INDUSTRIAL RESEARCH

SESAR PJ.13-Solution 111

Description of

Collision Avoidance Fast-time Evaluator (CAFE)

Revised Encounter Model for Europe (CREME)

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ENABLE RPAS (REMOTELY PILOTED AIRCRAFT SYSTEMS) INSERTION IN CONTROLLED AIRSPACE

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Executive summary

PJ.13-Solution 111 addresses Detect And Avoid (DAA) Systems for Remotely Piloted Aircraft Systems (RPAS). The operational scope of PJ.13-Solution 111 is focused on Instrument Flight Rules (IFR) operations within the airspace classes A-C where separation of RPAS is managed by Air Traffic Control (ATC) in the same or similar way as for manned aviation.

Encounter modelling is an established technique for generating a large set of representative test encounters for validating airborne collision avoidance systems (ACAS). This document describes the Collision Avoidance Fast-time Evaluator (CAFE) Revised Encounter Model for Europe (CREME). CREME encounters are intended for use by PJ13 partners in DAA validation exercises. The model is based on the US Lincoln Laboratory Correlated Encounter Model (LLCEM) with adaptations for Europe. The main differences are:

- Over 12 million flight hours of European radar data collected in the period 2015-18 from six Air Navigation Service Providers controlling nine countries (Belgium, Czech Republic, France, Germany, Luxembourg, Netherlands, Poland, Switzerland, UK).
- The effect of Resolution Advisories (RA) was removed for encounters where an RA downlink message was recorded.
- Adjustments to model network order, bin sizes and nodes (addition of aircraft class, controlled status, proximity, vertical separation from ATC level).
- An aircraft model instead of airspace model with aircraft performance classes including RPAS capable of lateral manoeuvres such as loitering patterns.
- A simple wind model with wind speed and direction changing with altitude is included in the CAFE tools but the functionality has not yet been exercised in CREME at time of publication.

The CAFE encounter modelling tools were developed by QinetiQ (UK), Egis Avia (France) and Polytechnic University of Catalonia (Spain) under contract in the period 2016-21. For some aspects of

model testing the ACAS simulator (CAVEAT) was developed under contract by NLR (Netherlands) and Everis (Spain) in the period 2018-21.

Eurocontrol staff used the above data and tools to produce three CREME variants where at least one of the aircraft in each encounter is under Air Traffic Control:

- *CREME safety* for safety studies of ACAS II in current traffic. Horizontal miss distances (HMD) are less than Near Mid Air Collision (NMAC) (500ft) and the encounter duration is from about a minute before the closest point of approach (CPA) to about 10s after.
- *CREME ATM* to support operational acceptance of ACAS II in current traffic. HMDs are less than 5NM and the encounter duration is from about a minute before CPA to about 10s after.
- *CREME RPAS safety* is intended to support evaluation of ACAS II and DAA with lateral manoeuvres in future traffic (after 2025). HMDs are less than 3NM and encounter duration is from about 4 minutes before CPA to about 30s after.

Encounters from the three model variants have been analysed by Eurocontrol using statistical and graphical tools and an ACAS simulator to check:

- Encounters are operationally realistic;
- Distributions are reasonably representative of real encounters;
- Safety metrics are similar to a previous European encounter model (AVAL 2008);
- Future traffic scenarios with new RPAS models perform as expected.

Sample encounter sets have been analysed by the following organisations using independent ACAS simulators:

- Egis Avia, Toulouse, France (*CREME ATM*, *CREME safety*).
- Lincoln Laboratory, Massachusetts, USA (*CREME safety*).
- Saab, Sweden (*CREME RPAS safety*).
- University of Catalonia, Barcelona, Spain (*CREME RPAS safety*).

With regard to validating the integration of ACAS X and DAA in Europe, the main limitations of CREME have been identified as:

- Pairwise encounters only i.e. no multi-aircraft. This may be a reasonable assumption for much of collision avoidance analysis but may not be realistic for DAA separation assurance.
- Lack of real RPAS input encounters. The ways RPAS trigger collision avoidance are assumed to be similar to piloted aircraft for the time being until real data is available.
- Lack of synchronisation between aircraft possibly leading to fewer level-off RAs than in reality.
- Lack of uncorrelated encounters where neither aircraft is under Air Traffic Control, as in airspace class G.
- Limited number of RPAS types e.g. no rotorcraft.
- Manoeuvre frequency in DAA region is based on collision avoidance frequencies.

CREME is currently being extended to enable:

- Multi-aircraft encounters;

- A richer variety of RPAS classes.

Future work may include encounters where neither aircraft is under Air Traffic Control for addressing uncontrolled airspace classes.

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1 Introduction

1.1 Purpose

This document describes the Collision Avoidance Fast-time Evaluator (CAFE) Revised Encounter Model for Europe (CREME). It was developed by Eurocontrol in the period 2015-2021 using CAFE tools[1] [3] [4] [5] [6] [7] part funded by the Single European Sky Air Traffic Management Research (SESAR) programme.

1.2 Scope of document

CREME is based on the US Lincoln Laboratory Correlated Encounter Model (LLCEM) [1] with adaptations for Europe and the integration of Remotely Piloted Aircraft Systems (RPAS). Three CREME variants for controlled airspace are described:

- *CREME safety* for safety studies of ACAS II with horizontal miss distances of less than NMAC and encounter duration of about a minute.
- *CREME ATM* to support operational acceptance of ACAS II with horizontal miss distances of less than 5NM and encounter duration of about a minute.
- *CREME RPAS safety* intended to support evaluation of ACAS II and DAA with horizontal miss distances of less than 3NM and encounter duration of about 4 minutes.

1.3 The need for encounter modelling

When designing and evaluating airborne collision avoidance systems (ACAS), it is necessary to test statistically their performance with close encounters that could result in a collision or could trigger an alert by the system.

Ideally, all these encounters would come from recordings of real aircraft trajectories. This would enable simulations on how ACAS will behave in typical encounters.

However, there are not enough mid-air collisions or near mid-air collisions to allow statistically significant testing of ACAS safety performance (i.e. how well it stops collisions happening without creating new collisions) using just real data of how aircraft behave in very close encounters.

[1] CAFE tools were developed by QinetiQ in UK assisted by Egis Avia in France and UPC in Barcelona.

To detect fractional percentage changes in risk ratio[2], an estimated 1000 mid-air collisions are required. Using fast-time simulations of full aircraft trajectories, running at approximately ten times real-time, this would take in the order of a thousand years.

Instead, we must build models of how aircraft are likely to behave when they come very close. Appendix A explains how encounter models allow the simulation of centuries of very close encounters in just a few hours.

Many safety encounter models have been built in the past [8]. The previous European model, developed in the project ACAS on Very Light Jets and Light Jets – Assessment of safety Level AVAL [9] used a design from 1999, updated with RVSM procedures and data from 2006. Since 2006, Lincoln Laboratories have created a newer encounter model design based on a (Bayesian) model of parameters describing the closest point of approach (CPA) and a (Markov) model describing aircraft state transitions changes before and after CPA [1] updated in 2018 [2].

It was decided to build a new European model improving upon the LLCEM [1], populated using encounters collected from recent European radar data. The CAFE project new European model and its variants are referred to as CAFE Revised Encounter Model for Europe (CREME) followed by the variant qualifier.

1.4 Structure of document

Chapter 2 describes how CREME was built. Chapter 3 describes how CREME generates encounters. Chapter 4 describes how CREME was tested by comparing distributions and metrics of generated encounters with real encounters and those of the previous European encounter model AVAL.

1.5 List of acronyms

ACAS	Airborne Collision Avoidance System
ASTERIX	All-purpose structured Eurocontrol surveillance information exchange
ATC	Air Traffic Control
ATM	Air Traffic Management
AVAL	ACAS on Very Light Jets and Light Jets – Assessment of safety Level
BADA	Base of Aircraft Data
CAFE	Collision Avoidance Fast-time Evaluator

[2] Risk ratio is a relative measure of the safety benefit resulting from the deployment of ACAS. It is not a measure of the absolute safety level.

CAVEAT	Collision Avoidance Validation and Evaluation Tool
CPA	Closest Point of Approach
CREME	CAFE Revised Encounter Model for Europe
DAA	Detect And Avoid
ERICA	Enable RPAS Insertion in Controlled Airspace
FTD	Flight Track Data
HMD	Horizontal Miss Distance
IAS	Indicated Air Speed
ISA	International Standard Atmosphere
LLCEM	Lincoln Laboratory Correlated Encounter Model
MSL	Mean Sea Level
MTOM	Maximum Take-Off Mass
NM	Nautical Mile
NMAC	Near Mid Air Collision
RA	Resolution Advisory
RPAS	Remotely Piloted Aircraft System
RVSM	Reduced Vertical Separation Minima
SESAR	Single European Sky ATM Research programme
TA	Traffic Advisory
TAS	True Air Speed
TCA	Time of Closest Approach
TCAS	Traffic alert and Collision Avoidance System
VLJ	Very Light Jet
VMD	Vertical Miss Distance

2 Building CREME

2.1 Process overview

CREME was built in several stages:

1. Radar track data was collected.
2. The radar data was processed with a coarse filter to produce an initial list of two-aircraft encounters.
3. The initial list of encounters was fine filtered and "cleaned" manually to remove:
    a. Split tracks;
    b. Military – military encounters that had not been detected by the filter;
    c. Encounters with miss distances outside the size of the model being populated;
    d. Effects of aircraft responding to TCAS resolution advisory (RAs);
    e. Encounters unlikely to trigger collision avoidance.
4. The encounter model structure was based on the LLCEM model and tuned for European data.
5. Radar data in encounters was smoothed so that parameter values could be estimated second by second. Parameter values at Time of Closest Approach (TCA) were used to populate the CPA model, and changes to parameter values were used to populate the transition model.

The following diagram Figure 1 gives an overview of the process.

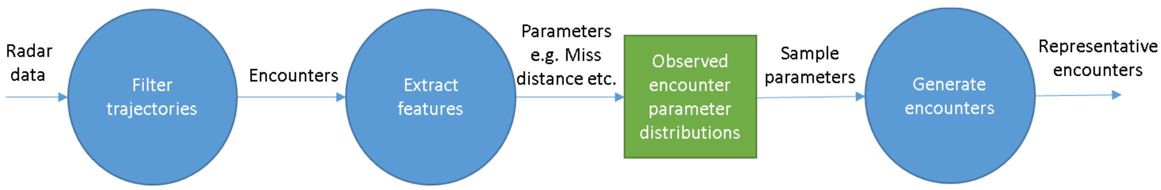

Figure 1 Data flow diagram of encounter modelling process

2.2 Encounter selection

2.2.1 Radar data collection

Over twelve million hours of radar data were collected from six air navigation service providers covering nine countries:

- CANI (Czech Republic)
- DSNA (France)
- Maastricht Upper Air Centre (MUAC) (Belgium, Germany, Luxembourg, Netherlands)
- NATS (UK)
- PANSA (Poland)
- Skyguide (Switzerland)

The data was either collected in, or converted to, ASTERIX category 62 format (All-purpose structured Eurocontrol surveillance information exchange). Non-disclosure agreements protect the original data.

2.2.2 Filters and smoothing

Encounters are pairs of aircraft trajectories. Encounters satisfying given criteria, e.g. distance at CPA , form an encounter set. Lincoln Laboratory defines encounters to be correlated where both aircraft involved are cooperative (i.e., have a transponder) and at least one is in contact with Air Traffic Control. It is then likely that at least one aircraft will receive some notification about the traffic conflict and begin to take action before a collision avoidance system gets involved. The trajectory of each aircraft may involve manoeuvres that are correlated to some degree due to this prior intervention.

Several iterations of specific filters, manual cleaning, and smoothing were performed. Encounters that were removed included:

- Split tracks;
- Uncorrelated encounters e.g. neither aircraft under ATC control;
- Small HMD with accepted separation e.g. military – military[3], helicopter parallel to runway;
- Encounters with miss distances outside the size of the model being populated;
- Encounters unlikely to trigger collision avoidance.

Where encounters had RA downlink messages, pilot responses were removed by an algorithm [3]. A TCAS like filter (TA+) removed encounters that were unlikely to trigger a TCAS TA. A cubic spline algorithm was used to smooth trajectories and to provide interpolation between radar plots at intervals of one second.

The TA+ filter, horizontal miss distance (HMD) filter at closest point of approach (CPA) and encounter duration were dependent on the CREME variant (see Table 1).

Table 1 Filters applied on input to each CREME model variant

Filter type	Safety model REV(9)	ATM model (REV2)	RPAS safety model (REV0)
Horizontal Miss Distance (NM)	<0.5	<5	<3
Time before CPA (s)	60	60	60
Time after CPA (s)	10	30	10
TA+ filter	Yes	No	Yes

[3] The recorded encounters involved few, if any, unmanned aircraft, therefore special care must be taken when using this model for RPAS studies.

Number of encounters contributing to model	23,401	381,530	149,526

2.3 Feature extraction

2.3.1 Introduction to Bayesian network

A Bayesian network is a probabilistic graphical model (a type of statistical model) that represents a set of random variables and their conditional dependencies via a directed acyclic graph.

- 'graph': means that the network can be represented by a diagram ('graph') in which the nodes represent the variables and arrows represent the connections between the variables.
- 'directed': means that each connection in the network represents a dependency in one direction only – if the probability of variable B depends on variable A (in the network) then the probability of variable A is determined independently of variable B.
- 'acyclic': means that there are no loops in the network – when the direction of the connections is respected it is not possible to start at any given variable and traverse the network arriving back at the same variable.

Bayesian and Markov networks are used to represent the relationship between variables for pairs of aircraft in encounters.

- A CPA model represents the velocities and relative positions of the two aircraft at the instant of the closest point of approach;
- A Transition model represents the evolution in time of the aircraft accelerations and velocities, both before and after the time of CPA.

2.3.2 CPA model

2.3.2.1 Overview

The CREME CPA model is very similar to that described in LLCEM (CPA is defined at minimum HMD). A number of significant adaptations have been made in order to make CREME more suited to the generation of realistic operational encounters, as well as easily adaptable by novice users. The CPA model for CREME is shown in Figure 2.

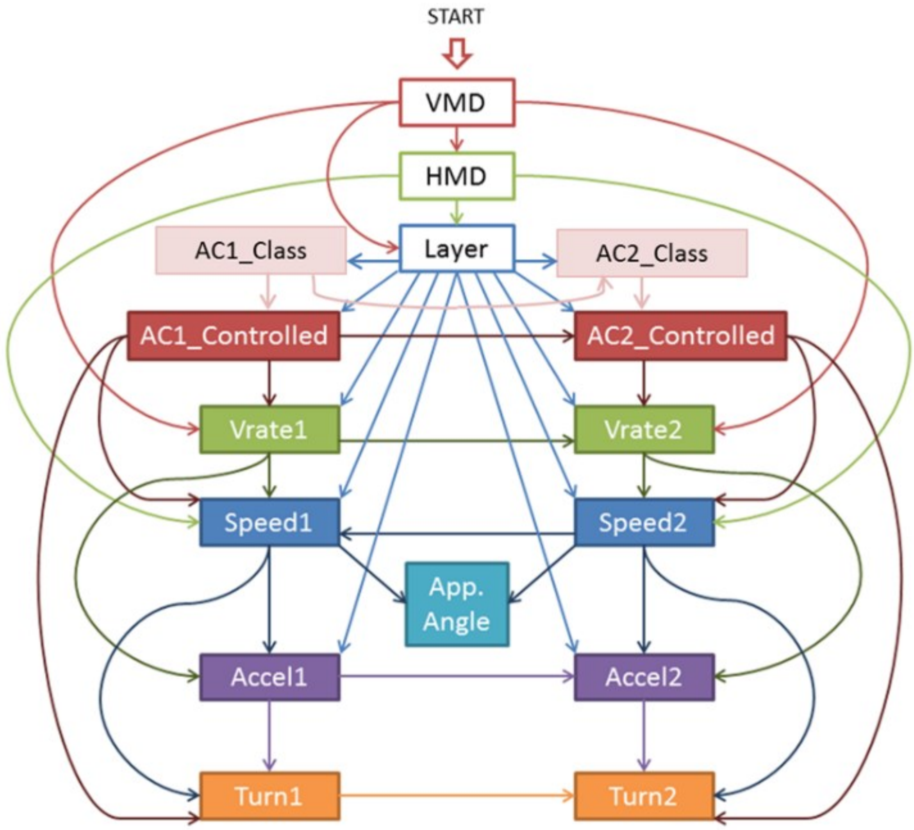

Figure 2 CREME CPA model (Bayesian network)

Each node of the network was represented as a set of discrete bins corresponding to a particular range of values as shown for example in Table 2 for *CREME ATM*. The numbers in the bins correspond to the number of encounters with those characteristics e.g. there are 15,765 encounters with HMD between 2 and 3 NM and VMD between 1,450 feet and 1,959 feet.

Table 2 *CREME ATM* CPA model table parameters and bins

HMD is in nautical miles		VMD			
Lower Bound	Upper Bound	1050 to 1450 ft	1450 to 1950 ft	1950 to 2050 ft	2050 to 2950 ft
0	0.5	6767	6468	1693	5822
0.5	0.75	3305	3263	852	2944
0.75	1	3765	3539	872	2905
1	2	16302	14913	3578	11510
2	3	16645	15765	3121	10047
3	5	26070	20816	4212	12886
5	10	0	0	0	0

The CREME CPA model copied the parameters and dependencies used by LLCEM. Changes were then made as follows:

- The inclusion of a wider range of parameter values;
- Adjustment of boundaries to better reflect operational sensitivities;
- The use of approach angle rather than bearing as a variable at CPA;
- Adjustment of the order of dependencies within the model;
- Inclusion of information about whether aircraft were controlled or uncontrolled;
- Inclusion of aircraft classes.

