAC probabilities at 7500 and 15000 ft altitude while the highest NMAC probability occurs at 36000 ft altitude. As before, the NMAC probabilities and influence of the different pilot delay times are analysed at one altitude.

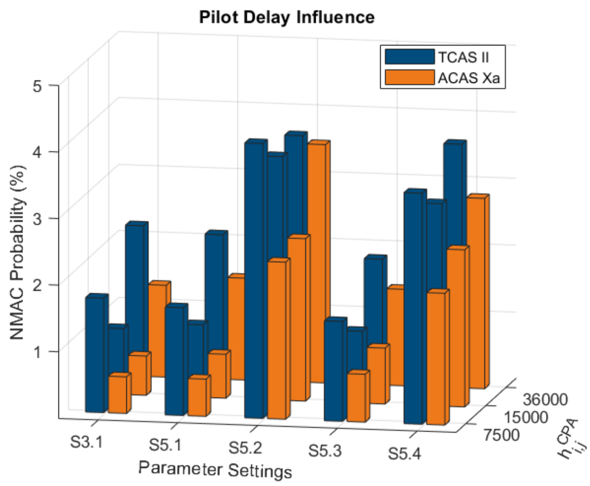


Figure 92. NMAC probability per pilot delay parameter setting for all three altitudes

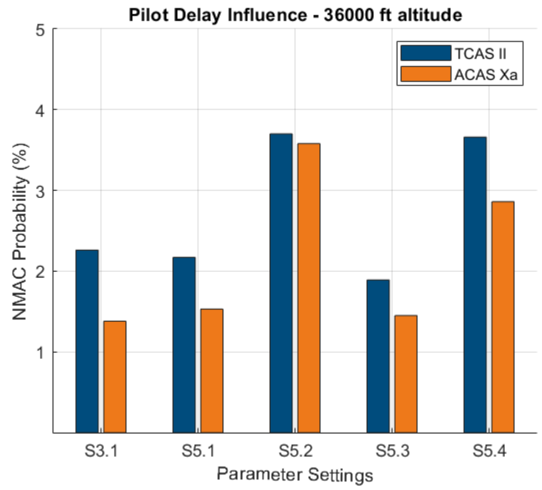


Figure 93. NMAC probability per pressure altitude parameter setting at 36000 ft altitude

In Figure 93 the results at 36000 ft altitude are included. The results of the S5.1, S5.2 and S5.3 parameter settings correspond to the findings from the normalised sensitivities in Table 48. For TCAS II the NMAC probabilities of parameter settings S5.1 and S5.3 slightly decrease with respect to the baseline parameter setting S3.1 results. For parameter setting S5.2 the NMAC probability increases to roughly 3.6%. Combining the worsened pilot delay settings in parameter setting S5.4 results in an NMAC probability that is comparable to the NMAC probability of when only the mean action delay is doubled. This was expected, since the influence of the preparation delay and the standard deviation was extremely small.

When looking at the ACAS Xa results an unexpected effect is seen. Parameter settings S5.1 and S5.3 do not influence the NMAC probability significantly. Parameter setting S5.2 increases the NMAC probability to 3.5%. When combining the three worsened pilot delay settings though, the NMAC probability only reaches 2.9%. One would expect the NMAC probability of parameter setting S5.4 to be near the 3.5% as well, because there is no indication that any of the pilot delay parameters have a decreasing influence on the NMAC probability.

One explanation could potentially be found in the types of RAs that are issued. It is possible that ACAS Xa issues different types of RAs only when a pilot does not react fast enough. The different types of RAs could be more effective in solving the encounter without an NMAC, hence the lower NMAC probability. Another possibility is that the number of MC runs is not sufficient to accurately capture the ACAS Xa behaviour in this encounter. This is why an additional simulation with more MC runs is performed.

This simulation contains 1 million runs of the type 1 encounter with 180° course angle and no HMD at 36000 ft altitude. This encounter is combined with both the S5.2 and S5.4 parameter settings, to obtain a more accurate view on the difference between TCAS II and ACAS Xa behaviour for these two parameter settings. In Table 49 the confidence intervals for NMAC probabilities for ACAS Xa in the two parameter sets are included for the original simulation with 10000 MC runs and for the extra simulation with 1 million MC runs. These intervals are calculated using the method in Appendix D.2. When the number of runs is 10000, the confidence intervals in both parameter settings lie against each other. This indicates that perhaps with more MC runs, they could overlap. If that is the case, the uncertainty in the simulations could be an explanation for the different NMAC probabilities. However, when 1 million MC runs are included, the confidence intervals move away from each other, with parameter setting S5.2 having the higher NMAC probability. This indicates that the NMAC probabilities are not due to uncertainty in the simulation and the confidence intervals indicate that this difference cannot be explained by a possible lack of MC runs.

Table 49. Confidence intervals of NMAC probability for ACAS Xa in parameter settings S5.2 and S5.4 for different number of MC runs at 36000 ft altitude

	10 000 MC runs	1 000 000 MC runs
Parameter setting S5.2	3.22% to 3.98%	3.40% to 3.48%
Parameter setting S5.4	2.53% to 3.22%	2.81% to 2.87%

Next, the advisories that were given by ACAS Xa are analysed. In Figure 94 and Figure 95 the advisory trees of aircraft 1 in the encounters with parameter settings S5.2 and S5.4 are displayed, respectively. The first RA that is issued is either a ‘Climb’ or ‘Descend’ RA and the percentages with which they are issued are nearly identical. Additionally, in parameter settings S5.4 there is an infinitesimal probability that the pilot receives a ‘Decrease Climb’ RA, but this RA is disregarded due to its extremely low probability of occurrence.

The differences for the second RA mostly lie in the percentage with which the ‘Level Off’ and ‘Clear of Conflict’ RAs are issued. In parameter set S5.2 more ‘Level Off’ RAs are issued to the pilot than in simulations with parameter set S5.4. On the other hand, in parameter set S5.2 less ‘Clear of Conflict’ RAs are issued. This indicates that in parameter set S5.4 ACAS Xa prefers less long RA sequences, which results in simpler and shorter solutions. This could be an explanation for the difference in NMAC probability between settings S5.2 and S5.4.

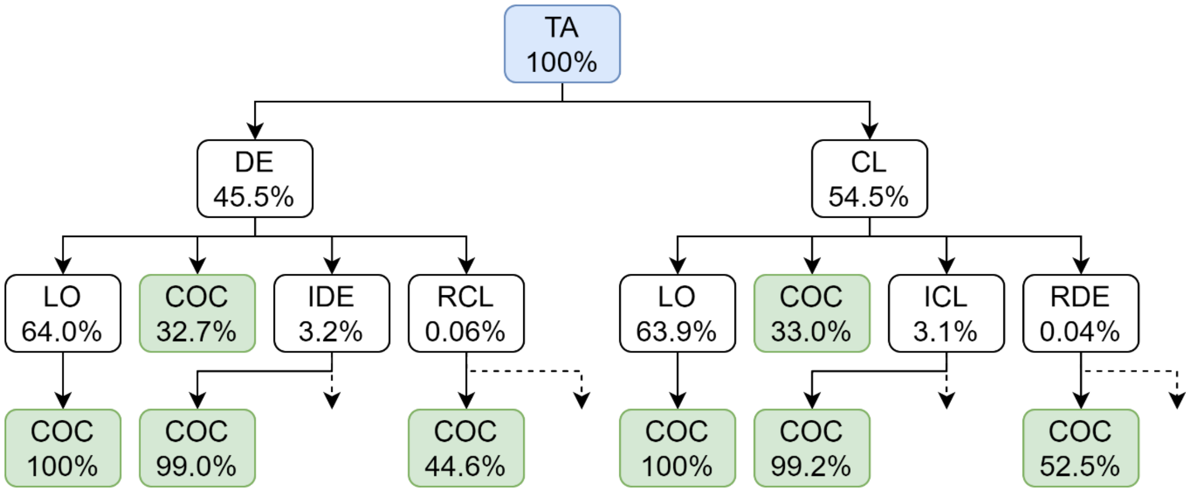


Figure 94. ACAS Xa Advisory Tree aircraft 1 in S5.2 parameter settings

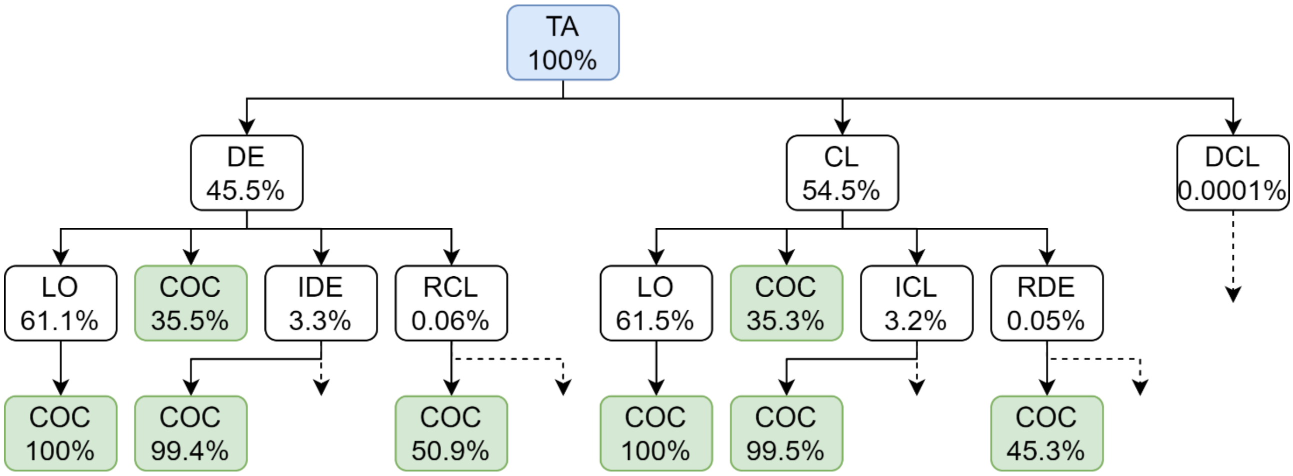


Figure 95. ACAS Xa Advisory Tree aircraft 1 in S5.4 parameter settings

Other than the differences in RAs, there are no significant differences between the results of parameter setting S5.2 and S5.4 in ACAS Xa equipped encounters.

The origin of the lower NMAC probability for the S5.4 parameter settings can also lie somewhere else. A range can be indicated located one standard deviation around the mean of the pilot delay. The majority of the selected pilot delays lie within this range. For parameter setting S3.1 this range is between 1.8 and 4.8 seconds. In parameter setting S5.2, only the mean is doubled, resulting in a range of between 4.5 and 7.5 seconds. In parameter setting S5.4 both the mean and standard deviation of the action delay are doubled. The majority of the pilot delays then lies in a range between 3 and 9 seconds. This means that the overlap between the pilot delay values in parameter settings S3.1 and S5.4 is largest.

Parameter settings S3.1 had a lower NMAC probability than both parameter setting S5.2 and S5.4.

Since the overlap is more significant with parameter settings S5.4, the effect of the lower NMAC probability is also more significant. This could by why parameter setting S5.4 results in lower NMAC probabilities than parameter setting S5.2. However, since the difference in NMAC probabilities is quite large, more elaborate analyses is required to find out where these results come from.

10.6 Pressure Altitude Parameter Settings

One of the default pressure altitude models in CAVEAT is the ACAS MOPS model. This is a pressure altitude model that describes the measured standard pressure altitude as the altitude of the aircraft plus jitter errors and bias errors. The default settings of the ACAS MOPS model are also used in the baseline stochastic parameter settings S3.1. Only the sensitivity of TCAS II and ACAS Xa to the standard deviations of the bias and jitter is investigated. This is chosen due to time constraint. The following parameter sets are used:

- S3.1 - the baseline stochastic parameter set
- S6.1 - fully stochastic and the altitude based SD of the bias is doubled
- S6.2 - fully stochastic and SD of jitter is doubled
- S6.3 - fully stochastic and both the SDs of the jitter and the bias are doubled

Their exact bias and jitter values are included in Table 50.

Table 50. Pressure altitude parameter settings used for sensitivity analysis

Setting	Altitude-based standard deviation of bias (ft)	Standard deviation of jitter (ft)
S3.1	$\begin{pmatrix} 0, & 5000, & 10000, & 15000, & 20000, & 25000, & 30000, & 35000, & 40000; \\ 45, & 48, & 52, & 58, & 65, & 71, & 78, & 86, & 95 \end{pmatrix}^T$	4.9
S6.1	$\begin{pmatrix} 0, & 5000, & 10000, & 15000, & 20000, & 25000, & 30000, & 35000, & 40000; \\ 90, & 96, & 104, & 116, & 130, & 142, & 156, & 172, & 190 \end{pmatrix}^T$	4.9
S6.2	$\begin{pmatrix} 0, & 5000, & 10000, & 15000, & 20000, & 25000, & 30000, & 35000, & 40000; \\ 45, & 48, & 52, & 58, & 65, & 71, & 78, & 86, & 95 \end{pmatrix}^T$	9.8
S6.3	$\begin{pmatrix} 0, & 5000, & 10000, & 15000, & 20000, & 25000, & 30000, & 35000, & 40000; \\ 90, & 96, & 104, & 116, & 130, & 142, & 156, & 172, & 190 \end{pmatrix}^T$	9.8

10.7 Sensitivity of TCAS II and ACAS Xa to Pressure Altitude

In Table 51 the normalised sensitivities of TCAS II and ACAS Xa to the two settings of the pressure altitude are included for the three altitudes. The altitude-based standard deviation of the bias influences both TCAS II and ACAS Xa behaviour significantly. For TCAS II the sensitivity is highest at 15000 ft altitude and lowest at 36000 ft altitude. For ACAS Xa the sensitivity is nearly identical at 7500 and 15000 ft altitude and only half that at 36000 ft altitude. During the sensitivity analysis of the pilot response mode and the pilot delay this behaviour of a lower sensitivity at higher altitude was also observed for both TCAS II and ACAS Xa.

Table 51. Normalised sensitivity of both TCAS II and ACAS Xa for settings of pressure altitude

s_i	TCAS II			ACAS Xa		
	7500	15000	36000	7500	15000	36000
Altitude-based standard deviation of bias	1.15	1.61	0.96	2.00	2.01	0.98
Standard deviation of jitter	0.10	0.06	-0.18	-0.17	0.07	-0.04

The standard deviation of the jitter has a smaller effect on the TCAS II and ACAS Xa behaviour. For both TCAS II and ACAS Xa the sensitivity is often within the uncertainty range or extremely close to it. The sensitivity to the bias is thus larger than the jitter sensitivity, which was expected.

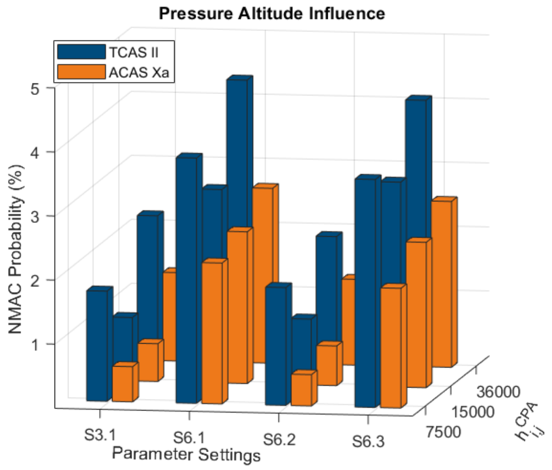


Figure 96. NMAC probability per pressure altitude parameter setting for all three altitudes

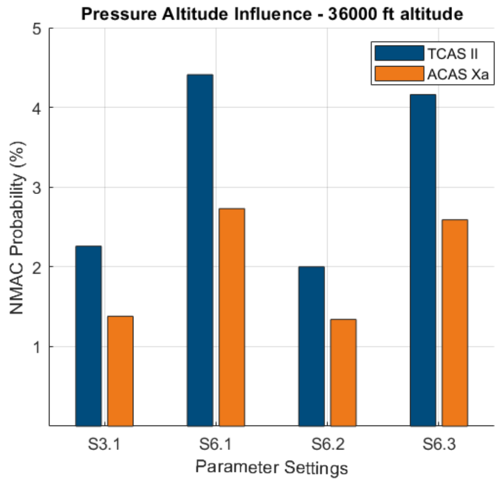


Figure 97. NMAC probability per pressure altitude parameter setting at 36000 ft altitude

In Figure 96 NMAC probabilities for the baseline parameter setting S3.1 and the three sensitivity parameter settings S6.1, S6.2 and S6.3 are included. The altitude of 36000 ft is selected for more detailed analysis and the NMAC probabilities are included in Figure 97. It can be seen that doubling the altitude-based standard deviation of bias in parameter setting S6.1 resulted in nearly twice the NMAC probability for both TCAS II and ACAS Xa, as was seen in the normalised sensitivity numbers. Doubling the standard deviation lowered the NMAC probability slightly with respect to baseline parameter S3.1. When doubling both the standard deviations of the bias and jitter, as in parameter setting S6.3, the NMAC probabilities are slightly lower than the NMAC probability of parameter setting S6.1. These results are thus an addition of the effects of parameter setting S6.1 and S6.2.

To conclude, both TCAS II and ACAS Xa are most sensitive to the same parameter settings:

- The initial RA response in the pilot response mode settings
- The mean of the action delay in the pilot delay settings
- The altitude-based standard deviation of the bias in the pressure altitude settings

Both TCAS II and ACAS Xa show the highest sensitivities at 7500 and 15000 ft altitude. ACAS Xa shows nearly linear sensitivity to parameter settings, meaning that doubling one of these three specific parameters results in double the NMAC probability. TCAS II generally shows less sensitivity to changes in parameter settings than ACAS Xa does. Both TCAS II and ACAS Xa show lower sensitivity to parameter setting changes at 36000 ft altitude.

The results of including the combined worsened settings for the pilot response mode and the pressure altitude were a logical combination of the results of each of the worsened settings separately. The combination of worsened settings for the pilot delay however gave less clear results. Here the NMAC probability reduced when all worsened settings were combined while the separate worsened settings indicated larger NMAC probabilities. More elaborate analyses is required to find out where this result come from.

11 Conclusion and Follow-up

This concluding chapter consists of four sections. Section 11.1 summarises how the research objectives of this thesis were reached. Section 11.2 summarises the main findings regarding the performance of ACAS Xa relative to TCAS II. Section 11.3 addresses starting points for follow-up research. Finally, Section 11.4 lists potential future improvements of CAVEAT that have been discussed in detail in Appendix E.

11.1 Realisation of Research Objectives

In chapter 1, the research objectives have been specified as follows:

To develop a systematic performance evaluation of TCAS II and ACAS Xa in which responses to various encounter geometries are evaluated and compared by using CAVEAT, specifically its stochastic mode.

The additional aim was:

To investigate and compare the sensitivity of TCAS II and ACAS Xa to variability in encounter geometries and uncertainty in sensor errors and pilot response using CAVEAT, specifically its stochastic mode.

These research objectives have been addressed following systematic steps in Chapters 2 to 10.

Chapter 2 provided background information on the Agent-Based Model (ABM) that was implemented in CAVEAT 3.4.0 and explained the procedure of modelling encounters using CAVEAT. CAVEAT uses two main inputs for a simulation of an encounter: the trajectories of all aircraft in the encounter and the settings of all agents in the ABM. These are then simulated using MC runs. The output consists of several files containing data of the encounter and pre-calculated statistics.

Chapter 3 explained how the trajectories of the two aircraft in the encounter were generated. Firstly, the parameters defining an encounter between two aircraft were defined. These were used to construct three encounter types, which each contained multiple encounter geometries based on the location of the aircraft in the encounter at the moment they were closest to each other, the Closest Point of Approach (CPA). Per type, one or more parameters that define the encounter geometry were systematically varied for the two aircraft in the encounter. These included the altitude, relative course angle, the horizontal miss distance, the Vertical Miss Distance (VMD), the airspeed, and the vertical velocity.

Chapter 4 included all ABM parameter settings used during the research. The settings of the agents in the CAVEAT ABM are either deterministic or stochastic. Several parameter settings were created which each contained combinations of agent settings. The two main parameter settings were fully deterministic and fully stochastic, each using default values. These parameter settings were constructed such that both aircraft in an encounter were either equipped with TCAS II or ACAS Xa.

Chapter 5 provided information about the specific indicators used during the performance evaluation. The main indicator was the Near Mid-Air Collision (NMAC) probability. An NMAC is an undesired event that occurs if aircraft are within 500 ft horizontally and 100 ft vertically of each other [3] [2]. The probability of the two aircraft crossing each other's paths, the VMD, the issued Resolution Advisories (RAs) and the timing of the RAs were also of interest. In case of stochastic simulations these indicators were given by probabilities and distributions while deterministic simulations resulted in binary and single values of the indicators. Deterministic results were compared to stochastic results to see the influence of the uncertainties on the TCAS II and ACAS Xa behaviour. TCAS II results were compared to ACAS Xa results to identify the differences in their behaviour.

Chapter 6 explored the visualisation of TCAS II and ACAS Xa policies by using ACAS policy plots, a suitable tool to use during analysis. These are 2D plots which show a section of the state space around one of the aircraft in an encounter, with timing to CPA in seconds on the x-axis and relative altitude in feet on the y-axis. They give insight in the state space around the aircraft in term of which RAs are issued where. Additionally, by evaluating both TCAS II and ACAS Xa using this same procedure the comparison between the behaviour of the two systems can contribute to the understanding of the black box ACAS Xa logic. To generate them, one deterministic simulation of the encounter in CAVEAT was used per combination of relative altitude and number of seconds before CPA. These encounters start at an increasing number of seconds before CPA to guide TCAS II and ACAS Xa in issuing RAs around these moments in time. The timing at which the RAs are issued cannot be specified by the user beforehand resulting in plots with an irregular grid.

