EUROCONTROL

Report on RA Downlink Contingency Tree Study

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Abstract

The carriage of ACAS is mandatory in European airspace, and has been demonstrated to reduce the risk of midair collision through the resolution advisories (RAs) that it issues.

The FARADS programme is assessing the feasibility of downlinking RAs to controllers. Part of the assessment is an investigation of whether downlinking RAs will further reduce the risk of midair collision. The current study has developed a PC based 'contingency tree' tool which, when supplied with accurate event probabilities, will enabled any safety benefit to be evaluated.

Keywords

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1.0	2007-02-04	Internal review
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1.2	2007-05-31	Final version

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EXECUTIVE SUMMARY

Background

Carriage of the Airborne Collision Avoidance System (ACAS) II is mandatory in European airspace. Operational experience and simulation based safety studies have demonstrated that ACAS reduces the risk of midair collision through the resolution advisories (RAs) that are issued when the system diagnoses a risk of imminent collision.

EUROCONTROL's FARADS programme is assessing the feasibility and desirability of downlinking ACAS RAs to the controller's working position. The downlink of ACAS RAs could increase controllers' situational awareness, improve the smooth running of ATC operations, and enhance safety by (among other things) suppressing deleterious interactions between controllers and pilots engaged in response to an ACAS RA.

It is this final aspect, the effect of RA downlink on the ability of ACAS RAs to reduce the risk of midair collision, that forms the subject of the study reported here. The study has developed a PC-based tool which, when populated with accurate probabilities of basic events, will allow the safety benefit, or disbenefit, of RA downlink to be assessed.

ACAS safety studies

Simulation based safety studies, commissioned by EUROCONTROL, have demonstrated the safety benefit that can be expected from the carriage of ACAS in European airspace. These studies used a 'contingency tree' (effectively a fault tree) to conduct full-system safety analyses that considered not only the operation of the ACAS collision avoidance algorithms but also external factors such as instructions from the controller, pilot responses, transponder equippage, surveillance, and visual acquisition.

Current study

The current study takes the contingency tree approach developed in the previous ACAS full-system safety studies as its starting point. The contingency tree has been extended to include: the potential downlink of RAs to the controller's working position; whether the controller subsequently communicates with the pilot; any reaction by the pilot to a controller communication; and the effect of any pilot reaction on the risk of collision.

The risk of midair collision, both when RA downlink is deployed and also without RA downlink, can be evaluated using the contingency tree. These two risks can then be compared to determine whether RA downlink provides a safety benefit compared to the risk of midair collision with ACAS alone.

Contingency tree tool

The contingency tree has been implemented using a purpose built PC-based tool called 'Quercus'. The tool enables contingency trees to be constructed, edited, and evaluated.

The contingency tree takes as its input the probabilities of basic events that are then combined, according to their interdependencies, using logic gates. Thus, the contingency tree performs a large (but essentially simple) probability calculation and outputs the probability of the top-level event – in this case the probability of a midair collision.

Event probabilities

The basic events, whose probabilities form the input to the contingency tree, consist of events defined in the previous ACAS safety studies as well as new events relating to the deployment of RA downlink. The determination of accurate values for the events forms a second part of the study (which has not yet been conducted) and will allow an accurate evaluation of the safety of RA downlink.

Preliminary results

Although accurate values for all the event probabilities are not yet available, a preliminary safety assessment has been conducted using ‘best guesses’ where appropriate.

The result of the preliminary safety assessment is not clear-cut but suggests that there may be a marginal safety benefit from the deployment of RA downlink. However, this nominal benefit could easily be eroded when accurate event probabilities are derived, and may be dependent on the precise details of RA downlink implementation (*e.g.* depending on the specific technology used to implement RA downlink, and on the airspace in which it is deployed).

1. INTRODUCTION

1.1 General

This document has been prepared by QinetiQ and presents the development of the structure of a ‘contingency tree’ with which it will be possible to assess the safety of the downlinking of RA information to controllers.

A potential second phase of the study will provide reliable estimates of the probability of occurrence of the events in the contingency tree so that the safety implications of RA downlink can be quantified.

The document has been developed as part of the EUROCONTROL FARADS programme.

1.2 Background

1.2.1 ACAS

ACAS stands for Airborne Collision Avoidance System and denotes a family of airborne avionics systems that use standard SSR transponder technology to provide a last resort safety-net against the risk of mid-air collision. There are two types of ACAS equipment:

- ACAS I issues Traffic Alerts (TAs) – alerts indicating the presence of another aircraft that might constitute a collision threat; and
- ACAS II issues TAs and in addition can issue vertical Resolution Advisories (RAs) against intruders that are diagnosed as posing a risk of imminent collision.

1.2.2 European mandate

The carriage of ACAS II by all civil fixed-wing turbine-engined aircraft having a maximum take-off mass exceeding 5,700kg or a maximum approved passenger seating configuration of more than 19 is mandatory in ECAC airspace.

ACAS II is standardised in ICAO SARPs [1] and currently the only compliant implementation is the Traffic alert and Collision Avoidance System (TCAS II) Version 7[1] defined in RTCA MOPS [2]. It is this equipment that is considered in this report (and which will generally be referred to simply as ‘ACAS’ for convenience).

[1] Although TCAS II Version 6.04A is permitted in the USA.

1.2.3 Principle of operation of ACAS

ACAS interrogates the Mode C and Mode S transponders of nearby aircraft (‘intruders’) and from the replies tracks their altitude and range.

‘Traffic alerts’ (TAs) alert the pilot to the presence of an intruder that may become a threat to his own aircraft. They are accompanied by an aural annunciation and a change of symbol on a cockpit display of traffic information (CDTI) intended to aid visual acquisition.

‘Resolution advisories’ (RAs) are issued if a diagnosed risk of collision becomes urgent. An RA provides the pilot with advice on how to regulate or adjust his vertical speed so as to avoid a collision. RAs can be displayed in a number of different ways depending on the specific installation (*e.g.* red and green arcs on a vertical speed indicator, or pitch cues on the primary flight display) and are accompanied by an aural annunciation reinforcing the advice provided by the RA display.

The vertical sense of RAs are coordinated with other ACAS II equipped aircraft so that two aircraft choose complementary manoeuvres.

The nominal warning times (*i.e.* time before predicted collision) for TAs range from 20s near the ground to 48s at high altitude, and the warning times for RAs range from 15s at 1,000ft AGL to 35s at high altitude. ACAS does not have the capability to diagnose a near collision course directly, so these alerts are based on calculations of the time remaining should the aircraft be on collision courses: this necessarily implies a high proportion of alerts in encounters where there is no risk of collision.

A very readable guide to the principals, functionality, and operation of ACAS can be found in EUROCONTROLS’s ACAS training brochure (available on-line) [3].

1.2.4 ACAS studies

Safety studies, such as those comprising part of the EUROCONTROL ACASA Project [4], have demonstrated the safety benefit that can be expected as a result of the widespread equipage with ACAS.

The EUROCONTROL ASARP Project [5] has assessed the safety benefits of ACAS above FL285 following the introduction of RVSM into European airspace.

Outputs from both of these studies have been used in the current study.

1.2.5 RA downlink

Complying with an ACAS RA will, in many instances, cause an aircraft to deviate from its ATC clearance. Currently, a controller can only become aware of this deviation if informed by the pilot or by noticing an unexpected variation in the Mode C altitude displayed at his Controller Working Position (CWP). This awareness can occur many seconds after the RA is issued on board the aircraft, engendering a lack of situational awareness in the controller. Controller instructions to manoeuvre in a sense contrary to an ACAS RA are currently commonplace. This is because controllers are not necessarily aware of the sense of any RA (or even that an RA has been issued) and the controller's resolution of a conflict can differ from the ACAS resolution. If a controller instruction that is contrary to an RA is followed the results can be catastrophic, as in the midair collision above Überlingen in 2002 [6].

There are several methods by which information about RAs could be downlinked and provided automatically to controllers in a more timely fashion. In all cases ground-based systems can detect detailed RA information transmitted from aircraft through their Mode S transponders and this information can then be processed and displayed to a controller at his CWP.

The feasibility of doing so is being addressed by the EUROCONTROL FARADS (Feasibility of ACAS RA Downlink Study) project. A crucial aspect in the assessment of any proposed method is the latency of the downlinked information, *i.e.* the time delay between an RA being presented to the pilot and the details of the RA being provided to the controller. The latency of RA downlink was investigated in a previous EUROCONTROL study [7].

1.3 FARADS

The high level European Action Group on ATM Safety (AGAS) [8] recommended a study to determine feasibility of downlinking ACAS RAs for display on controller screens. This led EUROCONTROL to instigate FARADS: the 'Feasibility of ACAS Resolution Advisory Downlink Study'.

The objective of the FARADS is to assess the technical and operational feasibility of displaying ACAS RA information on CWP. Some initial experiments have been conducted with the aim, among other things, of obtaining controller's views on different potential implementations of the RA Downlink concept. These experiments showed that the majority of controllers saw clear operational benefits, including:

- Improved air traffic controller situational awareness by helping them to anticipate aircraft manoeuvres.
- Reduced likelihood of contradictory ATC clearances to the conflict aircraft.
- Reduced risk of follow-up conflicts through better information and planning following the resolution advisory.

Whilst RA Downlink may be technically feasible, it is important that its use is carefully validated prior to implementation. Such validation should include examination of many issues, including:

- Evaluation of different technologies;

- Evaluation of different procedural options;
- Human factors assessment of different display options; and
- Safety impact.

Individual studies within FARADS are addressing all of these issues.

1.4 Structure of the report

The structure of the rest of this report is described below.

Chapter 2 describes full-system safety studies that have previously been performed on the deployment of ACAS. The method of using a contingency tree is introduced and illustrated with a simple example. The ‘Quercus’ tool, which has been adapted for the current study, is briefly described. The concept of ‘risk ratio’ as a safety metric is introduced and its calculation though the use of a contingency tree is described. Finally the important ideas relating to the way that controller and pilot behaviours are represented in the contingency tree are described.

Chapter 3 describes the approach used to develop an RA downlink contingency tree. The assumptions employed in the study are outlined. The division of the current risk according to pilot predilection scenarios is described, so that the introduction of sub-trees at this level determining the effect of RA downlink can be understood.

Chapter 4 describes the RA downlink sub-trees in more detail.

Chapter 5 describes the events in the RA downlink contingency tree: events inherited from the full-system contingency tree, and events new to the RA downlink contingency tree. The way in which the probabilities of key events can characterise different implementations of RA downlink is described.

Chapter 6 describes a preliminary calculation of RA downlink risk ratio to demonstrate the utility of the contingency tree. The areas in which further work is required in order to derive a definitive set of event probabilities are also discussed.