2.3.2.2 Parameter ranges and boundaries

The bin boundaries used in CREME do not correspond to those in LLCEM. In some cases, the range of the parameter was larger for CREME than for LLCEM. In other cases, some very narrow bins were chosen to clearly identify common situations such as level aircraft or aircraft on parallel tracks.

The following table (Table 3) shows the differences between the altitude layers used for LLCEM and those used by CREME.

Table 3 Altitude layers for LLCEM and CREME

Layer number	LLCEM		CREME	
	Min	Max	Min	Max
1	1000ft	3000ft	1000ft	3500ft
2	3000ft	10000ft	3500ft	FL065
3	10000ft	FL180	FL065	FL185
4	FL180	FL290	FL185	FL285
5	FL290	FL660	FL285	FL415
6	-	-	FL415	FL660

- Layer 1: Covers airspace (typically) below controlled airspace - typically non-controlled or mix of both.
- Layer2: Covers airspace which is probably below the Transition Altitude currently - Levelling off at non 1000ft levels expected - also below most holding stacks.
- Layer 3: Covers airspace which would be below a harmonised Transition Altitude at 18,000ft - future proof of the model.
- Layer 4: Airspace up to RVSM.
- Layer 5: RVSM airspace.
- Layer 6: Above RVSM airspace. Although a uniform altitude distribution from FL415 to FL660 is not representative of observed encounters, this will not affect safety evaluations with generated encounters.

2.3.2.3 Approach angle instead of bearing

'Bearing' (the bearing of one aircraft relative to the heading of the other) is no longer sampled from the network. Instead, 'Approach Angle' is sampled, and this (together with other sampled parameters) constrains the Bearing to two possible values which are 180° apart.

2.3.2.4 Change in order of dependencies

The CPA model is now topologically organised to start with the VMD parameter, followed by HMD. Note that the correlations between the parameters remain exactly the same (Airspace Class excepted) as the LLCEM model, and therefore the model retains mathematical equivalence to the LLCEM model (Airspace Class excepted).

VMD and HMD were chosen as places to start for two practical reasons:

- VMD and HMD will be relatively simple to express in two tables (one for VMD, one for HMD) in our model – making it easier for the non-expert user of CREME to override the VMD and HMD distributions (i.e. impose importance sampling to the most frequently adapted parameters).

- When performing importance sampling, it is easier to construct trajectories which reflect the VMD and HMD constraints without needing to resample parameters such as the aircraft vertical rates.

This approach was discussed with some Lincoln Laboratory personnel, and no problems were identified.

2.3.2.5 Controlled/uncontrolled parameter

LLCEM has airspace class as a parameter. The use within CREME of whether aircraft are controlled or uncontrolled has some similarities to this. Controlled status was qualitatively considered a good discriminator because this directly changes how separation assurance is performed.

2.3.2.6 Aircraft classes

Previous European encounter models have used aircraft classes to limit aircraft performance and determine aircraft equipage. CREME has an option to use aircraft classes. LLCEM does not use aircraft classes.

Each class groups together aircraft types with similar performance characteristics based on factors such as size and engine-type, e.g. turbojets with MTOM > 100 000 kg. Up to 20 aircraft classes can be defined by the user of CREME. Eight classes were set to those used in the PASS model [10]. Additional classes were set for Very Light Jets (VLJ), Mode C only aircraft, unknown Mode S equipped aircraft and a final “unknown” class was defined as a catch-all for any aircraft where no other aircraft class could be determined.

Each aircraft class, except for “unknown”, defines the following parameters:

- Maximum altitude (feet).
- Maximum vertical acceleration (*g*).
- Maximum turn rate (degrees/second).
- Maximum bank angle (degrees).

Also, the following parameters, which are a function of the altitude layer, are defined:

- Minimum speed (knots).
- Maximum speed (knots).
- Maximum descent rate (feet/min).
- Maximum climb rate (feet/min).

When populating the encounter model, a class is assigned to each aircraft in each encounter and this information is used to count how often each class of aircraft has an encounter against each other class.

The frequency table of observed encounters between aircraft classes is used to assign an aircraft class to each aircraft. These classes are then used to constrain the ranges of parameters sampled. Probabilities within the new ranges are proportionally adjusted.

When information about aircraft types is poor, many aircraft will be put into the unknown class, thereby making these aircraft unconstrained. Without looking up aircraft type from 24-bit addresses, most aircraft were in the unknown class. Therefore, a decision was made to implement aircraft class distributions in the model using a database relating 24-bit addresses to aircraft type.

2.3.3 Transition model

To determine the evolution of the encounter in time, CREME uses a Transition model (Markov network) very similar to that summarised in LLCEM, where the next future state is determined by the current state.

Significant adaptations have been made to this model in order to make CREME more suited to the generation of realistic operational encounters:

- The inclusion of a dependency on the distance from a standard ATC level, *dZ* allows the tendency of aircraft to reduce their vertical rate as they level-off at a standard ATC level to be reproduced.
- There are separate Turn Rate and Vertical Rate networks (both backward and forward) for aircraft based on their controlled status (*i.e.* 'non-controlled' or 'controlled', which is fixed for the whole encounter).
- There are separate Vertical Rate networks (both backward & forward, and 'non-controlled' & 'controlled', and based on 'proximity' category) for aircraft based on their 'attitude'. Initially (*i.e.* at CPA) this can be 'climb', 'level' or 'descend': if it is initially climb or descend then this is fixed for the whole encounter; if it is initially level then the attitude can change (and then remain fixed for the rest of the encounter construction process) based on the vertical profile produced by sampling the level Vertical rate networks). A detailed explanation of the process is given in [6] [7].

The Transition model for CREME is shown in Figure 3.

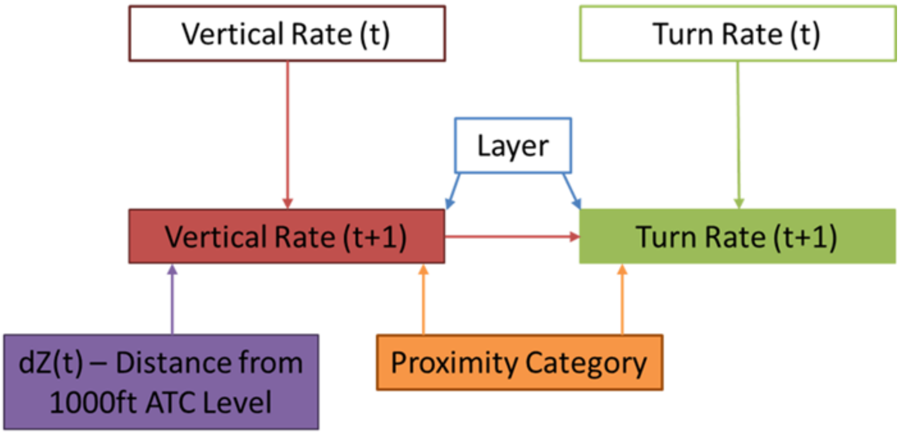

Figure 3 CREME Transition model (Markov network)

2.3.4 Populating the CPA model and Transition model

For each encounter, the values corresponding to each parameter at the CPA and transition models were estimated at one second intervals along the trajectories.

Given the multitude of aircraft types, the CAFE model is simplified by grouping aircraft types with similar characteristics into aircraft classes. A decision can then be made for each of a small number of classes whether their aircraft are ACAS II equipped.

CREME estimates the controlled/uncontrolled and Civil/Military status associated with aircraft using Aircraft ID, Mode A codes, Airline codes, and aircraft type. Look-up tables customised the interpretation of Mode A codes for each ANSP. Common look-up tables were used for Airline codes and aircraft type.

Each parameter value was recorded by adding a count to the corresponding bin in the appropriate range of the CPA model tables, transition model tables and class distribution table.

For the *CRÈME safety* model, it was considered that only luck prevented encounters with HMD less than 0.5NM from being within the NMAC HMD (500feet = 0.082NM). All encounters with HMD less than 0.5NM were 'condensed' into a bin with HMD <0.082NM to enrich the NMAC region of the model for testing vertical resolutions of ACAS II. This assumption was not made for the *CRÈME RPAS safety* model because of the possibility of lateral resolutions in DAA systems.

3 CREME encounter generation

3.1 Encounter construction

CREME constructs encounters firstly by determining the conditions at CPA by Monte Carlo sampling values from the CPA model (**Error! Reference source not found.**). Then the full encounter is generated f rom CPA, firstly in the backward direction, then in the forward direction by Monte Carlo sampling values from the appropriate Transition model table. The Transition model shown in Figure 3 illustrates the network when sampling forward in time from the current cycle (time, *t*) to the subsequent cycle (time, *t* + 1); an analogous network is used when sampling backward in time from the current cycle (time, *t*) to the subsequent cycle (time, *t* – 1).

The process is as follows:

- The following parameters are required to construct the vertical positions of the two aircraft at CPA:
  - VMD – sampled;
  - Layer – sampled;
  - Altitude – calculated from the Layer.
- The following parameters are required to construct the relative horizontal positions of the two aircraft at CPA:
  - HMD – sampled;
  - Approach_Angle – sampled;
  - Heading 1 – chosen arbitrarily, Heading 2 – consistent with Approach Angle and Heading 1;
  - Speed 1, Speed 2 – sampled;
  - Bearing – calculated from Approach Angle, Speeds, and Headings.
- There are two potential solutions for the Bearing. To choose between these the following parameters are required:
  - Acceleration 1, Acceleration 2 – sampled;
  - Turn 1, Turn 2 – sampled;
  - Curvature – the instantaneous curvature at CPA of the relative track is calculated from the Speeds, Accelerations, Headings, and Turn rates. If necessary the Bearing option that implies a curvature consistent with the miss distance is chosen, otherwise one of the two options is chosen randomly with equal probabilities.
- From the CPA positions the aircraft positions are constructed backward in time decrementing at one-second time steps using:
  - In the vertical: Vertical Rate 1, and Vertical Rate 2 – sampled;

- In the horizontal: the sampled longitudinal Accelerations (changes in Speed) and the sampled Turn rates (changes in Heading).

- From the CPA positions, the aircraft positions are also constructed forward in time incrementing at one-second time steps using the same parameters but with different sampled values (Figure 4).

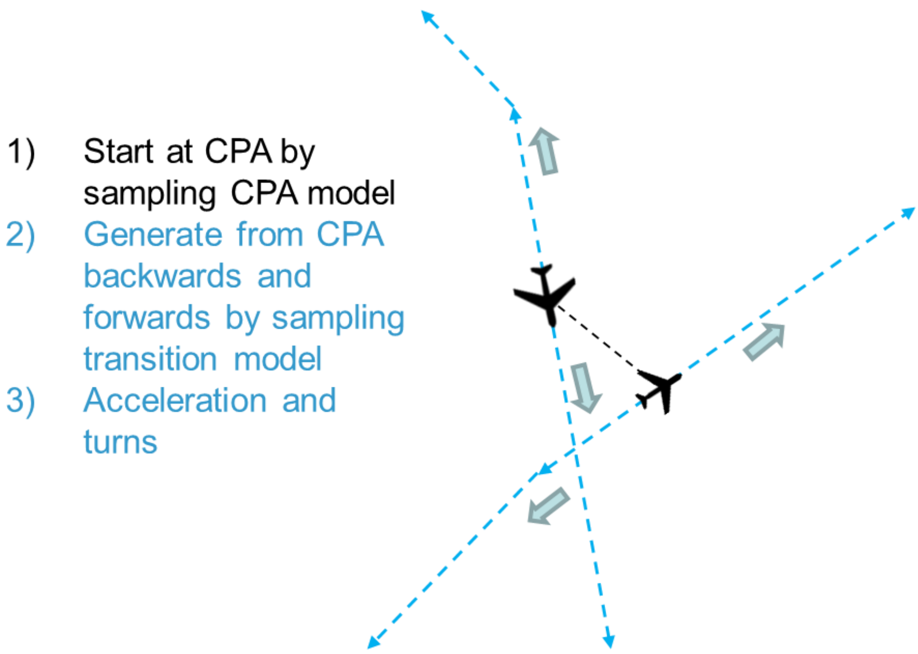

Figure 4 Construction of encounters

3.2 Aircraft performance classes

The Performance Class of each aircraft is determined by sampling the (user-defined) proportions from a Class combination table (one for each Layer).

For each Performance Class eight performance limits (set by the user) are defined:

- four limits applicable across all altitude layers:
  - Maximum altitude;
  - Maximum vertical acceleration;
  - Maximum turn rate; and
  - Maximum bank angle.

- four limits with (potentially) different values in each altitude layer:
  - Minimum ground-speed;

  - Maximum ground-speed;
  - Maximum descent rate; and
  - Maximum climb rate.

The performance limits are imposed on the original distributions according to the Performance Class of each aircraft before the relevant variables are sampled from the CPA model and the Transition model.

- At CPA:
  - The maximum altitude of both aircraft is taken into account when sampling the encounter altitude from the relevant layer in the CPA model;
  - The individual aircraft minimum and maximum ground speeds are taken into account when sampling each aircraft's speed from the CPA model;
  - The individual aircraft maximum descent rate and maximum climb rate are taken into account when sampling each aircraft's vertical rate from the CPA model;
  - The individual aircraft maximum turn rate and maximum bank angle (combined with aircraft speed) are taken into account when sampling each aircraft's turn rate from the CPA model.
- In the rest of the encounter:
  - The individual aircraft minimum and maximum ground speed are taken into account when applying longitudinal accelerations to the aircraft speed;
  - The individual aircraft maximum descent rate, maximum climb rate, and maximum vertical acceleration are taken into account when sampling each aircraft's vertical rate from the Transition Network;
  - The individual aircraft maximum turn rate and maximum bank angle (combined with aircraft speed) are taken into account when sampling each aircraft's turn rate from the Transition Network.

The aircraft performance classes are summarised in Table 4.

Table 4 CREME aircraft performance classes summary

Aircraft class	Engine type	Minimum Take-off Mass (kg)	Maximum altitude (ft)	Piloted
1	Piston	All	23,500	Yes
2	Turboprop	<5,700	28,500	Yes
3	Turboprop	5,700 - 15,000	28,500	Yes
4	Turboprop	>15,000	28,500	Yes
5	Military fast jet	All	66,000	Yes
6	Turbojet	5,700 - 15,000	46,000	Yes
7	Turbojet	15,000 – 100,000	46,000	Yes
8	Turbojet	>100,000	43,000	Yes

9	Turbojet	<5,700	46,000	Yes
10	RPAS piston	All	16,400	No
11	RPAS turboprop	All	45,000	No
12	RPAS jet	All	65,000	No
19	Unknown - Mode S transponder equipped	Unknown	Unknown	Unknown
20	Unknown – Mode C transponder equipped	Unknown	Unknown	Unknown

3.3 Flight models

Several flight models can be assigned to an aircraft class with different probabilities. A flight model is an extension of the standard horizontal aircraft behaviour associated with flying from point to point to more typical RPAS loitering behaviour. CAFE supports user configurable flight models, which include probabilities associated direction of turn, total heading change and duration of straight flight. Hence, a number of typical loitering patterns can be easily simulated. The flight models implemented for CRÈME RPAS safety were:

- Holding pattern. Aircraft orbits continuously for a specified duration clockwise one minute per orbit (Figure 6).
- Holding pattern. Aircraft performs racetrack continuously for a specified duration clockwise one minute per turn and one minute per straight leg (Figure 5).
- Combing pattern. Aircraft combs (alternating turns) continuously for specified duration 30 seconds per turn and two minutes per straight leg.
- Orbit left then orbit right. Aircraft performs figure-of-eight continuously for a specified duration alternating orbit directions one minute per orbit (Figure 6).

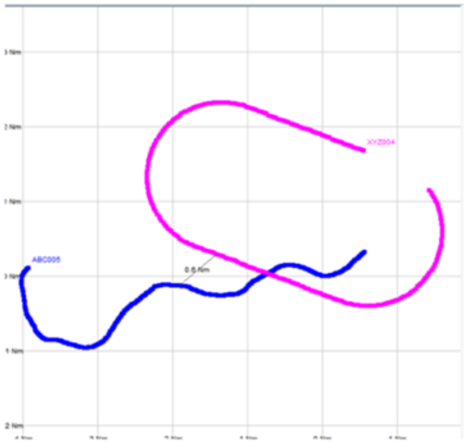

Figure 5 Racetrack

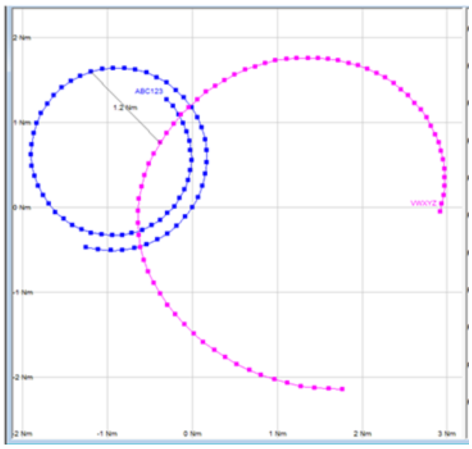

Figure 6 Orbital

3.4 Wind model

A simple wind model can be applied to the horizontal trajectories of the aircraft in each encounter. The wind model consists of a specified wind speed and wind direction, which are constant throughout any one encounter and are applied equally to the horizontal trajectories of both aircraft throughout the encounter – no vertical component of the wind is modelled.