Chapters 7 to 9 presented the simulation results obtained for TCAS II and ACAS-Xa for the user-generated encounter model of chapter 3, the parameter settings of chapter 4, and in terms of the performance indicators of chapter 5. Firstly, the VMD values and distributions were discussed. Next, the NMAC and crossing encounter probabilities were studied. Finally, one or more encounter geometries were highlighted by looking at the RAs that are issued along with their timings. The main findings of these simulation results are summarised in Section 11.2.

Chapter 10 provided information about the sensitivity of TCAS II and ACAS Xa behaviour to uncertainty in sensor errors and pilot response. The main findings of this sensitivity analysis are summarised in Section 11.2.

11.2 Main Findings

The results of the systematic performance evaluation complete one of the goals of this thesis, which was to capture how the TCAS II and ACAS Xa behaviour changed when the geometry of the encounter changed. While numerous trends were observed, only the most important and prevalent ones are included in this conclusion. These can be divided into trends that occurred regardless of encounter geometry and trends that were influenced by the encounter geometry. The observed trends that occurred regardless of encounter geometry are the following:

1. Every encounter with deterministic settings was solved without any NMACs by both TCAS II and ACAS Xa.
2. In stochastic settings ACAS Xa equipped aircraft nearly always have a lower NMAC probability than TCAS II equipped aircraft. The exact difference varies greatly per encounter geometry.
3. Initial and Clear of Contact RAs are issued around the same time for both TCAS II and ACAS Xa, but ACAS Xa lets the aircraft hold the RAs for several seconds longer than TCAS II equipped aircraft. This results in the following trend.
4. ACAS Xa equipped aircraft reach higher VMDs in deterministic settings and have a higher mean VMD in stochastic settings than TCAS II.

The range of NMAC probability for both TCAS II and ACAS Xa remained between 0 and 2.5%, depending on the encounter geometry. Below the most important findings of the influence of the encounter geometry are listed.

5. The altitude of CPA significantly influenced the NMAC probability for both TCAS II and ACAS Xa in all simulated encounters. TCAS II showed its highest NMAC probabilities at 7500 and 36000 ft while the NMAC probability at 15000 ft was lower. ACAS Xa on the other hand showed relatively low NMAC probabilities at 7500 and 15000 ft while the NMAC probability at 36000 ft altitude was significantly higher. The altitude also greatly influenced the VMDs that were reached by both ACAS Xa. The higher the altitude, the larger the VMD, especially in ACAS Xa equipped encounters. Additionally, the ACAS Xa VMD distribution also skewed more to the right.
6. The relative course angle influenced TCAS II behaviour by a great deal while it had little to no effect on ACAS Xa results. TCAS II showed larger NMAC probabilities with increasing course angle, varying from below 0.5% in encounters with a relative course angle of 45° to NMAC probabilities between 1 and 2.2% in encounters with a relative course angle of 180°.
7. The HMD in the original trajectories is only of influence to TCAS II and ACAS Xa when it is 500 ft or larger. For both TCAS II and ACAS Xa it can be concluded that NMAC probabilities are similar regardless of the HMD if the HMD is below 500 ft. A HMD of exactly 500 ft reduces the NMAC probability to 1/5th of that with a lower HMD. Encounters with a HMD above the 500 ft did not contain any NMAC probabilities, as is in line with the definition of an NMAC.
8. The VMD in the original trajectories influenced both TCAS II and ACAS Xa in the same manner. When increasing this VMD from 0 to 300, both TCAS II and ACAS Xa show a gradual decrease in NMAC probability, which is shown the strongest by TCAS II as it starts at higher NMAC probabilities. Encounters with VMDs above 300 ft did not contain any NMAC for both TCAS II and ACAS Xa.
9. The vertical velocity of one of the aircraft in the encounter that performs a level-off manoeuvre right before CPA only has a large influence at 36000 ft altitude. TCAS II shows higher NMAC probabilities when the vertical velocity is positive while ACAS Xa shows NMAC probabilities that are higher when the vertical velocity is negative.

10. When one of the aircraft has a non-zero vertical velocity and does not perform a level-off, the effect of this vertical velocity on the NMAC probability is opposite to the previous point. TCAS II now shows lower NMAC probabilities when the vertical velocity is positive while ACAS Xa shows higher NMAC probabilities when the vertical velocity is positive.

During the sensitivity analysis it was investigated how sensitive TCAS II and ACAS Xa are to uncertainties in sensor errors and pilot response. Since the number of possible ABM parameter settings is so vast, a selection was made to only investigate the effect of the most interesting and influential uncertainties on TCAS II and ACAS Xa behaviour. These uncertainties were identified to be the pilot response mode, the pilot delay and the pressure altitude based on exploratory runs and information from the CAVEAT manual. Each of these three elements contained more detailed settings, which were worsened one by one (e.g. the pilot response probability was halved or the delay time was doubled) and simulated to see the resulting ACAS behaviour.

Both TCAS II and ACAS Xa turned out to be most sensitive to the same parameters:

- The initial RA response probability in the pilot response mode
- The mean of the action delay in the pilot delay
- The altitude-based standard deviation of the bias in the pressure altitude

Both TCAS II and ACAS Xa showed the highest sensitivities at 7500 and 15000 ft altitude. ACAS Xa indicated nearly linear sensitivity to parameter settings, meaning that doubling one of these three specific parameters results in double the NMAC probability. TCAS II generally showed less sensitivity to changes in these parameter settings than ACAS Xa did. Both TCAS II and ACAS Xa displayed lower sensitivity to parameter setting changes at 36000 ft altitude.

It was also investigated how the TCAS II and ACAS Xa behaviour changed when all settings that together made up each of the three elements of pilot response mode, pilot delay and pressure altitude were worsened simultaneously. For the pilot response mode and the pressure altitude the results were a logical combination of the separate results of each of the worsened settings combined. The pilot delay however gave less clear results. Here the NMAC probability reduced when all worsened settings of an element were combined while the separate worsened settings indicated larger NMAC probabilities. More elaborate analysis is required to find out where this result comes from.

11.3 Follow-up Research

Follow-up research could build on the points discussed in this report. During the research several assumptions were made while deciding on the input of the simulations. While these do allow for simpler modelling, it is important to realise that they lack complete accurate representation of the events. For a more complete view it is recommended to expand the research in the following areas to capture ACAS behaviour that is more true to the workings in real life.

- Investigate the effect of wind or terrain elevation.
- Investigate the effect of the airspeed of the aircraft.

- Investigate the effect of horizontal acceleration of the aircraft and expand the research on the effect of the vertical acceleration of the aircraft beyond only including a level-off manoeuvre.
- Investigate the behaviour of ACAS at more altitudes. In this report the deliberate decision was made to only include a select number altitudes to reduce simulation time. Although they were selected such that a wide range of altitudes was included, at certain altitudes TCAS II and ACAS Xa might behave differently than the trends described in this report.
- Investigate encounters with more than two aircraft. These could represent situations where there is a higher traffic density.

The type 3 encounters contained a level-off manoeuvre in which the peak of the vertical acceleration was around -0.2g. It is recommended to investigate a larger set of type 3 encounters that contain trajectories with level-off manoeuvres with lower vertical accelerations as well. These level-off manoeuvres will have a longer duration. Additionally, the desired VMD that results after the level-off has been performed could also vary, as well as the time at which the level-off starts.

Furthermore, this report focusses on the effect of changing one single parameter in the encounter geometry. A next step in mapping the TCAS II and ACAS Xa behaviour could be to combine several of these parameter changes and generate encounter geometries that are somewhat more realistic. Additionally, once sufficient knowledge about the TCAS II and ACAS Xa behaviour is obtained, the transition from user-defined encounters to encounters generated by a dynamic Bayesian belief network encounter model could be made. This allows for encounter geometries tailored to a specific part of the airspace. This, for example, could be useful for the validation of ACAS Xa in Europe specifically.

Another situation that should be investigated is one where one aircraft is equipped with TCAS II and the other aircraft is equipped with ACAS Xa. In the research presented in this report it is assumed that both aircraft in the encounter are equipped with the same ACAS. However, once ACAS Xa is approved a transitional period will start where aircraft are either TCAS II or ACAS Xa equipped. Naturally, two or more aircraft in an encounter do then not automatically both have the same ACAS. Results of these simulations could demonstrate the co-operation between TCAS II and ACAS Xa, and if this co-operation influences the outcomes of the encounters differently than when the aircraft are equipped with identical ACAS.

Follow up research concerning ACAS policy plots could include the construction of stochastic policy plots. Instead of one RA per grid point, these would include an array of possible RAs per grid point, each with their own probability. To clearly indicate the probabilities with which the RAs are issued a digital, interactive plot could be used. From the front, the plot could still have an x-axis with the time to CPA and a y-axis with the relative altitude. In addition, a third dimension could be added which would include markers indicating the probability with which each of the RAs is issued at a certain grid point. The user could then scroll through the 3D stochastic ACAS policy plot and see the areas where certain RAs are favoured over others.

11.4 Potential CAVEAT Improvements

To improve the user experience, increase the flexibility of CAVEAT outputs and increase CAVEAT functionalities, several potential improvements can be identified. The tool can still function well without these improvements, but could benefit from including them. The potential improvements concern both deterministic and stochastic simulations. Appendix E.5 provides more detailed information about these possible CAVEAT improvements.

Firstly, the inclusion of an automated ACAS policy plot generator would provide the user with a powerful tool to analyse the state space around aircraft in an encounter. For now ACAS policy plots are generated deterministically, but this could be expanded once stochastic ACAS policy plots can be generated.

Secondly, the indication of the corrective type of RA that is issued per aircraft per encounter should be divided into ‘Reversal Rate RA’, ‘Reversal RA’, ‘Crossing RA’ and ‘Other RA’. The manual should also include clear definitions of all possible RA types as their absence might confuse users.

Thirdly, for more detailed analysis it would be useful for the user to be able to select part of the simulated set of encounters and see its results. This could be suitable for both deterministic and stochastic simulations.

Fourthly, an increased functionality of the command line could allow for more automated running of CAVEAT. It is recommended to at least include the possibility to generate and adjust parameter setting files and gather detailed results from the command line. Additionally, more detailed information to operate this command line should be included in the manual.

Fifthly, a tool that processes the automatically outputted STF files would allow the user to more easily collect and analyse results.

Sixthly, raw data about the timing of specific events in a stochastic simulation would allow the user to compute distributions per RA. This allows for more detailed comparison and analysis of the data than is currently possible with CAVEAT.

Finally, an increase in CPU usage by CAVEAT could reduce the runtime, which is especially long in case of stochastic simulations.

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A Systematic Performance Evaluation of TCAS II and ACAS Xa

Volume II – Appendices

Contents

Introduction

This report consists of two volumes. Volume I – Thesis Body and Volume II – Appendices.
This volume includes appendices that provide additional information related to A Systematic Performance Evaluation of TCAS II and ACAS Xa: Volume I – Thesis Body.

- In Appendix A a description of the structure of encounter files used as input by CAVEAT is given.
- In Appendix B all CAVEAT simulation parameters are included, organised in tables and presented in the order that they are defined in CAVEAT.
- In 0 the agent-based model parameter settings are given.
- In Appendix D it is explained how the number of MC simulations is determined and which considerations are taken into account in deciding on this number.
- In Appendix E an overview of improvements of CAVEAT that have been realised thanks to this MSc thesis research is given, as well as potential future improvements. Appendix E also explains how these improvement needs have been identified
- In Appendix F it is explained how the verification of the self-developed code was performed.

Appendix A Encounter File Description

This appendix includes the description of the encounter file in .ftd format. All trajectory information included in Table 52, Table 53 and Table 54 is stored in one file that can be uploaded into CAVEAT to define the encounter. The header of the file consists of the information in Table 52 and Table 53. The core of the encounter file consists of the information in Table 54, which in detail describes the 4D trajectory of all aircraft in the encounter.

Table 52. General encounter parameters [27]

Parameter	Definition
Category	This parameter indicates what type of data is included in the file • Synthetic: complete, second-by-second data generated by a model. • Radar: radar tracking data, needs to be reconstructed before the simulation. • Reconstructed: complete, second-by-second reconstructed encounters based on radar tracking data.
Number_AC	The number of aircraft in the encounter, with an absolute maximum of 10.

Table 53. Aircraft static parameters [27]

Parameter	Definition
AC_tracknumber	A unique integer to identify aircraft in the encounter
Mode_S_address	The Mode S address of the aircraft, 6-digit hexadecimal number
Mode_A_code	The Mode A code of the aircraft, 4-digit octal number
AC_callsign	The aircraft callsign, used for result visualisation
ACAS_version	The ACAS version with which the aircraft is equipped. • Unequipped • TCAS II 7.0 • TCAS II 7.1 • TCAS II 7.2 • ACAS Xa 15.2 • ACAS Xa 15.4 • ACAS Xa 15.4 CP1
Manual_SL	The setting of the sensitivity level. • 0: automatic, TAs and RAs are provided • 1: standby, no TAs or RAs are provided • 2: TA only, only TAs are provided

If any of the parameters in Table 52 are not defined in the encounter file, they are taken from the scenario data.

Table 54. Aircraft dynamic parameters [27]

Parameter	Unit	Definition
Time	-	A time stamp in the format hh:mm:ss:cc
AC_tracknumber	-	A unique integer to identify aircraft in the encounter
X-position	nm	X-position of the aircraft in ENU coordinate system
Y-position	nm	Y-position of the aircraft in ENU coordinate system
Altitude	ft	Geodetic altitude of the aircraft, with zero altitude at mean sea level in standard atmospheric conditions
BDS-30	-	Not applicable for synthetic data

The ENU coordinate system is the East, North Up cartesian coordinate system. During the thesis, synthetic data will be generated, which is why the BDS-30 is not explained in Table 54.

Appendix B CAVEAT Simulation Parameters

This appendix highlights all parameters that are implemented into CAVEAT scenarios for this thesis.

Appendix B.1 Airspace Environment Parameters

The airspace environment parameters include information about the reference frame, the wind and the terrain in which the encounter takes place, all included in Table 55. They are uploaded in the scenario-configuration file.

Table 55. Environment parameters [27]

Parameter	Unit	Definition	Default
$s_{t,GNSS,i}^{wg,\lambda}$	deg	Latitude of reference's frame origin	0
$s_{t,GNSS,i}^{wg,\varphi}$	deg	Longitude of the reference's frame origin	0
s_{wind}	kts	Wind speed	0
α_{wind}	deg	Wind direction in the North-East reference frame	0
$h_{terrain}$	ft	Terrain elevation	0

Appendix B.2 Aircraft Parameters

This appendix includes all parameters that are used by CAVEAT to define the aircraft, including its models and state estimations. The parameters are categorised into four sections.

- Appendix B.3 contains the equipment and operation information.
- Appendix B.4 defines the parameters in the pilot model.
- Appendix B.5 includes the ownship state estimation.
- Appendix B.6 contains the othership measurements.

All these four categories are specified for each and every aircraft in the encounter and included in the scenario-configuration file.

Appendix B.3 Equipment and Operation

The equipment and operation parameters specify the type of ACAS, SSR and ADS-B equipment the aircraft carries. They are nearly identical, regardless of a deterministic or stochastic modelling selection.

Unmanned Aircraft System

Table 56. Unmanned aircraft system parameter [27]

Parameter	Unit	Definition	Default
$\theta_{AC,i}^{UAS}$	-	Boolean indicating that aircraft is an unmanned aircraft system (UAS)	False

ACAS Equipment

Table 57. ACAS equipment parameters [27]

Parameter	Unit	Definition	Default
	-	ACAS equipment	ACAS Xa 15.4 CP1 or TCAS II v7.1
$\tau_{ACAS,i}^{pr,con}$	s	ACAS Processing time	0.5 s
$\tau_{ACAS,i}^{coor,send}$	s	Time to send a coordination message	0.04 s
$\tau_{ACAS,i}^{coor,proc}$	s	Time to process an incoming coordination message	0.05 s
$T_i^{sh,det}$	s	Deterministic sampling time shift of systems of aircraft i (only in deterministic mode)	0.0 s for AC 1 and 0.5 s for AC 2

Onboard Equipment

Table 58. Onboard equipment parameters [27]

Parameter	Unit	Definition	Default
-	-	SSR Equipment	Mode S
$\kappa_{TS,i}^{Sadr}$		Mode S address of aircraft i	Defined by encounter file
$\lambda_{TS,i}^{quan}$	ft	SSR Altitude Quantization	25 ft
-	-	ADS-B In	Yes
-	-	ADS-B Out	Yes
$\kappa_{ADSB,j}^{AV}$	-	ADS-B version of aircraft j	2
$\kappa_{ADSB,j}^{AV}$	ft	ADS-B Altitude Quantization	25 ft

Parallel Approach Operation

Table 59. Parallel approach operation parameter [27]

Parameter	Unit	Definition	Default
$\theta_{AC,i}^{PA}$	-	Aircraft I being on a Parallel Approach (PA) or not NoPA)	NoPA

Aircraft Altitude

Table 60. Aircraft attitude parameters [27]

Parameter	Unit	Definition	Default
$\alpha_{AC,i}^{c}$	Deg	Angle of attack of aircraft i	6 deg

APFD ACAS RA Mode

The Autopilot Flight Director (APFD) ACAS RA mode is selected by default, it contains parameters that determine automatic responses to RAs by the Automatic Flight Control System (AFCS).

Table 61. APFD ACAS RA mode parameters [27]

Parameter	Unit	Definition	Default
$\tau_{AFCS,i}^{ini}$	s	Initial RA Delay	5
$\tau_{AFCS,i}^{mod}$	s	Modified RA Delay	2.5
$\tau_{AFCS,i}^{coc}$	s	COC Delay	2.5
$\alpha_{AFCS,i}^{a,RA}\{NormAcc\}$	g	Normal vertical acceleration	0.25
$\alpha_{AFCS,i}^{a,RA}\{HighAcc\}$	g	High vertical acceleration	0.35
$\theta_{AFCS,i}^{CoCSt}$	-	Strategy following COC advisory	rate

Advances Options

The parameters in Table 62 are only available when the APFD ACAS RA Mode is selected.

Table 62. Advanced options APFD ACAS RA mode parameters [27]

Parameter	Unit	Definition	Default
λ_{AFCS}^{pc}	1/s	Position feedback control parameter	1 1/s
$\varepsilon_{AFCS,i}^{coc}$	fpm	Threshold for difference between vertical rate and vertical rate in flight plan, so as to end the COC phase	20 fpm
$\varepsilon_{AFCS,i}^{FP}$	fpm	Threshold for considering the actual vertical rate being equal to the vertical rate in the flight plan	20 fpm
$v_{AFCS,i}^{CoC,ns}$	fpm	Normal vertical speed in return-to-trajectory manoeuvre after a COC	1500 fpm
$v_{AFCS,i}^{CoC,\Delta v}$	fpm	Additional vertical speed in high-speed regime of return-to-trajectory manoeuvre after a COC	500 fpm
$\lambda_{PF,i}^{pc}$	1/s	PF Position feedback control	1 1/s
$\varepsilon_{PF,i}^{coc}$	fpm	PF Threshold vertical rate COC end	100 fpm

$\varepsilon_{PF,i}^{FP}$	fpm	PF Threshold within flight plan	100 fpm

Encounter File Override

The parameters in Table 63 indicate if the information specified is obtained from either the encounter file or the scenario file. They can be individually chosen.

Table 63. Encounter file override parameters [27]

Parameter	Unit	Definition	Default
-	-	ACAS Equipment	scenario
-	-	Manual SL	scenario
-	-	Mode A/C	scenario
-	-	Mode S	scenario

Appendix B.4 Pilot Model

The pilot model parameters indicate how the behaviour of the pilot is modelled in CAVEAT. The different parameters differ significantly, depending on the deterministic or stochastic model selection. They are therefore displayed in different tables for both of the selections.

Pilot Response Mode

Table 64. Deterministic pilot response mode parameters [27]

Parameter	Unit	Definition	Default
$\kappa_{PF,i}^{MT}$	-	Model type pilot model	Deterministic
$\kappa_{PF,i}^{RM}$	-	Pilot response mode. Re indicates response, NoRE indicates No response.	Re

For this thesis specifically, several pilot response modes are designed.