2. FULL-SYSTEM SAFETY STUDIES

2.1 Contingency tree

The current study aims ultimately to make a calculation of the safety (or otherwise) of RA downlink in terms of the risk of mid-air collision. This is a calculation similar in principal to the familiar calculation of the safety of ACAS itself, (the so-called ‘full-system safety’) performed (and led by QinetiQ) in WP1 of the ACASA study [3] and in the ASARP study [5]. Within a given set of assumptions and conditions the probability of a collision is calculated both with and without the deployment of the system of interest. These probabilities are then compared to form a risk ratio (see section 2.3).

The calculation of the overall probability is complex due to the many conditions and dependent event probabilities that must be considered. To set up and evaluate the calculation a structure referred to as a ‘contingency tree’ is used.

In other contexts such a structure is known as a ‘fault tree’ but the term ‘contingency tree’ is preferred here, to emphasise the fact that the undesirable top-level event can occur even though no fault occurs (*i.e.* a collision can occur even though ACAS and other systems operate to their design specification, and controllers and pilots follow the correct procedures once the risk of collision has arisen).

It should be noted that a contingency tree is concerned solely with calculating the probability of the undesirable outcome – it starts by assuming that the undesirable event occurs and then identifies the necessary conditions. Quantifying the probability of these conditions occurring allows the calculation of the probability of the undesirable outcome. Unlike an event tree it does not consider all possible outcomes.

The potential reduction in risk due to the deployment of a given system is analysed by effectively considering two contingency trees: one for the case that the system deployed; and on for the case without the system – in practice this is achieved by a single tree in which the probability that the system is deployed can be set to certainty (*i.e.* the system is present) or zero (*i.e.* the case without the system).

2.1.1 Description[2]

A contingency tree is a device that facilitates the evaluation of a complex probability. The output of the contingency tree is the probability of occurrence of the top-level event that is calculated by combining the probabilities of

[2] The description and the example that follows are taken from the ASARP study [9].

various base-level events. In the current study this top-level event is a mid-air collision.

As the name implies, a contingency tree is a branching structure in which the probability of the top-level event is progressively broken down into combinations of sub-events until base-level events, whose probability is known or can be calculated directly, are reached.

At each node of the tree probabilities on the branches are combined by ‘gates’ and the combined probability is passed up the tree to the next level. Three types of gate are used – ‘**AND**’ gates, ‘**OR**’ gates, and ‘**XOR**’ gates:

- If all of the sub-events must occur for the higher-level event to occur then they are combined with an **AND** gate. The probability of the higher-level event is the product of the probabilities of the sub-events.

$$\text{prob}(a \textbf{ AND } b) = \text{prob}(a)\times\text{prob}(b)$$

- If one, and only one, of the sub-events can occur for the higher-level event to occur then they are combined with an **XOR** gate. The probability of the higher-level event is the sum of the probabilities of the sub-events.

$$\text{prob}(a \textbf{ XOR } b) = \text{prob}(a) + \text{prob}(b)$$

- If any of the sub-events can occur for the higher-level event to occur then they are combined with an **OR** gate. The probability of the higher-level event is the sum of the probabilities of the sub-events minus their cross products.

$$\text{prob}(a \textbf{ OR } b) = \text{prob}(a \textbf{ XOR } b) - \text{prob}(a \textbf{ AND } b)$$

$$\text{prob}(a \textbf{ OR } b) = \text{prob}(a) + \text{prob}(b) - \text{prob}(a)\times\text{prob}(b)$$

In all cases gates with multiple inputs can be evaluated using the relationships:

$$\text{prob}(a \textbf{ AND } b \textbf{ AND } c) = \text{prob}((a \textbf{ AND } b) \textbf{ AND } c)$$

$$\text{prob}(a \textbf{ XOR } b \textbf{ AND } c) = \text{prob}((a \textbf{ XOR } b) \textbf{ XOR } c)$$

$$\text{prob}(a \textbf{ OR } b \textbf{ OR } c) = \text{prob}((a \textbf{ OR } b) \textbf{ OR } c)$$

The **XOR** gate (exclusive **OR**) combines sub-events when only one of the events can occur. The developer of the contingency tree must ensure that the sub-events are mutually exclusive. This is generally achieved by including each of a set of complementary events in the inputs to the **XOR** gate.

If a pair of complementary events are not explicitly provided in the set of events then the complement of an event can be formed by using the **NOT** gate (which takes a single input):

$$\text{prob}(\textbf{NOT}\ a) = 1 - \text{prob}(a)$$

The contingency tree often makes use of the following identity to simplify the structure of the tree, where x and y are complementary events (*i.e.* prob(x) + prob(y) = 1).

$$\text{prob}(x\ \textbf{XOR}\ (a\ \textbf{AND}\ y)) = \text{prob}(x\ \textbf{OR}\ a)$$

Events are decomposed into sub-events until a level is reached at which the probability of the event can be directly calculated by other means. These events are referred to as base-level events.

2.1.2 Simple example

A simple example serves to illustrate the principles and readily allows us to view a contingency in its entirety. All the types of 'gate' by which probabilities can be combined are included in the simple tree shown in Figure 1, which is a screen snapshot from the Quercus tool.

Imagine we wish to determine how likely it is that a certain man's trousers will fall down, on any particular day. This unfortunate event is the top-level event highlighted in Figure 1.

We assume that the man normally keeps his trousers up either by means of a leather belt or by means of a set of elastic braces. If his trousers fall down it will be because either his belt or his braces have failed to keep them up. This is shown by the fact that the top-level event is decomposed into the two events 'Belt fails to prevent embarrassment' and 'Braces fail to prevent embarrassment'. These two sub-events are combined with an **XOR** gate: one or other of the events can occur but not both together – this is because we are assuming that the man does not adopt a belt-and-braces approach to the task of keeping his trousers up.

We must ensure that the probabilities evaluated in the two branches below the top-level event are indeed mutually exclusive. This is achieved by including the event WBTY ('Wearing a belt') on one branch and the complementary event WBTX ('Wearing braces') on the other branch. For the sake of our example let us assume that the man habitually wears braces on Sundays and wears a belt the rest of the week. The probability of 'Wearing a belt' will then be WBTY = 6/7 and the probability of 'Wearing braces' will be the complement of this, *viz.* WBTX = 1/7.

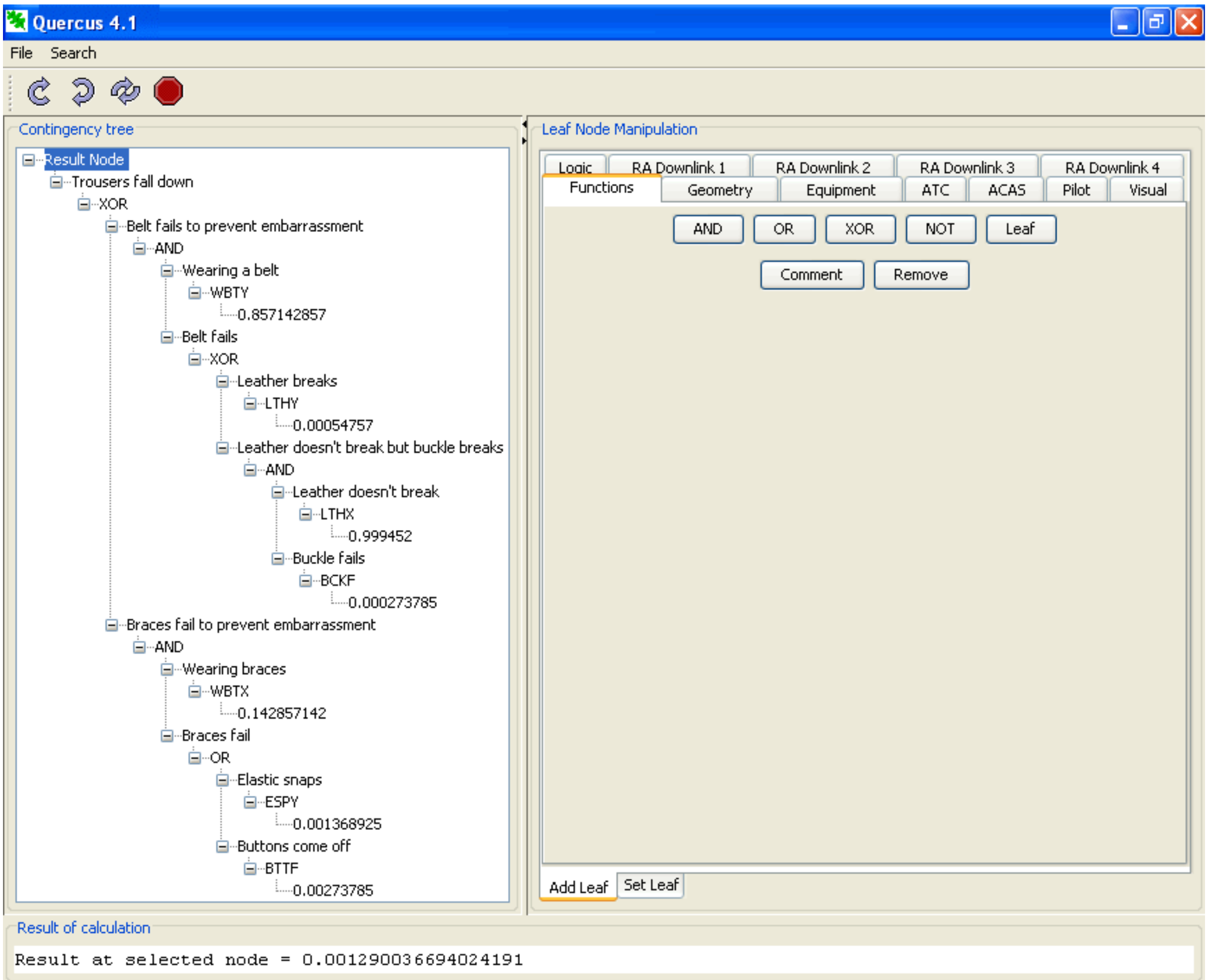

Figure 1: Simple contingency tree (viewed with Quercus tool)

<u>Upper branch – ‘Belt fails to prevent embarrassment’</u>

On the upper branch we must evaluate the probability that the belt fails to keep the trousers up, given that the man is wearing a belt. The first part is achieved by the sub-tree ‘Belt fails’, and the condition that he is wearing a belt is expressed by combining this with the event WBTY through an **AND** gate.

We assume that the belt can fail either because the leather breaks or because the buckle breaks. The probability that either of these events will occur in isolation, on any particular weekday, are LTHY and BCKF respectively. The converse event, that the leather does not break, is LTHX = 1 – LTHY.