The aircraft are modelled as maintaining the same airspeed at each instant as in the absence of wind, but adjusting their heading so that once wind is taken into account the direction of the ground track will be the same as if no wind was modelled. This means that at each instant of the encounter the direction of the ground track will be the same regardless of whether wind is modelled or not, but the ground-speed and position will be altered. The speed and direction of the wind in each encounter are sampled from distributions which are layer dependent and are specified by the user.

3.5 Importance sampling

Importance Sampling is the process by which a given distribution of variables can be imposed on the model. A specific use of this process is to concentrate on regions of the CPA model tables corresponding to encounters with variables of particular interest – this is achieved by replacing the variables in areas of the tables not of interest by zeros (thus ensuring that there is zero probability of these values being selected) and adding user defined values to the areas of interest. Alternatively, the tables can be multiplied against the corresponding model tables to keep the distribution in the areas of interest intact. Examples include selecting only encounters in certain altitude regimes (*e.g.* terminal area, or en-route); encounters with certain separation (*e.g.* losses of separation, or near mid-air collisions); or encounters with certain controlled status (*e.g.* encounters between controlled aircraft only).

In CREME, the variables that are amenable to importance sampling are:

- Vertical Miss Distance;
- Horizontal Miss Distance;
- Altitude Layer;
- Controlled status of aircraft 1 and 2;
- Encounter approach angle at CPA.

Table 5 shows the importance sampling multipliers used to weight HMD. The result is to increase the number of encounters to varying degrees in the region HMD < 1 NM and VMD < 800 feet. Figure 43 shows the result of Table 5.

Table 5 *CREME RPAS safety* importance sampling

HMD is in nautical miles		VMD (ft)											
Lower Bound	Upper Bound	0 to 200 ft	200 to 400 ft	400 to 600 ft	600 to 800 ft	800 to 950 ft	950 to 1,050 ft	1,050 to 1,450 ft	1,450 to 1,950 ft	1,950 to 2,050 ft	2,050 to 2,950 ft	2,950 to 3,050 ft	3,050 to 3,950 ft
0	0.082	1000	1000	10	10	1	1	1	1	1	1	1	1
0.082	0.5	1000	1000	10	10	1	1	1	1	1	1	1	1
0.5	1	10	10	10	10	1	1	1	1	1	1	1	1
1	2	1	1	1	1	1	1	1	1	1	1	1	1
2	3	1	1	1	1	1	1	1	1	1	1	1	1
3	5	0	0	0	0	0	0	0	0	0	0	0	0
5	10	0	0	0	0	0	0	0	0	0	0	0	0

Note that results should be weighted according to the amount of importance sampling.

3.6 Output

Encounters contain:

- Time stamps every second;
- X-position (NM), Y-position (NM);
- Altitude (feet);
- Aircraft label 1 or 2;
- Mode S equipage;
- Performance class of each aircraft; and
- Controlled status.

Options are available to group encounters by SESAR ACAS acceptance criteria altitude layers and ACAS equipage.

The relationship between CREME's six internal altitude layers and the SESAR acceptance criteria layers is given in Table 6.

Table 6 CREME internal v SESAR altitude layers

	CREME internal altitudes		SESAR ACAS acceptance criteria altitudes	
Layer number	Min	Max	Min	Max
1	1000ft	3500ft	Unlimited	FL50
2	3500ft	FL065	FL50	FL135
3	FL065	FL185	FL135	FL285
4	FL185	FL285	FL285	Unlimited
5	FL285	FL415	-	-
6	FL415	FL660	-	-

Mandated ACAS equipage is based on performance class where classes 3, 4, 6, 7 and 8 are mandated to be ACAS II equipped. To distinguish between mandated ACAS II equipage and future RPAS ACAS equipage, *CREME RPAS safety* contains three alternative models with three different class distributions corresponding to:

- Non RPAS v Non RPAS ;
- RPAS v Non RPAS; and
- RPAS v RPAS.

3.7 Output filter

A filter was applied to *CREME safety* and *CREME RPAS safety* encounters to reduce the number of encounters that were unlikely to trigger an ACAS RA. The filter was based on the algorithms used by LLCEM, but with slightly larger parameters (see [1], appendix D).

4 CRÈME tests

4.1 Tool testing

The CAFE encounter modelling tools were developed iteratively over several years and tested with increasingly large radar data samples:

- Visual plots of CPA model and transition model tables were used to check that the distributions were being filled as expected.
- A model was extracted from generated encounters and compared with the 'parent' model using a multi-dimensional chi-squared tool to check that model extraction and encounter generation processes were inverses of each other.
- An encounter analysis tool was used regularly by operational experts to check that samples of encounters were operationally realistic.
- A dashboard was used to check encounters for overall coverage and spot any unexpected holes, outliers or anomalous behaviour.

4.2 Encounter model variants

Three model variants *CREME safety*, *CREME ATM* and *CREME RPAS safety* have been generated and used in testing the model encounters. The main difference between variants is in the filtering of input radar encounters to each model (Table 1) and configuration of encounter generation (Table 7).

Table 7 Summary of CREME model variant encounter generator configurations

Model feature	Safety model REV9 for ACAS	ATM model REV2 for ACAS	RPAS safety model REV0 for DAA
Encounter generator revision	26	6	25
Importance sampling	No	No	HMD
Output time before CPA (s)	60	60	240
Output time after CPA (s)	10	10	30
Output filtering	RA+	-	RA+

Encounters from the three model variants have been analysed to check:

- Encounters are operationally realistic.
- Distributions are reasonably representative of real encounters (*CREME ATM* and *CREME safety*).
- Risk ratio safety metric for TCAS is similar to a previous European encounter model – AVAL 2008 (*CREME safety*).
- Future traffic scenarios with new RPAS models perform as expected (*CREME RPAS safety*).

4.3 Operational realism of encounters

4.3.1 Sample encounters

Figure 7 to Figure 15 show samples of typical *CREME safety* encounters. For SESAR altitude layer 1 equipped-equipped and equipped-unequipped, and Layer 4 equipped-equipped the following plots are shown:

- Horizontal tracks.
- Altitude v time profile.
- Speed v time profile.