Table 65. Stochastic pilot response mode parameters, 80% response to both initial and subsequent RAs [12]

Parameter	Unit	Definition	Default
$\kappa_{PF,i}^{MT}$	-	Model type pilot model	Stochastic
-	-	Standard parameter sets. Indicates if the parameters are non-dependent, altitude dependent or altitude-RR-PA dependent.	-
$d_{PF,i}^{alt}$	FL	Altitude Threshold	FL 50
$d_{PF,i}^{fl}$	fpm	Speed Threshold for constant FL	100 fpm
$p_{PF,i}^{res,ini,1}$	-	Probability of initial response given low altitude, rate reversal and parallel approach	0.8

$p_{PF,i}^{res,ini,2}$	-	Probability of initial response given low altitude, no rate reversal and parallel approach	0.8
$p_{PF,i}^{res,ini,3}$	-	Probability of initial response given low altitude, rate reversal and no parallel approach	0.8
$p_{PF,i}^{res,ini,4}$	-	Probability of initial response given low altitude, no rate reversal and no parallel approach	0.8
$p_{PF,i}^{res,ini,5}$	-	Probability of initial response given high altitude, rate reversal and parallel approach	0.8
$p_{PF,i}^{res,ini,6}$	-	Probability of initial response given high altitude, no rate reversal and parallel approach	0.8
$p_{PF,i}^{res,ini,7}$	-	Probability of initial response given high altitude, rate reversal and no parallel approach	0.8
$p_{PF,i}^{res,ini,8}$	-	Probability of initial response given high altitude, no rate reversal and no parallel approach	0.8
$p_{PF,i}^{res,mod,1}$	-	Probability of modified response given reversal RA and given response to a previous RA	0.8
$p_{PF,i}^{res,mod,2}$	-	Probability of modified response given no reversal RA and given response to a previous RA	0.8
$p_{PF,i}^{res,mod,3}$	-	Probability of modified response given reversal RA and given no response to a previous RA	0.8
$p_{PF,i}^{res,mod,4}$	-	Probability of modified response given no reversal RA and given no response to a previous RA	0.8
$p_{PF,i}^{res,coc}$	-	Probability of response to a clear-of-conflict advisory	0.8

Table 66. Stochastic pilot response mode parameters, 60% response to initial RAs and 80% response to any modified RAs

Parameter	Unit	Definition	Default
$\kappa_{PF,i}^{MT}$	-	Model type pilot model	Stochastic
-	-	Standard parameter sets. Indicates if the parameters are non-dependent, altitude dependent or altitude-RR-PA dependent.	-
$d_{PF,i}^{alt}$	FL	Altitude Threshold	FL 50
$d_{PF,i}^{fl}$	fpm	Speed Threshold for constant FL	100 fpm
$p_{PF,i}^{res,ini,1}$	-	Probability of initial response given low altitude, rate reversal and parallel approach	0.6
$p_{PF,i}^{res,ini,2}$	-	Probability of initial response given low altitude, no rate reversal and parallel approach	0.6
$p_{PF,i}^{res,ini,3}$	-	Probability of initial response given low altitude, rate reversal and no parallel approach	0.6
$p_{PF,i}^{res,ini,4}$	-	Probability of initial response given low altitude, no rate reversal and no parallel approach	0.6

$p_{PF,i}^{res,ini,5}$	-	Probability of initial response given high altitude, rate reversal and parallel approach	0.6
$p_{PF,i}^{res,ini,6}$	-	Probability of initial response given high altitude, no rate reversal and parallel approach	0.6
$p_{PF,i}^{res,ini,7}$	-	Probability of initial response given high altitude, rate reversal and no parallel approach	0.6
$p_{PF,i}^{res,ini,8}$	-	Probability of initial response given high altitude, no rate reversal and no parallel approach	0.6
$p_{PF,i}^{res,mod,1}$	-	Probability of modified response given reversal RA and given response to a previous RA	0.8
$p_{PF,i}^{res,mod,2}$	-	Probability of modified response given no reversal RA and given response to a previous RA	0.8
$p_{PF,i}^{res,mod,3}$	-	Probability of modified response given reversal RA and given no response to a previous RA	0.8
$p_{PF,i}^{res,mod,4}$	-	Probability of modified response given no reversal RA and given no response to a previous RA	0.8
$p_{PF,i}^{res,coc}$	-	Probability of response to a clear-of-conflict advisory	1

Table 67. Stochastic pilot response mode parameters, 80% response to initial RAs, 60% response to any modified RAs with a reaction to initial RAs and 80% response given no response to modified RA.

Parameter	Unit	Definition	Default
$\kappa_{PF,i}^{MT}$	-	Model type pilot model	Stochastic
-	-	Standard parameter sets. Indicates if the parameters are non-dependent, altitude dependent or altitude-RR-PA dependent.	-
$d_{PF,i}^{alt}$	FL	Altitude Threshold	FL 50
$d_{PF,i}^{fl}$	fpm	Speed Threshold for constant FL	100 fpm
$p_{PF,i}^{res,ini,1}$	-	Probability of initial response given low altitude, rate reversal and parallel approach	0.8
$p_{PF,i}^{res,ini,2}$	-	Probability of initial response given low altitude, no rate reversal and parallel approach	0.8
$p_{PF,i}^{res,ini,3}$	-	Probability of initial response given low altitude, rate reversal and no parallel approach	0.8
$p_{PF,i}^{res,ini,4}$	-	Probability of initial response given low altitude, no rate reversal and no parallel approach	0.8
$p_{PF,i}^{res,ini,5}$	-	Probability of initial response given high altitude, rate reversal and parallel approach	0.8
$p_{PF,i}^{res,ini,6}$	-	Probability of initial response given high altitude, no rate reversal and parallel approach	0.8
$p_{PF,i}^{res,ini,7}$	-	Probability of initial response given high altitude, rate reversal and no parallel approach	0.8

$p_{PF,i}^{res,ini,8}$	-	Probability of initial response given high altitude, no rate reversal and no parallel approach	0.8
$p_{PF,i}^{res,mod,1}$	-	Probability of modified response given reversal RA and given response to a previous RA	0.6
$p_{PF,i}^{res,mod,2}$	-	Probability of modified response given no reversal RA and given response to a previous RA	0.6
$p_{PF,i}^{res,mod,3}$	-	Probability of modified response given reversal RA and given no response to a previous RA	0.8
$p_{PF,i}^{res,mod,4}$	-	Probability of modified response given no reversal RA and given no response to a previous RA	0.8
$p_{PF,i}^{res,coc}$	-	Probability of response to a clear-of-conflict advisory	1

Table 68. *Stochastic pilot response mode parameters, 80% response to initial RAs, 80% response to any modified RAs with a reaction to initial RAs and 0.6 probability of modified response given no response to modified RA.*

Parameter	Unit	Definition	Default
$\kappa_{PF,i}^{MT}$	-	Model type pilot model	Stochastic
-	-	Standard parameter sets. Indicates if the parameters are non-dependent, altitude dependent or altitude-RR-PA dependent.	-
$d_{PF,i}^{alt}$	FL	Altitude Threshold	FL 50
$d_{PF,i}^{fl}$	fpm	Speed Threshold for constant FL	100 fpm
$p_{PF,i}^{res,ini,1}$	-	Probability of initial response given low altitude, rate reversal and parallel approach	0.8
$p_{PF,i}^{res,ini,2}$	-	Probability of initial response given low altitude, no rate reversal and parallel approach	0.8
$p_{PF,i}^{res,ini,3}$	-	Probability of initial response given low altitude, rate reversal and no parallel approach	0.8
$p_{PF,i}^{res,ini,4}$	-	Probability of initial response given low altitude, no rate reversal and no parallel approach	0.8
$p_{PF,i}^{res,ini,5}$	-	Probability of initial response given high altitude, rate reversal and parallel approach	0.8
$p_{PF,i}^{res,ini,6}$	-	Probability of initial response given high altitude, no rate reversal and parallel approach	0.8
$p_{PF,i}^{res,ini,7}$	-	Probability of initial response given high altitude, rate reversal and no parallel approach	0.8
$p_{PF,i}^{res,ini,8}$	-	Probability of initial response given high altitude, no rate reversal and no parallel approach	0.8
$p_{PF,i}^{res,mod,1}$	-	Probability of modified response given reversal RA and given response to a previous RA	0.8
$p_{PF,i}^{res,mod,2}$	-	Probability of modified response given no reversal RA and given response to a previous RA	0.8

$p_{PF,i}^{res,mod,3}$	-	Probability of modified response given reversal RA and given no response to a previous RA	0.6
$p_{PF,i}^{res,mod,4}$	-	Probability of modified response given no reversal RA and given no response to a previous RA	0.6
$p_{PF,i}^{res,coc}$	-	Probability of response to a clear-of-conflict advisory	1

Table 69. Stochastic pilot response mode parameters, 60% response to both initial and subsequent RAs [12]

Parameter	Unit	Definition	Default
$\kappa_{PF,i}^{MT}$	-	Model type pilot model	Stochastic
-	-	Standard parameter sets. Indicates if the parameters are non-dependent, altitude dependent or altitude-RR-PA dependent.	-
$d_{PF,i}^{alt}$	FL	Altitude Threshold	FL 50
$d_{PF,i}^{fl}$	fpm	Speed Threshold for constant FL	100 fpm
$p_{PF,i}^{res,ini,1}$	-	Probability of initial response given low altitude, rate reversal and parallel approach	0.6
$p_{PF,i}^{res,ini,2}$	-	Probability of initial response given low altitude, no rate reversal and parallel approach	0.6
$p_{PF,i}^{res,ini,3}$	-	Probability of initial response given low altitude, rate reversal and no parallel approach	0.6
$p_{PF,i}^{res,ini,4}$	-	Probability of initial response given low altitude, no rate reversal and no parallel approach	0.6
$p_{PF,i}^{res,ini,5}$	-	Probability of initial response given high altitude, rate reversal and parallel approach	0.6
$p_{PF,i}^{res,ini,6}$	-	Probability of initial response given high altitude, no rate reversal and parallel approach	0.6
$p_{PF,i}^{res,ini,7}$	-	Probability of initial response given high altitude, rate reversal and no parallel approach	0.6
$p_{PF,i}^{res,ini,8}$	-	Probability of initial response given high altitude, no rate reversal and no parallel approach	0.6
$p_{PF,i}^{res,mod,1}$	-	Probability of modified response given reversal RA and given response to a previous RA	0.6
$p_{PF,i}^{res,mod,2}$	-	Probability of modified response given no reversal RA and given response to a previous RA	0.6
$p_{PF,i}^{res,mod,3}$	-	Probability of modified response given reversal RA and given no response to a previous RA	0.6
$p_{PF,i}^{res,mod,4}$	-	Probability of modified response given no reversal RA and given no response to a previous RA	0.6
$p_{PF,i}^{res,coc}$	-	Probability of response to a clear-of-conflict advisory	0.6

Vertical Rate

Table 70. Deterministic Vertical Rate Parameters [27]

Parameter	Unit	Definition	Default
$\kappa_{PF,i}^{MT}$	-	Model type pilot actions model	Deterministic

Table 71. Stochastic Vertical Rate Error Parameters [27]

Parameter	Unit	Definition	Default
$\kappa_{PF,i}^{MT}$	-	Model type pilot actions model	Stochastic
$\mu_{PF,i}^{v,RA}$	fpm	Mean value of error in the vertical rate implemented by the pilot	0
$\sigma_{PF,i}^{v,RA}$	fpm	Standard deviation of error in the vertical rate implemented by the pilot	100 fpm

Delay

Table 72. Deterministic delay in pilot response parameters [27]

Parameter	Unit	Definition	Default
$\kappa_{PF,i}^{MT}$	-	Model type pilot delay model	Deterministic
$\tau_{PF,i}^{ini}$	s	Delay in preparation	2.5 s
$\tau_{PF,i}^{mod}$	s	Mean of delay in action	2.5 s
$\tau_{PF,i}^{coc}$	s	Standard deviation of delay in action	-

Table 73. Default stochastic delay in pilot response parameters [27]

Parameter	Unit	Definition	Default
$\kappa_{PF,i}^{MT}$	-	Model type pilot delay model	Stochastic
$\mu_{PF,i}^{\tau,ini}$	s	Delay in preparation	1.5 s
$\mu_{PF,i}^{\tau,ini}$	s	Mean of delay in action	3.3 s
$\mu_{PF,i}^{\tau,mod}$	s	Standard deviation of delay in action	1.5 s

Table 74. Stochastic delay in pilot response parameters used in parameter setting S5.1

Parameter	Unit	Definition	Default
$\kappa_{PF,i}^{MT}$	-	Model type pilot delay model	Stochastic
$\mu_{PF,i}^{\tau,ini}$	s	Delay in preparation	3.0 s
$\mu_{PF,i}^{\tau,ini}$	s	Mean of delay in action	3.3 s
$\mu_{PF,i}^{\tau,mod}$	s	Standard deviation of delay in action	1.5 s

Table 75. Stochastic delay in pilot response parameters used in parameter setting S5.2

Parameter	Unit	Definition	Default
$\kappa_{PF,i}^{MT}$	-	Model type pilot delay model	Stochastic
$\mu_{PF,i}^{\tau,ini}$	s	Delay in preparation	1.5 s
$\mu_{PF,i}^{\tau,ini}$	s	Mean of delay in action	6.6 s
$\mu_{PF,i}^{\tau,mod}$	s	Standard deviation of delay in action	1.5 s

Table 76. Stochastic delay in pilot response parameters used in parameter setting S5.3

Parameter	Unit	Definition	Default
$\kappa_{PF,i}^{MT}$	-	Model type pilot delay model	Stochastic
$\mu_{PF,i}^{\tau,ini}$	s	Delay in preparation	1.5 s
$\mu_{PF,i}^{\tau,ini}$	s	Mean of delay in action	3.3 s
$\mu_{PF,i}^{\tau,mod}$	s	Standard deviation of delay in action	3.0 s

Table 77. Stochastic delay in pilot response parameters used in parameter setting S5.4

Parameter	Unit	Definition	Default
$\kappa_{PF,i}^{MT}$	-	Model type pilot delay model	Stochastic
$\mu_{PF,i}^{\tau,ini}$	s	Delay in preparation	3.0 s
$\mu_{PF,i}^{\tau,ini}$	s	Mean of delay in action	6.6 s
$\mu_{PF,i}^{\tau,mod}$	s	Standard deviation of delay in action	3.0 s

Vertical Acceleration

The data from Table 79 and Table 80 is based on the pilot responses in terms of acceleration and vertical speed presented in *[28]*.

Table 78. Deterministic vertical acceleration parameters, according to ICAO standard pilot response [27]

Parameter	Unit	Definition	Default
$\kappa_{PF,i}^{MT}$	-	Model type pilot actions model	Deterministic
$a_{PF,i}^{a,RA}$ {*NormAcc*}	g	Intercept of linear regression of vertical acceleration w.r.t. speed (normal acceleration)	0.25 g
$a_{PF,i}^{a,RA}$ {*HighAcc*}	g	Intercept of linear regression of vertical acceleration w.r.t. speed (high acceleration)	0.35 g

$\beta^{a,RA}_{PF,i}$ {*NormAcc*}	g/fpm	Gradient of linear regression of vertical acceleration w.r.t. speed (normal acceleration)	0 g/fpm
$\beta^{a,RA}_{PF,i}$ {*HighAcc*}	g/fpm	Gradient of linear regression of vertical acceleration w.r.t. speed (high acceleration)	0 g/fpm

Table 79. Deterministic vertical acceleration parameters, speed dependent [27]

Parameter	Unit	Definition	Default
$\kappa^{MT}_{PF,i}$	-	Model type pilot actions model	Deterministic
$a^{a,RA}_{PF,i}$ {*NormAcc*}	g	Intercept of linear regression of vertical acceleration w.r.t. speed (normal acceleration)	0.1 g
$a^{a,RA}_{PF,i}$ {*HighAcc*}	g	Intercept of linear regression of vertical acceleration w.r.t. speed (high acceleration)	0.1 g
$\beta^{a,RA}_{PF,i}$ {*NormAcc*}	g/fpm	Gradient of linear regression of vertical acceleration w.r.t. speed (normal acceleration)	0.00005 g/fpm
$\beta^{a,RA}_{PF,i}$ {*HighAcc*}	g/fpm	Gradient of linear regression of vertical acceleration w.r.t. speed (high acceleration)	0.00005 g/fpm

Table 80. Stochastic vertical acceleration parameters, ICAO defaults [27]

Parameter	**Unit**	**Definition**	**Default**
$\kappa^{MT}_{PF,i}$	-	Model type pilot actions model	Stochastic
$a^{a,RA}_{PF,i}$ {*NormAcc*}	g	Intercept of linear regression of vertical acceleration w.r.t. speed (normal acceleration)	0.25 g
$a^{a,RA}_{PF,i}$ {*HighAcc*}	g	Intercept of linear regression of vertical acceleration w.r.t. speed (high acceleration)	0.35 g
$\beta^{a,RA}_{PF,i}$ {*NormAcc*}	g/fpm	Gradient of linear regression of vertical acceleration w.r.t. speed (normal acceleration)	0 g/fpm
$\beta^{a,RA}_{PF,i}$ {*HighAcc*}	g/fpm	Gradient of linear regression of vertical acceleration w.r.t. speed (high acceleration)	0 g/fpm
$\sigma^{a,RA}_{PF,i}$	g	Standard deviation of the vertical acceleration implemented by the pilot flying in response to an RA	0.04 g

Appendix B.5 Ownship State Estimation

The ownship state estimation parameters define how different sensor errors of the own aircraft are taken into account. The difference between the deterministic and stochastic parameters differs significantly, hence why they are displayed in separate tables per error model.

GNSS-based Position Error Model

Table 81. Deterministic GNSS-based position error model parameters [27]

Parameter	Unit	Definition	Default
$\kappa_{GNSS,i}^{MT,s}$	-	Model type of GNSS-based position error model	Deterministic
$\kappa_{GNSS,i}^{NACp}$	-	Navigation Accuracy Category for Position (NACp). $\kappa_{GNSS,i}^{NACp} \in \{0,1,\ldots,11\}$	8
$\kappa_{GNSS,i}^{NIC}$	-	Navigation Integrity Category (NIC)	8
$\kappa_{GNSS,i}^{SIL}$	-	Surveillance Integrity Level (SIL)	3

Table 82. Stochastic GNSS-based position error model parameters [27]

Parameter	Unit	Definition	Default
$\kappa_{GNSS,i}^{MT,s}$	-	Model type of GNSS-based position error model	Stochastic
$\kappa_{GNSS,i}^{NACp}$	-	Navigation Accuracy Category for Position (NACp). $\kappa_{GNSS,i}^{NACp} \in \{0,1,\ldots,11\}$	8
$\kappa_{GNSS,i}^{NIC}$	-	Navigation Integrity Category (NIC)	8
$\kappa_{GNSS,i}^{SIL}$	-	Surveillance Integrity Level (SIL)	3
$\alpha_{GNNS,i}^{s,auto}$	-	Autocorrelation factor in AR(1) process of jitter in the geodetic position error model	0.9970

GNSS-based Velocity Error Model

Table 83. Deterministic GNSS-based velocity error model parameters [27]

Parameter	Unit	Definition	Default
$\kappa_{GNSS,i}^{MT,v}$	-	Model type of GNSS-based velocity error model	Deterministic
$\kappa_{GNSS,i}^{NACv}$	-	Navigation Accuracy Category for horizontal velocity (NACv). $\kappa_{GNSS,i}^{NACv} \in \{0,1,\ldots,4\}$	1

Table 84. Stochastic GNSS-based velocity error model parameters [27]

Parameter	Unit	Definition	Default
$\kappa_{GNSS,i}^{MT,v}$	-	Model type of GNSS-based velocity error model	Stochastic
$\kappa_{GNSS,i}^{NACv}$	-	Navigation Accuracy Category for horizontal velocity (NACv). $\kappa_{GNSS,i}^{NACv} \in \{0,1,\ldots,4\}$	1
$\alpha_{GNNS,i}^{v,auto}$	-	Autocorrelation factor in AR(1) process of jitter in the geodetic velocity error model	0.9970

Pressure Altitude

Table 85. Deterministic pressure altitude parameters [27]

Parameter	Unit	Definition	Default
$\kappa_{PAS,i}^{MT}$	-	Model type of pressure altimetry error model	Deterministic

Table 86. Stochastic pressure altitude parameters according to ACAS MOPS [27]

Parameter	Unit	Definition	Default
$\kappa_{PAS,i}^{MT}$	-	Model type of pressure altimetry error model	Stochastic
$\kappa_{PAS,i}^{bias}$	-	Choice of probability distribution for the bias in the pressure altimetry error model	Normal
$A_{PAS,i}^{bias}$	ft	Matrix containing points of the altitude – standard deviation mapping of the bias of the pressure altitude system	(0 , 45; 5000 , 48; 10000 , 52; 15000 , 58; 20000 , 65; 25000 , 71; 30000, 78; 35000 , 86; 40000 , 95)
$\alpha_{PAS,i}^{auto}$	-	Autocorrelation factor in AR(1) process of jitter in the pressure altimetry error model	0.88
$\sigma_{PAS,i}^{z,jitter}$	ft	Standard deviation of the jitter in the pressure altimetry error	4.9

Table 87. Stochastic pressure altitude parameters used in parameter setting S6.1

Parameter	Unit	Definition	Default
$\kappa_{PAS,i}^{MT}$	-	Model type of pressure altimetry error model	Stochastic
$\kappa_{PAS,i}^{bias}$	-	Choice of probability distribution for the bias in the pressure altimetry error model	Normal
$A_{PAS,i}^{bias}$	ft	Matrix containing points of the altitude – standard deviation mapping of the bias of the pressure altitude system	(0 , 90; 5000 , 96; 10000 , 104; 15000 , 116; 20000 , 130; 25000 , 142; 30000, 156; 35000 , 172; 40000 , 190)
$\alpha_{PAS,i}^{auto}$	-	Autocorrelation factor in AR(1) process of jitter in the pressure altimetry error model	0.88
$\sigma_{PAS,i}^{z,jitter}$	ft	Standard deviation of the jitter in the pressure altimetry error	4.9

Table 88. Stochastic pressure altitude parameters used in parameter setting S6.2

Parameter	Unit	Definition	Default
$\kappa_{PAS,i}^{MT}$	-	Model type of pressure altimetry error model	Stochastic
$\kappa_{PAS,i}^{bias}$	-	Choice of probability distribution for the bias in the pressure altimetry error model	Normal
$A_{PAS,i}^{bias}$	ft	Matrix containing points of the altitude – standard deviation mapping of the bias of the pressure altitude system	(0 , 45; 5000 , 48; 10000 , 52; 15000 , 58; 20000 , 65; 25000 , 71; 30000, 78; 35000 , 86; 40000 , 95)
$\alpha_{PAS,i}^{auto}$	-	Autocorrelation factor in AR(1) process of jitter in the pressure altimetry error model	0.88
$\sigma_{PAS,i}^{z,jitter}$	ft	Standard deviation of the jitter in the pressure altimetry error	9.8

Table 89. Stochastic pressure altitude parameters used in parameter setting S6.3

Parameter	Unit	Definition	Default
$\kappa_{PAS,i}^{MT}$	-	Model type of pressure altimetry error model	Stochastic
$\kappa_{PAS,i}^{bias}$	-	Choice of probability distribution for the bias in the pressure altimetry error model	Normal
$A_{PAS,i}^{bias}$	ft	Matrix containing points of the altitude – standard deviation mapping of the bias of the pressure altitude system	(0 , 90; 5000 , 96; 10000 , 104; 15000 , 116; 20000 , 130; 25000 , 142; 30000, 156; 35000 , 172; 40000 , 190)
$\alpha_{PAS,i}^{auto}$	-	Autocorrelation factor in AR(1) process of jitter in the pressure altimetry error model	0.88
$\sigma_{PAS,i}^{z,jitter}$	ft	Standard deviation of the jitter in the pressure altimetry error	9.8

Radio Altitude

Table 90. Deterministic radio altitude parameters [27]

Parameter	Unit	Definition	Default
$\kappa_{RAS,i}^{MT}$	-	Model type of radio altimetry error model	Deterministic

Table 91. Stochastic radio altitude parameters [27]

Parameter	Unit	Definition	Default
$\kappa_{RAS,i}^{MT}$	-	Model type of radio altimetry error model	Stochastic
$\beta_{RAS,i}^{\sigma,h}$	-	Height-dependency factor standard deviation of error of radio altimetry system	0.010
$\alpha_{RAS,i}^{auto}$	-	Autocorrelation factor in AR(1) process of jitter in the radio altimetry error model	0

Heading

Table 92. Deterministic heading parameters [27]

Parameter	Unit	Definition	Default
$\kappa_{HRS,i}^{MT}$	-	Model type of heading estimation error model	Deterministic

Table 93. Stochastic heading parameters [27]

Parameter	Unit	Definition	Default
$\kappa_{HRS,i}^{MT}$	-	Model type of heading estimation error model	Stochastic
$\alpha_{HRS,i}^{auto}$	-	Autocorrelation factor in AR(1) process of jitter in the heading error model	0
$\sigma_{HRS,i}^{noise}$	deg	Standard deviation of the noise of the heading estimation process	1 deg

Appendix B.6 Othership Measurements

The othership measurement parameters indicate how the errors with respect to the state of the other aircraft are included in the encounter. Since the deterministic and stochastic parameters differ significantly, they are displayed in separate tables.