There are two possibilities that could result in the belt failing: either the leather breaks (LTHY); or the leather doesn’t break but the buckle fails (BCKF, with the dependent condition that the leather doesn’t break):

prob(Belt fails) = prob(Leather breaks) + prob(Buckle fails | Leather doesn’t break)

The two possibilities are mutually exclusive and are therefore combined through an **XOR** gate. Exclusivity is ensured in the contingency tree by the complementary events LTHY and LTHX on the two branches. The dependent condition is expressed by combining the two events through an **AND** gate. The probability that the belt fails is therefore evaluated in the contingency tree as

prob(Belt fails) = LTHY **XOR** (BCKF **AND** LTHX)

<u>Lower branch – 'Braces to prevent embarrassment'</u>

On the lower branch we must evaluate the probability that the braces fail to keep the trousers up, given that the man is wearing braces. This is achieved by the sub-tree 'Braces fail', and the condition that he is wearing braces is expressed by combining this with the event WBTX through an **AND** gate.

We assume that the braces can fail either because the elastic snaps or because the buttons come off the trousers. The probabilities that either of these events will occur, in isolation, on any particular weekday are ESPY and BTTF respectively. The converse event, that the elastic does not snap, is ESPX = 1 – ESPY.

The situation is analogous to that on the upper branch and the required probability can be expressed as

prob(Braces fail) = prob(Elastic snaps) + prob(Buttons come off | Elastic doesn't snap)

This could be evaluated in the contingency tree using a similar construction to that on the upper branch, thus:

prob(Braces fail) = ESPY **XOR** (BTTF **AND** ESPX)

However, the contingency tree in Figure 1 uses the simpler, and mathematically equivalent, construction:

prob(Braces fail) = ESPY **OR** BTTF

This simpler construction could also be used on the upper branch of the contingency tree in Figure 1.

To complete the example we can use it to calculate an actual value. Four more probabilities are required:

- For the sake of argument assume that the leather of the belt has an average life of five years regardless of whether it is used or not. The probability that the leather will break on any given day is then LTHY = 0.000548.

- Let us assume that the buckle, if used every day, would have an average life of ten years. The probability that the buckle will break on any given day when a belt is worn is then BCKF = 0.000274.

- Let us assume that the elastic has an average life of two years regardless of whether it is used or not. The probability that the elastic will snap on any given day is then ESPY = 0.001369.

- Finally, let us assume that if braces were worn every day at least one button would come off, on average, every year. The probability that a button will come off on any given day when braces are worn is then BTTF = 0.002738.

Combining these probabilities we can calculate the reliability of each method for keeping trousers up. We find that the probability that the belt will fail, when worn, is 0.000821; the probability that the braces will fail, when worn, is 0.004103. Using a belt to keep one's trousers up is therefore almost five times more reliable than using braces.

However, when we combine these reliability values with the frequency with which the man relies on each of the alternative support mechanisms we find that the probability that the belt will let him down is 7.04×10^{-4} whilst the probability that the braces will let him down is 5.86×10^{-4}. Combining these two values gives the overall risk of the trousers falling down each day as 1.29×10^{-3} or once every 2.1 years. Note that although the belt is five times more reliable than braces, if the man's trousers do fall down it is more likely to have been the belt that failed rather than the braces, because he relies on the belt more often.

2.2 Quercus

The contingency tree in the current study has been developed using QinetiQ's Contingency Tree Tool which is known as 'Quercus'[3]. Quercus is a Java application that can be run on any PC hosting the Java Runtime Environment. It allows the development of a contingency tree structure and the evaluation of a contingency tree that uses a specific restricted set of events

Version 4.1 of Quercus was used to develop the contingency tree in the current study. A user guide to Quercus 4.1 is given in [10].

2.3 Risk ratio

As in previous studies, the contingency tree will allow the risk of a collision – the probability, given a specific set of conditions – to be determined. The risk is determined for the case that the system is deployed and is compared with the risk that exists if the system is not deployed. These two risks can then be compared by calculating the risk ratio:

$$\text{risk ratio} = \frac{\text{risk with system deployed}}{\text{risk without system deployed}}$$

[3] From the botanical name of the oak-tree genus.

A risk ratio of zero would indicate that the system is perfect and eliminates the risk of collision; a risk ratio of unity would indicate that the system has no effect on the risk of collision – in practice a beneficial system will have a risk ratio somewhere between these extremes. A risk ratio greater than unity would indicate that the system does positive harm and increases the risk of collision.

It is also possible to partition the risk with the system deployed (and therefore, similarly, the risk ratio) into unresolved risk – circumstances in which the system fails to prevent a collision that would have occurred anyway; and induced risk – circumstances in which the system causes a collision that would not otherwise have occurred.

2.4 Deployment of ACAS

The situation for the deployment of ACAS itself is illustrated by the biliteral Carroll diagram[4] shown in Figure 2. The diagram is divided horizontally into those encounters in which two aircraft are on a collision course (*i.e.* a collision would occur without ACAS) or are not on a collision course; the diagram is divided vertically into those encounters in which, with ACAS deployed, there is a collision or there is not a collision. Thus the rows represent the precursors of RAs; the columns represent the outcomes of RAs.

	no collision with ACAS	collision with ACAS
not on collision course	A	B
collision course	C	D

Figure 2: Partition of encounters with ACAS

The proportions of encounters in the various regions correspond to the following circumstances:

A : 'safe' encounters

B : collisions induced by ACAS (*i.e.* would not have been a collision without ACAS)

C : collisions resolved by ACAS (*i.e.* would have been a collision without ACAS)

[4] Carroll diagrams are a special case of Venn diagrams and were first developed by Lewis Carroll (the author of *'Alice in Wonderland'*) in [11].

D : collisions unresolved by ACAS (*i.e.* would have been a collision with or without ACAS)

In principle all possible encounters between two aircraft correspond to one of the four regions of the diagram; in practice we limit our attention to encounters in which the two aircraft are on ‘a close encounter course’ – encounters (in the absence of ACAS) in which:

- the horizontal miss distance between the two aircraft is sufficiently small that variations in the vertical profiles (such that the vertical separation becomes negligible) could result in a near mid-air collision;

and also in which

- the combined vertical profiles are such an ACAS alert can be expected to occur (assuming nominal equipage and operation of ACAS and related systems).

By limiting our attention to ‘close encounters’ we discard the vast majority of encounters in which there is adequate separation (these encounters form a subset of the encounters in region A and make no contribution to the risk of collision either with or without ACAS). We are left with the encounters in which the aircraft are on a collision course together with those encounters in which the aircraft are not on a collision course but in which variations in the vertical profile could result in a collision.

The regions corresponding to encounters in which there is a collision either with or without ACAS can be identified:

$B + D$: collisions when ACAS is deployed

$C + D$: collisions when ACAS is not deployed

The numbers or rates of collisions corresponding to regions B, C, and D represent absolute measures of the risk, and risk ratios can be derived from them.

The overall risk ratio for ACAS can then be determined as:

$$R_{\text{ACAS}} = \frac{B+D}{C+D}$$

and the induced component as:

$$I_{\text{ACAS}} = \frac{B}{C+D}$$

2.4.1 Simple contingency tree

These calculations can be performed by a simple contingency tree as shown in Figure 3.

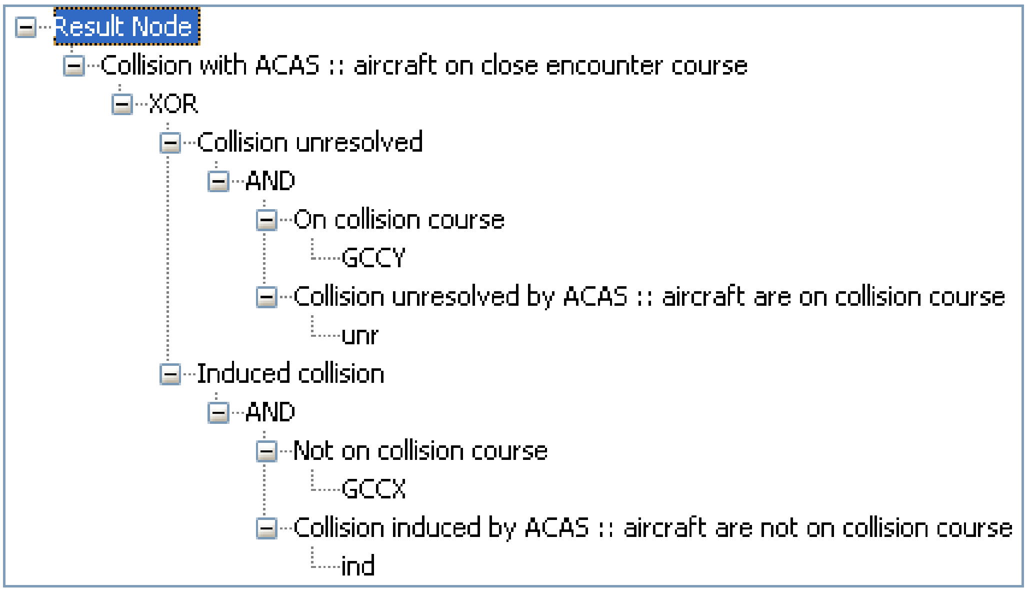

Figure 3: Simple contingency tree

The probability that the aircraft are on a collision course is labelled event 'GCCY'. The probability that the aircraft are not on a collision course is the complement of this and is labelled 'GCCX'. In terms of the number of encounters in the regions of Figure 2 we have:

$$\mathrm{GCCY} = \frac{C + D}{A + B + C + D}$$

$$\mathrm{GCCX} = \frac{A + B}{A + B + C + D}$$

When the aircraft are on a collision course ACAS may fail to resolve the collision: the event 'unr' – the probability that ACAS will fail to resolve a collision given that the aircraft are on a collision course. When the aircraft are not on a collision course ACAS may nevertheless induce a collision that would not otherwise have occurred: the event 'ind' – the probability that ACAS will induce a collision given that the aircraft are not on a collision course.