4.3.1.1 SESAR Layer 1

4.3.1.1.1 Equipped-Equipped

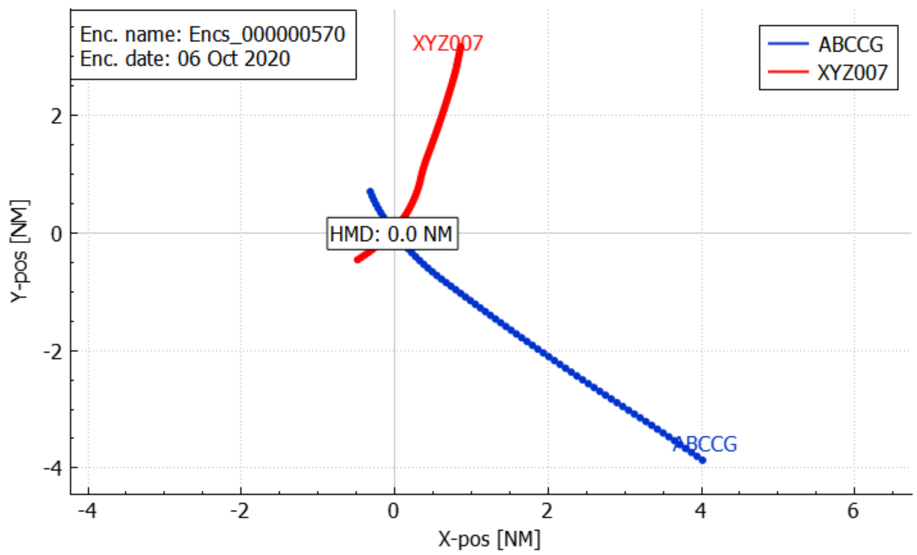

Figure 7 Horizontal tracks

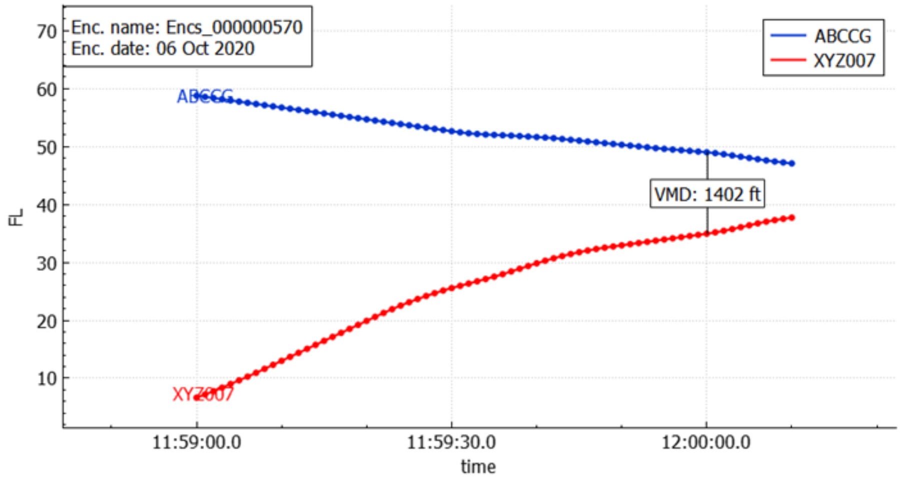

Figure 8 Altitude v time

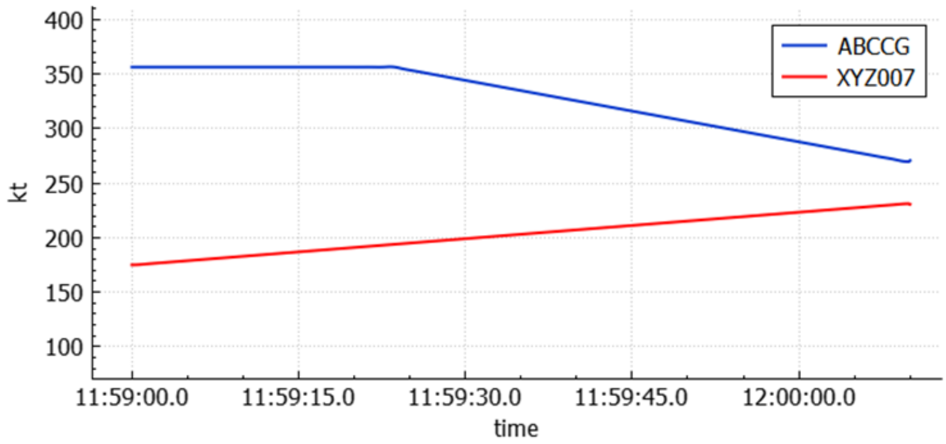

Figure 9 Speed v time

4.3.1.1.2 Equipped-Unequipped

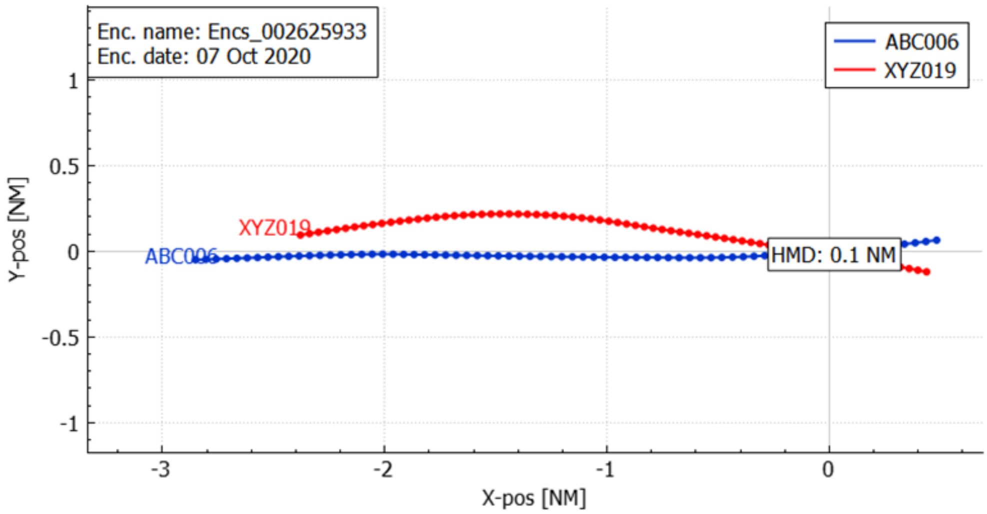

Figure 10 Horizontal tracks

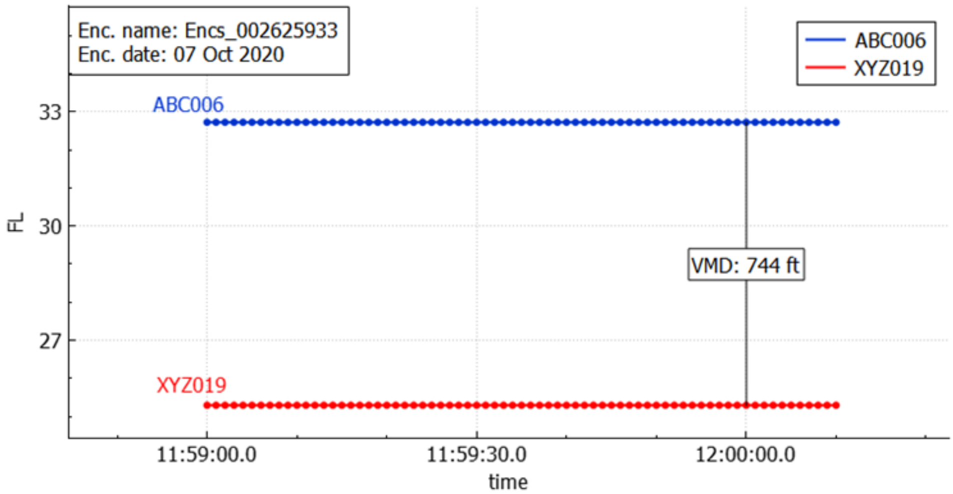

Figure 11 Altitude v time

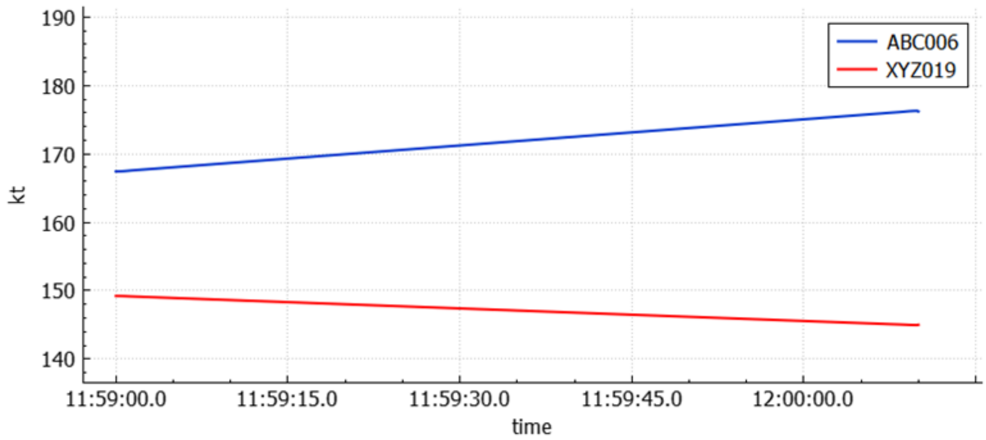

Figure 12 Speed v time

4.3.1.2 SESAR Layer 4

4.3.1.2.1 Equipped-Equipped

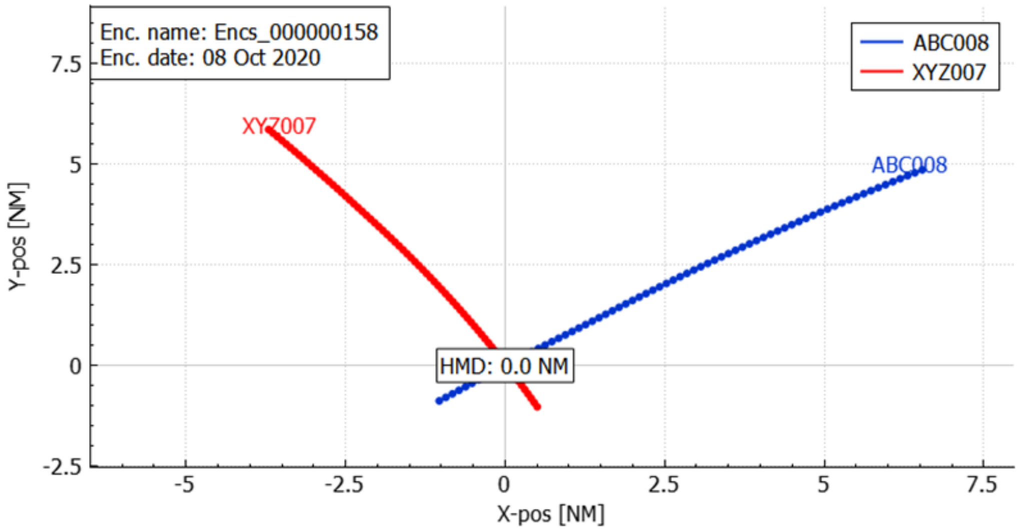

Figure 13 Horizontal tracks

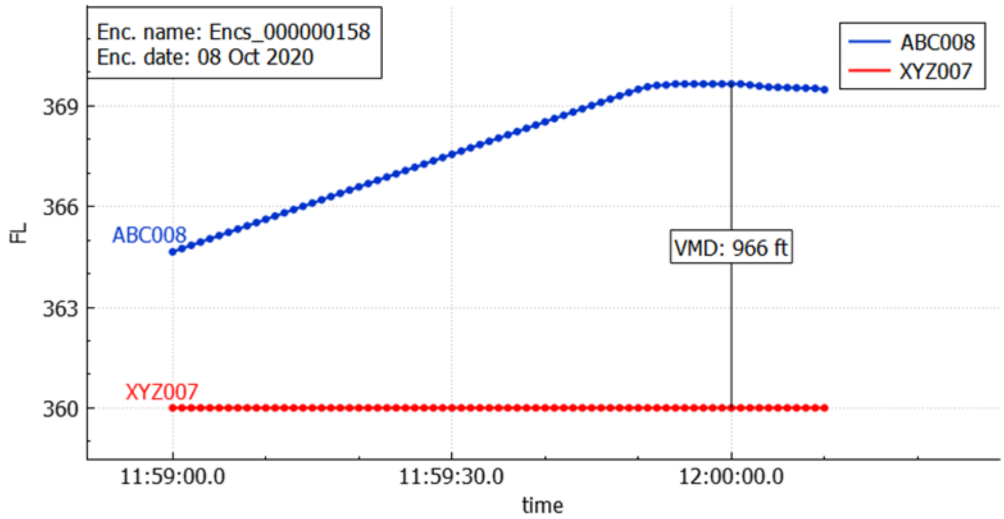

Figure 14 Altitude v time

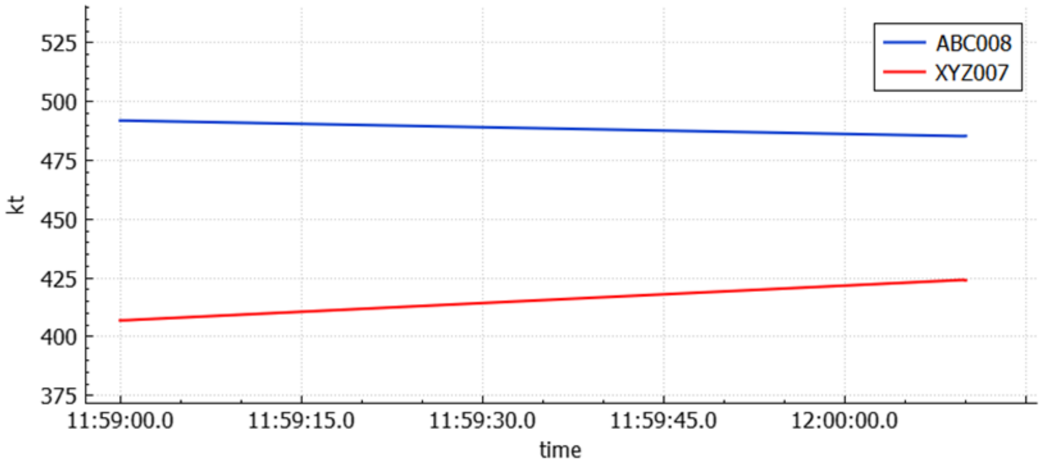

Figure 15 Speed v time

4.4 Representativeness of distributions

4.4.1 Vertical profile coverage

The CAFE dashboard tool was used to plot heat maps of *CREME safety* encounters per SESAR altitude layer and equipage combination (Figure 16 to Figure 23). A sample of vertical profiles are superimposed at the same altitude and CPA to check that there is a reasonable spread within a realistic envelope i.e. no anomalous looking outliers or gaps. Some slow converging or diverging encounters extend beyond the nominal times before and after CPA.

4.4.1.1 SESAR Layer 1

4.4.1.1.1 Equipped-Equipped

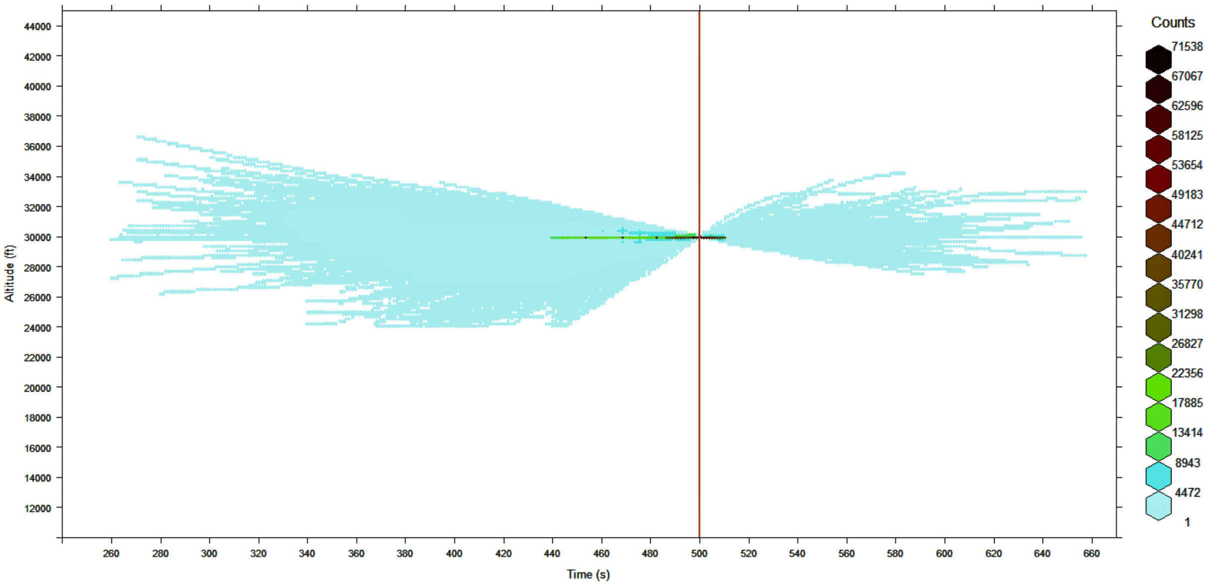

Figure 16 Heat plot of vertical profiles Layer 1 Equipped-Equipped *CREME safety*

4.4.1.1.2 Equipped-Unequipped

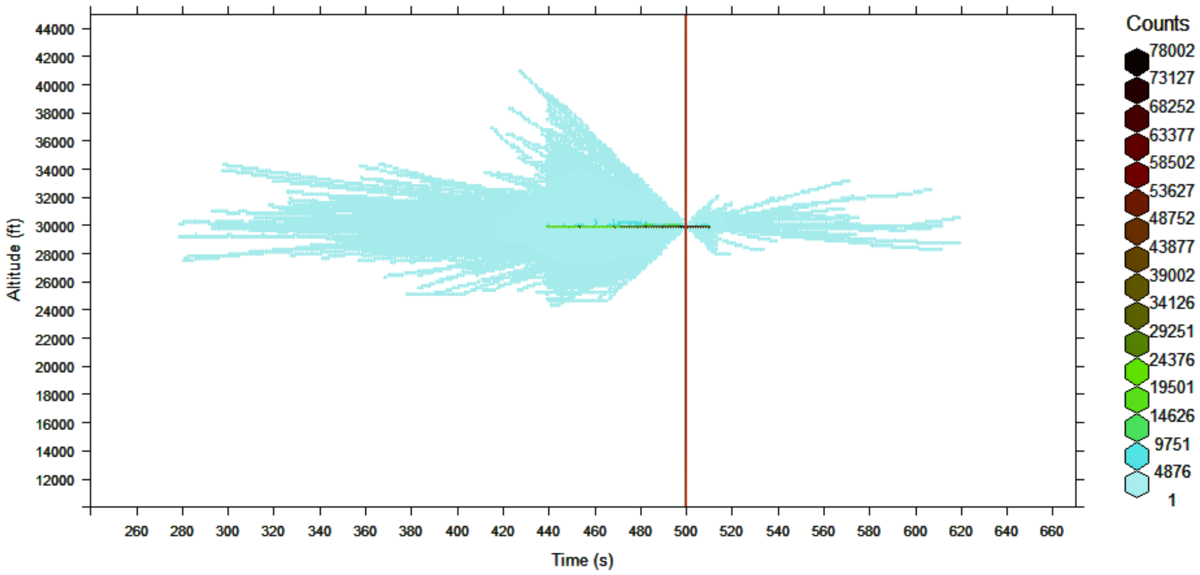

Figure 17 Heat plot of vertical profiles Layer 1 Equipped-Unequipped *CREME safety*

4.4.1.2 SESAR Layer 2

4.4.1.2.1 Equipped-Equipped

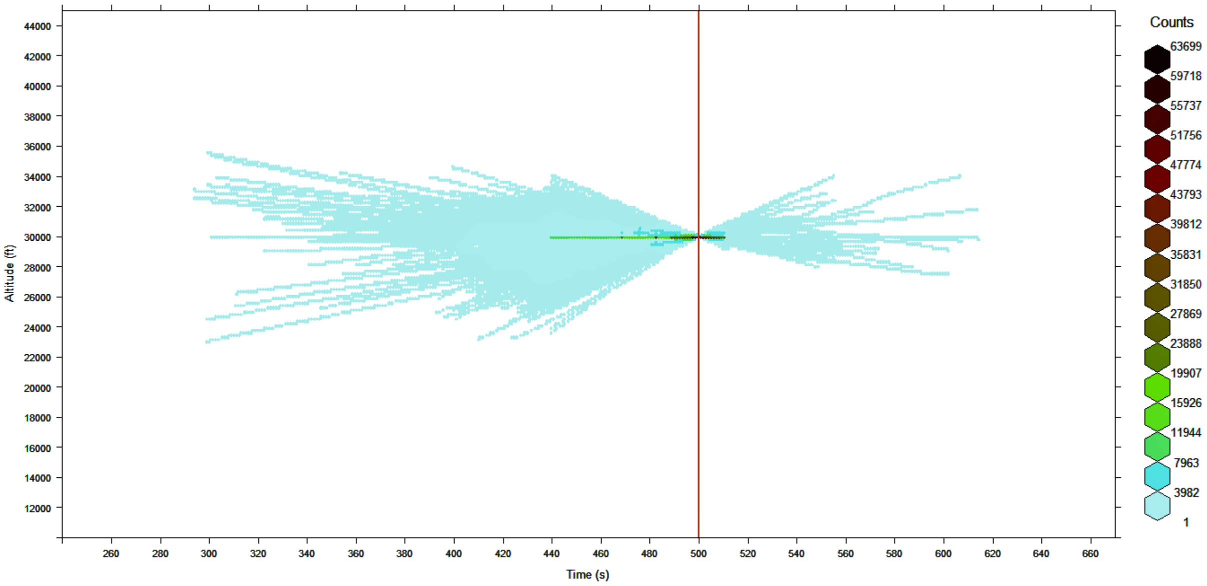

Figure 18 Heat plot of vertical profiles Layer 2 Equipped-Equipped *CREME safety*

4.4.1.2.2 Equipped-Unequipped

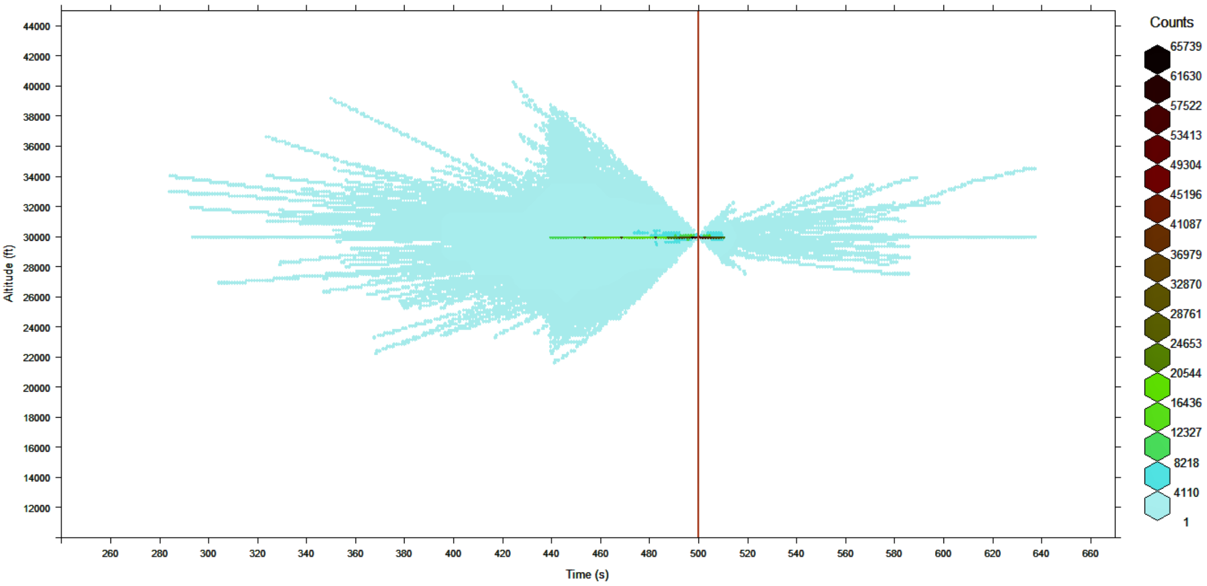

Figure 19 Heat plot of vertical profiles Layer 2 Equipped-Unequipped *CREME safety*

4.4.1.3 SESAR Layer 3

4.4.1.3.1 Equipped-Equipped

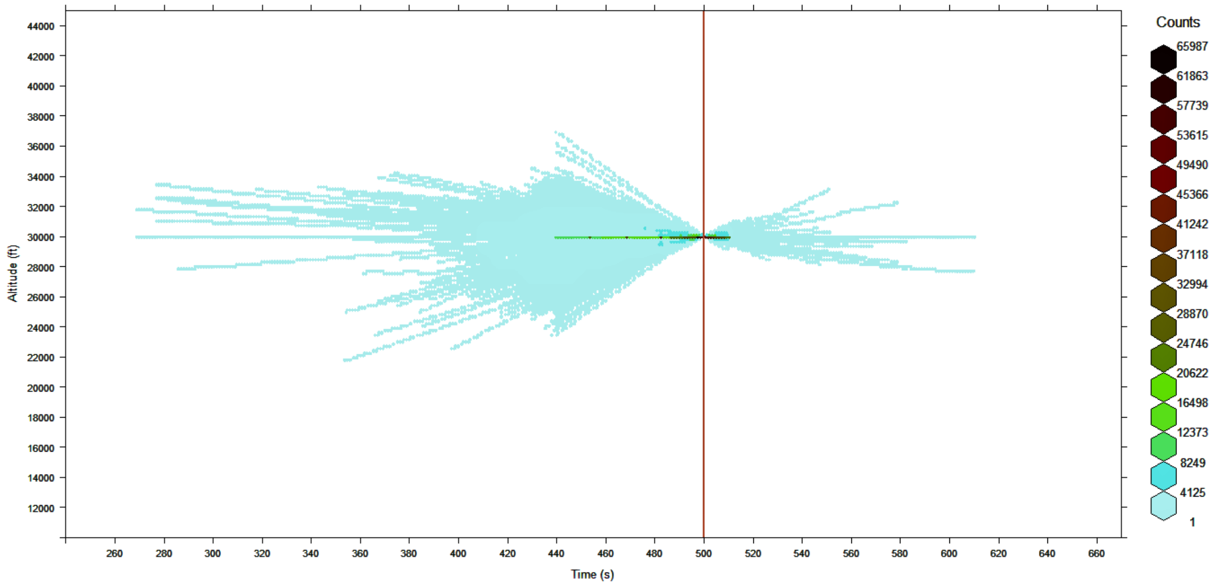

Figure 20 Heat plot of vertical profiles Layer 3 Equipped-Equipped *CREME safety*

4.4.1.3.2 Equipped-Unequipped

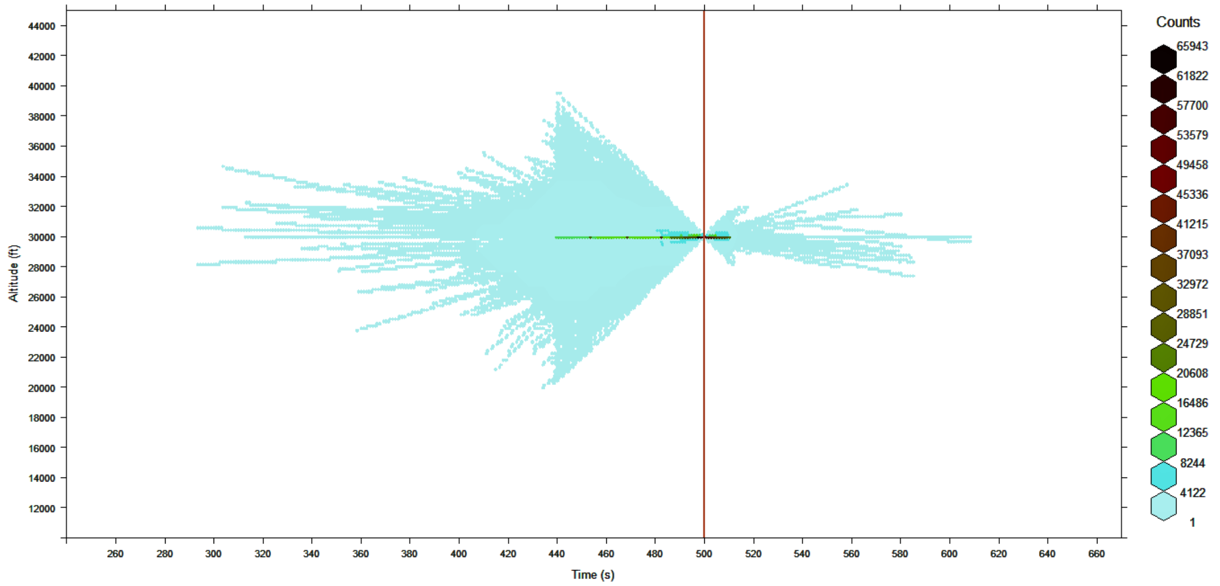

Figure 21 Heat plot of vertical profiles Layer 3 Equipped-Unequipped *CREME safety*