Transponder-based slant range

Table 94. Deterministic transponder-based slant range parameters [27]

Parameter	Unit	Definition	Default
$\kappa_{TS,i}^{MT,r}$	-	Model type of transponder-based slant range error model	Deterministic

The ACAS MOPS and ICAO Annex 10 state different settings as standard transponder-based slant range measurements. Both can be selected in CAVEAT, their default parameters are included in Table 95 and Table 96, respectively.

Table 95. Stochastic transponder-based slant range parameters according to ACAS MOPS [27]

Parameter	Unit	Definition	Default
$\kappa_{TS,i}^{MT,r}$	-	Model type of transponder-based slant range error model	Stochastic
$\alpha_{TS,i}^{auto,r}$	-	Autocorrelation factor in AR(1) process of jitter in the transponder-based slant range measurement error model	0
$\sigma_{TS,ModeS,i}^{r,bias}$	ft	Standard deviation of bias in slant range measurement using Mode S transponder signals	125 ft
$\sigma_{TS,ModeS,i}^{r,jitter}$	ft	Standard deviation of jitter in slant range measurement using Mode S transponder signals	50 ft
$\sigma_{TS,ModeC,i}^{r,bias}$	ft	Standard deviation of bias in slant range measurement using Mode C transponder signals	250 ft
$\sigma_{TS,ModeC,i}^{r,jitter}$	ft	Standard deviation of jitter in slant range measurement using Mode C transponder signals	50 ft

Table 96. Stochastic transponder-based slant range parameters according to ICAO Annex 10 [27]

Parameter	Unit	Definition	Default
$\kappa_{TS,i}^{MT,r}$	-	Model type of transponder-based slant range error model	Stochastic
$\alpha_{TS,i}^{auto,r}$	-	Autocorrelation factor in AR(1) process of jitter in the transponder-based slant range measurement error model	0
$\sigma_{TS,ModeS,i}^{r,bias}$	ft	Standard deviation of bias in slant range measurement using Mode S transponder signals	0 ft
$\sigma_{TS,ModeS,i}^{r,jitter}$	ft	Standard deviation of jitter in slant range measurement using Mode S transponder signals	50 ft
$\sigma_{TS,ModeC,i}^{r,bias}$	ft	Standard deviation of bias in slant range measurement using Mode C transponder signals	0 ft
$\sigma_{TS,ModeC,i}^{r,jitter}$	ft	Standard deviation of jitter in slant range measurement using Mode C transponder signals	50 ft

Transponder-based bearing

Table 97. Deterministic transponder-based bearing parameters [27]

Parameter	Unit	Definition	Default
$\kappa_{TS,i}^{MT,\xi}$	-	Model type of transponder-based bearing error model	Deterministic

The ACAS MOPS and ICAO Annex 10 state different settings as standard transponder-based bearing measurements. Both can be selected in CAVEAT, their default parameters are included in Table 98 and Table 99, respectively.

Table 98. Stochastic transponder-based bearing parameters according to ACAS MOPS [27]

Parameter	Unit	Definition	Default
$\kappa_{TS,i}^{MT,\xi}$	-	Model type of transponder-based bearing measurement model	Stochastic
$\alpha_{TS,i}^{auto,\xi}$	-	Autocorrelation factor in AR(1) process of jitter in the bearing error model	0
$\vartheta_{TS,i}^{\xi}$	deg	Threshold in elevation angle impacting standard deviation of bearing error	10 deg
$\sigma_{TS,ModeS,L,i}^{\xi,noise}$	deg	Standard deviation of bearing error for low elevation angles and Mode S replies	12 deg
$\sigma_{TS,ModeS,H,i}^{\xi,noise}$	deg	Standard deviation of bearing error for high elevation angles and Mode S replies	18 deg
$\sigma_{TS,ModeC,L,i}^{\xi,noise}$	deg	Standard deviation of bearing error for low elevation angles and Mode C replies	10 deg
$\sigma_{TS,ModeC,H,i}^{\xi,noise}$	deg	Standard deviation of bearing error for high elevation angles and Mode C replies	16 deg

Table 99. Stochastic transponder-based bearing parameters according to ICAO Annex 10 [27]

Parameter	Unit	Definition	Default
$\kappa_{TS,i}^{MT,\xi}$	-	Model type of transponder-based bearing measurement model	Stochastic
$\alpha_{TS,i}^{auto,\xi}$	-	Autocorrelation factor in AR(1) process of jitter in the bearing error model	0
$\vartheta_{TS,i}^{\xi}$	deg	Threshold in elevation angle impacting standard deviation of bearing error	10 deg
$\sigma_{TS,ModeS,L,i}^{\xi,noise}$	deg	Standard deviation of bearing error for low elevation angles and Mode S replies	10 deg
$\sigma_{TS,ModeS,H,i}^{\xi,noise}$	deg	Standard deviation of bearing error for high elevation angles and Mode S replies	10 deg
$\sigma_{TS,ModeC,L,i}^{\xi,noise}$	deg	Standard deviation of bearing error for low elevation angles and Mode C replies	10 deg
$\sigma_{TS,ModeC,H,i}^{\xi,noise}$	deg	Standard deviation of bearing error for high elevation angles and Mode C replies	10 deg

Appendix C Agent-Based Model Parameter Settings

This appendix contains tables with the ABM parameter settings not included in Chapter 4. As all detailed information on parameter set 1 was already included in the main body of the report, this appendix contains parameter set 2 and further.

Appendix C.1 Parameter Set 2

Stochastic Setting – S2.1

Table 100. Agent-based model parameter settings, stochastic setting – S2.1

CAVEAT Element		Table Reference
Pilot Response Mode	Deterministic	Table 64
Vertical Rate Error	Deterministic	Table 70
Delay	Deterministic	Table 72
Vertical Acceleration	Deterministic, ICAO model	Table 78
GNSS-based Position Error Model	Stochastic	Table 82
GNSS-based Velocity Error Model	Deterministic	Table 83
Pressure Altitude	Deterministic	Table 85
Radio Altitude	Deterministic	Table 90
Heading	Deterministic	Table 92
Transponder-based Slant Range	Deterministic	Table 94
Transponder-based Bearing	Deterministic	Table 97

Stochastic Setting – S2.2

Table 101. Agent-based model parameter settings, stochastic setting – S2.2

CAVEAT Element		Table Reference
Pilot Response Mode	Deterministic	Table 64
Vertical Rate Error	Deterministic	Table 70
Delay	Deterministic	Table 72
Vertical Acceleration	Deterministic, ICAO model	Table 78
GNSS-based Position Error Model	Deterministic	Table 81
GNSS-based Velocity Error Model	Stochastic	Table 84
Pressure Altitude	Deterministic	Table 85
Radio Altitude	Deterministic	Table 90
Heading	Deterministic	Table 92
Transponder-based Slant Range	Deterministic	Table 94

Transponder-based Bearing	Deterministic	Table 97

Stochastic Setting – S2.3

Table 102. Agent-based model parameter settings, stochastic setting – S2.3

CAVEAT Element		Table Reference
Pilot Response Mode	Deterministic	Table 64
Vertical Rate Error	Deterministic	Table 70
Delay	Deterministic	Table 72
Vertical Acceleration	Deterministic, ICAO model	Table 78
GNSS-based Position Error Model	Deterministic	Table 81
GNSS-based Velocity Error Model	Deterministic	Table 83
Pressure Altitude	Stochastic, MOPS	Table 86
Radio Altitude	Deterministic	Table 90
Heading	Deterministic	Table 92
Transponder-based Slant Range	Deterministic	Table 94
Transponder-based Bearing	Deterministic	Table 97

Stochastic Setting – S2.4

Table 103. Agent-based model parameter settings, stochastic setting – S2.4

CAVEAT Element		Table Reference
Pilot Response Mode	Deterministic	Table 64
Vertical Rate Error	Deterministic	Table 70
Delay	Deterministic	Table 72
Vertical Acceleration	Deterministic, ICAO model	Table 78
GNSS-based Position Error Model	Deterministic	Table 81
GNSS-based Velocity Error Model	Deterministic	Table 83
Pressure Altitude	Deterministic	Table 85
Radio Altitude	Stochastic	Table 91
Heading	Deterministic	Table 92
Transponder-based Slant Range	Deterministic	Table 94
Transponder-based Bearing	Deterministic	Table 97

Stochastic Setting – S2.5

Table 104. Agent-based model parameter settings, stochastic setting – S2.5

CAVEAT Element		Table Reference
Pilot Response Mode	Deterministic	Table 64
Vertical Rate Error	Deterministic	Table 70
Delay	Deterministic	Table 72

Vertical Acceleration	Deterministic, ICAO model	Table 78
GNSS-based Position Error Model	Deterministic	Table 81
GNSS-based Velocity Error Model	Deterministic	Table 83
Pressure Altitude	Deterministic	Table 85
Radio Altitude	Deterministic	Table 90
Heading	Stochastic	Table 93
Transponder-based Slant Range	Deterministic	Table 94
Transponder-based Bearing	Deterministic	Table 97

Stochastic Setting – S2.6

Table 105. Agent-based model parameter settings, stochastic setting – S2.6

CAVEAT Element		Table Reference
Pilot Response Mode	Deterministic	Table 64
Vertical Rate Error	Deterministic	Table 70
Delay	Deterministic	Table 72
Vertical Acceleration	Deterministic, ICAO model	Table 78
GNSS-based Position Error Model	Deterministic	Table 81
GNSS-based Velocity Error Model	Deterministic	Table 83
Pressure Altitude	Deterministic	Table 85
Radio Altitude	Deterministic	Table 90
Heading	Deterministic	Table 92
Transponder-based Slant Range	Stochastic, MOPS	Table 95
Transponder-based Bearing	Deterministic	Table 97

Stochastic Setting – S2.7

Table 106. Agent-based model parameter settings, stochastic setting – S2.7

CAVEAT Element		Table Reference
Pilot Response Mode	Deterministic	Table 64
Vertical Rate Error	Deterministic	Table 70
Delay	Deterministic	Table 72
Vertical Acceleration	Deterministic, ICAO model	Table 78
GNSS-based Position Error Model	Deterministic	Table 81
GNSS-based Velocity Error Model	Deterministic	Table 83
Pressure Altitude	Deterministic	Table 85
Radio Altitude	Deterministic	Table 90
Heading	Deterministic	Table 92

Transponder-based Slant Range	Deterministic	Table 94
Transponder-based Bearing	Stochastic, MOPS	Table 98

Appendix C.2 Parameter Set 3

Deterministic Setting – D1.1

Table 107. Agent-based model parameter settings, Deterministic Settings – D1.1

CAVEAT Element		Table Reference
Pilot Model		
Pilot Response Mode	Deterministic	Table 64
Vertical Rate Error	Deterministic	Table 70
Delay	Deterministic	Table 72
Vertical Acceleration	Deterministic, ICAO model	Table 78
Ownship State Estimation		
GNSS-based Position Error Model	Deterministic	Table 81
GNSS-based Velocity Error Model	Deterministic	Table 83
Pressure Altitude	Deterministic	Table 85
Radio Altitude	Deterministic	Table 90
Heading	Deterministic	Table 92
Othership State Estimation		
Transponder-based Slant Range	Deterministic	Table 94
Transponder-based Bearing	Deterministic	Table 97

Stochastic Setting – S3.1

Table 108. Agent-based model parameter settings, Stochastic Setting – S3.1

CAVEAT Element		Table Reference
Pilot Response Mode	Stochastic	Table 65
Vertical Rate Error	Stochastic	Table 71
Delay	Stochastic	Table 73
Vertical Acceleration	Stochastic, speed dependent	Table 80
GNSS-based Position Error Model	Stochastic	Table 82
GNSS-based Velocity Error Model	Stochastic	Table 84
Pressure Altitude	Stochastic, MOPS model	Table 86
Radio Altitude	Stochastic	Table 91
Heading	Stochastic	Table 93
Transponder-based Slant Range	Stochastic, MOPS model	Table 95

Transponder-based Bearing	Stochastic, MOPS model	Table 98

Appendix C.3 Parameter Set 4

Stochastic Setting – S4.1

Table 109. Agent-based model parameter settings, Stochastic Setting – S4.1

CAVEAT Element		Table Reference
Pilot Response Mode	Stochastic, 60% pilot response to initial RAs and 80% pilot response to any modified RAs	Table 66
Vertical Rate Error	Stochastic	Table 71
Delay	Stochastic	Table 73
Vertical Acceleration	Stochastic, ICAO defaults	Table 80
GNSS-based Position Error Model	Stochastic	Table 82
GNSS-based Velocity Error Model	Stochastic	Table 84
Pressure Altitude	Stochastic, MOPS model	Table 86
Radio Altitude	Stochastic	Table 91
Heading	Stochastic	Table 93
Transponder-based Slant Range	Stochastic, MOPS model	Table 95
Transponder-based Bearing	Stochastic, MOPS model	Table 98

Stochastic Setting – S4.2

Table 110. Agent-based model parameter settings, Stochastic Setting – S4.2

CAVEAT Element		Table Reference
Pilot Response Mode	Stochastic, 80% pilot response to initial RAs, 60% response to modified RAs with a positive reaction to initial RAs and 80% response to modified RAs with no reacting to initial RAs	Table 67
Vertical Rate Error	Stochastic	Table 71
Delay	Stochastic	Table 73
Vertical Acceleration	Stochastic, ICAO defaults	Table 80
GNSS-based Position Error Model	Stochastic	Table 82
GNSS-based Velocity Error Model	Stochastic	Table 84
Pressure Altitude	Stochastic, MOPS model	Table 86
Radio Altitude	Stochastic	Table 91
Heading	Stochastic	Table 93

Transponder-based Slant Range	Stochastic, MOPS model	Table 95
Transponder-based Bearing	Stochastic, MOPS model	Table 98

Stochastic Setting – S4.3

Table 111. Agent-based model parameter settings, Stochastic Setting – S4.3

CAVEAT Element		Table Reference
Pilot Response Mode	Stochastic, 80% pilot response to initial RAs, 80% response to modified RAs with a positive reaction to initial RAs and 60% response to modified RAs with no reacting to initial RAs	Table 68
Vertical Rate Error	Stochastic	Table 71
Delay	Stochastic	Table 73
Vertical Acceleration	Stochastic, ICAO defaults	Table 80
GNSS-based Position Error Model	Stochastic	Table 82
GNSS-based Velocity Error Model	Stochastic	Table 84
Pressure Altitude	Stochastic, MOPS model	Table 86
Radio Altitude	Stochastic	Table 91
Heading	Stochastic	Table 93
Transponder-based Slant Range	Stochastic, MOPS model	Table 95
Transponder-based Bearing	Stochastic, MOPS model	Table 98

Stochastic Setting – S4.4

Table 112. Agent-based model parameter settings, Stochastic Setting – S4.4

CAVEAT Element		Table Reference
Pilot Response Mode	Stochastic, 60% pilot response to initial RA and any modified RAs	Table 69
Vertical Rate Error	Stochastic	Table 71
Delay	Stochastic	Table 73
Vertical Acceleration	Stochastic, ICAO defaults	Table 80
GNSS-based Position Error Model	Stochastic	Table 82
GNSS-based Velocity Error Model	Stochastic	Table 84
Pressure Altitude	Stochastic, MOPS model	Table 86
Radio Altitude	Stochastic	Table 91
Heading	Stochastic	Table 93
Transponder-based Slant Range	Stochastic, MOPS model	Table 95

Transponder-based Bearing	Stochastic, MOPS model	Table 98

Appendix C.4 Parameter Set 5

Stochastic Setting – S5.1

Table 113. Agent-based model parameter settings, Stochastic Setting – S5.1

CAVEAT Element		Table Reference
Pilot Response Mode	Stochastic	Table 65
Vertical Rate Error	Stochastic	Table 71
Delay	Stochastic	Table 74
Vertical Acceleration	Stochastic, speed dependent	Table 80
GNSS-based Position Error Model	Stochastic	Table 82
GNSS-based Velocity Error Model	Stochastic	Table 84
Pressure Altitude	Stochastic, MOPS model	Table 86
Radio Altitude	Stochastic	Table 91
Heading	Stochastic	Table 93
Transponder-based Slant Range	Stochastic, MOPS model	Table 95
Transponder-based Bearing	Stochastic, MOPS model	Table 98

Stochastic Setting – S5.2

Table 114. Agent-based model parameter settings, Stochastic Setting – S5.2

CAVEAT Element		Table Reference
Pilot Response Mode	Stochastic	Table 65
Vertical Rate Error	Stochastic	Table 71
Delay	Stochastic	Table 75
Vertical Acceleration	Stochastic, speed dependent	Table 80
GNSS-based Position Error Model	Stochastic	Table 82
GNSS-based Velocity Error Model	Stochastic	Table 84
Pressure Altitude	Stochastic, MOPS model	Table 86
Radio Altitude	Stochastic	Table 91
Heading	Stochastic	Table 93
Transponder-based Slant Range	Stochastic, MOPS model	Table 95
Transponder-based Bearing	Stochastic, MOPS model	Table 98

Stochastic Setting – S5.3

Table 115. Agent-based model parameter settings, Stochastic Setting – S5.3

CAVEAT Element		Table Reference
Pilot Response Mode	Stochastic	Table 65

Vertical Rate Error	Stochastic	Table 71
Delay	Stochastic	Table 76
Vertical Acceleration	Stochastic, speed dependent	Table 80
GNSS-based Position Error Model	Stochastic	Table 82
GNSS-based Velocity Error Model	Stochastic	Table 84
Pressure Altitude	Stochastic, MOPS model	Table 86
Radio Altitude	Stochastic	Table 91
Heading	Stochastic	Table 93
Transponder-based Slant Range	Stochastic, MOPS model	Table 95
Transponder-based Bearing	Stochastic, MOPS model	Table 98

Stochastic Setting – S5.4

Table 116. Agent-based model parameter settings, Stochastic Setting – S5.4

CAVEAT Element		Table Reference
Pilot Response Mode	Stochastic	Table 65
Vertical Rate Error	Stochastic	Table 71
Delay	Stochastic	Table 77
Vertical Acceleration	Stochastic, speed dependent	Table 80
GNSS-based Position Error Model	Stochastic	Table 82
GNSS-based Velocity Error Model	Stochastic	Table 84
Pressure Altitude	Stochastic, MOPS model	Table 86
Radio Altitude	Stochastic	Table 91
Heading	Stochastic	Table 93
Transponder-based Slant Range	Stochastic, MOPS model	Table 95
Transponder-based Bearing	Stochastic, MOPS model	Table 98

Appendix C.5 Parameter Set 6

Stochastic Setting – S6.1

Table 117. Agent-based model parameter settings, Stochastic Setting – S6.1

CAVEAT Element		Table Reference
Pilot Response Mode	Stochastic	Table 65
Vertical Rate Error	Stochastic	Table 71
Delay	Stochastic	Table 73
Vertical Acceleration	Stochastic, ICAO defaults	Table 80
GNSS-based Position Error Model	Stochastic	Table 82

GNSS-based Velocity Error Model	Stochastic	Table 84
Pressure Altitude	Stochastic	Table 87
Radio Altitude	Stochastic	Table 91
Heading	Stochastic	Table 93
Transponder-based Slant Range	Stochastic, MOPS model	Table 95
Transponder-based Bearing	Stochastic, MOPS model	Table 98

Stochastic Setting – S6.2

Table 118. Agent-based model parameter settings, Stochastic Setting – S6.2

CAVEAT Element		Table Reference
Pilot Response Mode	Stochastic	Table 65
Vertical Rate Error	Stochastic	Table 71
Delay	Stochastic	Table 73
Vertical Acceleration	Stochastic, ICAO defaults	Table 80
GNSS-based Position Error Model	Stochastic	Table 82
GNSS-based Velocity Error Model	Stochastic	Table 84
Pressure Altitude	Stochastic	Table 88
Radio Altitude	Stochastic	Table 91
Heading	Stochastic	Table 93
Transponder-based Slant Range	Stochastic, MOPS model	Table 95
Transponder-based Bearing	Stochastic, MOPS model	Table 98

Stochastic Setting – S6.3

Table 119. Agent-based model parameter settings, Stochastic Setting – S6.3

CAVEAT Element		Table Reference
Pilot Response Mode	Stochastic	Table 65
Vertical Rate Error	Stochastic	Table 71
Delay	Stochastic	Table 73
Vertical Acceleration	Stochastic, ICAO defaults	Table 80
GNSS-based Position Error Model	Stochastic	Table 82
GNSS-based Velocity Error Model	Stochastic	Table 84
Pressure Altitude	Stochastic	Table 89
Radio Altitude	Stochastic	Table 91
Heading	Stochastic	Table 93
Transponder-based Slant Range	Stochastic, MOPS model	Table 95
Transponder-based Bearing	Stochastic, MOPS model	Table 98

Appendix D Set-up of Simulation of ACAS Encounters

This chapter discusses the considerations that were taken into account with respect to the simulations that were run for this research. In Appendix D.1 the required number of Monte Carlo runs is obtained and reasoned. The confidence levels of these runs are discussed in Appendix D.2. Appendix D.3 presents how the required number of runs in the MC simulations is obtained. Lastly, several factors that were taken into account when selecting the encounter type and parameter setting combinations to be simulated are discussed in Appendix D.4.