The calculation performed by the simple contingency tree is:

$$\mathrm{risk} = (\mathrm{unr} \times \mathrm{GCCY}) + (\mathrm{ind} \times \mathrm{GCCX})$$

When ACAS is not deployed it is certain that encounters in which the aircraft are on a collision course will be unresolved (unr = 1), and in no encounters in which the aircraft are not on a collision course will a collision be induced (ind = 0). The resultant risk of collision calculated by the contingency tree is simply GCCY (the probability that the aircraft are on a collision course):

$$\text{risk (no ACAS)} = \left(1 \times \frac{C+D}{A+B+C+D}\right) + \left(0 \times \frac{A+B}{A+B+C+D}\right) = \frac{C+D}{A+B+C+D}$$

When ACAS is deployed it can be seen from Figure 2 that the probabilities of the events ‘unr’ and ‘ind’ become:

$$\text{unr} = \frac{D}{C+D}$$

$$\text{ind} = \frac{B}{A+B}$$

The calculation performed by the simple contingency tree is then:

$$\text{risk (ACAS)} = \left(\frac{D}{C+D} \times \frac{C+D}{A+B+C+D}\right) + \left(\frac{B}{A+B} \times \frac{A+B}{A+B+C+D}\right) = \frac{B+D}{A+B+C+D}$$

The risks with and without ACAS can then be compared to give the risk ratio (and confirm that using the contingency tree gives the same result as in section 2.4):

$$R_{\text{ACAS}} = \frac{\text{risk(ACAS)}}{\text{risk(no ACAS)}} = \frac{B+D}{A+B+C+D} \div \frac{C+D}{A+B+C+D} = \frac{B+D}{C+D}$$

2.4.2 Full-system risk ratio

When the only factor determining the risk of unresolved or induced collisions is the operation of ACAS (and the associated pilot response to ACAS alerts) then the partition of encounters shown in Figure 2 can be calculated directly from the output of fast-time computer simulations of the operation of the ACAS collision avoidance algorithms and modelled pilot response, on a representative set of close encounters (*e.g.* a large set of encounters generated by an encounter model, as in the ACASA and ASARP studies).

The risk ratio calculated in this way is known as the ‘logic risk ratio’ and can be calculated straightforwardly without the need for a contingency tree. The logic risk ratio represents the idealised performance of the ACAS logic in isolation.

A calculation of the performance of ACAS that can be expected in practice must also take account of additional factors (beyond just the operation of the ACAS collision avoidance algorithms) to produce what is termed a ‘full-system risk ratio’. These factors modify each of the unresolved and induced inputs to the contingency tree of Figure 3 and it is at this stage that a contingency tree becomes useful. The unresolved and induced contributions are no longer determined by simple proportions, but rather by complex sub-trees that combine the results of ACAS simulations with other factors.

These other factors include:

- the effects of varying equipage and performance of ACAS (including the effects of imperfect tracking, and aircraft with ACAS in TA-only mode);
- varying equipage and performance of Mode C and Mode S transponders (including aircraft that do not report altitude);
- visual acquisition and the possibility that see-and-avoid (prompted by ACAS) will prevent an RA;
- the involvement of ATC and the possibility that a controller will attempt to resolve the encounter when alerted by contact from the pilot of an ACAS equipped aircraft; and
- the behaviour of pilots in contacting ATC and their response to any controller instructions and/or RAs they receive.

The most important of these other factors, for the current study, are the behaviour of controllers and pilots. These are discussed in more detail in the following sections.

2.5 Controller and pilot behaviour

Even in the absence of RA downlink there can be an interaction between the controller and the pilots involved in the encounter. Generally any resolution advisory will be preceded by a traffic alert and this may prompt the pilot or pilots of the ACAS equipped aircraft to contact the controller for advice (these possibilities are handled as events in the contingency tree).

Depending on the controller's involvement in the original encounter, any instructions he issues may have some prospect of resolving the conflict, or not. These possibilities are discussed in more detail in section 2.5.1.

The controller instruction will arrive at the aircraft at about the same time as any ACAS RA is generated and consequently the pilots of ACAS equipped aircraft will potentially be presented with a choice of whether to follow a controller instruction or the RA. The predilection of the pilots to ignore or take note of controller instructions, (in the case of the pilots of ACAS equipped aircraft) to ignore or take note of RAs and there preference when taking note of both, is discussed in section 2.5.3.

The following sections discuss how the controller's and pilots' behaviour are considered in the ACAS contingency trees (and by extension in the RA downlink contingency tree). It should be noted that the possibilities presented here are not intended to represent a chronological sequence of events nor to mimic the thought processes of either the controller or pilots. Rather, the possibilities are handled in a simplified manner to ensure that a logically complete set of outcomes is considered, and that individual events are used whose probabilities can be readily quantified.

2.5.1 Controller behaviour

It is assumed that the same controller is controlling both aircraft (or at least that if two controllers are involved they are in close communication with one another). When considering the efficacy of ACAS itself the controller can be absent or present – when considering the efficacy of RA downlink we are naturally only concerned with the cases where there is a controller.

When the aircraft are on a collision course a controller is either 'involved' or 'not involved'. These conditions are precursors to any RA that might be generated.

- A controller is 'involved' if he is aware of, and unconcerned by, the encounter even though the aircraft are on a collision course – the collision course might be a direct consequence of a recent (incorrect) controller instruction, or the controller may have observed the aircraft flight-paths and (incorrectly) judging the situation to be safe refrained from giving an instruction to resolve the conflict. Thus a controller who is involved may have committed an error of commission or an error of omission. If the controller is involved, ACAS cannot save the day by (via the pilot) alerting the controller, because the controller has already got it wrong[5] – the controller is part of the problem and so he cannot form part of the solution. Any controller instruction given under these circumstances is termed a 'bad CI' in the contingency tree. A bad controller instruction cannot resolve the conflict and following a bad controller instruction results in a collision.

- A controller who is 'not involved' can give a potentially useful instruction if alerted to the situation by contact from at least one of the pilots (prompted by an ACAS traffic alert). Any controller instruction given under these circumstances is termed a 'good CI' in the contingency tree. 'Good' in this context does not mean that the instruction necessarily resolves the conflict, nor that the instruction ought to have been issued: merely that it has been issued under circumstances that give it some prospect of success. When one pilot follows a good controller instruction and the other pilot follows the RA the tree includes a probability factor that a collision occurs. The probability varies depending on whether the controller instruction is consistent with the RA (*i.e.* has the same vertical sense) or not.[6]

[5] Of course, ACAS can save the day by other means.

[6] In the ACASA and ASARP studies it was implicitly assumed that when one pilot followed a good controller instruction and the other pilot followed the RA that a collision could occur only if the

The options for controller instruction are different when the aircraft are not on a collision course. Without ACAS, the controller would not have caused a problem, because the aircraft would be on a collision course if he had. Thus the possibility that the controller is already involved and is part of the problem does not arise. However, the possibility that the pilot responds to an ACAS alert by speaking to the controller still exists, and the consequential controller instruction is treated in the same way as a controller instruction prompted by ACAS when the aircraft are on collision course.

The full-system contingency trees assume that when a controller gives an instruction the instruction is passed to both pilots in the encounter who successfully receive it (whether they act on the instruction is a separate matter discussed in section 2.5.3 below).

2.5.2 Short-term conflict alert

The current study is based on the full-system safety studies of ACAS performed in ACASA [4] and ASARP [5] and therefore, like these previous studies, does not include the operation of short-term conflict alert (STCA). This is for two reasons – the first principled, the second pragmatic:

- if deployed, ACAS (and ACAS RA downlink) need to be safe in their own right without relying on other safety net systems (and indeed there are many airspaces in which STCA is not implemented);
- STCA is not a specific system (but rather a class of systems), which is implemented differently and behaves differently in different airspaces.

Naïvely, one would expect STCA alerts to precede ACAS alerts due to the nominal warning times used by the two systems. In this case the effect of STCA could be incorporated by modifying the probability that the controller was already involved in the ACAS encounter. In practice, we know that STCA alerts may be triggered at about the same time as an ACAS alert, after an RA, or even not at all (see, *e.g.* [12]): consequently a full consideration of STCA would require significant restructuring of the contingency tree producing a degree of complexity that goes beyond the scope of the current study.

2.5.3 Pilot behaviour

Pilots will potentially receive advice as to how to resolve the encounter, from the controller and/or from ACAS. For the purpose of the contingency tree each pilot is assumed to have a predisposed predilection to ignore, or conversely take note of, each piece of advice he may receive. The predilection of each pilot is taken to be independent of the other.

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controller instruction were inconsistent with the RA. This assumption has been relaxed in the current study and a (lower) probability has been included to cover the circumstance that an RA and a consistent controller instruction nevertheless cause a collision.

When the only advice given to a pilot is a controller instruction there is a probability that the pilot will ignore the instruction, or conversely that he will take note of instruction and follow it.

Similarly when the only advice given to a pilot (of an ACAS equipped aircraft) is an RA there is a probability that the pilot will ignore the RA, or conversely will take note of the RA and respond to it.

The full-system safety contingency tree treats these two possibilities independently: that is to say that probability that a pilot will ignore an RA is independent of whether he also receives a controller instruction or not (and vice versa). Consequently the situation can arise where the pilot of an ACAS equipped aircraft is considered to note both a controller instruction and an RA. In this situation, which of the two pieces of advice the pilot complies with is determined by a probability giving the pilot's preference.

The combination of the three events 'pilot ignores/notes controller instruction', pilot notes/ignores RA', and 'pilot prefers CI to RA/prefers RA to CI' gives five possible pilot predilections resulting in three possible behaviours depending on what advice (controller instruction and/or RA, or neither) the pilot receives. The three possible behaviours (for an ACAS equipped aircraft) are shown in Table 1 and are: that a pilot takes no action; follows the controller instruction; or responds to the RA.

label	pilot predilection	no advice	CI only	RA only	CI and RA
0	ignores RA, ignores CI	no response	no response	no response	no response
1	ignores RA, follows CI	no response	follows CI	no response	follows CI
2	responds to RA, ignores CI	no response	no response	responds to RA	responds to RA
3	notes RA, notes CI, prefers CI	no response	follows CI	responds to RA	follows CI
4	notes RA, notes CI, prefers RA	no response	follows CI	responds to RA	responds to RA

Table 1: Pilot behaviour in the full-system contingency tree (ACAS aircraft)

The only advice the pilot of an unequipped aircraft can receive is from the controller. This reduces the predilections we need to consider to just two (the pilot ignores any controller instruction, or conversely follows the instruction). There are two possible behaviours (for an unequipped aircraft: a pilot takes no action; or follows the controller instruction) and these are shown in Table 2.

label	pilot predilection	no advice	CI only
0	ignores CI	no response	no response
1	follows CI	no response	follows CI

Table 2: Pilot behaviour in the full-system contingency tree (unequipped aircraft)

3. RA DOWNLINK SAFETY STUDY

3.1 Assumptions

The current study of the safety of RA downlink takes as its starting point the contingency trees developed to assess the full-system safety of ACAS itself. It therefore inherits certain basic assumptions from those studies, as well as using certain assumptions specific to the current study. These are detailed in sections 3.1.1 and 3.1.2 below.

These assumptions are intended to keep the contingency tree tractable without compromising the accuracy of the calculation. In many cases it might seem that a part of the tree could be split into several sub-trees by relaxing an assumption and considering separate circumstances. However, it should be realised that this does not necessarily mean that a more accurate calculation can be performed if the probabilities of the new events needed to describe the separate circumstances cannot be known with precision.

3.1.1 Basic assumptions

ACAS equipage is assumed in line with the European mandate (*i.e.* carriage of ACAS required by all civil fixed-wing turbine-engined aircraft having a maximum take-off mass exceeding 5,700kg or a maximum approved passenger seating configuration of more than 19). Specifically only TCAS II Version 7 is considered.