4.4.1.4 SESAR Layer 4

4.4.1.4.1 Equipped-Equipped

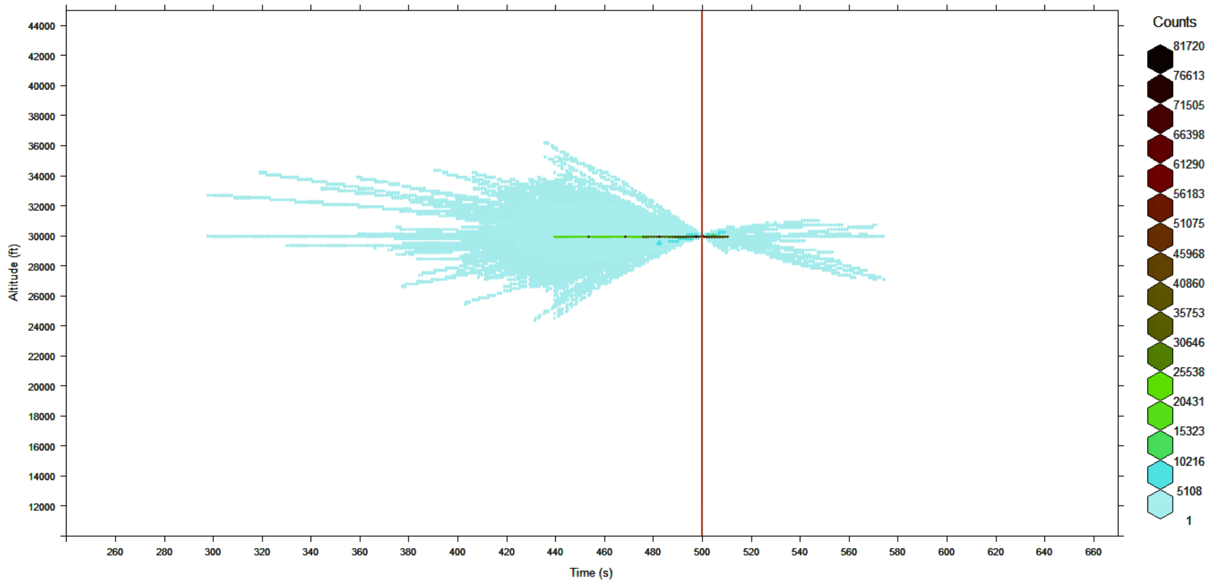

Figure 22 Heat plot of vertical profiles Layer 4 Equipped-Equipped *CREME safety*

Equipped-Unequipped

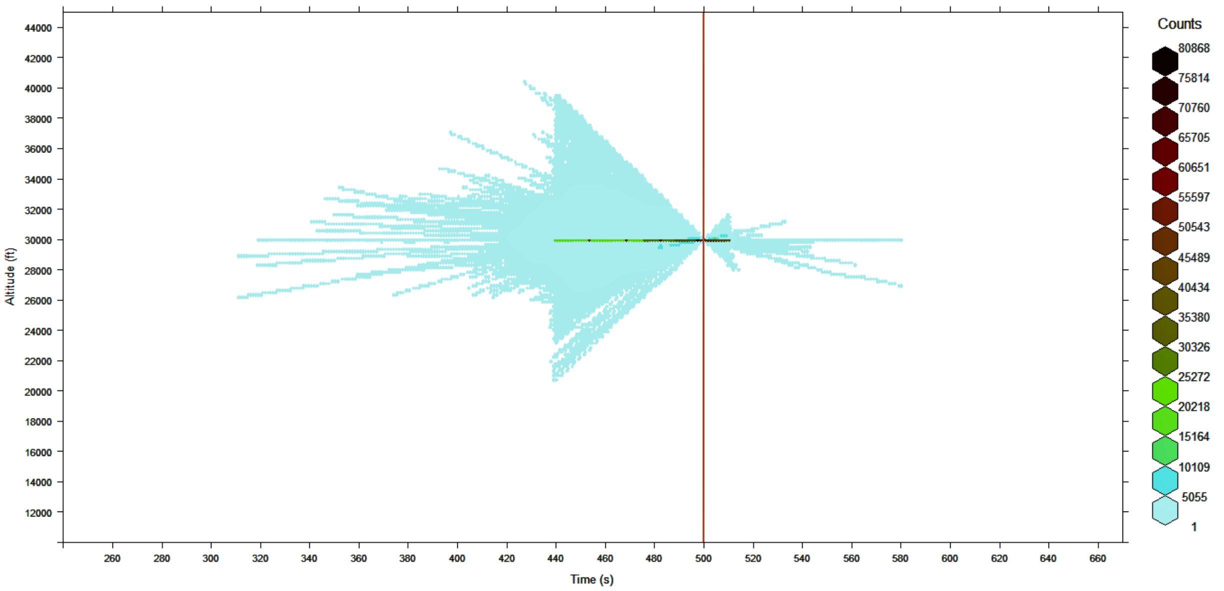

Figure 23 Heat plot of vertical profiles Layer 4 Equipped-Unequipped *CREME safety*

4.4.2 Encounter geometry at CPA distributions

20,000 encounters were generated using *CREME ATM* and distributions compared with those of real data. Figure 24 to Figure 26 show the two respective distributions of VMD, HMD and approach angle at CPA.

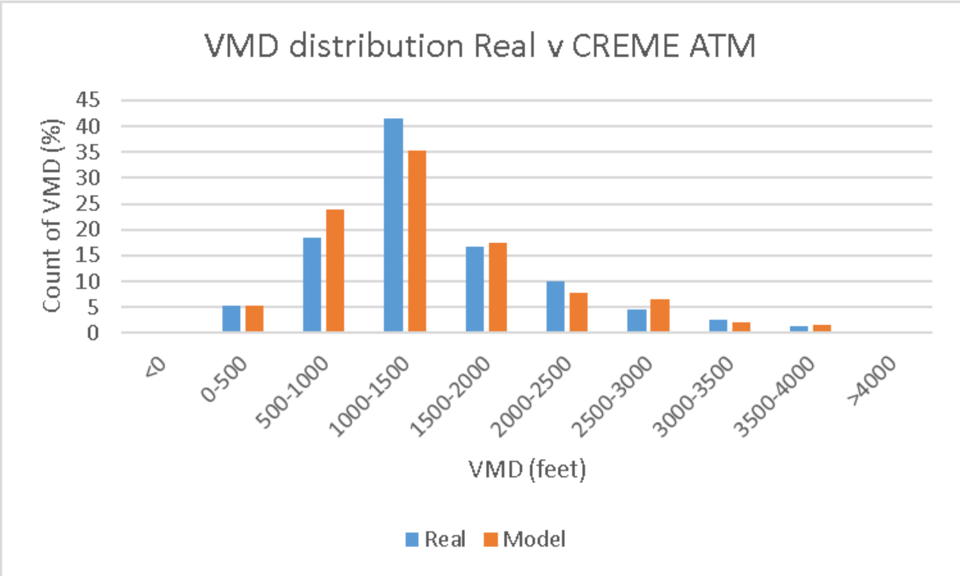

Figure 24 VMD at CPA distribution Real v *CREME ATM*

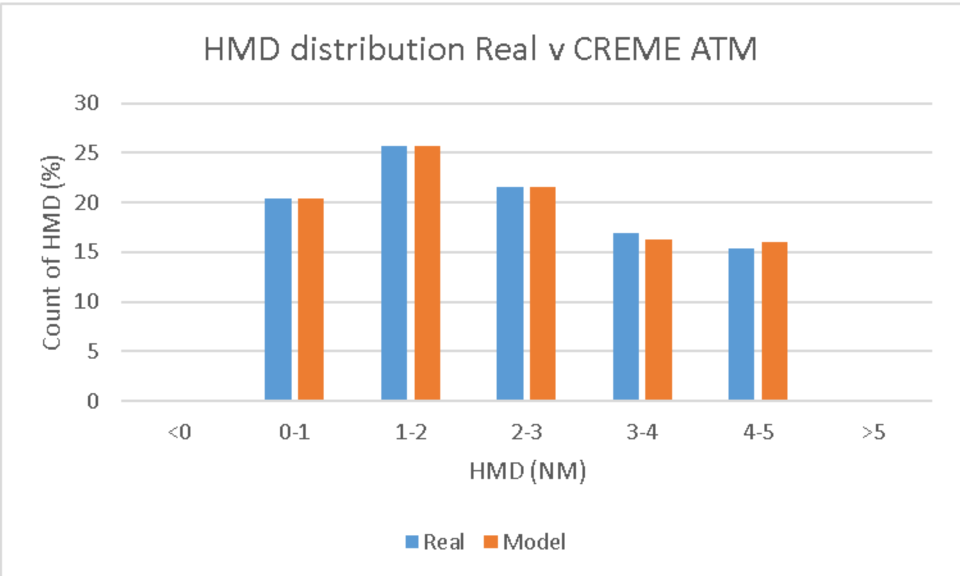

Figure 25 HMD at CPA distribution Real v *CREME ATM*

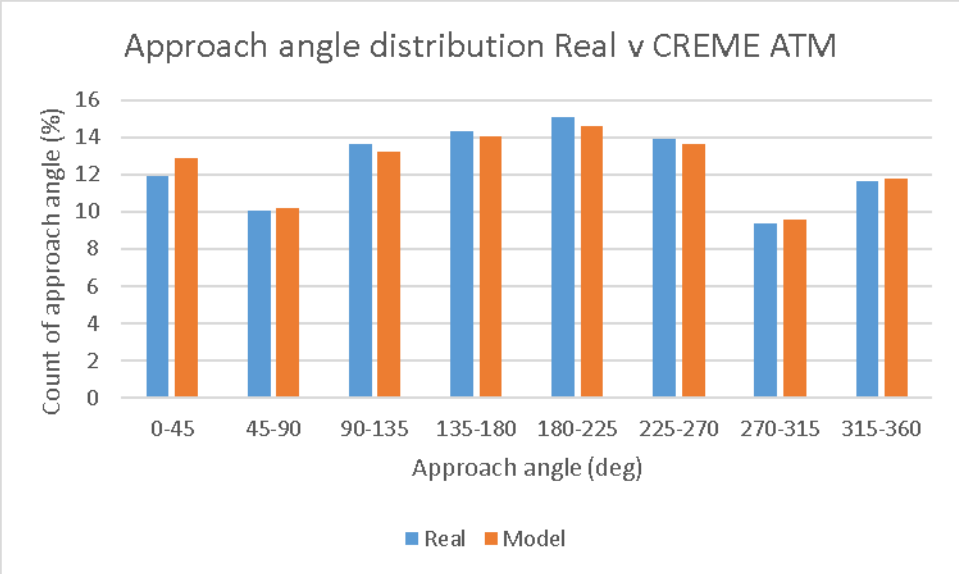

Figure 26 Approach angle at CPA distribution Real v *CREME ATM*

4.4.3 Aircraft state at CPA distributions

- 20,000 encounters were generated using *CREME ATM* and distributions compared with those of real data. Figure 27 to Figure 32 show the two respective distributions for Altitude, Speed, Vertical rate, Approach angle, Aircraft class, Acceleration and Turn rate.