Appendix D.1 Number of Runs in a Monte Carlo Simulation

This section provides insight in how to choose the number of runs n_{run} per Monte Carlo (MC) simulation that will be performed for each combination of encounter with parameter settings. The number of combinations of encounter geometries and parameter settings is defined as the number of MC simulations n_{MC} . At the end of Chapter 4 it was concluded that there are 1272 interesting combinations that can be simulated for this thesis. Since these differ significantly in terms of encounter geometry and parameter setting, it could be that the required number of runs differs per combination of encounter with parameter settings.

When deciding on the required number of runs in a MC simulation several considerations need to be taken into account. First of all, the parameter settings can influence the required number of runs. If a certain parameter setting is fully deterministic, only 1 run per MC simulation is necessary. In this case, the output of TCAS II and ACAS Xa will be identical to the output of an additional run with the same parameter settings and encounter, so 1 run will provide all data necessary. If a parameter setting contains one or multiple stochastic settings, a sufficient number of runs is needed per MC simulation. Since the agents in the model are now expressed by a different elements that together form the stochastic model for that agent, the outcome of the model differs per run. By running the MC simulation numerous times and using all the runs to compute the indicators, the outcome of the model and thus the indicators settle around a certain value, which gives statistics about the indicators.

Next to that, the type of indicator that is used for the analysis also has an effect on the required number of runs. Since some of the indicators are based on events that occur during an encounter, it is important to realise that not every type of event has the same probability of occurrence. Thus, the number of runs must be chosen based on the occurrence of the event that concerns the indicator. To obtain the required number of runs, two indicators are used. The probability of an NMAC encounter is an indicator that has a relatively low occurrence, and the probability of a modified crossing encounter has a relatively high occurrence. Both indicators are easy to compute and can easily be compared between encounter geometries or ACAS equipages. Using different types of indicators ensures that the obtained required number of runs is sufficient for all indicators used during this research.

Appendix D.2 Confidence Levels and Intervals

Confidence levels and intervals are used to determine the required number of runs. This section gives the reader insight in the accuracy of the MC simulations and derives the equations for the confidence intervals.

In risk analysis, common practise is to make use of 95% confidence intervals. A 95% confidence interval is the range of values of which you can indicate with a 95% probability that the interval contains the true mean of a set of sample values. In case of a small set of samples, the confidence interval will be larger than in case of a large set of sample values, as in the latter case the mean can be obtained with more precision.

Estimating the confidence intervals requires several equations and derivations, summarised as follows. The idea of an MC based estimation is to take the expected value $\mu = E(Y)$ of a random variable Y as quantity of interest. From simulation, the values for $Y_1,...,Y_n$ can be obtained independently and used to compute the average as in (12.1, which then serves as an estimate of μ. In Eq. (12.1) n is the number of samples.

$$\hat{\mu}_n = \frac{1}{n}\sum_{i=1}^{n} Y_i \tag{12.1}$$

This can be justified when looking at the laws of large numbers. Let Y be a random variable for which $E(Y) = \mu$ exists. Assume that $Y_1,...,Y_n$ are independent and identically distributed with the same distribution as Y. The weak law of large numbers then states that as the sample size grows, the mean μ approaches the average of the complete population μ_n, as ε goes to zero. This mathematically defined by Eq. (12.2).

$$\lim_{n\to\infty} P\left(\left|\hat{\mu}_n - \mu\right| \le \varepsilon\right) = 1 \tag{12.2}$$

More information can be gathered from the strong law of large numbers, which indicates that the absolute error eventually gets below ε and remains to stay there forever.

$$P\left(\lim_{n\to\infty}\left|\hat{\mu}_n - \mu\right| = 0\right) = 1 \tag{12.3}$$

These laws thus indicate that eventually the error will decrease to an error which is as low as is desired, however they do not indicate the size of n that is required for that. To acquire an idea about the error, the sample values can be used. Since a good estimate of μ is usually more valuable to the user than a good estimate of the error, a rough approximation is good enough. For this, the standard error is used, σ^2 / n. The value for the variance σ^2 is often not known, but can easily be estimated from the sample values. Two commonly used formulas for this estimation are Eq. (12.4) and Eq. (12.5).

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(Y_i - \hat{\mu}_n\right)^2 \tag{12.4}$$

$$\hat{\sigma}^2 = \frac{1}{n}\sum_{i=1}^{n}\left(Y_i - \hat{\mu}_n\right)^2 \tag{12.5}$$

When the value of n is large, these two estimates lie closer to each other than they are to the actual value of the variance σ^2. An often cited reason to use Eq. (12.4) is that it is unbiased, namely the expectancy of the estimation of the variance is equal to the actual variance: $E\left(s^2\right) = \sigma^2$. In [29] it is explained and shown how these error estimates in combination with the Central Limit Theorem can lead to the approximate confidence interval in the form of Eq. (12.6), which has a confidence level of $100\left(1-\alpha\right)$ percent, where α can be chosen by the user.

$$\hat{\mu}_n \pm \Phi^{-1}\left(1-\alpha/2\right)\frac{s}{\sqrt{n}} \tag{12.6}$$

Here, μ_n is the average of the population, s is the standard deviation and n the sample size. $\Phi\left(a\right)$ is the cumulative distribution function as in Eq. (12.7).

$$\Phi\left(a\right) = \int_{-\infty}^{a} \varphi\left(z\right)dz, \qquad -\infty < z < \infty \tag{12.7}$$

where $\varphi\left(z\right)$ is the probability density function. When the variable Y that is to be averaged only has two possible values, 0 and 1, the variance is completely determined by the mean. Let's say that the probability that $Y=1$ can be expressed by $p \in \left[0,1\right]$. Then $E\left(Y^2\right) = E\left(Y\right) = p$, because for a binary variable $Y^2 = Y$. Then Eq. (12.6) can be expressed by Eq. (12.8).

$$\hat{p}_n \pm \Phi^{-1}\left(1-\alpha/2\right)\sqrt{\frac{\hat{p}_n\left(1-\hat{p}_n\right)}{n}} \tag{12.8}$$

This equation results in a confidence interval with a $100(1-\alpha)$ percent confidence level, where α can be chosen by the user. It must be noted that this equation does not exactly match the values that are obtained when implementing the binary Y_i into Eq. (12.6), but the difference is small and commonly accepted [29].

The confidence intervals of the NMAC probability in an encounter and the probability of a modified crossing encounter can both be determined by using Eq. (12.8). Both are comprised of a set of binary variables, indicating if encounter contains an NMAC or modified crossing encounter or does not. The confidence intervals are calculated with the commonly used confidence level of

95%. In that case, the α in Eq. (12.8) is 0.05, changing the equation Eq. (12.8) to the formulas in Eq. (12.9) [29].

$$\hat{p}_n \pm 1.96\sqrt{\frac{\hat{p}_n\left(1-\hat{p}_n\right)}{n}} \tag{12.9}$$

Appendix D.3 Required Number of Runs in MC simulation

Now that the equations are presented, the data from several MC simulations, each with an increasing amount of runs is used to compute confidence intervals per indicator.

NMAC Probability

Out of the 18 different original type 1 encounter geometries per altitude, 12 contain an NMAC, namely the geometries with the zero lateral HMD. Thus, 67% of the original type 1 encounters contains an NMAC, since the altitude does not have any influence on the NMAC probability in the original encounter. Not all of these encounter geometries are of interest for the probability of a modified encounter containing an NMAC. Only the most pressing encounters are used for this part of the analysis. These are the encounters that occur at flight levels where aircraft are most likely to fly level, such as FL300 or FL430. The encounter geometries that are of most interest are the encounter with a 90° course angle and the encounter with the 180° course angle without any HMD. In the latter situation, the relative velocity between the aircraft is the largest. Hence, the four encounter geometries in Table 120 are simulated to obtain insight in the number of simulation runs required to gather usable data on the NMAC probability.

Table 120. Selected type 1 encounter geometries for determining number of runs for NMAC probability indicator

Altitude (ft)	Vertical Velocity (KTS)	Course angle (°)	Lateral HMD (ft)
30000	470	90	0
30000	470	180	0
43000	490	90	0
43000	490	180	0

These four encounter geometries are simulated for TCAS II and ACAS Xa, resulting in a total of eight MC simulations for eight encounters. From the results in Table 121 it is seen that in general, the NMAC probability of an encounter lies around the 1%.

Table 121. NMAC probabilities for selected encounters per number of runs, used to calculate the confidence intervals

Encounter geometry		NMAC probability

Altitude (ft)	Course angle (deg)	HMD (ft)	ACAS Type	1000 runs	2000 runs	3000 runs	5000 runs	10000 runs	15000 runs	20000 runs
30000	90	0	ACAS Xa	1.0	1.5	0.8	1.3	1.2	1.2	1.0
30000	90	0	TCAS II	0.6	0.8	0.9	0.8	0.8	0.9	0.8
30000	180	0	ACAS Xa	1.0	0.9	1.1	1.3	1.0	0.9	1.1
30000	180	0	TCAS II	2.0	1.6	1.9	2.0	1.8	1.8	2.1
43000	90	0	ACAS Xa	2.2	1.2	1.5	1.4	1.4	1.5	1.4
43000	90	0	TCAS II	1.4	1.5	1.1	1.3	1.1	1.1	1.1
43000	180	0	ACAS Xa	1.5	1.5	1.7	1.5	1.6	1.5	1.4
43000	180	0	TCAS II	2.7	2.8	2.4	2.2	2.1	2.5	2.2

The combination of these NMAC probabilities, the number of runs and a confidence level of 95% yields the confidence interval. Detailed results are included in Table 122.

Table 122. Exact confidence intervals for NMAC probabilities for selected encounter geometries per number of runs, with confidence level of 95%

Encounter geometry			ACAS Type	Confidence intervals for NMAC probability					
				5000 runs		10000 runs		15000 runs	
Altitude (ft)	Course angle (deg)	HMD (ft)		Lower limit	Upper limit	Lower limit	Upper limit	Lower limit	Upper limit
30000	90	0	ACAS Xa	1.00	1.64	0.95	1.37	1.06	1.42
30000	90	0	TCAS II	0.54	1.02	0.62	0.96	0.73	1.03
30000	180	0	ACAS Xa	1.02	1.66	0.82	1.22	0.76	1.07
30000	180	0	TCAS II	1.58	2.34	1.52	2.04	1.57	2.00
43000	90	0	ACAS Xa	1.09	1.75	1.13	1.59	1.30	1.69
43000	90	0	TCAS II	0.95	1.57	0.90	1.30	0.93	1.26
43000	180	0	ACAS Xa	1.20	1.88	1.34	1.82	1.32	1.72
43000	180	0	TCAS II	1.83	2.65	1.87	2.43	2.21	2.71

In Figure 98 the average width of the confidence intervals per number of runs is displayed. Since the encounter geometries used to obtain the several different confidence intervals are similar, the average is taken as expected (e.g. [29]). A clear trend is observed; when the number of runs is increased, the confidence interval can be determined with more accuracy and the width of the confidence interval decreases.

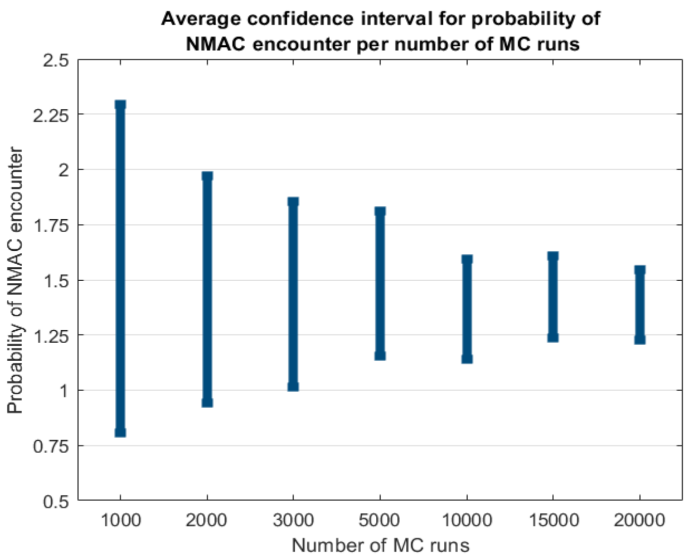

Figure 98. Average width of confidence intervals with 95% confidence level for NMAC probability

At 1000 runs, the width of most of the confidence intervals is around the 1.5% or even higher. At 5000 runs, all confidence interval widths are below 1%, at 10000 runs the widths of the intervals are around the 0.45% and at 20000 runs the widths are decreased to around 0.3%.

In Figure 99 and Figure 100 the confidence intervals for the four selected encounter geometries are visualised for TCAS II and ACAS Xa, respectively. In these figures only the confidence intervals for 5000, 10000 and 15000 runs are included, as they are most relevant.

For events that do not occur very often, such as an NMAC, a rule of thumb is to obtain at least about 100 occurrences per simulation. For the NMAC probability indicator, this means that the MC simulation must run repeatedly, until roughly 100 of the runs contain an encounter with an NMAC. This method prevents, till a certain extent, that conclusions are drawn on a dataset that is too small and has outcomes that deviate significantly from the settling values. By the time 100 NMACs occurred, the NMAC probability has stabilised enough to be able to draw conclusions from this number.

100 occurrences in 5000 runs indicates an NMAC probability of 2%. It can be seen in Figure 99 and Figure 100 that this percentage lies within the confidence interval in two of the eight encounter geometries, but the majority of the time it falls outside of the confidence interval for 5000 runs. This indicates that 5000 runs is not sufficient. The 100 NMAC occurrences in 10000 runs indicate a probability of at least 1%. This is reached in all confidence intervals for 10000 runs and is thus sufficient. For the confidence intervals that originate from 10000 runs it can also be seen that there is a dilation in the orange bars in the figures. This dilation indicated the estimated NMAC probability at that encounter geometry.

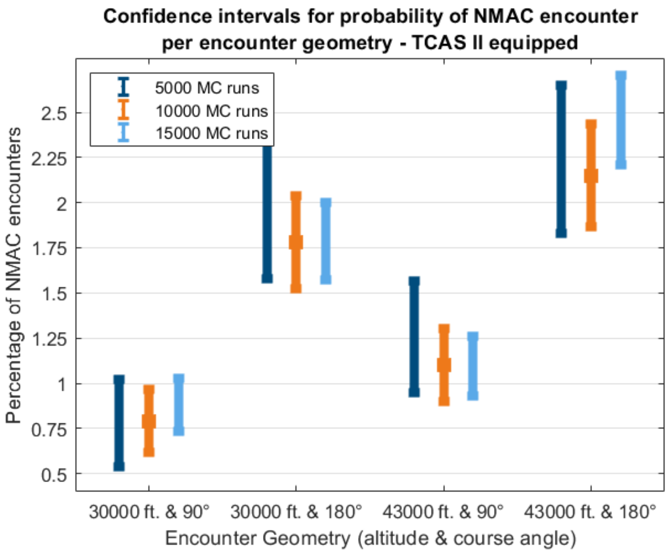

Figure 99. Confidence intervals for NMAC probability of encounter - TCAS II equipped

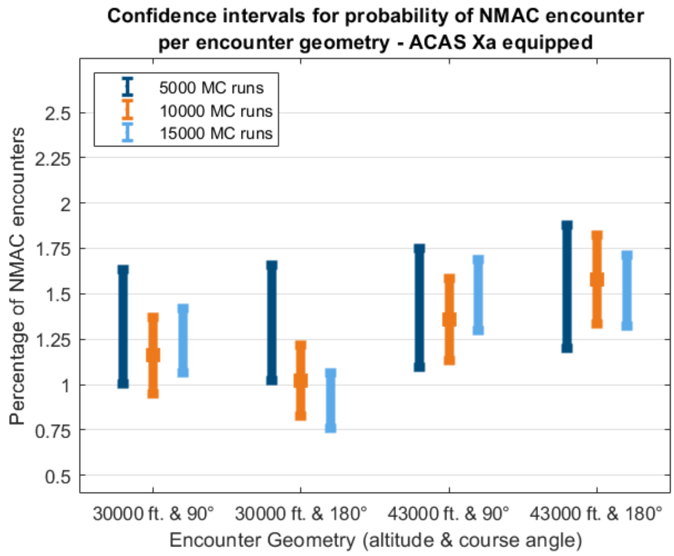

Figure 100. Confidence intervals for NMAC probability of encounter - ACAS Xa equipped

The lower limit of the confidence interval with 10000 runs is located roughly 20% from the estimated value lower than the estimated value itself. The upper limit of the confidence interval with 10000 runs is located roughly 20% from the estimated value higher than the estimated value itself. For example, for the geometry at 30000 ft with a relative course angle of 180° in an ACAS Xa equipped encounter, the estimated probability of an NMAC occurrence is 1.02%. The lower and upper limit of the confidence interval based on 10000 runs are 0.82% and 1.22%. The size of this interval can be a guideline of other confidence intervals that need to be obtained.

For 15000 runs, the 100 NMAC occurrences mean at least a 0.66% NMAC probability, which is also reached by all confidence intervals. However, the computation time also needs to be taken into account; the more runs are required, the more time it takes to perform the simulation. Hence, 10000 runs is sufficient to compute the NMAC probability with plentiful accuracy.

Probability of Modified Crossing Encounter

The set of encounters used to determine the required amount of runs for the modified crossing encounter indicator is displayed in Table 123, note that this set is different from the set of encounters in Table 120. The encounters in this set cover all altitudes and the encounter geometries are based on the type 1 encounter geometries. The six selected encounters are run for both TCAS II and ACAS Xa using the fully stochastic parameter setting S3.1. The number of runs starts at 1000, and then increases to 2000, 3000, 5000, 10000, 15000 and finally 20000.

Table 123. Selected type 1 encounter geometries for determining number of runs for crossing encounter probability indicator

Encounter number	Altitude (ft)	Speed (KTS)	Course angle (degrees)	Lateral HMD (ft)

1	2000	185	30	0
2	3500	200	180	2000
3	7500	295	120	0
4	15000	295	0	1000
5	30000	470	0	500
6	43000	490	60	0

Since a modified crossing encounter occurs significantly more often than an NMAC, the required number of runs is likely to be lower than 10000. The rule of thumb of 100 occurrences is also not required anymore, since it is likely that this number is reached relatively quickly. In Table 124 the probabilities of modified crossings for these selected encounters are displayed, per number of MC runs. These are used to calculate the confidence intervals.