It is assumed that all equipment works to specification. In particular, this means that there are no false alerts[7] (and that no errors are introduced into the RA information during the downlinking process).

All the aircraft involved in an encounter are assumed to be under the control of a single controller (or equivalently by controllers in close communication with one another).

In each encounter only the direct interaction of two aircraft is considered. This point is discussed in more detail in section 3.1.2 that follows.

3.1.2 Multiple aircraft incidents

The ACAS collision avoidance logic includes algorithms to deal with the situation in which two or more intruders are simultaneously diagnosed as collision threats.

[7] A ‘false alert’ implies that some aspect of the equipment is not performing to specification. ACAS can routinely generate alerts when there is no risk of collision, but (provided the equipment is performing to specification) these are termed ‘nuisance alerts’.

Such situations in which there is a risk of collision with at least one out of multiple threats are much rarer than the 'normal' case of a collision risk with a single threat (*i.e.* an encounter involving only two aircraft). Specific studies within the ACASA and ASARP studies aimed to assess the efficacy of RAs in multiple threat encounters. The results were encouraging, indicating that true multiple threat encounters were rare [13] and suggesting that ACAS can provide a safety benefit in these situations [14]. However, their very rarity makes a statistically significant analysis difficult and a complete safety study of the efficacy of ACAS RAs in multiple threat encounters has yet to be conducted. Bearing this in mind, the consideration of true multiple threat encounters was considered beyond the scope of the contingency tree studies in ACASA and ASARP and is similarly considered to be beyond the scope of the current study.

However, in common parlance 'multiple RAs' include those incidents where an RA against one threat (which then ceases) is followed closely by a new RA against another threat. Such a sequential RA, in which there is a risk of collision, can be handled by the contingency tree in the same way as the 'normal' case of a collision risk with a single threat.

The 'domino' effect, whereby a pilot reaction to an initial RA or to a communication from the controller (ultimately prompted by an ACAS alert), causes a sequential RA that would not otherwise have occurred, can be taken into account by suitably modifying the probability when a close encounter occurs and the probability that the aircraft are on a collision course given that a close encounter occurs.

3.1.3 Specific assumptions

The current study is concerned with efficacy of downlinking ACAS RAs to controllers. Consequently we are concerned only with those encounters in which at least one of the aircraft generates an ACAS RA, and in which there is a controller.

These conditions restrict the scope of the RA downlink safety study compared to the ACAS full-system safety and are implemented by assuming:

- there is always a controller;
- at least one of the aircraft in each encounter is ACAS equipped;
- all aircraft are equipped with a transponder capable of reporting altitude;
- all aircraft transponders report altitude;
- visual acquisition (prompted by an ACAS alert) fails to prevent the occurrence of an RA.

Other aspects of the full-system safety studies of ACAS still apply – effectively we are limiting our attention to instrument meteorological conditions in controlled airspace in which airborne systems (*i.e.* ACAS and altitude reporting transponders) are operated as intended.

Further assumptions need apply to only one of the aircraft in potentially coordinated encounters (encounters in which both aircraft are ACAS equipped), but for simplicity are applied to all ACAS aircraft:[8]

- all ACAS equipped aircraft operate in full RA mode (*i.e.* no ACAS aircraft operate ACAS in TA-only mode – only 0.5% of ACAS equipped aircraft were assumed to be in TA-only mode in the ASARP study);

- all ACAS equipped aircraft successfully track altitude reporting (*i.e.* all) intruders (only 0.5% of ACAS equipped aircraft were assumed to not track an altitude reporting Mode S intruder in the ASARP study).

In view of the timescale on which RA downlink might be introduced and the impending requirement for the carriage of Mode S, it is assumed that transponder equipped (*i.e.* all) intruders are equipped with Mode S.

A pilot's predilection to comply with a controller instruction (or to respond to an RA) is assumed to be the same with regard to an initial controller instruction (resulting from contact from one or both of the pilots prompted by an ACAS alert) and a subsequent controller instruction prompted by RA downlink.

Other assumptions will make more sense when detailed in context and will be introduced as the appropriate part of the RA downlink contingency tree is expounded.

3.2 Deployment of RA downlink

The current study is aimed at assessing the direct effect of RA downlink on the risk of collision in conflicts between aircraft: the manner in which RA downlink can affect the interaction between controller and pilot, and thence the behaviour of the pilot in situations in which there is potentially an immediate risk of midair collision.

The starting point for the current study is the full-system safety contingency tree (described in section 2) which calculates the current risk of collision given the deployment of ACAS.

The introduction of RA downlink can be represented by developing the Carroll diagram used in section 2.4 (see Figure 2) as shown in Figure 4. Each of the four regions in Figure 2 is split in two depending on whether a collision occurs with RA downlink (subscript '1') or not (subscript '0'): the four regions at the

[8] It is known from analyses performed in the ASARP study that these assumptions have a nugatory effect (less than 1%) on the estimate of the base-line risk with ACAS and yet they considerably reduce the complexity of the contingency tree.

centre of the diagram represent those circumstances in which a collision occurs with RA downlink.

A_1 : collision induced by RA downlink

B_1 : ACAS induced collision unresolved by RA downlink

C_1 : encounter resolvable by ACAS but collision caused by RA downlink

D_1 : encounter not resolved by ACAS nor by RA downlink

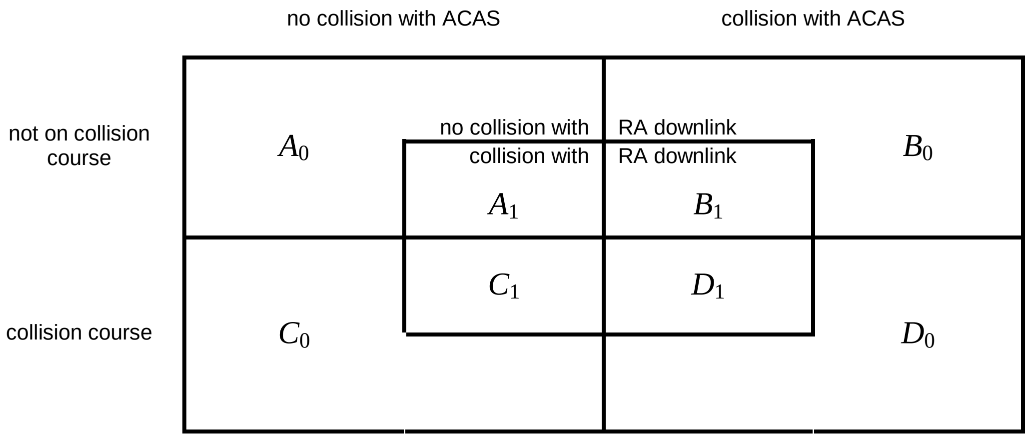

Figure 4: Partition of encounters with ACAS and RA downlink

The efficacy of the entire system (ACAS + RA downlink) can be determined by comparing the risk of collision with RA downlink ($A_1 + B_1 + C_1 + D_1$) with the risk of collision without ACAS ($C + D$), thus:

$$R_{\text{TOTAL}} = \frac{A_1 + B_1 + C_1 + D_1}{C + D}$$

However, the efficacy of RA downlink is determined by comparing the risk of collision with RA downlink not with the risk of collision without ACAS, but rather by making the more demanding comparison to the risk of collision with ACAS but without RA downlink ($B + D$).

The risk ratio for RA downlink can then be determined as:

$$R_{\text{RADL}} = \frac{A_1 + B_1 + C_1 + D_1}{B + D}$$

and the induced component as:

$$I_{\text{RADL}} = \frac{A_1 + C_1}{B + D}$$

Note that the risk ratio for the entire system is the product of the individual risk ratios for the initial deployment of ACAS and then the subsequent deployment of RA downlink:

$$R_{\text{TOTAL}} = R_{\text{ACAS}} \times R_{\text{RADL}}$$

Thus it can be seen that even though ACAS with RA downlink may reduce the overall risk of collision (*i.e.* $R_{\text{TOTAL}} < 1$), the risk ratio for RA downlink might still be disadvantageous (*i.e.* $R_{\text{RADL}} > 1$, and therefore $R_{\text{TOTAL}} > R_{\text{ACAS}}$).

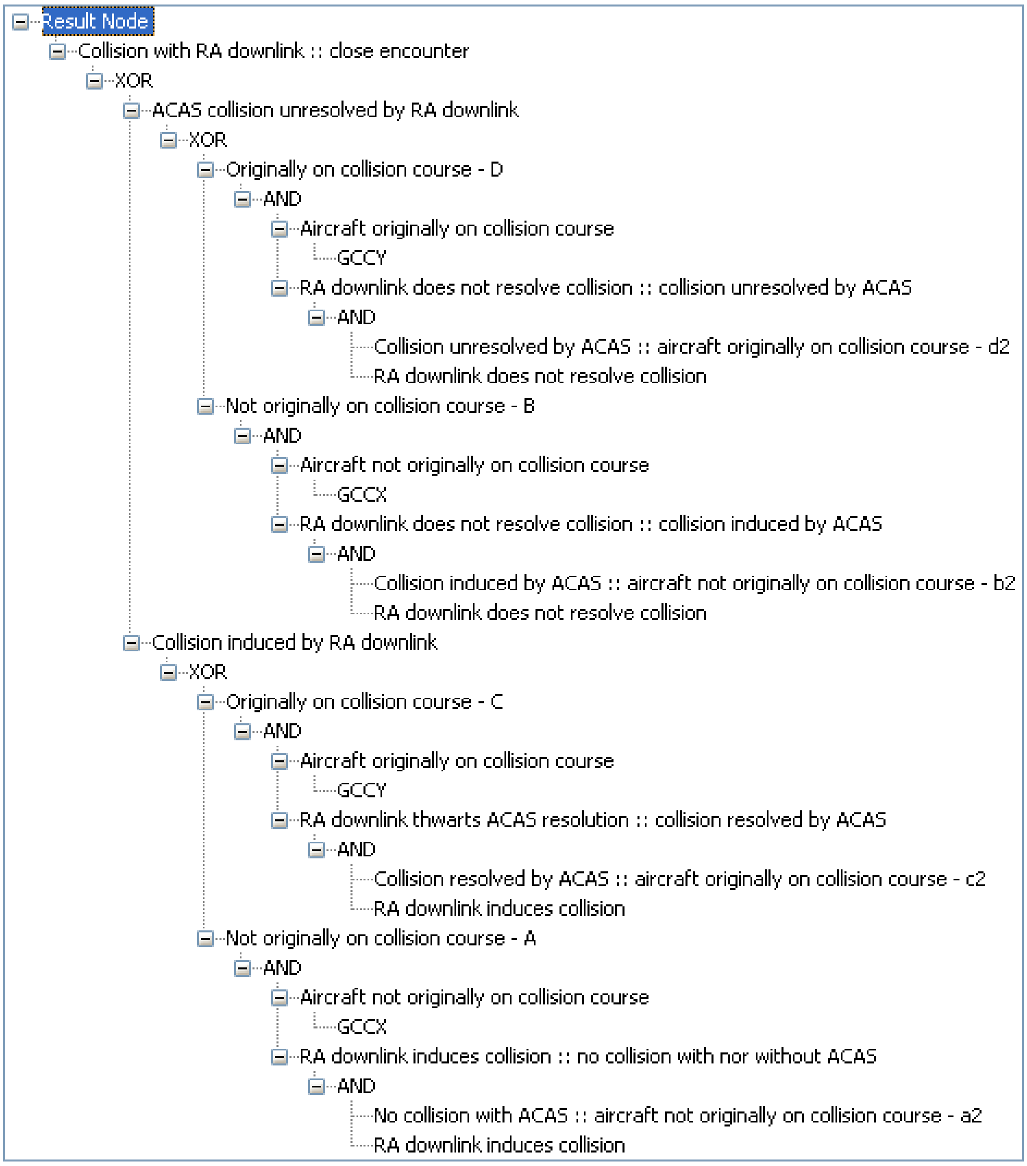

Figure 5: High-level contingency tree for RA downlink

3.3 High-level contingency tree

A simplified high-level contingency tree for evaluating the risk of collision with RA downlink is shown in Figure 5. The risk of collision is partitioned into the four mutually exclusive cases of section 2.4 (*A*, *B*, *C*, and *D*).