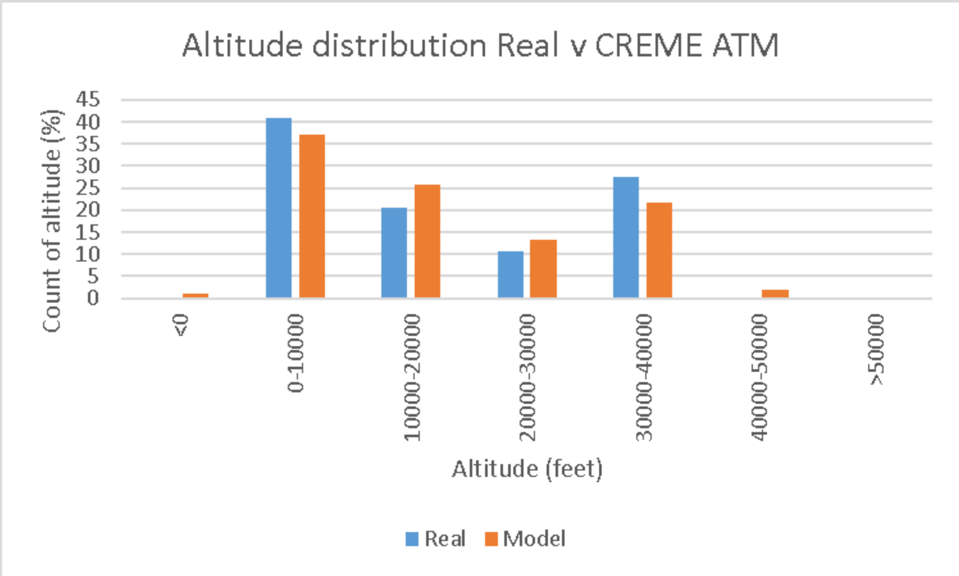

Figure 27 Average altitude at CPA distribution Real v *CREME ATM*

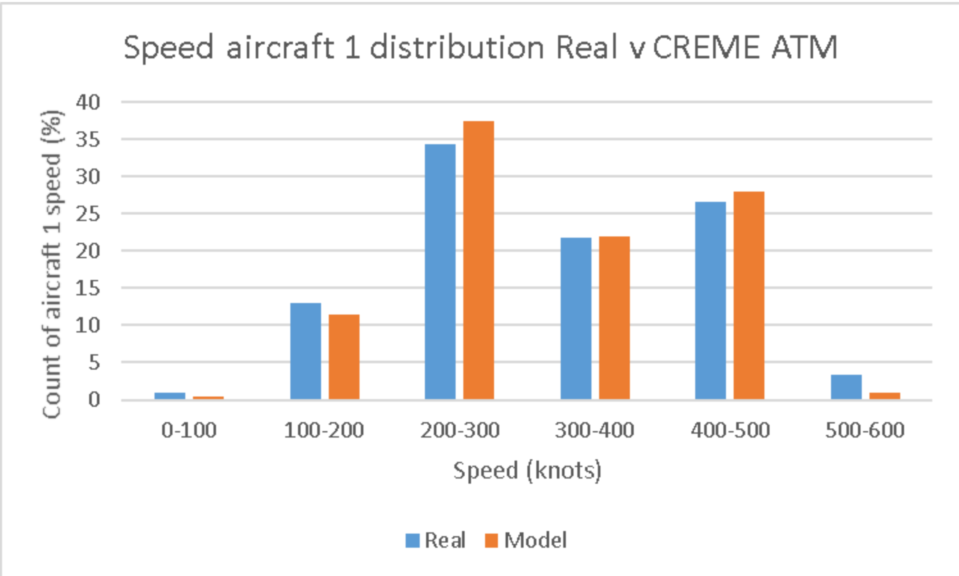

Figure 28 Speed of aircraft 1 at CPA distribution Real v *CREME ATM*

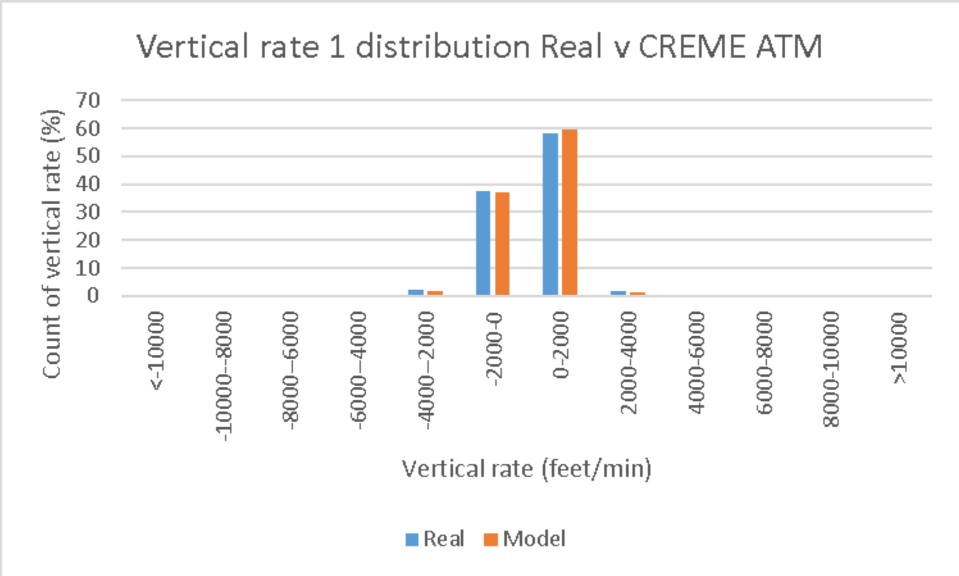

Figure 29 Vertical rate of aircraft 1 at CPA distribution Real v *CREME ATM*

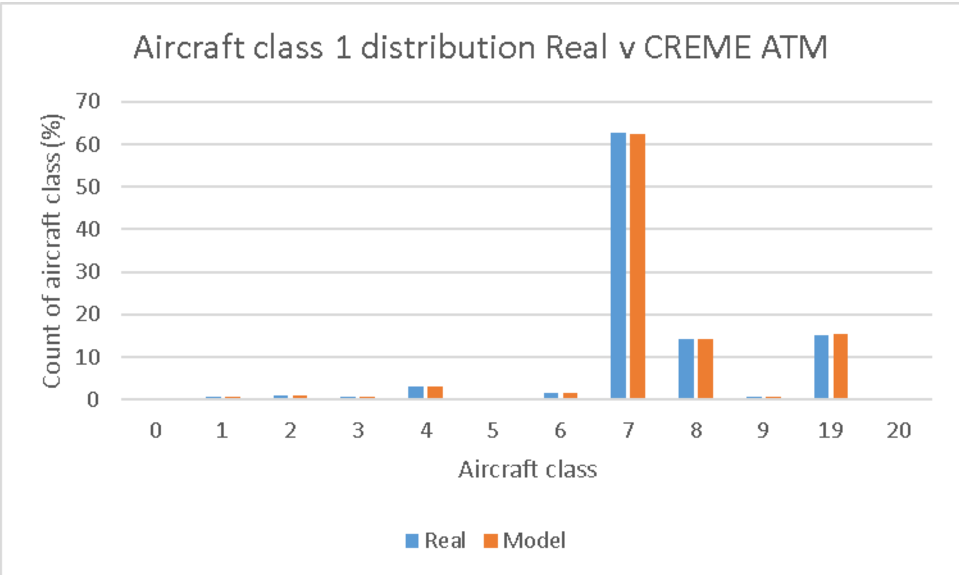

Figure 30 Aircraft 1 class distribution Real v *CREME ATM*

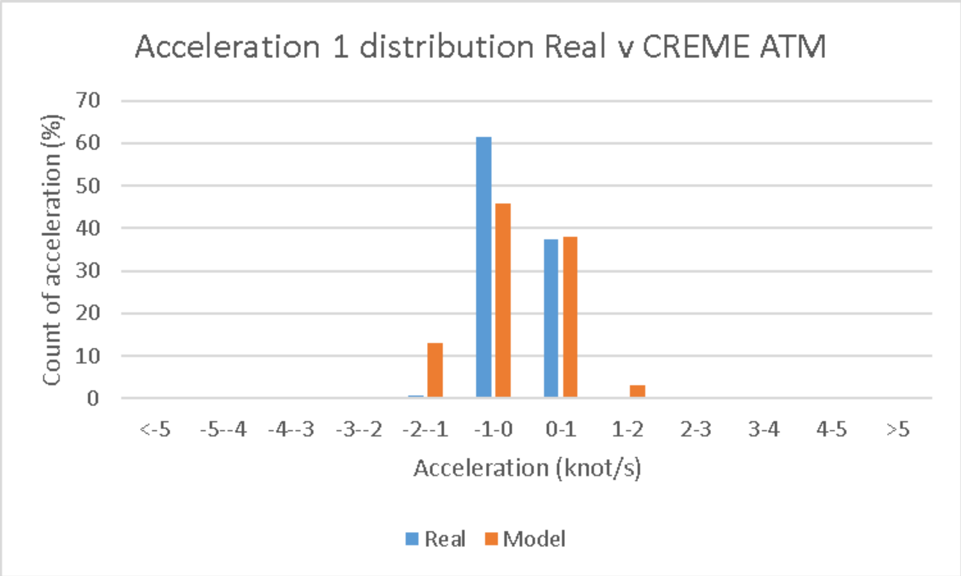

Figure 31 Acceleration at CPA distribution *CREME ATM* v Real

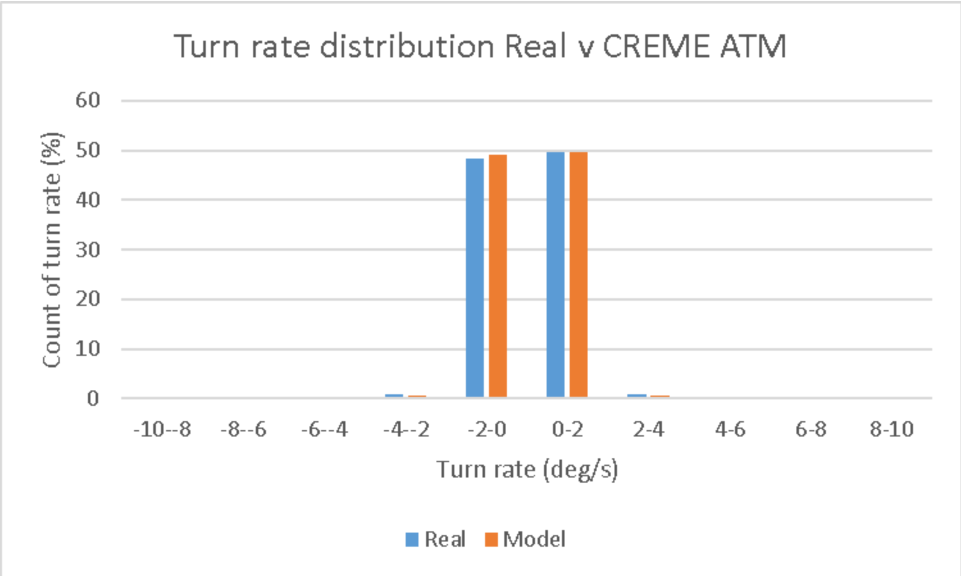

Figure 32 Turn rate at CPA distribution Real v *CREME ATM*

4.4.4 Tails of vertical rate distribution

The batches of 50,000 *CREME safety* encounters were checked for excessive vertical rates. It was found that rates over +/-7,000 feet/min were less than a fraction of a percent overall (Figure 33 and Figure 34 – note vertical axes have logarithmic scales).

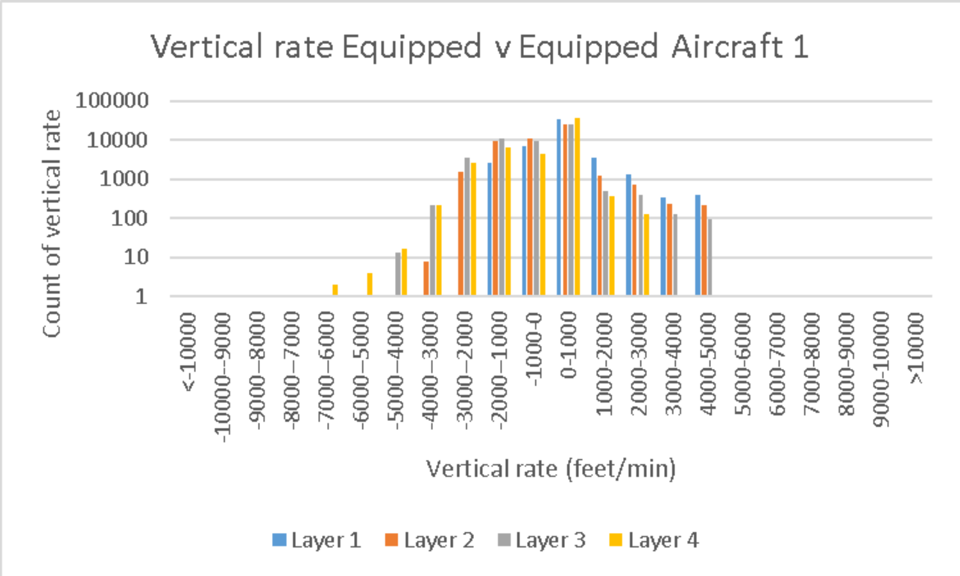

Figure 33 Vertical rate aircraft 1 at CPA distribution for Equipped v Equipped *CREME safety*

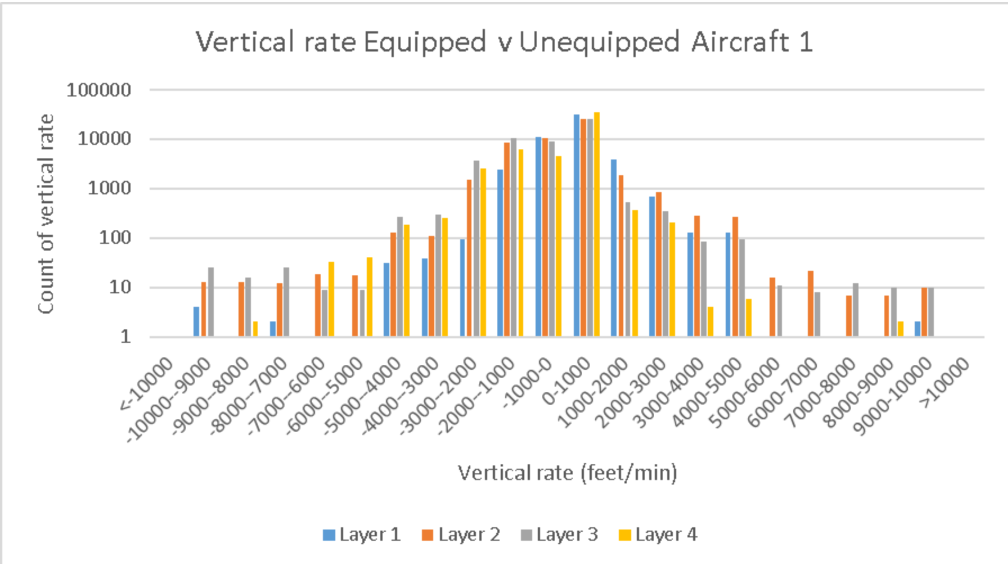

Figure 34 Vertical rate aircraft 1 at CPA distribution for Equipped v Unequipped *CREME safety*

4.4.5 Level-off distributions

Level-offs are known to be responsible for a significant number of RAs so it was important to have an appreciable proportion of level-offs in CREME. A tool was developed to check the proportion of level-off encounters for each SESAR layer and equipage combination. This was based on a DSNA design. Simple level-off means one of the aircraft levels off and double level-off means both aircraft level off. Level-level is where the aircraft is level throughout the encounter. Over 4,000 real encounters were passed through a RA+ filter and classified by SESAR level and equipage combination. For comparison about 50,000 *CREME safety* encounters and AVAL encounters were classified for each SESAR layer and equipage combination. Figure 35 to Figure 40 show that overall both models have fewer level-offs than in the real encounter set. This is noted as an area for improvement in future versions of CREME.