Table 124. Probability of modified crossing encounter for selected encounters per number of runs, used to calculate the confidence intervals

Encounter geometry			ACAS Type	Probability of modified crossing encounter						
Altitude (ft)	Course angle (deg)	HMD (ft)		1000 runs	2000 runs	3000 runs	5000 runs	10000 runs	15000 runs	20000 runs
2000	30	0	ACAS Xa	22.8	24.2	25.5	24.4	23.1	23.6	23.9
2000	30	0	TCAS II	22.4	24.2	24.0	23.4	24.6	23.3	23.4
3500	180	2000	ACAS Xa	20.1	20.3	20.9	20.4	20.7	20.4	21.4
3500	180	2000	TCAS II	21.5	21.3	20.6	20.5	21.9	21.4	21.3
7500	120	0	ACAS Xa	7.0	8.5	7.6	6.8	7.5	7.5	7.7
7500	120	0	TCAS II	7.5	7.3	7.7	7.9	7.3	7.3	7.3
15000	0	1000	ACAS Xa	5.3	6.8	6.5	6.2	6.2	6.3	6.1
15000	0	1000	TCAS II	6.8	8.4	74.7	75.8	7.5	7.3	7.6
30000	0	500	ACAS Xa	5.9	6.7	6.0	5.8	6.3	6.2	6.1
30000	0	500	TCAS II	7.0	7.8	7.9	6.6	7.8	7.5	7.3
43000	60	0	ACAS Xa	15.2	15.0	14.8	16.3	16.1	16.0	15.6
43000	60	0	TCAS II	15.0	16.5	16.2	16.5	15.4	16.0	15.9

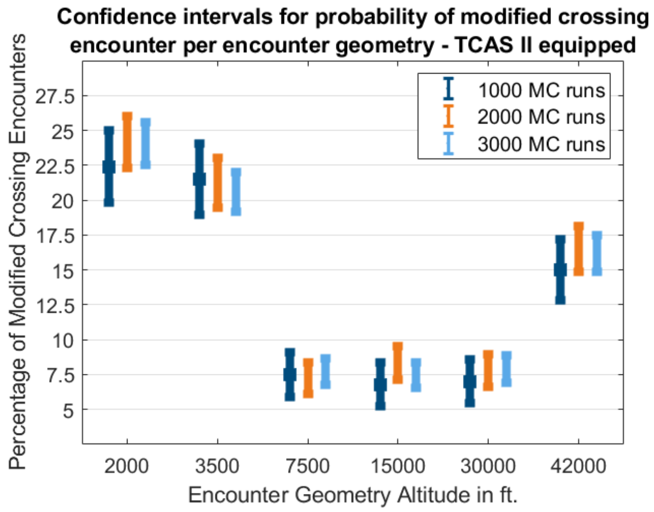

Figure 101. Confidence intervals for probability of modified crossing encounter - TCAS II equipped

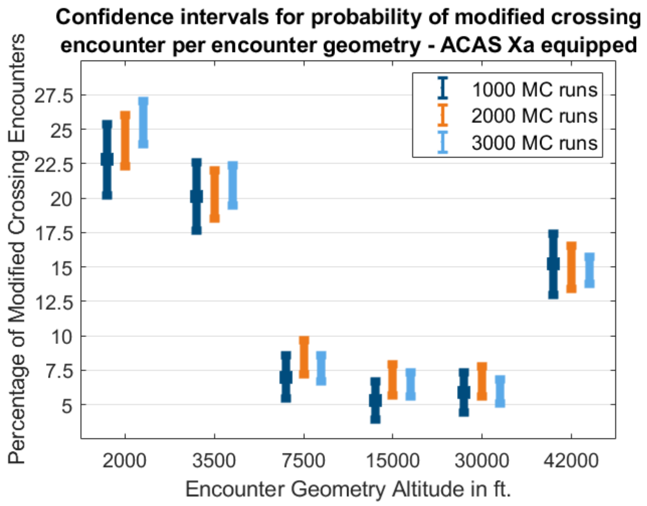

Figure 102. Confidence intervals for probability of modified crossing encounter – ACAS Xa equipped

In Figure 101 and Figure 102 the confidence intervals for the percentages of modified crossing encounters are displayed for the selected encounter geometry at each altitude, for TCAS II and ACAS Xa respectively. At each altitude three 95% confidence level confidence intervals are calculated, for simulations with 1000 runs, 2000 runs and 3000 runs. To obtain confidence intervals that are comparable in size to the confidence intervals of the NMAC probability, it is checked when the confidence interval is comparable to the confidence intervals determined for the NMAC probability. This is again done by taking the estimated probability of the modified crossing encounter and computing the interval that has lower and upper limits that deviate roughly 20% of the estimated modified crossing encounter probability. For example, the confidence interval based on 1000 runs for TCAS II equipped encounter at 2000 ft altitude spans from 19.82% to 24.98% and the estimated probability of a modified crossing encounter is 22.4%. This means that the confidence interval based on 1000 runs is already smaller than the standard set before. Since the width of the confidence intervals decreases when the number of MC runs increases, this means that 1000 runs is already more than enough to accurately estimate the probability of a modified crossing encounter. When repeating this simple comparison for the other encounter geometries, it is seen that the confidence intervals based on 1000 all are smaller than the 20% deviation confidence interval used as a standard.

However, as the required number of runs for the NMAC probability indicator is higher, every stochastic simulation in this report will be run 10000 times. This number corresponds to the number of MC runs in [12].

Appendix D.4 Considerations for Encounter Geometry and Parameter Setting Combinations

Due to the vast amount of possible combinations of encounter geometries and parameter settings, the analysis is be done in an iterative process. This process was started by an exploratory analysis, which provided insight in the behaviour of the agents in the model and the outcome of the simulations.

Together, the encounter types presented in Section 3.8 and the parameter sets included in Chapter 4 result in a total of 1272 unique simulation combinations for both TCAS II and ACAS Xa. Not all of these combinations are relevant in general or for this research in particular. There for this section contains several points that need to be considered when picking the encounter type and scenario category combinations that are to be simulated.

Relevance of Encounter Geometry

The encounter geometries that belong to the encounter types presented in Section 3.8 all form complete sets that cover a large range in altitude, velocity, course angle, HMD, VMD and vertical velocity to allow for systematic performance evaluation. However, several of the encounter geometries have a low probability of occurring in real life.

- Type 1 encounters all occur in the same horizontal plane, but these types of encounters occur less often at low altitudes. At low altitudes, commercial aircraft climb or descend from and to an airport. At higher altitudes, the aircraft do fly level more often, since they are then in the cruise phase of flight.
- Type 2 encounters represent the cruise phase of flight even more, as this type contains encounters where aircraft fly level with a vertical distance between the two aircraft. This situation can represent the highways in the sky.
- Type 3 encounters contain one aircraft that flies level and one aircraft that climbs or descends. This situation could occur at lower altitudes where aircraft are following designated routes towards the runway, but is also possible at higher altitudes when aircraft change flight level during cruise.

Influence of Sensor Errors

Position errors can be investigated by combining parameter settings with types of encounters where the aircraft behave exactly on the perimeter of the volume where ACAS are triggered or behave exactly on the perimeter of the NMAC definition (500 ft hor. & 100 ft vert.).

Velocity errors are interesting to investigate when both aircraft fly at the same (or almost the same) velocity. Errors in the velocity could potentially favour certain advisories (desired and/or undesired) for the faster or slower aircraft. There are no certain encounter types that are of particular interest for these errors.

Since the pressure altitude sensor errors influence the estimation of the altitude of the aircraft, it is interesting to look at type 1 encounters. Since the aircraft all fly on the same level in encounter type 1, it is interesting to investigate how much influence the pressure altitude parameters have on the solution of TCAS II and ACAS Xa and if this influence results in more desirable outcomes.

The radio altitude is used to obtain the an estimate of the aircraft's altitude above the ground. An accurate radio altitude is required to prevent aircraft from receiving descend advisories at a low altitude. Since the an estimate of ground level is determined if the radio altitude value indicates less than 1700 ft (among other conditions stated in [24]), the encounters to investigate the influence of ratio altitude errors should only happen at altitudes close to this threshold. These situation can occur of an aircraft is taking off or landing. If the aircraft dips below the 1700 ft it should not receive any advisories. Thus, the altitudes should be varied in small steps around the 1700 ft altitude.

Time Required for Simulation

Simulating many encounter geometries and parameter setting combinations is time intensive. In Table 125 the runtimes for fully deterministic and fully stochastic simulations for both TCAS II and ACAS Xa are included, for one encounter geometry. The stochastic simulations were run 10000 times. These simulations were done with CAVEAT 3.4.0 on a HP ZBook Studio G5 with a Intel CORE i7-8750H processor. It can be seen that especially the stochastic simulations require a lot of time to compute.

Table 125. Runtimes in minutes and seconds for TCAS II and ACAS Xa of CAVEAT 3.4.0 simulations with 1 encounter geometry, the stochastic simulations include 10000 MC runs

	TCAS II	ACAS Xa
Deterministic parameter settings	0 minutes 9 seconds	0 minutes 17 seconds
Stochastic parameter settings	8 minutes 39 seconds	117 minutes 21 seconds

Additionally, since the use of CAVEAT cannot be automated for the application of this thesis the results have to be downloaded by hand for analysis. Opening the stochastic simulations in CAVEAT on the laptop is a time consuming process as well, since CAVEAT calculates the statistics internally. The time required to perform a complete simulation with analysis thus has to be kept in mind when choosing the required number of simulations.

Appendix E Improvements of CAVEAT

During this MSc thesis research explicit use was made of CAVEAT in the stochastic mode setting. Because this was the first time that the stochastic mode of CAVEAT was used on large data sets, this led to identification of relevant CAVEAT improvements. These improvements and the underlying evaluations to identify these improvements are reported in this appendix.

Appendix E.1 CAVEAT issues identified during MSc research

During the use of CAVEAT in the stochastic mode, some code issues have been identified and reported to NLR and everis. Most of these issues have already been repaired. Table 126 includes an overview of all the identified seven issues during the use and verification of CAVEAT. Per issue a small description is included. Next, the CAVEAT version in which the issue was found is stated as well as the specific part of CAVEAT where the problem relates to. Finally, the status of the problem regards to if the problem was solved before the simulation runs of this thesis work were performed. Five of the seven issues have been timely resolved in CAVEAT 3.4.0, i.e. the version that is used in producing the simulation results in this thesis. In Appendix E.2 and Appendix E.3 the simulation results are given that identified resolved issues one to five. In Appendix E.4 the simulation identified effects of issues six and seven are explained.

In using CAVEAT for this research, the following means were available:

- The input to the tool, which consists of the encounter propagation files and the ABM settings, can be fully modified and verified by the user.
- Every simulation contains configuration and log files that can be used to check if all ABM settings are correctly selected by the user and are correctly taken into account by CAVEAT once the program is running.
- The calculations of the statistics cannot be verified by the user, only the output of the statistics are available for verification.
- The raw output is only logged for a maximum number of 100 runs per simulation, which is not sufficient to draw conclusions from. It is, however, enough to identify trends that can be used for verification.
- The CAVEAT Manual and the CAVEAT Models and Algorithm Report can be used to see which definitions are used and how the agent-based models are defined.

Focus of the verification of the stochastic mode of CAVEAT was on the elements of the pilot model and the state estimation models. This was done using the parameter settings in Sections 4.2 and 4.3. These settings are deterministic except for one element which is modelled stochastically. The results should thus all contain stochastic outcomes, such as distributions of VMDs or timings. The focus was on checking the presence of this behaviour, rather than the behaviour itself. This is why the number of MC runs was brought down to 100, which was enough to check for presence of stochastic behaviour. It was verified that all pilot delay elements and state estimation elements were stochastically modelled in CAVEAT. Additionally, elements that on itself resulted in NMACs using default settings were identified: the pilot response mode and the pressure altitude. Details and outcomes of this process can be found in Appendix E.2 and Appendix E.3.

Inaccuracies in the results were found by using CAVEAT throughout the thesis process, not only during verification. If an inaccuracy was found, it was notified to the developers, which contributed to the verification of the tool. Most of these reports resulted in updates of the tool, which were presented in new versions of CAVEAT. Throughout this thesis work seven different CAVEAT versions were used. The actual results in this report come from simulations with the latest CAVEAT version, version 3.4.0.

Table 126 includes an overview of all the found issues during the use and verification of CAVEAT. Per issue a small description is included. Next the CAVEAT version in which the issue was found is stated as well as the specific part of CAVEAT where the problem relates to. Finally, the status of the problem regards to if the problem was solved before the simulation runs of this thesis work were performed. It thus states if the problem was still prevalent in CAVEAT 3.4.0. If so, it is possible that the identified CAVEAT issue influenced the results of this thesis.

Table 126. Overview of identified issues in CAVEAT

Number	Identification date	Problem description	CAVEAT version	Affected part of CAVEAT	Status
1	February 2021	When selecting encounter files and scenarios for simulation, they appear in a list. When the user then selects a combination from this list to simulate and scrolls down to select more combinations, the checkmarks that indicate the selected combinations do no correspond to the selected combinations anymore, they start to move	CAVEAT 3.1.0	HMI	Solved (March 2021)
2	April 2021	Memory access violation pop-up occurs when viewing and downloading batch of data in statistics module for prolonged period of time (15-25 minutes). When clicking 'OK' on the pop up CAVEAT shuts down without saving the data.	CAVEAT 3.1.2	HMI	Solved (April 2021)
3	April 2021	Pilot response standard altitude dependent set or standard altitude-RR_PA dependent set in	CAVEAT 3.1.2	HMI	Solved (April 2021)

		the scenario configurator cannot be selected			
4	June 2021	Certain pilot response mode settings were shown to the user in the HMI while other different settings were saved in the log files. These saved settings were what was used during simulation.	CAVEAT 3.2.0	HMI/ABM	Solved (July 2021)
5	June 2021	Stochastic pilot delay settings did not result in stochastic results, as explained in Appendix E.2.	CAVEAT 3.2.0	HMI/ABM	Solved (July 2021)
6	August 2021	The advisory tree of aircraft 2 is incorrect in the statistics module.	CAVEAT 3.4.0	Statistics module	Open
7	August 2021	VMDs of 100 ft are inconsistently marked as NMAC encounters, as explained in Appendix E.4 and included in Table 128.	CAVEAT 3.4.0	Results	Open

Appendix E.2 Pilot Model Elements in CAVEAT

In this section the separate pilot model elements of the CAVEAT ABM are verified. To speed up this verification process, the set of type 1 encounters is reduced for these sections only. Since the goal of the verification of the stochastic elements is mainly to investigate if they are taken into account by CAVEAT, the exact differences between the numerous encounters are of less interest. The small amount of encounter geometries included in Table 127 still represent the set of type 1 encounters while reducing the necessary simulation time.

Table 127. Modified Type 1 encounters, for verification of stochastic pilot model and state estimation elements

AC	Symbol	Unit	Values		
	$h_{t_{CPA},i,j}$	Ft	7500	15000	36000
i	v_i^{xy}	KTS	295	295	480
	v_i^z	Ft/min	0	0	0
j	v_j^{xy}	KTS	295	295	480
	v_j^z	Ft/min	0	0	0
	$d_{i,j}^{VMD}$	Ft	0		
	$d_{i,j}^{HMD,lon}$	Ft	0		
	$d_{i,j}^{HMD,lat}$	Ft	0, 500,		
	θ_{ref}	Deg. (°)	90, 180		

Together, these parameters result in a maximum of 9 unique trajectories:

- 3 different altitudes times 2 positive course angles with zero HMD (6 unique trajectories)
- 3 different altitudes times 1 180° course angle with positive HMD (3 unique trajectories)

They are used for the verification of the pilot model elements and state estimation elements in this section and the following section only. The results should all contain stochastic outcomes, such as distributions of VMDs or timings. The two sections are focussed on checking the presence of this behaviour, rather than the behaviour itself. This is why the number of MC runs is brought down to 100, which is enough to check for presence of stochastic behaviour.

Next to verifying the inclusion of the different stochastic pilot model elements and state estimation elements in CAVEAT, it is also interesting to see which of these separate elements generate NMACs, as these are to be prevented at all times. Again, it is only of interest if NMACs are generated or not. Detailed results regarding the influence of specific settings that generate NMACs are discussed during sensitivity analysis in Chapter 10.

It is important to verify that each of the uncertainties is implemented correctly into the ABM in CAVEAT. This section focusses on the pilot model elements. For the verification, parameter set 1 is used. All parameter settings in this set, introduced in Section 4.2, are based on a fully deterministic setting of elements. In each of the parameter settings the element that is to be verified is modelled stochastically as follows:

- S1.1 shows the influence of a stochastic pilot response mode
- S1.2 shows the influence of a stochastic vertical rate error
- S1.3 shows the influence of a stochastic response delay
- S1.4 shows the influence of a stochastic vertical acceleration

The results of the simulations are then checked for stochastic behaviour.

When generating the stochastic parameter settings S1.1 it was seen that they were not saved correctly. The user could select a certain stochastic setting of the pilot response mode but in simulation, default stochastic settings would be taken into account. This was narrowed down to a disconnect between the HMI and the backend of CAVEAT. The settings were shown correctly to the user, but in the log files the settings were not altered correctly. This was communicated to everis and corrected in a future version of CAVEAT. After this correction, S1.1 settings resulted in stochastic behaviour as well as the presence of percentages of NMACs.

Results from simulations with stochastic parameter setting S1.2 included distributions stochastic behaviour.

The initial results that were seen with stochastic setting S1.3 were unexpected. In the S1.3 settings only the pilot response delay is modelled stochastically while the rest of the agents are modelled deterministically. It is expected for each stochastic setting to result in distributions of values when looking at the VMDs and timings, as stated in Chapter 5. When checking the VMD distributions for different encounter geometries and altitudes, it became apparent that all 10000 runs would result in an identical VMD per geometry and altitude. An example of this is added in Figure 103, where the VMD distributions for a type 1 encounter with a relative course angle of 45° at 7500 ft are added. On the left a typical VMD distribution from the S1.1 parameter setting are added and on the right the results from the S1.3 parameter settings that show no distribution are displayed.

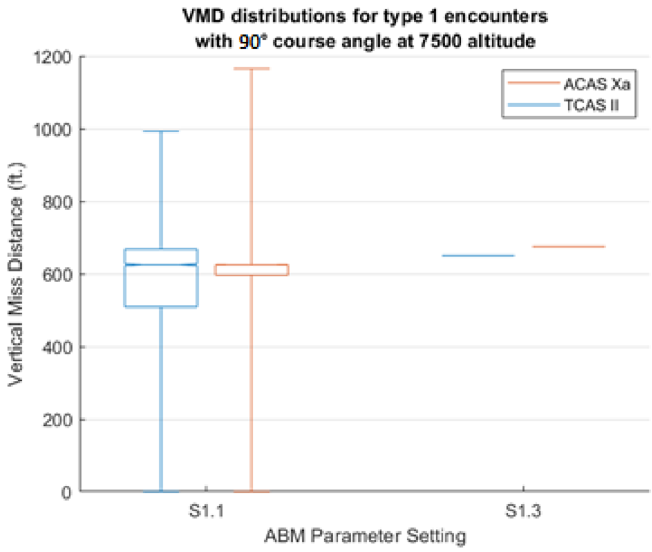

Figure 103. VMD distributions for type 1 encounters with 90° course angle at 7500 ft. altitude in S1.1 and S1.3 settings

The CAVEAT input was verified to be correct. This was confirmed by the configuration.xml file. This indicates that the ABM parameter settings did not contain mistakes. Most likely there was an error in the modelling or use of the parameter setting S1.3. Since there was no other way to see where this problem came from with only the CAVEAT frontend available, this problem was reported to Everis, who corrected it and issued a new CAVEAT version. In the results of simulations with S1.3 parameter settings in the new CAVEAT version, stochastic behaviour was seen.

The stochastic setting S1.4 resulted in distributions of timing of events and VMDs, which means all four stochastic pilot elements are thus verified to be taken into account in the newest CAVEAT version. Additionally, one of the pilot model elements result in positive NMAC percentages: the pilot response mode.

Appendix E.3 State Estimation Elements in CAVEAT

In this section the separate state estimation elements of the CAVEAT ABM are verified. This is done using the same type 1 encounter geometries presented in previous section in Table 127 are used.

To verify the state estimation errors, parameter set 2 is used. This set was introduced in Section 4.3 and contains seven parameter settings of which each element is modelled deterministically except for one stochastic element:

- S2.1 shows the influence of a GNSS-based position error model

- S2.2 shows the influence of a GNSS-based velocity error model
- S2.3 shows the influence of the pressure altitude error
- S2.4 shows the influence of the radio altitude error
- S2.5 shows the influence of the heading error
- S2.6 shows the influence of the transponder-based slant range
- S2.7 shows the influence of the transponder-based bearing

Stochastic settings S2.1 and S2.2 show stochastic behaviour only in encounters where the aircraft are equipped with ACAS Xa. This is to be expected, as the position estimation model is based on GNSS, which is not used by TCAS II [22].

Stochastic setting S2.3 results in stochastic behaviour for both TCAS II and ACAS Xa which verified the presence of the stochastic pressure altitude in CAVEAT. Although these settings did not result in positive NMAC percentages, switching from the ACAS MOPS pressure altitude model to the ICAO Annex 10 pressure altitude model did result in positive NMAC percentages.

Stochastic setting S2.4 of the radio altitude only results in stochastic behaviour in the outcomes when the altitude of the encounter is close to the upper limit of the minimum operational range as specified in [27]. Above this upper limit, which is set at 1850 ft, the radio altitude is not used by TCAS II and ACAS Xa and will thus also not influence the results. It is also verified that the RAs given when flying at this upper limit with stochastic setting S2.4 are often climb RAs, which is to be expected at such a low altitude.

The heading estimates, as included in stochastic setting S2.5, do not result in distributions of timing of events of VMDs. For TCAS II, this is correct, as TCAS II uses the heading estimates for the orientation of the TCAS II display [2]. The effect of the heading estimates on ACAS Xa solutions is stated to be non-critical in [27], so it is possible to not see any influence in the results.

Stochastic setting S2.6 resulted in distributions of timing of events and VMDs. However, it only noticeably did so when the standard deviations of the transponder-based range were increased to be four times the default values stated in Table 95. Increasing the standard deviations allows for a larger range of slant range errors and thus the slant range varies more. As these values are not realistic, the regular default values of the standard deviations of the transponder-based range are used for the rest of the research.

The influence of the transponder-based bearing did not result in visible distributions of VMDs and timings of RAs. Several exploratory simulation runs were done where standard deviation of the transponder-based bearing was larger than in stochastic setting S2.7, none of these showed a visible distribution if timing of events or VMDs. However, in the raw data extremely small deviations in bearing were seen. This indicates that the stochastic behaviour of the transponder-based bearing is present in CAVEAT but has little to no impact on the CAVEAT results.

In conclusion, it is verified that all state estimation elements are stochastically modelled in CAVEAT. Additionally, next to the pilot response mode, a second element that on itself results in NMACs using default settings is identified: the pressure altitude.

Appendix E.4 Simulations that Identified Issues 6 and 7

This section shows the analysis conducted to identify issues 6 and 7. Additionally, it presents possible solutions to these issues. The results in this section all come from simulations that were run 10000 times.