The branches corresponding to cases *B* and *D* calculate the risk unresolved by RA downlink, and the branches corresponding to cases *A* and *C* calculate the risk induced by RA downlink.

When RA downlink is not deployed it cannot resolve a collision that occurs with ACAS (prob[RA downlink does not resolve collision] = 1); similarly it cannot induce a collision (prob[RA downlink induces collision] = 0). Implementing these probabilities effectively prunes off the *A* and *C* branches of the simplified contingency tree, leaving just the *D* and *B* branches which represent the current risk of collision with the deployment of ACAS alone.

The branch labelled d_2 calculates the probability that ACAS will not resolve a collision when the aircraft are on a collision course; the branch labelled b_2 calculates the probability that ACAS will induce a collision when the aircraft are not on a collision course. These are the risks calculated in the full-system contingency tree, which now constitute the conditions under which we wish to determine the probabilities that RA downlink will not resolve an ACAS collision.

The c_2 branch calculates the probability that ACAS will resolve a collision when the aircraft are on a collision course; the a_2 branch calculates the probability that there is no collision induced by ACAS when the aircraft are not on a collision course. These probabilities are not calculated directly by the full-system contingency tree (since they constitute collisions successfully avoided) but they can be determined as they are the complements of the probabilities evaluated at d_2 and at b_2 respectively. These outcomes constitute the conditions under which we wish to determine the probabilities that RA downlink will induce a collision.

The high-level contingency tree is a simplification because the probabilities corresponding to the branches labelled a_2, b_2, c_2, and d_2 are not simple events but rather must be represented by sub-trees that allow for the possibilities arising from:

- aircraft equipage – encounters between two ACAS equipped aircraft ('ACAS/ACAS encounter') or between an ACAS equipped aircraft and an aircraft not equipped with ACAS ('ACAS/uneq encounter');
- controller behaviour – when the aircraft are originally on a collision course (c_2 and d_2), 'no controller instruction (CI)', 'bad CI', or 'good CI'; when the aircraft are originally not on a collision course (a_2 and b_2), 'no CI', or 'good CI'; see section 2.5.1);

- pilot behaviour (the pilot predilections described in section 2.5.3 and there combinations which are described in more detail in section 3.4 below).

Each of these sub-trees calculates the risk of an unresolved or induced collision with ACAS given a particular combination of circumstances. Each risk (or its complement) then constitutes the condition under which RA downlink might fail to resolve (or induce) a collision.

The branches are first divided into ACAS/ACAS or ACAS/uneq encounters[9] (as shown for the *D* branch in Figure 6 – branches *A*, *B*, and *C* are similarly divided). These are then sub-divided according to pilot behaviour scenarios (discussed in section 3.4 below). Those scenarios that require it are then further subdivided according to the controller behaviour.

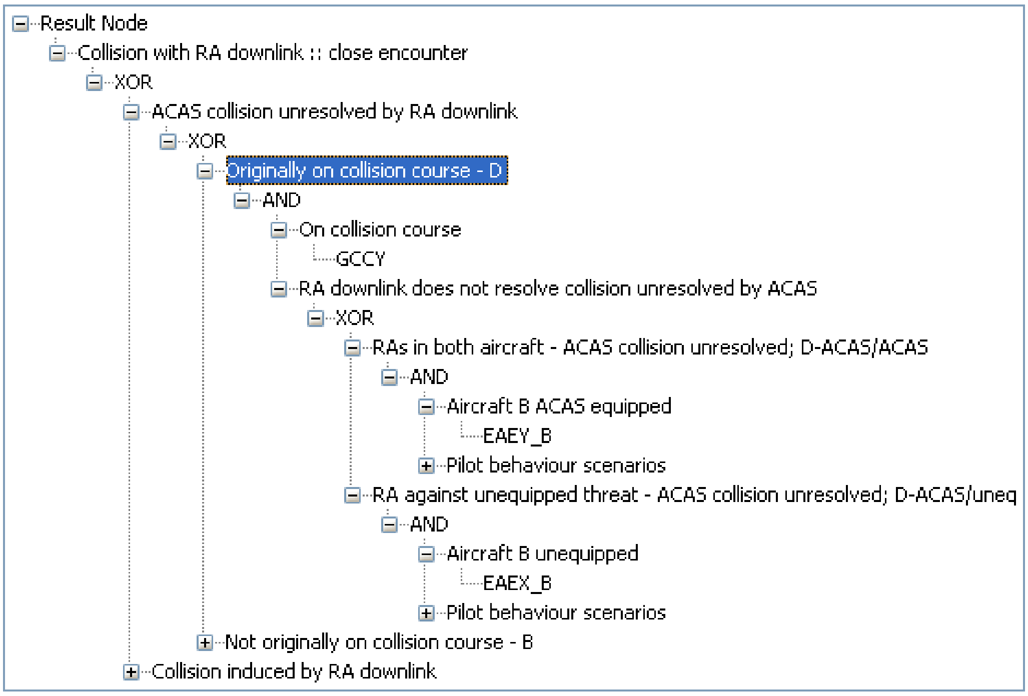

Figure 6: RA downlink tree – '*D*' branch divided according to aircraft equipage

3.4 Pilot behaviour scenarios

Pilot predilections (and the resulting pilot behaviour) as implemented in the full-system contingency tree were described in section 2.5.3.

The pilot predilections in the RA downlink study are slightly simpler because there is always an RA. This means that predilection 4 (notes RA, notes CI,

[9] The two aircraft in each encounter are labelled 'aircraft A' and 'aircraft B' in the contingency tree. In ACAS/uneq encounters we arbitrarily assume (without loss of generality) that it is aircraft A that is ACAS equipped.

prefers RA) results in the same behaviour as predilection 2 (responds to RA ignores CI). The two are effectively equivalent as in both cases the pilot always follows the RA, and so in the RA downlink study predilection 4 has been combined with predilection 2.

The pilot behaviour for each possible predilection in the RA downlink contingency tree is shown in Table 3 (for the pilot of an ACAS equipped aircraft), and in Table 4 (for the pilot of an unequipped aircraft).

label	pilot predilection	RA only	CI and RA
0	ignores RA, ignores CI	no response	no response
1	ignores RA, follows CI	no response	follows CI
2	responds to RA, ignores CI or notes RA, notes CI, prefers RA	responds to RA	responds to RA
3	notes RA, notes CI, prefers CI	responds to RA	follows CI

Table 3: Pilot behaviour in the RA downlink contingency tree (ACAS aircraft)

label	pilot predilection	no advice	CI
0	ignores CI	no response	no response
1	follows CI	no response	follows CI

Table 4: Pilot behaviour in the RA downlink contingency tree (unequipped aircraft)

The RA downlink contingency tree must consider all possible combinations of the predilection of two pilots to give pilot predilection scenarios. This results in 4×4=16 scenarios for ACAS/ACAS encounters and 4×2=8 scenarios for ACAS/uneq encounters. All twenty-four of these scenarios must be considered on each of the *A*, *B*, *C*, and *D* branches, and in each case three or four controller behaviours must also be considered ('no CI', 'good CI – consistent with the RA', and 'good CI – counter to the RA' on the *A* and *B* branches (*i.e.* when the aircraft not originally on a collision course)[10]; 'no CI', 'bad CI', 'good CI – consistent with the RA', and 'good CI – counter to the RA' on the *C* and *D* branches (*i.e.* when the aircraft are originally on a collision course)) to give individual conditions under which we must determine the risk of a collision with RA downlink with a suitable sub-tree. This means that a total of 336 conditions must be included in the RA downlink contingency tree, each potentially with its corresponding RA downlink sub-tree. We will see later that the total number of separate RA downlink sub-trees that must be derived is reduced (to 206) because some sub-trees are trivial whilst others are redundant.

[10] The 'bad CI' case is not considered on the *A* and *B* branches because 'bad CI', by definition, implies that the aircraft are on a collision course.

The scenarios describing combined pilot predilections are labelled by two digits corresponding to the digits of the individual predilections. *E.g.* if in an ACAS/ACAS encounter aircraft A responds to the RA and ignores any controller instruction (predilection 2), while aircraft B notes both the RA and any controller instruction but (when there is one) prefers the controller instruction (predilection 3), then this scenario is labelled ‘23’.