4.4.5.1 Equipped-Equipped

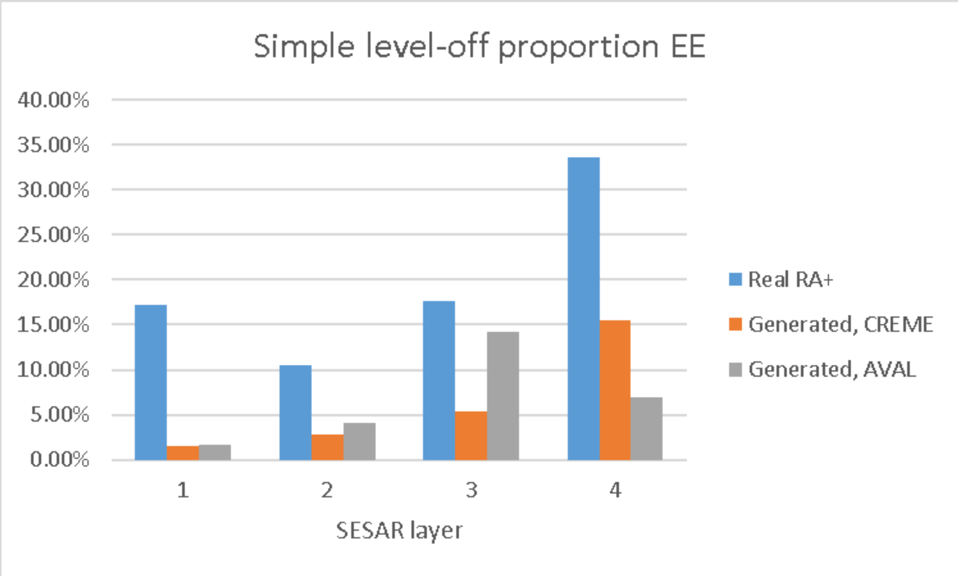

Figure 35 Simple level-off proportion Equipped-Equipped Real v *CREME safety*

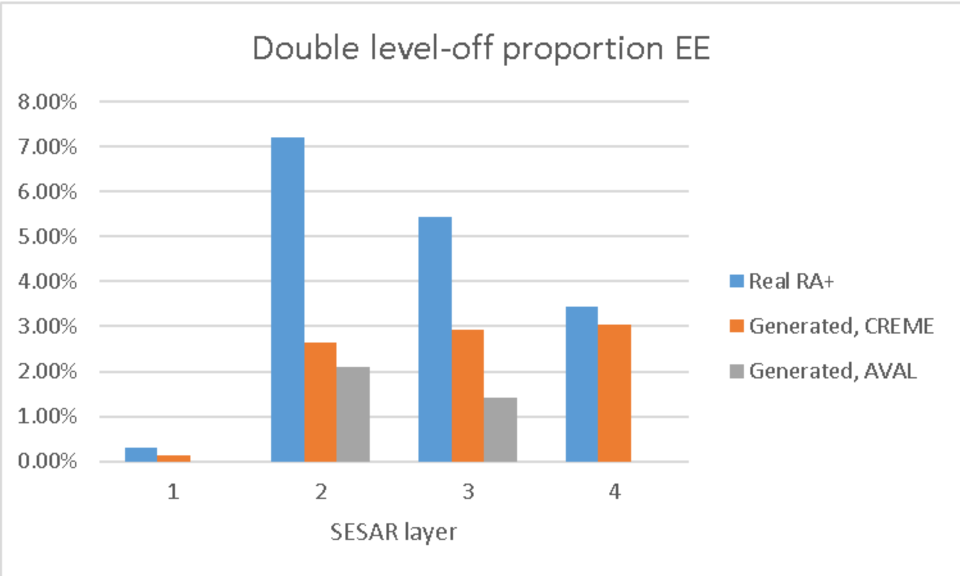

Figure 36 Double level-off proportion Equipped-Equipped Real v *CREME safety*

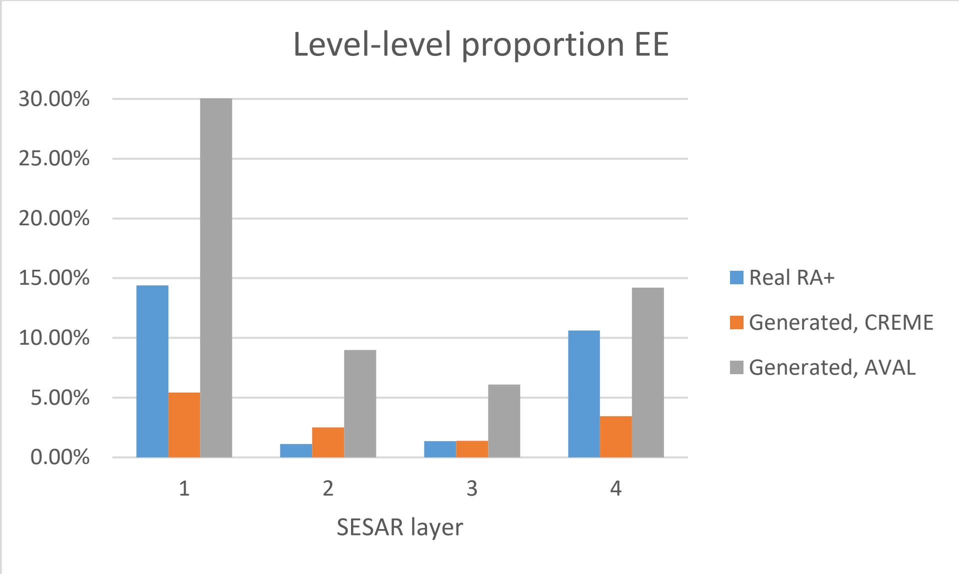

Figure 37 Level-level proportion Equipped-Equipped Real v *CREME safety*

4.4.5.2 Equipped-Unequipped

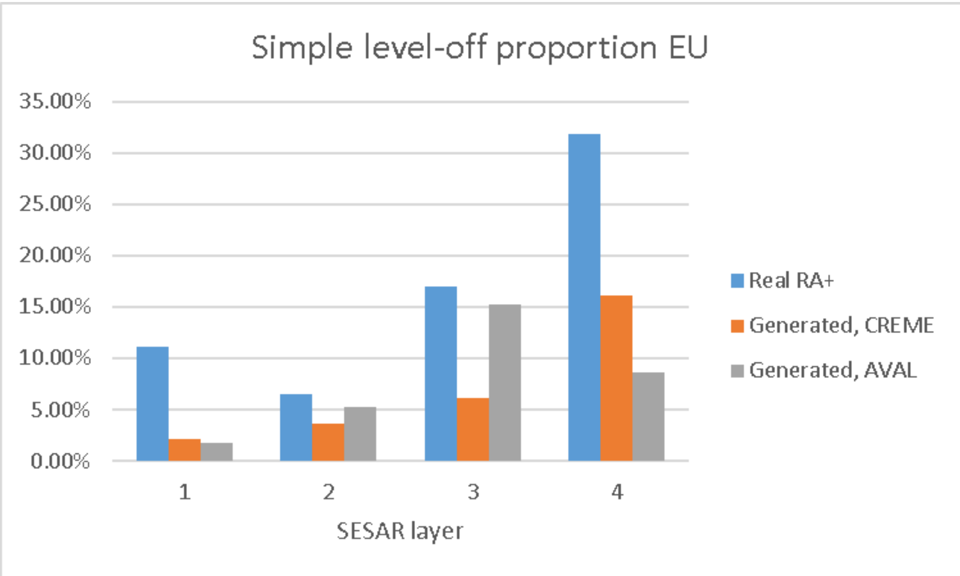

Figure 38 Simple level-off proportion Equipped-Unequipped Real v *CREME safety*

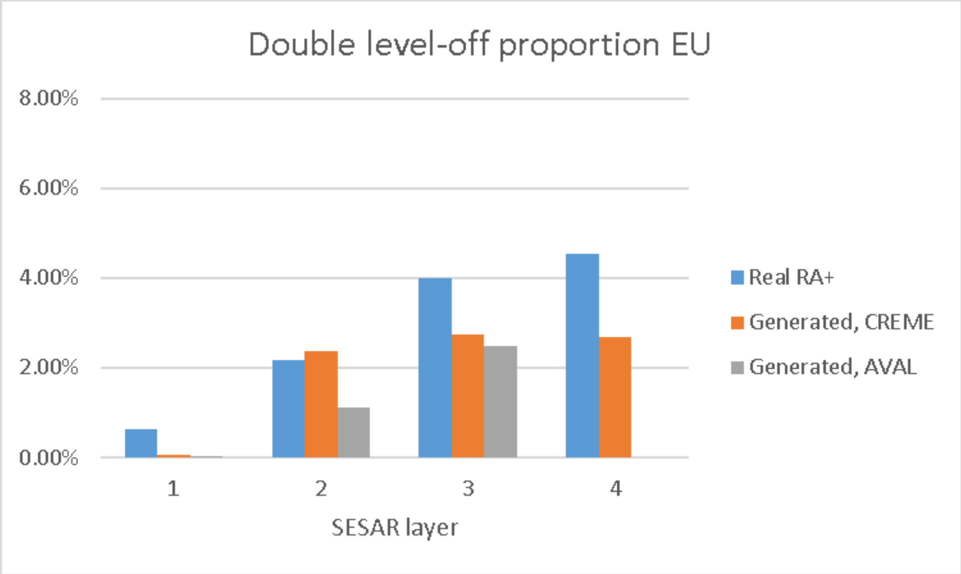

Figure 39 Double level-off proportion Equipped-Unequipped Real v *CREME safety*

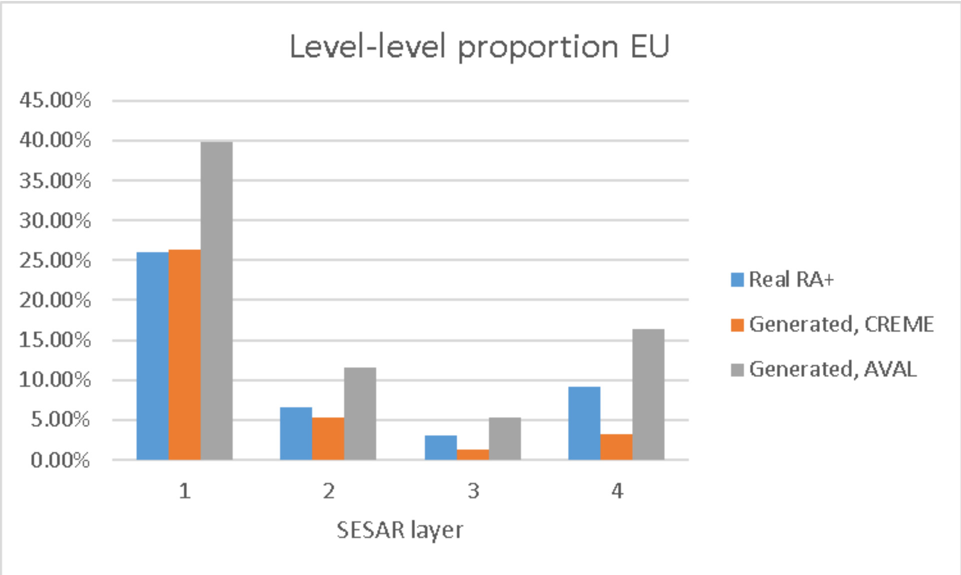

Figure 40 Level-level proportion Equipped-Unequipped Real v *CREME safety*

4.5 Safety

4.5.1 Miss distance distributions

Figure 41 shows an example of how the VMD and HMD at CPA frequency distributions vary in layer 1 between aircraft equipped with TCAS (before TCAS is triggered) for 2,000 encounters. Note the HMD is restricted to the NMAC dimension of 0.082 NM after being artificially 'condensed' from 0.5 NM to increase the concentration of risk bearing encounters. The VMD is concentrated around 1,000 feet corresponding to the minimum legal separation.

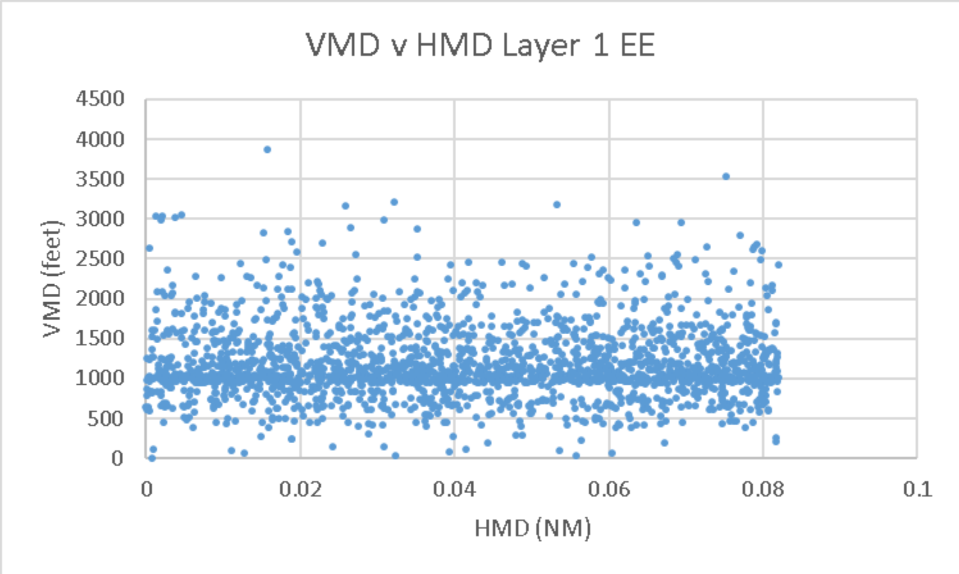

Figure 41 VMD v HMD at CPA distribution for layer 1 Equipped v Equipped

4.5.2 TCAS risk ratio

A *CREME safety* encounter set of 1 million encounters was used to simulate encounters where both aircraft were equipped with TCAS V7.1. The risk ratio was compared with the previous European encounter model developed in the project ACAS on Very Light Jets and Light Jets – Assessment of safety Level (AVAL, 2008 [9]). As can be seen from Figure 42, most of the CREME and AVAL risk ratios for each SESAR layer were below 1.5%. This difference could be due to the difference in traffic as well as the models.

Table 8 AVAL v *CREME safety*

Criteria	AVAL	*CREME safety*
Period of radar data collection	2007-2008	2015-2018
Countries covered	France, United Kingdom, Netherlands, Switzerland, Czech Republic	France, United Kingdom, Netherlands, Switzerland, Czech Republic, Belgium, Germany, Luxembourg, Poland
Flight hours	1.3×10^6	1.2×10^7

Number of encounters contributing to safety model	2,154	23,809

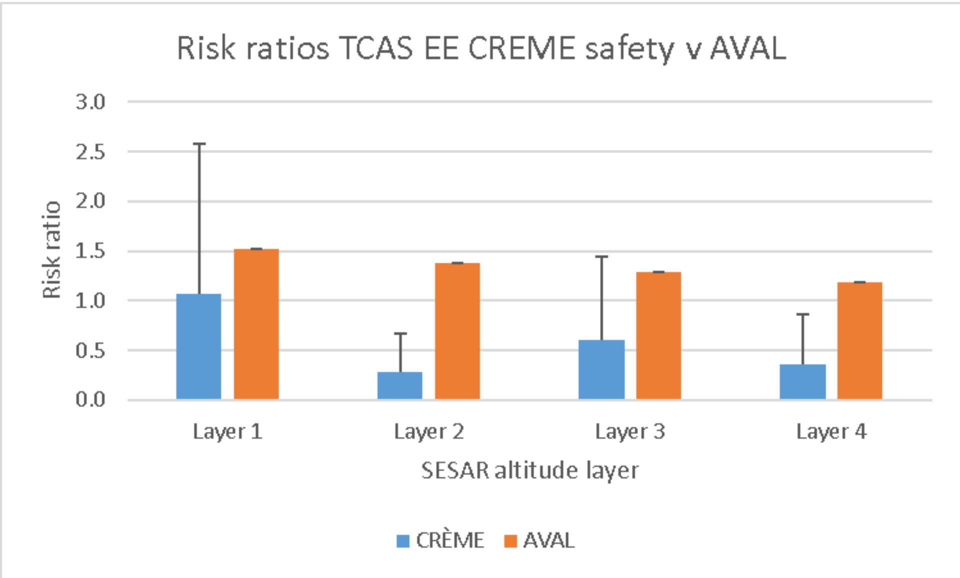

Figure 42 Equipped-Equipped risk ratios for AVAL[4] v *CREME safety* per SESAR altitude layer

[4] The error bars for AVAL are unknown

4.6 RPAS scenarios

4.6.1 Miss distance distributions

Figure 43 shows the distribution of miss distances of 2,000 *CREME RPAS safety* encounters using importance sampling to weight encounters with HMD up to 0.5 NM and VMD up to 400 feet by a factor of a thousand, and up to 1 NM and 800 feet by a factor ten. To obtain statistically correct risk ratios, the corresponding risks have to be divided by the corresponding weighting. These encounters were conventional point to point with no loitering patterns.

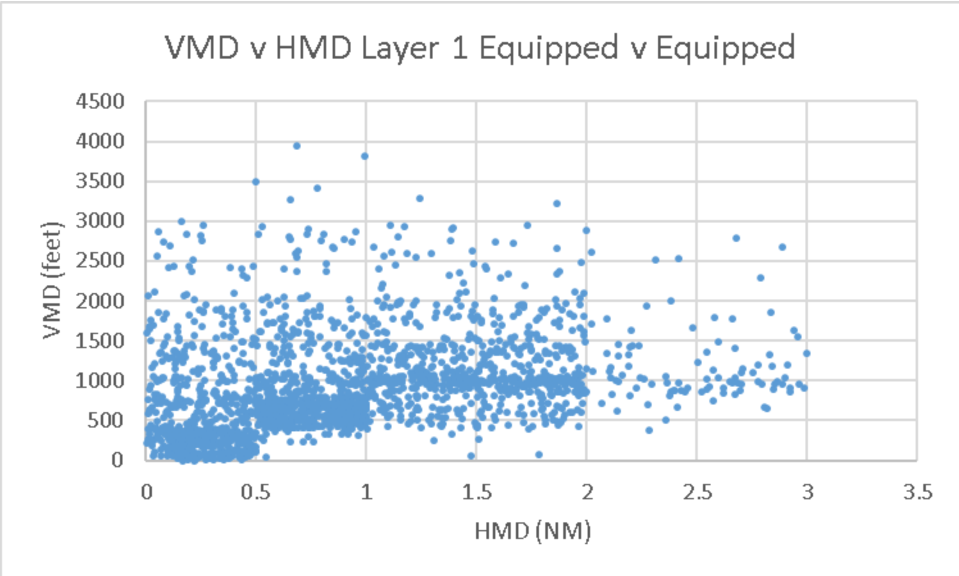

Figure 43 *CREME RPAS safety* VMD v HMD at CPA distribution Layer 1 Equipped v Equipped

4.6.2 RPAS performance

In general RPAS vertical rates and speeds tend to be slower than other traffic at any particular altitude. Figure 44 and Figure 45 confirm that both vertical rate and speed distributions are significantly less than the corresponding manned traffic of *CREME ATM* (Figure 28, Figure 33 and Figure 34).

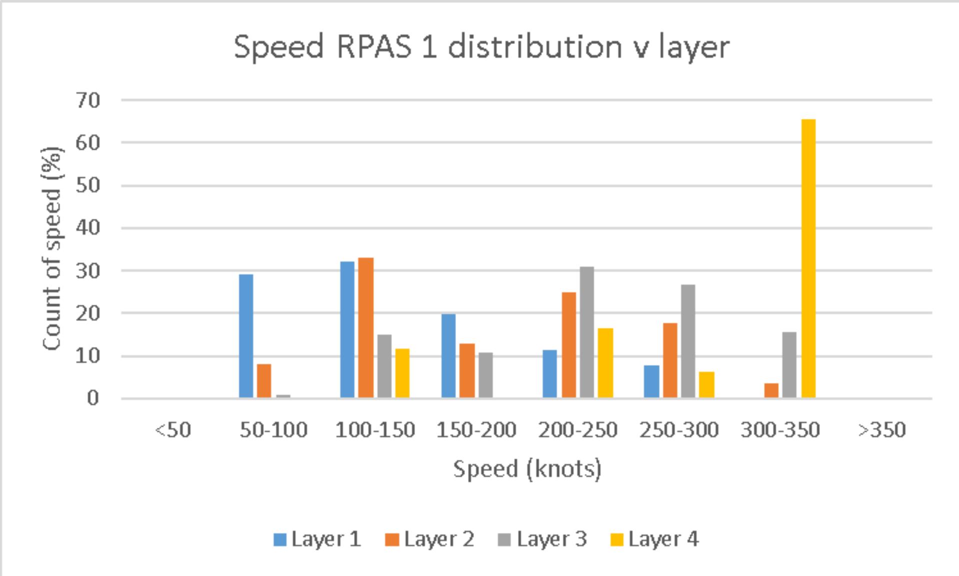

Figure 44 Speed RPAS aircraft 1 distribution *CREME RPAS safety*

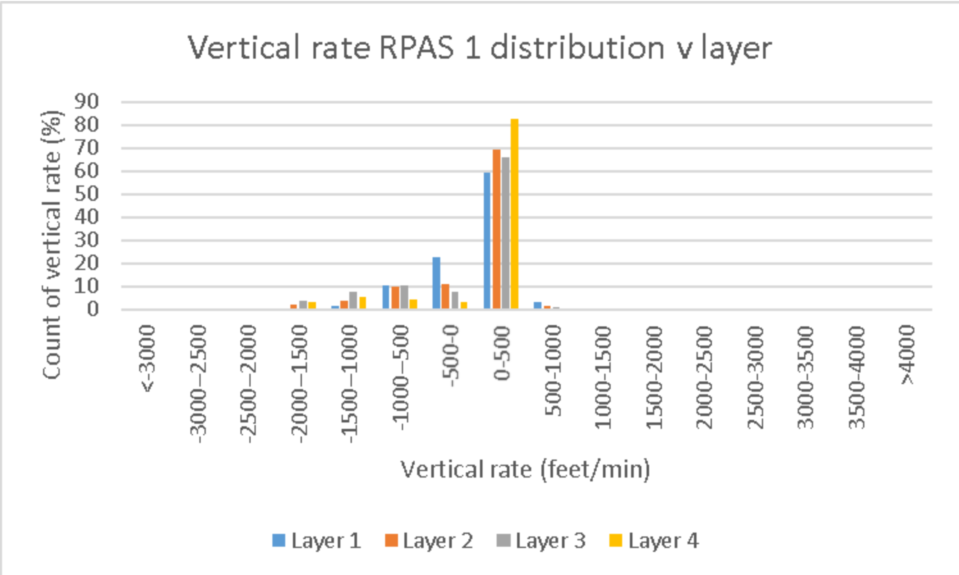

Figure 45 Vertical rate RPAS aircraft 1 distribution *CREME RPAS safety*

4.7 Cross-checking by independent organisations

4.7.1 Egis Avia, France

In 2019, Egis Avia analysed 2 million *CREME safety* encounters and 200,000 *CREME ATM* encounters using their ACAS simulator (Table 9). Detailed feedback was given on SESAR acceptance metrics and consequently improvements were made in particular to the realism of the proportion of level-off encounters.

4.7.2 Lincoln Laboratory, Massachusetts, USA

In 2019, Lincoln Laboratory analysed two sets of 400,000 *CREME safety* encounters using their ACAS simulator. Detailed feedback was given by Lincoln Laboratory on realism of encounters and safety metrics and consequently improvements were made in particular to the realism of proportion of excessive height rate encounters.

In 2021, an updated set of 2.7 million *CRÈME safety* encounters were sent and used in the further refinement of distributions.

4.7.3 Saab, Sweden

In 2020, sets of four million and two million *CREME RPAS safety* encounters were analysed by Saab. Detailed feedback was given by Saab on risk safety metrics and proportion of risk bearing encounters. Consequently, the number of NMACs before CAS was increased using importance sampling. A set of fast-time ACAS simulations was performed where feedback was given on refining trajectory realism after CPA and at Remain Well Clear distances.

4.7.4 Polytechnic University of Catalonia, Spain

In 2020, sets of four million and two million *CREME RPAS safety* encounters were analysed by UPC. Detailed feedback was given and model performance improved.

4.7.5 Thales, France

In 2021, Thales used the two million CREME RPAS encounter set in fast-time simulations with ACAS Xu. The simulations compared ACAS Xu with TCAS performance and feedback was given on tuning RPAS piston performance classes.

4.7.6 Honeywell, Czech Republic

In 2021, Honeywell used 1.2 million CREME RPAS encounters in fast-time simulations with ACAS Xu. The simulations compared ACAS Xu with ACAS Xa performance and there was no negative feedback on the realism of the encounters.