Probability of NMACs

After simulating type 2 encounters in combination with deterministic settings D1.1, it was seen in the statistics section of CAVEAT that some of the encounters with exactly 100 ft original VMD were not marked as encounters that contained an original NMAC. The encounters that were marked to contain original NMACs are indicated by a cross in Table 128.

Table 128. Type 2 encounter geometries with 100 ft VMD marked as original NMACs in setting D1.1

Altitude	Original NMAC encounters	
	TCAS II	ACAS Xa
7500 ft		
15000 ft	x	x
36000 ft		

An encounter is defined to contain an NMAC if '*two aircraft come within 100 ft vertically and 500 ft horizontally*' by EUROCAE in both the minimum operational standards of TCAS II and ACAS Xa [2] [3]. In the CAVEAT manual and its more detailed Phase 2 Models and Algorithm report, no definitions of an NMAC are found. It is deducted from other statistics that CAVEAT uses the EUROCAE definition.

At CPA in a type 2 encounter, the aircraft have zero feet separation horizontally and in a particular encounter they have 100 feet separation vertically. From the raw input and output data, it cannot be deducted why CAVEAT does not mark the encounter geometries with 100 ft VMD at 7500 and 36000 ft as NMACs, while it should according to the definition by EUROCAE. When running the simulations with type 2 encounters with slightly different VMDs such as 99 and 101 ft at all altitudes, CAVEAT is correct in marking the former as NMAC and the latter as no NMAC. Hence, it is likely that the incorrect marking of the encounters containing NMACs can be attributed to a numerical inaccuracy.

In the deterministic simulations, raw data can be checked to verify if the NMAC indication is correct or not. For stochastic simulations it would be too time consuming to check the results of each MC run. However, it is highly unlikely that the difference between the two aircraft is exactly 100 ft. A VMD just slightly smaller or larger than 100 ft is marked correctly by CAVEAT, so if there is an effect on the results, it will be extremely small and will not influence the conclusions. This possible effect is accepted for this thesis.

Probability of Modified Crossing Encounters

While analysing the data from the D1.1 settings in combination with the first encounter type, the probability of modified crossing encounters raised questions. In the CAVEAT manual, a modified crossing encounter is defined as '*an encounter where the sign of altitude difference at CPA between any two aircraft has the opposite sign as the altitude difference between those two aircraft at the time of the first TA (as measured by any aircraft) or at the beginning of the encounter (if there is no such first TA)*' [22].

This definition implies that for a modified crossing encounter to occur, there must be an altitude difference between the two aircraft at the time of the first TA (as measured by any aircraft) or at the beginning of the encounter if there is no first TA. Aircraft in encounters that belong to the first encounter type all fly level at the exact same altitude, according to their flight plan. Since the deterministic D1.1 parameter settings do not contain any uncertainties regarding the measurements of the altitude, there is no altitude difference between the aircraft in the type 1 encounter geometries before the intervention of TCAS II and ACAS Xa. According to the definition in the manual, there thus should not be any modified crossings in these encounter types in combination with the parameter settings.

However, simulation resulted in certain type 1 encounter geometries that are marked as modified crossing encounters. There was no trend observed in the altitude, relative course angle or HMD of the encounter geometries that were marked to be modified crossing, they seemed to be completely random. As an example, in Table 129, the encounter geometries of type 1 that were marked as modified crossing using the D1.1 parameter settings are included.

Table 129. Type 1 encounter geometries marked as modified crossing encounters in setting D1.1 at 36000 ft altitude

Course angle (deg.)	HMD (ft)	Modified Crossing Encounter	
		TCAS II	ACAS Xa
45	0	x	
90	0		x
135	0		
180	0	x	x
180	500	x	x
180	1000	x	x
180	2000	x	

Several attempts at clarifying were taken, starting with a visual inspection of the encounter trajectories after simulation. As an example, Figure 104 and Figure 105 display the side view of the trajectories of two encounters with 45 course angle, 0 HMD at 36000 ft for TCAS II and ACAS Xa, also included in the first row of Table 129. The trajectory of the first aircraft is displayed in blue and the trajectory of the second aircraft is displayed in red. The different TAs and RAs that are issued during the encounter are pointed to a specific part of the trajectory. PT stands for Proximate Traffic and indicates to the pilot as a heads up that there is traffic near. During this thesis, most focus is on the RAs, which are displayed in red.

When looking at the shape of the modified encounters, they are extremely similar. The aircraft start out both flying level at identical altitudes. When they reached the point in the trajectory with the yellow dot, they receive their first TA. Moments later, the first RAs are issued. In both encounters the first RA is either a ‘Climb’ or ‘Descend’ RA, after which both aircraft divert. After they receive the ‘Level Off’ RA, they level off and receive the COC RA. One of the main differences between the two modified encounters is the direction of the aircraft. In the encounter not marked as modified crossing, the first aircraft gets issued a ‘Descend’ RA and the second aircraft receives a ‘Climb’ RA. In the encounter marked as modified crossing, this is the other way around. Although the difference is very clear in this particular encounter, this trend is not followed for every TCAS II and ACAS Xa solution in every encounter and thus cannot be used to draw conclusions from.

Next, the raw data was inspected to see if CAVEAT influenced the altitudes of the aircraft before the RAs are issued. This data is automatically outputted by CAVEAT and contains the position of the aircraft per time step in the simulation. The altitudes of the aircraft before the issuing of the first RA were as desired and identical to the altitudes in the flight plan and did not show any relative altitudes between the aircraft.

Lastly, the way CAVEAT models the control of the flight in the vertical plane prior to an RA was inspected. In the ABM an Automatic Flight Control System (AFCS) is present, as was introduced in Figure 1. The AFCS controls the aircraft, such that the flight plan with the original trajectory is closely followed prior to responses to RAs. The responses to the RAs are then done by the pilot flying. In [27] it is described how the AFCS directly controls the airspeed vector such that the trajectory in the flight plan is reached according to Eq. (12.1).

$$\bar{\boldsymbol{v}}^{a}_{t,AFCS,i} = \boldsymbol{v}^{FP,g}_{t,AFCS,i} - \boldsymbol{w}_{t,AFCS,i} + \lambda^{pc}_{AFCS}\left(\boldsymbol{s}_{t,AFCS,i} - \boldsymbol{s}^{FP}_{t,AFCS,i}\right) \tag{12.1}$$

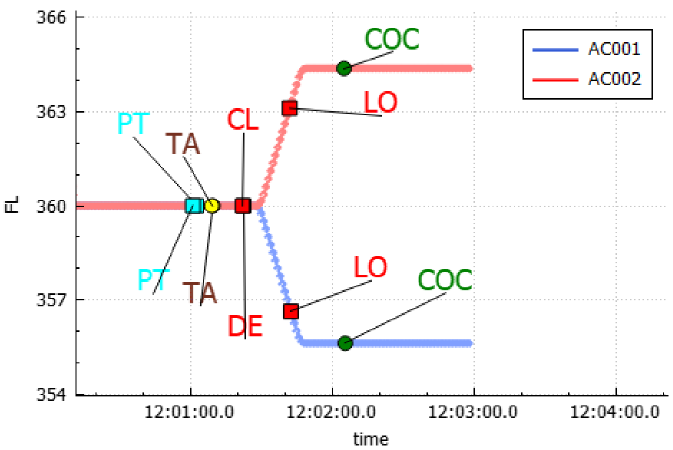

Figure 104. TCAS II modified encounter geometry with 45° course angle, 0 HMD at 36000 ft., marked modified crossing

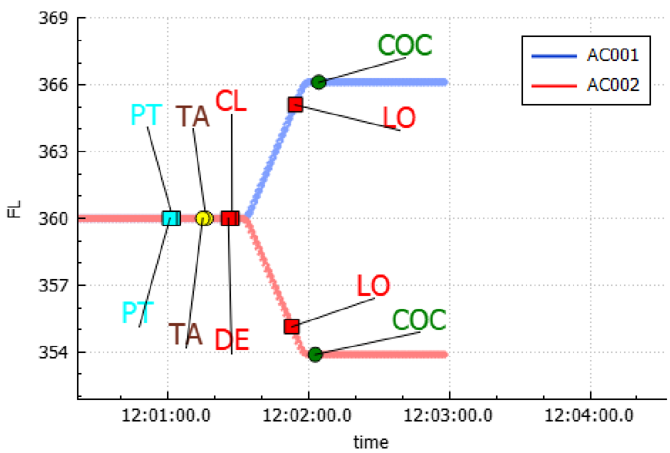

Figure 105. ACAS Xa modified encounter geometry with 45° course angle, 0 HMD at 36000 ft., not marked as modified crossing

This equation states that the airspeed of the aircraft $\bar{\boldsymbol{v}}^{a}_{t,AFCS,i}$ is equal to the ground speed of the aircraft in the flight plan $\boldsymbol{v}^{FP,g}_{t,AFCS,i}$ minus the vertical wind velocity $\boldsymbol{w}_{t,AFCS,i}$ plus a position feedback. Since wind is assumed to be non-existent in the environment, the ABM parameter setting for wind velocity is zero. This leaves the ground speed in the flight plan and the position feedback. The ground speed in the flight plan is calculated by numerical differentiation of the consecutive trajectory coordinates in the flight plan. During this process, small rounding errors may introduce a drift from the trajectory coordinates in the flight plan. These are then partially corrected by the position feedback. The position feedback consists of the situational awareness by the AFCS of positions and time stamps for the trajectory in the flight plan $\boldsymbol{s}_{t,AFCS,i}$ minus the position information of the aircraft in the ENU frame $\boldsymbol{s}^{FP}_{t,AFCS,i}$, scaled by the position feedback control parameter λ^{pc}_{AFCS} . The latter has a standard value of [1/s], a more suitable value is determined by simulation [27].

However, after adding the position feedback, the airspeed of the aircraft will not exactly be the ground speed in the flight plan, but rather an extremely close estimate. The trajectory that the AFCS follows is thus also not identical to the trajectory positions in the flight plan. Since the trajectories of the two aircraft in the flight plan differ due to the encounter geometry, the position feedback differs per aircraft. This results in two airspeeds that differ slightly, which in turn result in extremely small deviations from the flight plan altitude. When CAVEAT then compares the two altitudes to count the number of modified crossing encounters, the small deviation from the flight plan altitude can result in a modified crossing. However, these rounding errors and deviations from the flight plan only occur if there is a vertical velocity in the flight plan. If the aircraft fly with zero vertical velocity, no errors in the numerical differentiation occur and thus is the deviation zero. Since the found modified crossings all originated from type 1 encounters which do not include trajectories with positive vertical velocities, this approximation of the flight plan is not the origin of the incorrectly marked modified crossings in the level encounters.

To completely map the behaviour of the modified crossings and to see if the positive probability of modified crossings was only present in case the aircraft flew at exactly the same altitude, several additional simulation were run. These included the encounter geometries in Table 129, along with a small vertical distance between the two aircraft. From this analysis the encounters could the sorted into three groups.

1. Level encounters with aircraft that fly on exactly the same altitude.
   These encounters thus have a zero original VMD and should, according to the definition of a modified crossing encounter, not be marked as such. It is ruled out that these are marked as such due to anomalies in the raw data or due to numerical differentiation errors in the modelling of the vertical velocity of the aircraft. Why they are marked as modified crossings by CAVEAT remains unknown.
2. Level encounters with aircraft that have an original VMD lower than 13 ft.
   Encounters in this group were sometimes marked to be modified crossing. In the case that an encounter was marked a modified crossing, the upper aircraft received a ‘Descend’ RA while the lower aircraft received a ‘Climb’ RA. An overview of such an encounter is

included in Figure 106 and a detailed view of the crossing is displayed in Figure 107. So although this modified situation is counter intuitive, the modified crossing indicator in CAVEAT is correct. In this situation one would expect that the upper aircraft receives a 'Climb' RA and vice versa, such that an unnecessary crossing is avoided. However, both TCAS II and ACAS Xa show unexpected behaviour by proposing solutions that do not follow this reasoning. Both the TCAS II and ACAS Xa logic implemented in CAVEAT have to be investigated in detail to see if this behaviour is according to their logics in [3] and [2]. This is impossible to do without access to CAVEAT code and is thus outside of the scope of this thesis.

3. Level encounters with aircraft that have an original VMD equal to or larger than 13 ft. The upper aircraft received a 'Climb' RA and the lower aircraft received a 'Descend' RA, as is expected in this situation. Thus, encounters in this group were not marked crossing.

From these three points it can be concluded that the crossing encounter marker in CAVEAT is correct and that the cause of the unexpected crossings are the TCAS II and ACAS Xa logics. Since the exact origin of the behaviour of the first and second point remain unknown, it is decided that all type 1 encounters will be simulated with a standard original VMD of 14 ft. This way the unanticipated ACAS behaviour in encounters with zero or low original VMDs below 13 ft are avoided if the encounters are modelled with deterministic settings. In addition, an original VMD of 14 ft is relatively small compared to the size of the aircraft in real life. When aircraft are 14 ft apart an NMAC would still occur due to the size of their bodies and tails. This small original VMD will thus have no or a relatively small influence on the results while preventing the unexplained behaviour from influencing the outcomes.

So, for deterministic simulations, the original VMD of 14 ft eliminates the unexplained behaviour. This is, however, not the case for stochastic simulations, which are subjected to several uncertainties in the ABM elements. Here, the percentages of the modified crossing are relatively high when the original VMD is at 14 ft, around 45%. This percentage decreases with increasing original VMD, as displayed in Figure 108. In this graph the original VMD is varied from 10 to 150 ft in steps of 20 ft. The inclusion of the intrinsic uncertainties in the ABM parameter settings thus result in undesired behaviour. It is impossible to eliminate these high probabilities of modified crossing with the relatively low original VMD of 14 ft.

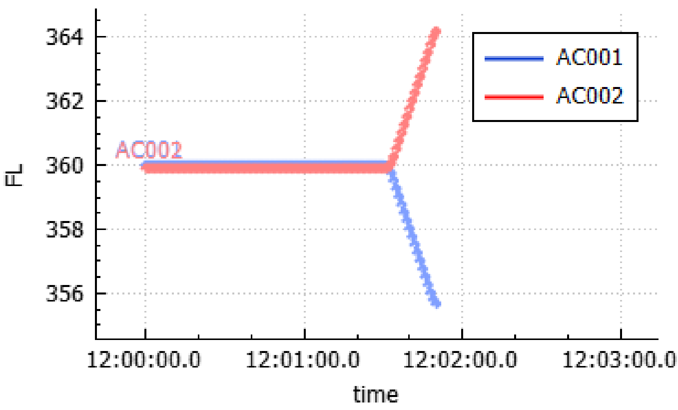

Figure 106. Vertical view of complete trajectory of modified crossing encounter with a VMD at CPA of 10 ft. and a course angle of 180° at 36000 ft.

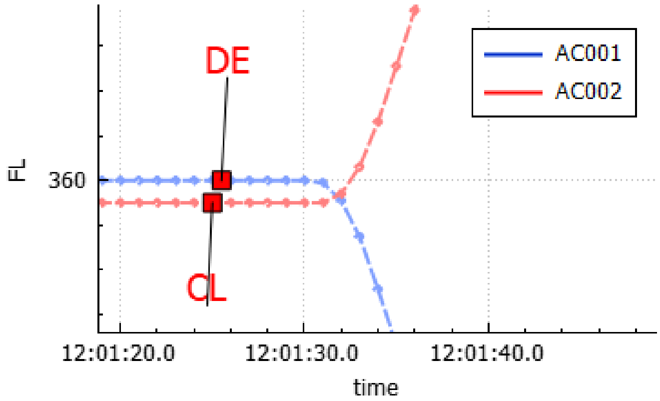

Figure 107. Vertical view of zoomed in section of trajectory of modified crossing encounter with a VMD at CPA of 10 ft. and a course angle of 180° at 36000 ft. Including RAs.

The single source of modified crossing probabilities is identified to be the stochastic modelling of the pressure altitude in the ABM parameter settings. From simulations with parameter setting S2.3, with all settings deterministic except for the stochastic pressure altitude, similar probabilities of modified crossing were found as with S3.1 settings. With parameter setting S4.1, where all settings are stochastic except for a deterministic pressure altitude, a zero crossing probability was found.

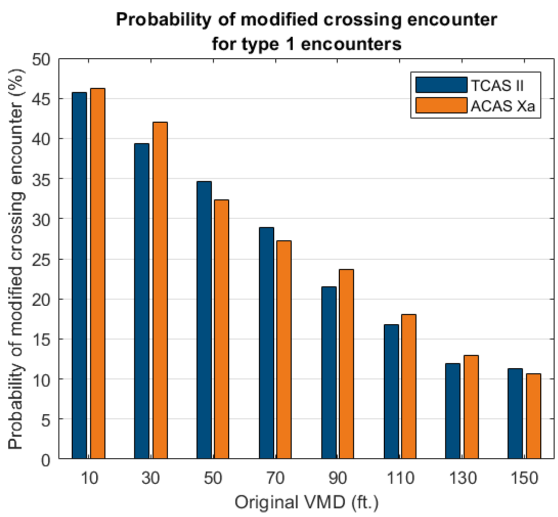

Figure 108. Probability of crossing encounters fc type 1 encounters with S3.1 settings. Encounter geometry with 180° course angle at 36000 ft. altitude.

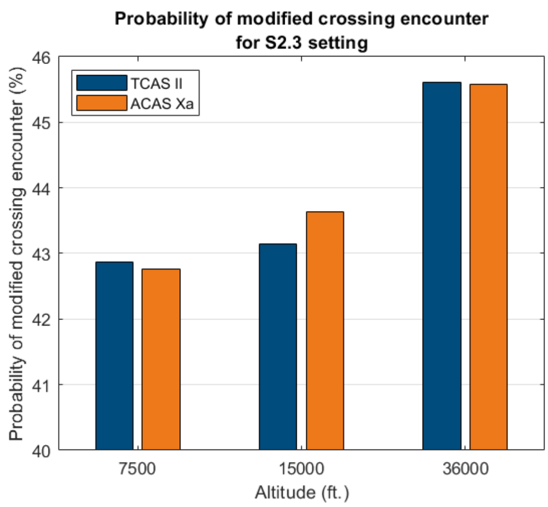

Figure 109. Probability of crossing encounters for type 1 encounter with 180° course angle an zero HMD, simulated with stochastic S2.3 settings.

Since the pressure altitude settings differ per altitude, the crossing probability also varies per altitude. In Table 86 in Appendix B.5 the stochastic ABM parameter settings of the pressure altitude according to the ACAS MOPS are included. It is seen that the standard deviation increases with altitude. For example, at 10000 ft altitude, the standard deviation is 52 ft while this is increased to 86 ft at 35000 ft altitude. This indicates that the higher the altitude, the larger the uncertainty in the pressure altitude is and thus, the larger the modified crossing probability will be. This is verified by looking at results that were generated with the stochastic parameter settings S2.3, as introduced in Section 4.3. These settings include all deterministic settings, except for the pressure altitude, which is modelled with the default stochastic parameters according to the ACAS MOPS. For demonstrational purposes, the results of only one encounter are displayed, however, other encounters show similar trends. The encounter that is simulated is the type 1 encounter with 180° course angle and zero HMD. In the graph, there is a difference of a few percent between the altitudes, which confirms the theory of the standard deviation.

Advisory Tree Aircraft 2

The advisory tree of aircraft 2 in CAVEAT version 3.4.0 is consistently incorrect. It indicates incorrect RAs, incorrect RA probabilities as well as incorrect sequences of RAs. This means the advisory tree of aircraft 2 should not be used for analysis. Since the complete set of raw data cannot be accessed, it is impossible for a CAVEAT user to generate such an advisory tree by filtering the data. Therefor only the advisory tree of aircraft 1 is used during this research.

Appendix E.5 Discussion of Simulation-Based Generation of ACAS Policy Plots

This appendix opens a discussion regarding simulation-based generation of TCAS II and ACAS Xa policy plots. In Chapter 6 the method of generating ACAS policy plots is explained, tested and demonstrated. Based on this process the the advantages and limitations of using CAVEAT to generate TCAS II and ACAS Xa policy plots are considered in this appendix.

Firstly, since all ACAS policy plots in literature are likely to be generated using the direct TCAS II and ACAS Xa logics, and access to these logics is not easy to obtain, CAVEAT offers a suitable alternative. CAVEAT is generally more accessible for use than the TCAS II and ACAS Xa logics.

Secondly, once the code and its automation are in place, it is relatively easy and quick to generate an ACAS policy plot using CAVEAT. All ACAS Xa policy plots included in this chapter took around 45 minutes to generate, from generating the CAVEAT encounter files to the finished product in a saved image. Since ACAS policy plots are mainly used to obtain an overview of the situation, using them to pinpoint areas of interest is quicker than analysing all separate encounters covering the state space by hand.

One of the downsides of using simulations to generate ACAS policy plots is the lack of possibility to completely define the grid in which the RAs are gathered. This results in the grid effect such as sawtooths and coves, as introduced earlier in this chapter. This, however, is not a major problem as an ACAS policy plot is meant to provide an overview of the situation, rather than indicate precisely a single RA at one single altitude and time before CPA.

Although there is no industry wide definition of what an ACAS policy plot is and how it should be generated, this chapter presents a method to generate an ACAS policy plot based on policy plots found in literature. Using CAVEAT simulations is found to be a viable way of generating an ACAS policy plot. In the future, the method presented in this chapter could be implemented in CAVEAT such that ACAS policy plots can automatically be generated and become an integrated part of the result presentation in the CAVEAT GUI. This also eliminates the method's dependency on the output format of the CAVEAT data and allows for some explanation and definitions about ACAS policy plots in the CAVEAT documentation.

In the future investigation could also be done to generate ACAS policy plots based on stochastic data. These could give a more complete view on the situation. Since stochastic data give a range of RAs that are issued along with the percentage with which they are issued, one data point contains more than one RA. One of the main challenges then lies in visualising these RAs in an organised manner.