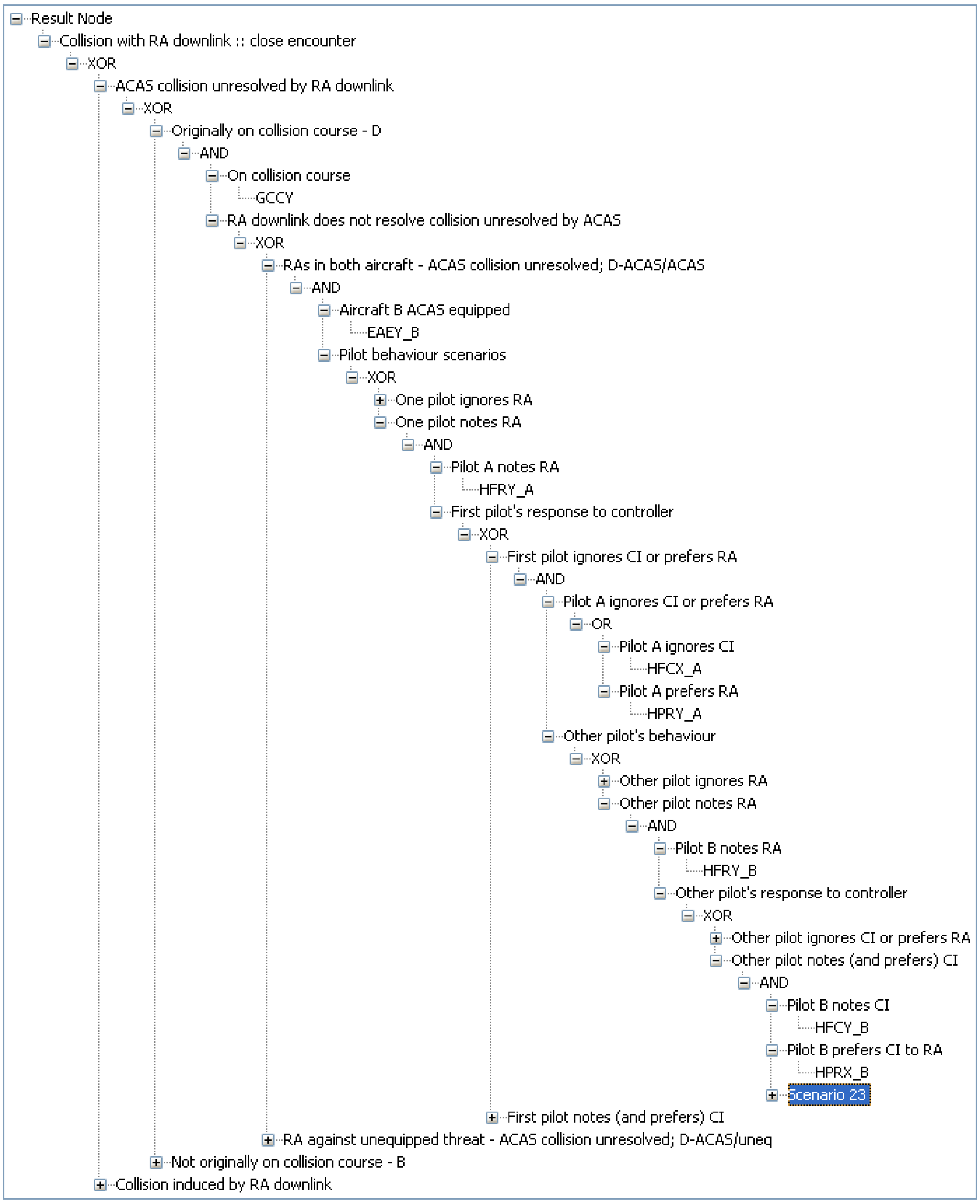

Figure 7: RA downlink tree – ‘D’ branch, ACAS/ACAS encounter, scenario 23

As an illustration the representation of scenario 23 on branch D (ACAS/ACAS) of the RA downlink contingency tree is shown in Figure 7. The tree implements the requirement

('Pilot A notes RA' **AND** ('Pilot A ignores CI' **OR** 'Pilot A prefers RA'))[11]
AND
('Pilot B notes RA' **AND** 'Pilot B notes CI' **AND** 'Pilot B prefers CI to RA')

as

HFRY_A **AND** (HFCX_A **OR** HPRY_A)
AND
HFRY_B **AND** HFCY_A **AND** HPRX_B

We now proceed to describe the pilot behaviours and the resultant risk of collision (with ACAS alone) for all the scenarios in the case of 'no CI' (section 3.4.1), 'bad CI' (section 3.4.2), and 'good CI' (section 3.4.3).

3.4.1 Pilot behaviour – no controller instruction

<u>ACAS/ACAS encounters (no CI)</u>

When there is no controller instruction the pilot of an ACAS equipped aircraft either ignores the RA ('no response') or responds to the RA ('responds to RA').

Consequently there are three possible combinations of pilot behaviour, as shown in Table 5 together with the accompanying risk of collision:

- **'no response / no response'** – neither pilot responds to the RA. When neither pilot responds, the risk of collision remains unchanged. If the aircraft are on a collision course it is certain that the collision will not be resolved; if the aircraft are not on a collision course it is certain that a collision will not be induced:
    - unresolved collision risk = 1
    - induced collision risk = 0
- **'no response / responds to RA'** or **'responds to RA / no response'** – one pilot responds to the RA. When one pilot responds to the RA but the other pilot does not, the collision risk is calculated from ACAS simulations:
    - unresolved collision risk = LTNU
    - induced collision risk = LTNI
- **'responds to RA / responds to RA'** – both pilots respond to the RA. When both pilots respond to the RA, the collision risk is calculated from ACAS simulations:

[11] The demonstration that this expression is equivalent to predilection 2 in Table 3 is left as an exercise for the reader.

- unresolved collision risk = LTTU
- induced collision risk = LTTI

ACAS/uneq encounters (no CI)

When there is no controller instruction the pilot of an ACAS equipped aircraft either ignores the RA ('no response') or responds to the RA ('responds to RA'). The pilot of the unequipped aircraft naturally receives no RA and so does not modify his trajectory ('no response')

Consequently there are two possible combinations of pilot behaviour, as shown in Table 6, together with the accompanying risk of collision:

- **'no response / no response'** – the ACAS pilot does not respond to the RA. When neither pilot responds, the risk of collision remains unchanged. If the aircraft are on a collision course it is certain that the collision will not be resolved; if the aircraft are not on a collision course it is certain that a collision will not be induced:
    - unresolved collision risk = 1
    - induced collision risk = 0
- **'responds to RA / no response'** – the ACAS pilot responds to the RA. When an ACAS pilot responds to the RA in an uncoordinated encounter the collision risk is calculated from ACAS simulations:
    - unresolved collision risk = LTSU
    - induced collision risk = LTSI

3.4.2 Pilot behaviour – bad controller instruction

A 'bad' controller instruction implies that the controller is already involved and that the aircraft are on a collision course (see section 2.5.1). Consequently scenarios in which there is a bad CI contribute only to the unresolved risk with ACAS alone; they make no contribution to the induced risk.

ACAS/ACAS encounters (bad CI)

When there is a bad controller instruction the pilot of an ACAS equipped aircraft either ignores the RA ('no response'), responds to the RA ('responds to RA'), or follows the controller instruction ('follows CI').

Consequently there are six possible combinations of pilot behaviour, as shown in Table 7 together with the accompanying risk of collision:

- **'no response / no response'** – neither pilot responds to the RA nor to the controller instruction. When neither pilot responds, the risk of collision remains unchanged. If the aircraft are on a collision course it is certain that the collision will not be resolved:

- o unresolved collision risk = 1

- **'no response / follows CI'** or **'follows CI / no response'** – one pilot ignores both the RA and the controller instruction while the other pilot follows the controller instruction. The aircraft are on a collision course and the controller instruction is 'bad' (*i.e.* is unable to resolve the collision):
  - o unresolved collision risk = 1

- **'no response / responds to RA'** or **'responds to RA / no response'** – one pilot ignores both the RA and the controller instruction while the other pilot responds to the RA. When one pilot responds to the RA but the other pilot does not, the collision risk is calculated from ACAS simulations:
  - o unresolved collision risk = LTNU

- **'follows CI / follows CI'** – both pilots follow the controller instruction. The aircraft are on a collision course and the controller instruction is 'bad' (*i.e.* is unable to resolve the collision):
  - o unresolved collision risk = 1

- **'follows CI / responds to RA'** or **'responds to RA / follows CI'** – one pilot follows the controller instruction while the other responds to the RA. The controller instruction is 'bad' and responding to it is equivalent to not responding at all (*i.e.* both fail to resolve the collision). Consequently the result of this behaviour is the same as 'no response / responds to RA' above:
  - o unresolved collision risk = LTNU

- **'responds to RA / responds to RA'** – both pilots respond to the RA. When both pilots respond to the RA, the collision risk is calculated from ACAS simulations:
  - o unresolved collision risk = LTTU

ACAS/uneq encounters (bad CI)

When there is a bad controller instruction the pilot of an ACAS equipped aircraft either ignores the RA ('no response'), responds to the RA ('responds to RA'), or follows the controller instruction ('follows CI'). The pilot of the unequipped aircraft receives no RA and so either does not modify his trajectory ('no response') or follows the controller instruction ('follows CI').

Consequently there are five possible combinations of pilot behaviour as shown in Table 8, together with the accompanying risk of collision:

- **'no response / no response'** – the ACAS pilot ignores both the RA and the controller instruction while the unequipped pilot ignores the controller instruction. When neither pilot responds, the risk of collision remains unchanged. If the aircraft are on a collision course it is certain that the collision will not be resolved:
    - unresolved collision risk = 1
- **'no response / follows CI'** or **'follows CI / no response'** – one pilot ignores the controller instruction (and in the case of an ACAS pilot, ignores the RA) while the other pilot follows the CI. The aircraft are on a collision course and the controller instruction is 'bad' (*i.e.* fails to resolve the collision):
    - unresolved collision risk = 1
- **'responds to RA / no response'** – the ACAS pilot responds to the RA while the unequipped pilot ignores the controller instruction. The collision risk is calculated from ACAS simulations:
    - unresolved collision risk = LTSU
- **'follows CI / follows CI'** – both pilots follow the controller instruction. The aircraft are on a collision course and the controller instruction is 'bad' (*i.e.* fails to resolve the collision):
    - unresolved collision risk = 1
- **'responds to RA / follows CI'** – the ACAS pilot responds to the RA while the unequipped pilot follows the controller instruction. The controller instruction is 'bad' and responding to it is equivalent to not responding at all (*i.e.* both fail to resolve the collision). Consequently the result of this behaviour is the same as 'responds to RA / no response' above:
    - unresolved collision risk = LTSU

3.4.3 Pilot behaviour – good controller instruction

ACAS/ACAS encounters (good CI)

When there is a good controller instruction the pilot of an ACAS equipped aircraft either ignores the RA ('no response'), responds to the RA ('responds to RA'), or follows the controller instruction ('follows CI').