Table 9 Summary of organisations that analysed CREME encounter sets

Organisation	Model variant	Year	Size
Egis Avia, France	Safety	2019	2 million
	ATM	2019	200 thousand
Lincoln Laboratory, Massachusetts, USA	Safety	2019	800 thousand
	Safety	2021	2.7 million
Saab, Sweden	RPAS	2020	6 million
	RPAS multi-aircraft	2021	3,000
Polytechnic University of Catalonia, Spain	RPAS	2020	6 million
Thales, France	RPAS	2021	2 million
Honeywell, Czech Republic	RPAS	2021	1.2 million

4.8 Model limitations

CREME is targeted at ACAS Xa and DAA validation in Europe. The main limitations identified are:

- Pairwise encounters only i.e. no multi-aircraft. This may be a reasonable assumption for much of collision avoidance analysis but may not be realistic for DAA.
- Lack of real RPAS input encounters.

- Lack of correlation between aircraft possibly leading to fewer level-off RAs than in reality for example.
- No uncorrelated encounters as in airspace class G.
- Limited number of RPAS types e.g. no rotorcraft.
- Manoeuvre frequency in DAA region is based on collision avoidance frequencies.

5 Future work

CREME is currently being extended to cope with:

- Multi-aircraft encounters[5].
- Richer variety of RPAS classes including rotorcraft.
- More realistic manoeuvre frequency by adjusting DAA region relative to collision avoidance.
- Increasing proportion of level-offs by updating Markov process with Markov chain in transition network.

Future work could be to include uncorrelated encounters for addressing uncontrolled airspace classes.

[5] Multi-aircraft encounters have been generated by combining encounter pairs but these have yet to be related to frequencies of actual occurrence.

6 References

The following documents were referred to in the text:

[1] Correlated Encounter Model for Cooperative Aircraft in the National Airspace System, Version 1.0, Kochenderfer, M. J., Espindle, L. P., Kuchar, J. K., Griffith, J. D., Lincoln Laboratory, Project Report ATC 344, 24th October 2008.

[2] Correlated Encounter Model for Cooperative Aircraft in the National Airspace System, Version 2.0, Underhill, N. K., Harkleroad, E. P., Guendel, R. E., Weinert, A. J., Maki, D. E., Edwards, M. W. M., Lincoln Laboratory, Project Report ATC 440, 8th May 2018.

[3] Encounter Model Extractor Tool (EMET), User guide, Version 1.11, Collision Avoidance Fast-time Evaluator (CAFÉ), Raynaud, B., Ibanez, J., Egis Avia for QinetiQ, Eurocontrol contract No 15220453C, 16th March 2021.

[4] Encounter Model Extractor Tool (EMET), Software Design document (SDD), Version 1.10, Collision Avoidance Fast-time Evaluator (CAFÉ), Raynaud, B., Drevillon, H., Vuillaume, J., Egis Avia for QinetiQ, Eurocontrol contract No 15220453C, 25th March 2021.

[5] Automatic Resolution Advisory response removal, V1.1, Collision Avoidance Fast-time Evaluator (CAFÉ), Raynaud, B., Drevillon, H., Egis Avia for QinetiQ, Eurocontrol contract No 15220453C, 27th October 2017

[6] Encounter Generator Tool (EGT), User guide, Version 1.6, Collision Avoidance Fast-time Evaluator (CAFÉ), Howell, R., Hutchinson, H., Morton-Orr, T., Lam, C., QinetiQ, Eurocontrol contract No 15220453C, 15th March 2021.

[7] Encounter Generator Tool (EGT), Software Design Document (SDD), Version 1.10, Collision Avoidance Fast-time Evaluator (CAFÉ), Howell, R., Hutchinson, H., Morton-Orr, T., QinetiQ, Eurocontrol contract No 15220453C, 25th March 2021.

[8] Roadmap for European (or global) encounter models, Edition 0.03, Bakker, B., Graner, Y., Safety Nets Project 4.8.1, Single European Sky Air traffic management Research (SESAR) programme, Eurocontrol/European Commission, 8th August 2014.

[9] European safety encounter model incorporating Very Light Jet operations, Issue 1.1, Hutchinson, H., Airborne Collision Avoidance System (ACAS) on Very light Jets and Light Jets – Assessment of safety Level (AVAL), 13th May 2009

[10] Performance and safety Aspects of Short-term Conflict Alert – full Study (PASS) Final report – Synthesis and Guidelines, V1.1, 17th November 2010.

7 Acknowledgements

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DGAC, France

DSNA, France

Egis Avia, France

FAA, USA

Honeywell, Czech Republic

Johns Hopkins University, USA

Lincoln Laboratory, USA

MUAC, Netherlands

NATS, UK

PANSA, Poland

Polytechnic University of Catalonia

QinetiQ, UK

Saab, Sweden

Skyguide, Switzerland

Stanford University, USA

Thales, France

Appendix A Aircraft performance modelling

A.1 CREME aircraft class derivation from BADA types

BADA or Base of Aircraft Data, is the Eurocontrol database of aircraft performance. The BADA model parameters are calculated using aircraft manufacturers' performance data.

For the purpose of CREME, data from BADA Family 3 version 15 original aircraft models was used to compute the encounter speed boundaries. BADA 3.15 (2018) covers 99.97% of the European air traffic. The 250 original aircraft models account for 96.78%, while 1159 synonym aircraft account for 3.19% of the traffic. The remaining traffic share is composed of special designators that cannot be modelled in BADA (0.03%).

The CREME performance classes are defined following three criteria:

(1) Type of engine
(2) Maximum mass
(3) Minimum mass

A Matlab algorithm matches each BADA aircraft type to the relevant CREME performance class based on the criteria above (Table 10).

Table 10 Mapping of CREME aircraft performance classes to BADA aircraft types

CREME Class	Engine type	Mass range (tonnes)	Number of mapped BADA aircraft types
1	Piston	All	47
2	Turboprop	0 - 5.7	20
3	Turboprop	5.7 - 15	15
4	Turboprop	>=15	22
5	Jet	All	CREME special military class
6	Jet	5.7 - 15	25
7	Jet	15 - 100	69
8	Jet	>=100	41
9	Jet	0 – 5.7	10

For each aircraft type, BADA includes the following fields:

- v_mo: Maximum operating Indicated Air Speed (IAS) in knots at Mean Sea Level (MSL)
- m_mo: Maximum operating Mach at MSL
- h_mo: Maximum operating altitude

- v_stall_cr: Operational stall IAS in knots with cruise configuration at MSL
- v_stall_ap: Operational stall IAS in knots with approach configuration at MSL
- v_stall_id: Operation stall IAS in knots with landing configuration at MSL

CREME True Air Speed (TAS) envelopes were calculated using the following steps:

1) Select the BADA aircraft types relevant to the CREME class.
2) Apply normal distribution and filter outliers.
3) Convert minimum and maximum speeds into TAS for each layer.

A.2 Estimating CREME speed limits

Each BADA aircraft type has a specific flight envelope. Several BADA types correspond to a single CREME aircraft class. CREME aircraft class speed limits were estimated by averaging over the corresponding BADA aircraft types. The graph below (Figure 46) shows the distribution of minimum operating speed in clean configuration at MSL – referenced as **v_stall_cr** in the BADA data frame – of the class 7 (turbojet ranging from 15 to 100 tonnes) population:

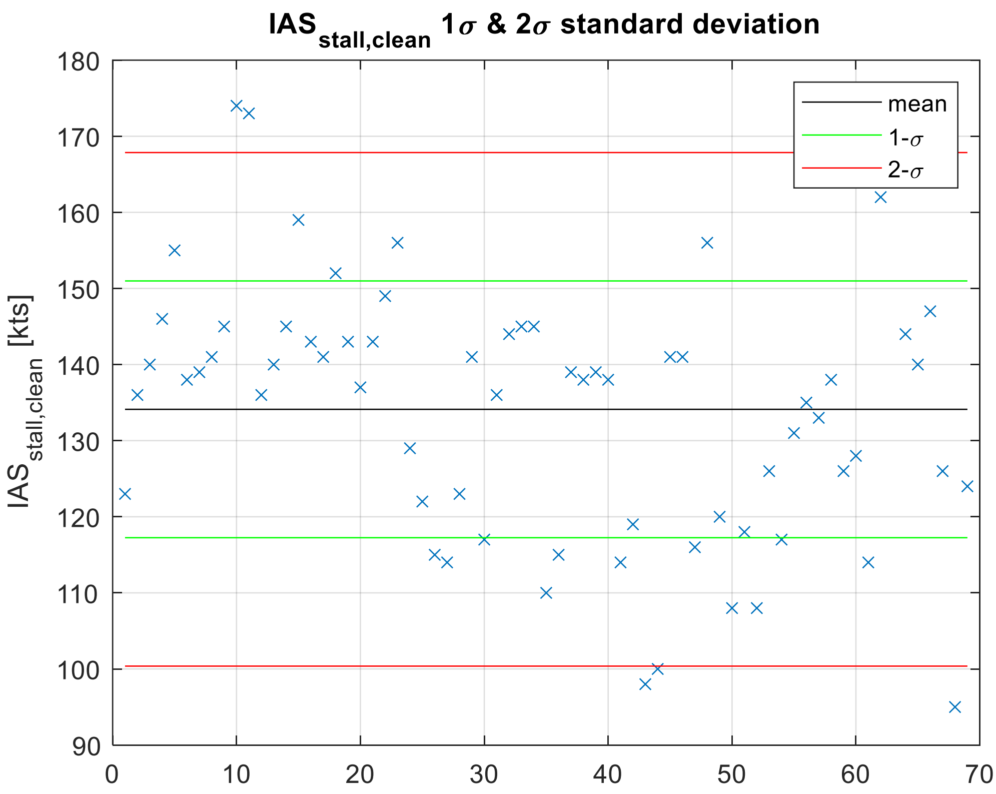

Figure 46 Distribution of class 7 stall speed in clean configuration

Applying a normal distribution to the dataset, the distribution's characteristics are:

$$\mu_{v_{stall_{cr}},7} = 134.11\ kts$$

$$\sigma_{v_{stall_{cr}},7} = 16.9\ kt$$

For the same class, the maximum speed distribution in clean configuration at MSL – referenced as **v_mo_cr** in BADA data frame – is as follows (Figure 47):

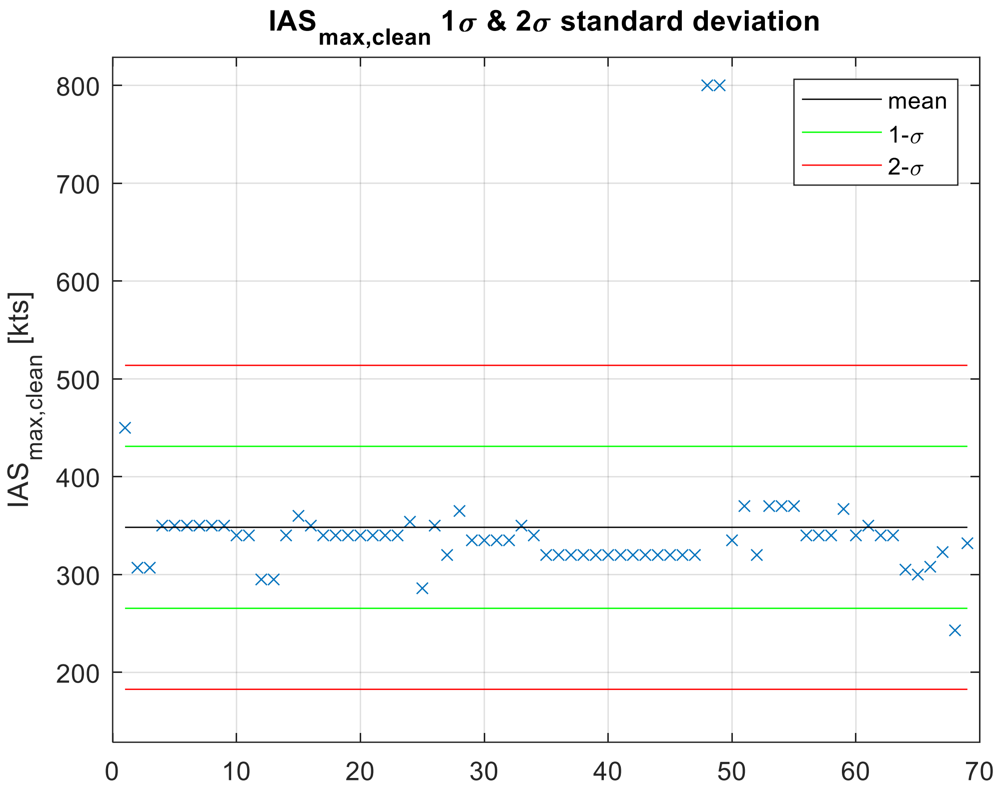

Figure 47 Distribution of class 7 maximum speed in clean configuration

with the characteristics:

$$\mu_{v_{mo_{cr}},7} = 348.29\ kt$$
$$\sigma_{v_{mo_{cr}},7} = 82.78\ kt$$

The larger standard deviation is explained by the outliers present in the population.

Only the subset within 1-sigma level was considered to determine the speed envelope. Filtering the data outside this decision threshold allows the outliers to be removed and especially those with extreme performance differences used by the military.

The mean value of the 1-sigma subset is then calculated for each characteristic speeds (v_mo, m_mo, v_stall_cr, v_stall_ap, v_stall_ld):

$$v_\sigma = mean(v_i)\ \forall i \in \{index\ of\ \sigma\ subset\}$$

The resulting 1-sigma mean speeds are taken as the reference Indicated Air Speeds for the CREME aircraft class:

$$Envelope_n = \{v_{\sigma,mo,n}, m_{\sigma,mo,n}, v_{\sigma,stall\ cr,n}, v_{\sigma,stall\ ap,n}, v_{\sigma,stall\ ld,n}\}$$

where: $n \in \{1,9\}$ is the class number.

BADA IAS was converted to CREME TAS using standard atmosphere and assuming negligible difference between Calibrated Air Speed and IAS.

The CREME layers are defined by altitude ranges. Within each layer, the reference speeds are converted into TAS on ten equally spaced intervals. The mean value of this set is then calculated and used as the reference speed for that particular layer.

BADA specifies speeds as a function of flap configurations: Landing < 3,000 feet; 3,000 feet < Approach < 8,000 feet; and Clean > 8,000 feet. A specific algorithm was used to map these to CREME layers.

A specific algorithm also calculates the crossover altitude and switches between maximum operational IAS to the maximum operational Mach. To determine the crossover altitude, it is assumed that the aircraft is flying in the International Standard Atmosphere (ISA) with no temperature deviation.

Appendix B Encounter output format

The Flight Track Data format FTD format contains an initial header, indicated by a line containing "HEADER".

The content of the header is:

- Encounter information stored in the first line of the header: category, number_AC (Table 11).

Table 11 FTD Header general information format

Name	Description
category	Category of the encounter file, which can be one of the following values: • "synthetic": encounter data generated by a model (e.g. CAFE) • "raw": radar tracking data • "radar": radar tracking data • "reconstructed": reconstructed encounter based on radar tracking data
number_AC	Number of aircraft in an encounter, being an integer larger than zero

- Aircraft info (Table 12):

Table 12 FTD Header aircraft information format

Name	Description
AC_tracknumber	Positive integer used to uniquely identify every aircraft in the encounter
mode_S_address	Mode S address (or ICAO 24-bit address) of the aircraft, being a 6-digit hexadecimal number
mode_A_code	Mode A code of the aircraft, being a 4-digit octal number
AC_callsign	Aircraft callsign, being a string
ACAS_version	ACAS version, which is a string with the following options currently supported: • "Unknown" • "Unequipped" • "TCAS II 7.0" • "TCAS II 7.1" • "TCAS II 7.2" • "ACAS Xa 15.2" • "ACAS Xa 15.4"
manual_SL	Manual setting of the ACAS sensitivity level (SL). The following settings are supported: • 0: Automatic, implying that both TAs and RAs are provided; • 1: Standby, implying that no TAs or RAs are provided; • 2: TA only, implying that only TAs are provided.

After the header, the body (indicated by a line with "BODY") contains the encounter info (Table 13):

Table 13 FTD Record format

Name	Description
time	Time stamp in hh:mm:ss.cc format
AC_tracknumber	Aircraft track number, integer larger than zero
X-position	X-position of the aircraft in ENU (East North Up) coordinate system, floating point value in nautical miles
Y-position	Y-position of the aircraft in ENU coordinate system, floating point value in nautical miles
altitude	Altitude of the aircraft, floating point value in feet.
BDS-30	RA information as a subset of BDS-30 downlinked data.

Call-sign (alpha-numeric string) is used to record aircraft number, Performance Class, and Controlled status:

- aircraft 1 non-controlled:
  - performance classes not in use:
    - call-sign = ‘ABCDE’;
  - performance classes in use:
    - call-sign = ‘ABCCZ’ for not-constrained, ‘ABCCA’ for class 1, ‘ABCCB’ for class 2, *etc.*
- aircraft 1 controlled:
  - performance classes not in use:
    - call-sign = ‘ABC123’;
  - performance classes in use:
    - call-sign = ‘ABC000’ for not-constrained, ‘ABC001’ for class 1, ‘ABC002’ for class 2 *etc.*
- aircraft 2 non-controlled:
  - performance classes not in use:
    - call-sign = ‘VWXYZ’;
  - performance classes in use:
    - call-sign = ‘VWXCZ’ for not-constrained, ‘VWXCA’ for class 1, ‘VWXCB’ for class 2, *etc.*
- aircraft 2 controlled:
  - performance classes not in use:
    - call-sign = ‘XYZ123’;

- performance classes in use:
  - call-sign = 'XYZ000' for not-constrained, 'XYZ001' for class 1, 'XYZ002' for class 2 *etc.*