Appendix E.6 Potential Improvements of CAVEAT in Evaluating Parameter Settings

During the work on this research potential improvement were identified regarding both the deterministic and the stochastic use of CAVEAT. The program can still function well without the improvements presented in this appendix. However, bettering on these points could make the program easier to use, increase the flexibility of its outputs and increase its functionalities.

In Table 130 an overview of the suggested improvements is included. Per improvement presented it is clearly indicated if it is applicable to deterministic use of CAVEAT, stochastic use of CAVEAT or both.

Table 130. Overview of Potential Improvements of CAVEAT

Number	Deterministic/ Stochastic	Regarding	Improvement description
1	Deterministic	ACAS Policy Plots	Include function in CAVEAT in which you can automatically generate and see ACAS policy plot of a specific encounter encounter
2	Deterministic & Stochastic	Metrics of RA Types	Include clear distinction between Corrective RA, Increase Rate RA, Reversal RA and Crossing RA in both the statistics module of CAVEAT and the CAVEAT manual.

3	Deterministic & Stochastic	Detailed Results of Section of Batch Simulation	Additional function in which metrics for selected parts of a simulated set of encounters can be calculated.
4	Deterministic & Stochastic	Use of Command Line	Increase the functionality of the command line to include generating and adjusting parameter setting files and gathering detailed results.
5	Deterministic & Stochastic	Decoding STF Files	Include a decoding tool that gives access to the STF files.
6	Stochastic	Timing of Events	Include the raw data of timing of each separate TA and RA that is given during an encounter.
7	Stochastic	CPU Usage	Increase CPU usage for more time efficient simulation.

1. ACAS Policy Plots

In Chapter 6 a viable way of generating ACAS Policy plots using CAVEAT was explained. Appendix E.5 discussed this method of generating and there it was mentioned that once all code and automation are in place, it is rather easy to obtain ACAS policy plots. A next step in user-friendliness would be to integrate the method of generating an ACAS policy plot into CAVEAT. The presentation of the output could be a separate section of the tool, comparable to the statistics module, where ACAS policy plots could automatically be visualised and downloaded if desired. The user would then benefit from access to a powerful tool to explore the state space around an aircraft in an encounter. An added advantage is that this also eliminates the method's dependency on the output format of the CAVEAT data and allows for some explanation and definitions about ACAS policy plots in the CAVEAT documentation.

2. Metrics of RA Types

In the CAVEAT statistics module the metrics for type of RA are calculated automatically. These metrics indicate the number of the types of RAs that are issued to each aircraft in the encounter in case of a deterministic encounter. In a stochastic encounter, the mean number of each type of RA issued per aircraft is given. The four types of RAs that are calculated by CAVEAT are the Corrective RA, the Increase Rate RA, the Reversal RA and the Crossing RA. Their occurrences for a deterministic encounter are displayed per aircraft as in Figure 110. From this figure it seems as if all four are separate types of RAs, together capturing the complete set of possible RAs that can be given.

Metrics for type of RA

		Aircraft 1 (AC001)	Aircraft 2 (AC002)
Corrective RA	All	2	3
	EE-Only	2	3
Increase Rate RA	All	1	1
	EE-Only	1	1
Reversal RA	All	0	0
	EE-Only	0	0
Crossing RA	All	0	0
	EE-Only	0	0

Figure 110. Screen capture with of part of CAVEAT statistics module. Example RA metrics from a deterministic TCAS II equipped encounter with 90 course angle at 2000 ft.

However, this is not the case. Every RA is either corrective or preventive as defined by ICAO [2] and stated in Section 5.2. The other three RA types displayed in the statistics module, the Increase Rate RA, the Reversal RA and the Crossing RA, all belong to the Corrective RA type, as they all require an action from the pilot. On the other hand, a Corrective RA is not necessarily an Increase Rate, Reversal of Crossing RA. Displaying all four RA types in one list insinuates that one RA can belong to only one of the four RA types in the list, while it is possible that the specific RA belongs two of the stated RA types.

This possible misunderstanding could be cleared up by changing the name 'Corrective RA' in the metrics table to 'Other RA' and to name the table 'Corrective RA Metrics'. Additionally, clear definitions of Corrective, Preventive, Increase Rate, Reversal and Crossing RAs must be added to the CAVEAT manual, which are currently partly or completely lacking.

During preliminary analysis of the RA type metrics of type 1 encounters, in some encounter geometries both aircraft received a different number of RAs. Since type 1 encounters are at the same altitude with only the course angle of the second aircraft that varies, they are symmetrical. One would thus expect that the number of types of RAs to each aircraft in the encounter is the same. The difference in RAs could originate from the difference in Mode S addresses between the aircraft. The aircraft with the lower Mode S address has priority over the aircraft with the higher Mode S address. If two RAs are issued at the same time, the aircraft with the higher Mode S could receive an additional reversal RA, such that the previous RA is overturned [8].

The different number of advisories mostly occurred in encounters at lower altitudes such as 2000 ft and 3500 ft as was seen during exploratory simulation. In Figure 111 the number of RAs that is received per aircraft per encounter is displayed, for various course angles and RA types. The left part of the figure displays the results for aircraft 1, the right part includes the numbers for aircraft 2. It can be seen that in the encounter with a course angle of 90 degrees, TCAS II issues one less Other RA to the first aircraft then it issues to the second aircraft, as was also seen in Figure 110.

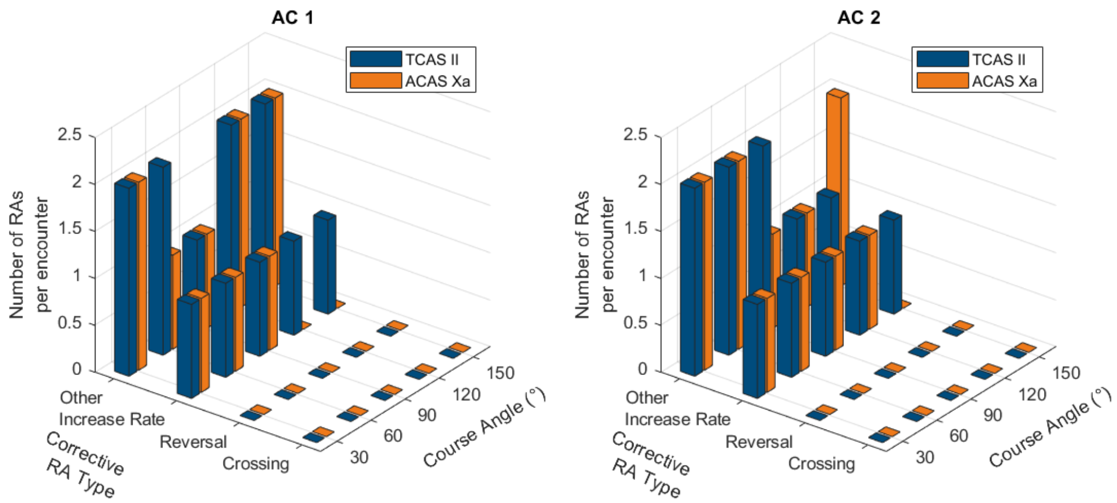

Figure 111. RA metrics for the deterministic type 1 encounter at 2000 ft with positive course angle and 0 HMD. Aircraft 1 on the left and aircraft 2 on the right.

When looking at the specific RAs that are issued, it becomes clear that there are two common RAs that are given to just one of the two aircraft.

- In encounters where one aircraft receives more Other RAs than the other aircraft and the number of increase rate RAs is the same for both aircraft, this is often due to a 'Level Off' RA. In such an encounter only one of the aircraft receives a 'Level Off' RA before the COC is issued. The other aircraft then does not receive a 'Level Off', but levels off after the COC regardless. It is unknown as to why only one 'Level Off' RA is issued.

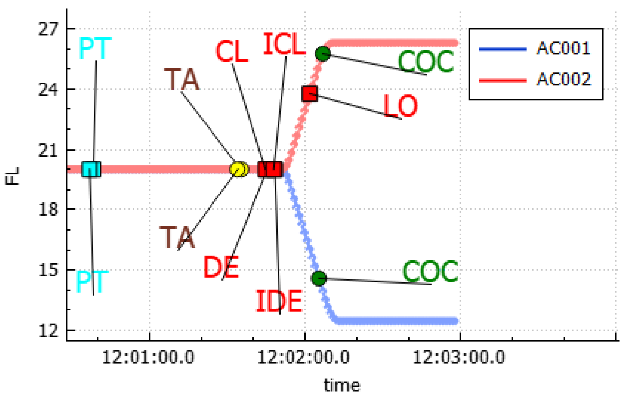

Figure 112. TCAS II encounter with 90° course angle at 2000 ft. altitude

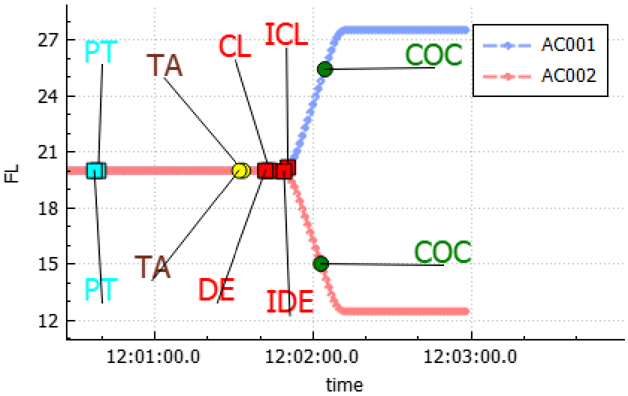

Figure 113. ACAS Xa encounter with 90° course angle at 2000 ft. altitude

- In encounters where one aircraft receives more Other and Increase Rate RAs than the other aircraft, this is often due to a 'Increase Climb' of 'Increase Descend' RA. This could be explained by arguing that in some encounters the required separation can be reached by having just one of the two aircraft increase their rate. A possibility is that by the time one of the aircraft received their Increase Rate RA, the other aircraft is already responding to the original RA such that the increase Rate RA is not needed anymore for the second aircraft.

In both of these cases, there seems to be no preference to issue the respective RAs to the climbing or descending aircraft.

3. Detailed Results of Section of Batch Simulation

During the analysis of the type 2 encounters in Section 8.2 it was mentioned that it is interesting to see the distinction in metrics between unresolved, resolved and induced risk in a larger set of encounters. It is possible to calculate the NMAC probability for these different types of encounters.

However, additional metrics such as probability of crossing encounter, VMD and RA types and timings are not possible to compute for these separate situations, except when they are simulated individually. An addition to CAVEAT would be a function in which all metrics of the four types of encounters, as explained in Table 32, could be analysed separately.

Expanding on this, it would ideally be such that it is possible for the user to select for which section of a simulated set of encounters he or she would like to see the metrics. Possible choices would then be to select:

- The complete set of encounters. This is the way CAVEAT currently works. When you input several encounters you receive the metrics for this complete set of encounters at once.
- A certain part of the set of the encounters. The selection could be based on the encounters that include unresolved, resolved or induced NMACs. This function is useful for both deterministically and stochastically simulated encounters.
- A certain number of runs in a simulation. This function is only possible for stochastically simulated encounters. The selection is then made based on one of the output metrics. For example, if there is clear multimodal behaviour in the VMD distribution of a simulated encounter set, it would be interesting to see exactly what type of RAs are given with which probability for the encounters that are located in one of the peaks of the VMD distribution. Or, when an encounter has a positive NMAC probability, the RAs that were issued in the runs that contained NMACs could be compared to the RAs that were issued in the runs that did not contain any NMACs. This way the cause of the NMAC could be uncovered in more detail than is currently possible.

4. Use of Command Line

Another improvement point is the lack of available automation in CAVEAT. Using the CAVEAT backend to automatically set up and start batches of simulations and gather results could be used to speed up the analysis process, as well as making it more reliable. There is a possibility to use the command line to operate CAVEAT, which could potentially be programmed if found to be useful. Limited information about operating CAVEAT from the command line was available in the manual, but it was found that no specific encounter geometries or parameter settings could be altered from the command line.

Without the use of the command line, the user can only set up simulations and gather results by hand through the CAVEAT HMI. While this process works perfectly fine when only a handful simulations are run, it is effort demanding for the number of simulations that is used during the research presented in this report. Additionally, several issues for improvement were found when using the HMI, as reported in Appendix E.4.

Also related to the automation of CAVEAT is that results need to be downloaded and saved by hand for each and every simulated encounter, which takes a considerable amount of manual labour. Automating this process would not only save time, but also ensure that all downloaded files are saved with the correct names in the correct folders 100% of the time. Using the command line for gathering results was found to be not possible.

In conclusion it is recommended that the CAVEAT functions that can be operated from the command line are expanded to at least include the possibility to generate and adjust parameter setting files and the possibility to gather detailed results. Additionally, these functions should be described in detail in the manual.

5. Decoding STF Files

Another way of automating the process of gathering the results could be by computing the results using one of the files that CAVEAT automatically outputs. In Section 2.3, the four types of automatic output are described. Of these four documents, only the STF file is suitable to compute results from, since this is the only file that includes parameters of all runs of a certain encounter in a simulation. Other automatic output documents contain data of a maximum of 100 runs in a simulation, which is too small for significant results, as explained in Appendix D.1. In order to allow a CAVEAT user to more easily collect and analyse results from STF files, it is recommended to include an STF file decoding program with CAVEAT.

6. Timing of Events

As described in Section 7.2 the timing distribution of each separate RA in a stochastic encounter can be obtained through CAVEAT. However, it cannot be obtained using any of the standard output files. In Figure 114 part of the timing of events .csv, as introduced in Section 2.3 is included. It can be seen that the RAs are grouped per order in the sequence. The RAs issued first are grouped together, the RAs issued second are grouped together, etc. For each RA and group of RAs

Type	Subtype	N. Realisations	Probability (%)	Mean [s]	Std. Dev [s]	Minimum [s]	Percentile 0.5% [s]	Percentile 2.5% [s]	Percentile 25% [s]	Median [s]	Percentile 75% [s]	Percentile 97.5% [s]	Percentile 99.5% [s]	Maximum [s]
Traffic Event 1		10000	100	74.3804	0.646171	71.5	72.5	73.5	74.5	74.5	74.5	75.5	76.5	78.5
	TA	10000	100	74.3804	0.646171	71.5	72.5	73.5	74.5	74.5	74.5	75.5	76.5	78.5
Resolution Advisory 1		10000	100	86.8985	1.06649	84.5	84.5	84.5	86.5	87.5	87.5	88.5	88.5	92.5
	CL	5017	50.17	86.8985	1.06649	84.5	84.5	84.5	86.5	87.5	87.5	88.5	88.5	92.5
	DE	4983	49.83	86.8985	1.06649	84.5	84.5	84.5	86.5	87.5	87.5	88.5	88.5	92.5
Resolution Advisory 2		6677	66.77	111.369	3.23542	98.5	104.5	104.5	109.5	111.5	113.5	117.5	119.5	121.5
	ICL	168	2.5161	111.369	3.23542	98.5	104.5	104.5	109.5	111.5	113.5	117.5	119.5	121.5
	IDE	150	2.24652	111.369	3.23542	98.5	104.5	104.5	109.5	111.5	113.5	117.5	119.5	121.5
	LO	6352	95.1325	111.369	3.23542	98.5	104.5	104.5	109.5	111.5	113.5	117.5	119.5	121.5
	RCL	2	0.029954	111.369	3.23542	98.5	104.5	104.5	109.5	111.5	113.5	117.5	119.5	121.5
	RDE	5	0.074884	111.369	3.23542	98.5	104.5	104.5	109.5	111.5	113.5	117.5	119.5	121.5

Figure 114. Part of output .csv 'timing of events', including RAs, their probability of occurrence and timings

first two columns include the number of realisations and their probability of occurrence. In the columns that follow computed statistics about the timing of the RA are stated, such as the mean, standard deviation, minimum, median and maximum. These are used by CAVEAT to construct the boxplots in the statistics module. However, for each RA in the an RA group these statistics are the same according to this .csv. This is incorrect, the timing statistics displayed in this excel file only belong to the complete RA group and not to the separate RAs in each group.

Additionally, these pre-computed statistics give a limited view on the timings. For example, raw data and outliers can thus not be obtained from this .csv file. A boxplot generally cannot indicate if there is multimodal behaviour in data, which makes it more difficult to see if the timings of the RAs are also multimodal or behave differently based on current output of CAVEAT data.

The timing data of each separate RA can be found in CAVEAT by selecting a certain RA in the statistics module and clicking on the 'show pdf' button on the bottom of the screen. A pdf as in Figure 49 is then displayed. The data for the timing distribution of this specific RA can then be downloaded manually. Note that this is not raw data, but the same statistics as included in the timing of events .csv. To increase user friendliness it is recommended that the pre-computed statistics that are currently in the timing of events .csv are replaced by raw data. This way the user has easier access to all data, can compute the pdf and obtain the full view on the timing situation. The minimum, maximum, mean, median and other statistics can then be easily calculated by the user while allowing for more detailed comparison and analysis of the data.

7. CPU Usage

In Appendix D.4 it was discussed that the simulations in CAVEAT have a considerable runtime. Runtime data from Table 125 indicates that especially stochastic simulations take a long time to complete. This runtime could be decreased by improving the limited CPU (Central Processing Unit) usage. CAVEAT does have multithreading implementation, however this does not seems to be functional all the time, which results in simulations often running only single core. During batch simulations, it was observed that the CPU usage was always around and often below the 10%. If large sets of data need to be simulated, this is not efficient, as it takes a long time while the CPU is not used to its full capacity. To speed up the simulation process for this thesis many CAVEAT HMIs were launched simultaneously till the CPU was at a user percentage of around 90-95%. Each of these CAVEAT HMIs then simulated part of the stochastic simulation batches. The disadvantage of this approach is that the simulation batches had to be split into smaller batches. If the CPU usage could be increased, large batches of stochastic simulations can be done much faster without having to split all the large batches into smaller ones.

Appendix F Verification of Self-Developed Code

The verification that was performed on codes that were written specifically for this research is presented in this appendix. Three types of code are included: trajectory generation code, ACAS policy plot code and analysis code.

While writing each of these codes, syntax errors were immediately solved. Static analysis, such as checking program structure, is partly build in in Matlab. Unit testing was performed by testing each function in the code separately. Intermediate results were verified with by-hand calculations before continuing the check with the next step of code. Additionally, the integration of the different modules of the code was verified.

Below the function requirements for each of the three codes are included.

Trajectory Generation Code

The trajectory code was presented in Section 3.7. Several functional requirements for the trajectory generation code can be identified and tested for compliance.

- *The trajectory code shall have a flexible input format.*
  The format of the code is completely flexible with respect to its input, all input parameters can be chosen freely by the user. A simple .txt file is used to store the parameters that are used to define the encounter geometries. Next to that, several additional parameters are used as input in the code, such as the duration of the encounter before and after CPA. These can only be altered in the trajectory generation code itself.

- *The trajectory code shall be able to compute the full correct trajectories for two aircraft that fly straight, without acceleration and do not experience any wind defined by the parameters presented in Table* 2.
  There were several example trajectory files provided in the CAVEAT environment that were developed by Everis. One of these trajectory files was simulated and viewed in CAVEAT, after which the ten input parameters were gathered from this visualisation and calculated based on the data in the files. Then, these ten parameters were used as input to the Matlab code. The result of this code was identical to that of the example trajectory file, indicating that the Matlab code produced the .ftd files in a correct manner.

  Additionally a set .ftd files of random encounter geometries, all part of the types identified in Section 3.8, was generated and simulated in CAVEAT. Using the visualisation function, it was checked by hand if all the encounter geometries in the set were as desired.

- *The trajectory code shall have an output format that adheres to the input format required by CAVEAT.*
  To check if the output format of the trajectory code adheres to the input format of CAVEAT it was simply loaded in the CAVEAT environment. If the .ftd file does not adhere to the correct input format, CAVEAT gives an error and the .ftd file cannot be loaded. This

guarantees the correct input format. Additionally, CAVEAT includes a validation tool, which checks the encounter in the .ftd file for corruption.

ACAS Policy Plot Code

The policy plot code was presented in Section 6.2. The requirements for the proper functioning of the policy plot code are the following.

- *The policy plot code shall automatically filter useful information from provided data.*
  The useful information per datapoint (time to CPA, relative altitude and RA) is filtered from the summary.csv file. This file is automatically output by CAVEAT and needs not to be downloaded by hand.

- *The policy plot code shall output correct and relevant graphs that resemble policy plots found in literature.*
  The output of CAVEAT was directly compared with the output graphs of the policy plot code, for several policy plots with varying encounter geometries. The type of plot was only decided on after checking multiple potentially suitable plot displaying the same set of data.

Analysis Code

The code used to compute and analyse the results consists of numerous small parts that can be used separately. Each part can generate a specific plot or visualisation. Since they all have similar functional requirements, they are verified and validated in the same manner. The functional requirements for are the following.

- *The analysis code shall automatically import all relevant data using a flexible input format.*
  All parts of analysis code start with locating the required file for the graph. These files consist of different types of data, this can be a percentage, an amount, text or timestamp for example. When an output file is located its contents are saved into a Matlab table. The Matlab table is able to store variables with different data types and sizes into one array, which allows for a flexible input format.

- *The analysis code shall correctly compute all relevant statistics about indicators.*
  For each parts of the analysis code at least one by-hand calculation is compared to the results from the code to ensure the results are correct. Additionally, Excel was used to compute and compare the results as well.

- *The analysis code shall correctly display relevant statistics in clear manner.*
  Using one set of data, graphs are generated by the analysis code and Excel, such that the visualisation can be verified. Additionally, it is checked if the graphs unambiguously display the results. The most suitable of graph is chosen by comparing different types of graphs that Matlab offers.