Consequently there are six possible combinations of pilot behaviour, as shown in Table 9 together with the accompanying risk of collision:

- **'no response / no response'** – neither pilot responds to the RA nor to the controller instruction. When neither pilot responds, the risk of collision remains unchanged. If the aircraft are on a collision course it is certain that the collision will not be resolved; if the aircraft are not on a collision course it is certain that a collision will not be induced:
    - unresolved collision risk = 1
    - induced collision risk = 0
- **'no response / follows CI'** or **'follows CI / no response'** – one pilot ignores both the RA and the controller instruction while the other pilot follows the controller instruction. The controller was not previously involved and so there is some prospect of the instruction working. When the aircraft are on a collision course the probability that the controller instruction will work (in the absence of any response to the RA) is expressed by the probability LCWY – the risk of collision is the converse, LCWX. When the aircraft are not on collision course it is assumed that a controller instruction (in the absence of any response to the RA) will not induce a collision:
    - unresolved collision risk = LCWX
    - induced collision risk = 0
- **'no response / responds to RA'** or **'responds to RA / no response'** – one pilot ignores both the RA and the controller instruction while the other pilot responds to the RA. When one pilot responds to the RA but the other pilot does not, the collision risk is calculated from ACAS simulations:
    - unresolved collision risk = LTNU
    - induced collision risk = LTNI
- **'follows CI / follows CI'** – both pilots follow the controller instruction. The controller was not previously involved and so there is some prospect of the instruction working. When the aircraft are on a collision course the probability that the controller instruction will work (in the absence of any response to the RA) is expressed by the probability LCWY – the risk of collision is the converse, LCWX.[12] When the aircraft are not on collision course it is assumed that a controller instruction (in the absence of any response to the RA) will not induce a collision:

[12] In the ACAS full-system safety studies a good controller instruction is assumed to be equally effective when followed by both aircraft as when followed by only one aircraft (when the other aircraft does not respond to an RA).

  - o unresolved collision risk = LCWX
  - o induced collision risk = 0

- **'follows CI / responds to RA'** or **'responds to RA / follows CI'** – one pilot follows the controller instruction while the other pilot responds to the RA. The controller was not previously involved and so there is some prospect of the instruction working. This will depend on whether the controller instruction is consistent with the RA or not. When the controller instruction is consistent with RA we have:[13]

  - o unresolved collision risk = LRYU
  - o induced collision risk = LRYI

  When the controller instruction is counter to RA we have:

  - o unresolved collision risk = LRXU
  - o induced collision risk = LRXI

- **'responds to RA / responds to RA'** – both pilots respond to the RA. When both pilots respond to the RA, the collision risk is calculated from ACAS simulations:

  - o unresolved collision risk = LTTU
  - o induced collision risk = LTTI

<u>ACAS/uneq encounters (good CI)</u>

When there is a good controller instruction the pilot of an ACAS equipped aircraft either ignores the RA ('no response'), responds to the RA ('responds to RA'), or follows the controller instruction ('follows CI'). The pilot of the unequipped aircraft receives no RA and so either does not modify his trajectory ('no response') or follows the controller instruction ('follows CI').

Consequently there are five possible combinations of pilot behaviour as shown in Table 10, together with the accompanying risk of collision:

- **'no response / no response'** – the ACAS pilot does not respond to the RA. When neither pilot responds, the risk of collision remains unchanged. If the aircraft are on a collision course it is certain that the collision will not be resolved; if the aircraft are not on a collision course it is certain that a collision will not be induced:

  - o unresolved collision risk = 1

[13] It is implicitly assumed in the ACAS full-system studies that a controller instruction followed by one aircraft, that is consistent with the RA followed by the other aircraft, will not result in a collision (*i.e.* LRYU = 0, and LRYI = 0). That implicit assumption has been relaxed in the current study.

  - induced collision risk = 0

- **'no response / follows CI'** or **'follows CI / no response'** – one pilot ignores the controller instruction (and in the case of an ACAS pilot, ignores the RA) while the other pilot follows the CI. The controller was not previously involved and so there is some prospect of the instruction working. When the aircraft are on a collision course the probability that the controller instruction will work (in the absence of any response to the RA) is expressed by the probability LCWY – the risk of collision is the converse, LCWX. When the aircraft are not on collision course it is assumed that a controller instruction (in the absence of any response to the RA) will not induce a collision:

  - unresolved collision risk = LCWX

  - induced collision risk = 0

- **'responds to RA / no response'** – the ACAS pilot responds to the RA while the unequipped pilot ignores the controller instruction. The collision risk is calculated from ACAS simulations:

  - unresolved collision risk = LTSU

  - induced collision risk = LTSI

- **'follows CI / follows CI'** – both pilots follow the controller instruction. The controller was not previously involved and so there is some prospect of the instruction working. When the aircraft are on a collision course the probability that the controller instruction will work (in the absence of any response to the RA) is expressed by the probability LCWY – the risk of collision is the converse, LCWX. When the aircraft are not on collision course it is assumed that a controller instruction (in the absence of any response to the RA) will not induce a collision:

  - unresolved collision risk = LCWX

  - induced collision risk = 0

- **'responds to RA / follows CI'** – the ACAS pilot responds to the RA while the unequipped pilot follows the controller instruction. The controller was not previously involved and so there is some prospect of the instruction working. This will depend on whether the controller instruction is consistent with the RA or not. When the controller instruction is consistent with RA we have:

  - unresolved collision risk = LRYU

  - induced collision risk = LRYI

  When the controller instruction is counter to RA we have:

- o unresolved collision risk = LRXU
- o induced collision risk = LRXI

3.5 Sub-trees

As mentioned earlier, the collision risk with ACAS alone on the *B* and *D* branches, divided up according to pilot predilection scenarios and controller behaviour, forms the conditions under which we need to determine the risk of a collision with RA downlink by combining each condition with a corresponding sub-tree. Continuing with the example of scenario 23 on branch *D* (ACAS/ACAS), Figure 8 shows: the risk of collision with no controller instruction (LTTU) and the sub-tree (10230)[14] which evaluates the probability that RA downlink will fail to resolve this risk; the risk of collision with a good controller instruction consistent with the RA (LRYU) and the corresponding sub-tree (10231); the risk of collision with a good controller instruction that is counter to the RA (LRXU) and the corresponding sub-tree (10232); and the risk of collision with a bad controller instruction RA (LTNU) and the corresponding sub-tree (10233).

[14] Nomenclature of sub-trees – Each sub-tree is identified by a five digit label: the first digit indicates the branch (1 = *D*, 2 = *B*, 3 = *C*, 4 = *A*); the second digit indicates whether the encounter is coordinated (0) or uncoordinated (1); the third and fourth digits indicate the pilot predilection scenario; the fifth digit indicates the initial controller involvement (0 = no CI, 1 = good CI (consistent with RA), 2 = good CI (counter to RA), 3 = bad CI).

scenario	behaviour of pilot A	behaviour of pilot B	unresolved collision risk	induced collision risk
00	*no response*	*no response*	1	0
01	*no response*	*no response*	1	0
02	*no response*	responds to RA	LTNU	LTNI
03	*no response*	responds to RA	LTNU	LTNI
10	*no response*	*no response*	1	0
11	*no response*	*no response*	1	0
12	*no response*	responds to RA	LTNU	LTNI
13	*no response*	responds to RA	LTNU	LTNI
20	responds to RA	*no response*	LTNU	LTNI
21	responds to RA	*no response*	LTNU	LTNI
22	responds to RA	responds to RA	LTTU	LTTI
23	responds to RA	responds to RA	LTTU	LTTI
30	responds to RA	*no response*	LTNU	LTNI
31	responds to RA	*no response*	LTNU	LTNI
32	responds to RA	responds to RA	LTTU	LTTI
33	responds to RA	responds to RA	LTTU	LTTI

Table 5: Pilot behaviour and risk of collision (ACAS/ACAS) – no CI

scenario	behaviour of ACAS pilot	behaviour of uneq pilot	unresolved collision risk	induced collision risk
00	*no response*	*no response*	1	0
01	*no response*	*no response*	1	0
10	*no response*	*no response*	1	0
11	*no response*	*no response*	1	0
20	responds to RA	*no response*	LTSU	LTSI
21	responds to RA	*no response*	LTSU	LTSI
30	responds to RA	*no response*	LTSU	LTSI
31	responds to RA	*no response*	LTSU	LTSI

Table 6: Pilot behaviour and risk of collision (ACAS/uneq) – no CI

scenario	behaviour of pilot A	behaviour of pilot B	unresolved collision risk
00	*no response*	*no response*	1
01	*no response*	*follows bad CI*	1
02	*no response*	responds to RA	LTNU
03	*no response*	*follows bad CI*	1
10	*follows bad CI*	*no response*	1
11	*follows bad CI*	*follows bad CI*	1
12	*follows bad CI*	responds to RA	LTNU
13	*follows bad CI*	*follows bad CI*	1
20	responds to RA	no response	LTNU
21	responds to RA	*follows bad CI*	LTNU
22	responds to RA	responds to RA	LTTU
23	responds to RA	*follows bad CI*	LTNU
30	*follows bad CI*	no response	1
31	*follows bad CI*	*follows bad CI*	1
32	*follows bad CI*	responds to RA	LTNU
33	*follows bad CI*	*follows bad CI*	1

Table 7: Pilot behaviour and risk of collision (ACAS/ACAS) – bad CI

scenario	behaviour of ACAS pilot	behaviour of uneq pilot	unresolved collision risk
00	*no response*	*no response*	1
01	*no response*	*follows bad CI*	1
10	*follows bad CI*	*no response*	1
11	*follows bad CI*	*follows bad CI*	1
20	responds to RA	*no response*	LTSU
21	responds to RA	*follows bad CI*	LTSU
30	*follows bad CI*	*no response*	1
31	*follows bad CI*	*follows bad CI*	1

Table 8: Pilot behaviour and risk of collision (ACAS/uneq) – bad CI

scenario	behaviour of pilot A	behaviour of pilot B	unresolved collision risk	induced collision risk
00	*no response*	*no response*	1	0
01	*no response*	follows good CI	LCWX	0
02	*no response*	responds to RA	LTNU	LTNI
03	*no response*	follows good CI	LCWX	0
10	follows good CI	*no response*	LCWX	0
11	follows good CI	follows good CI	LCWX	0
12	follows good CI	responds to RA	LRYU/LRXU	LRYI/LRXI
13	follows good CI	follows good CI	LCWX	0
20	responds to RA	*no response*	LTNU	LTNI
21	responds to RA	follows good CI	LRYU/LRXU	LRYI/LRXI
22	responds to RA	responds to RA	LTTU	LTTI
23	responds to RA	follows good CI	LRYU/LRXU	LRYI/LRXI
30	follows good CI	*no response*	LCWX	0
31	follows good CI	follows good CI	LCWX	0
32	follows good CI	responds to RA	LRYU/LRXU	LRYI/LRXI
33	follows good CI	follows good CI	LCWX	0

Table 9: Pilot behaviour and risk of collision (ACAS/ACAS) – good CI

scenario	behaviour of ACAS pilot	behaviour of uneq pilot	unresolved collision risk	induced collision risk
00	*no response*	*no response*	1	0
01	*no response*	follows good CI	LCWX	0
10	follows good CI	*no response*	LCWX	0
11	follows good CI	follows CI	LCWX	0
20	responds to RA	*no response*	LTSU	LTSI
21	responds to RA	follows good CI	LRYU/LRXU	LRYI/LRXI
30	follows good CI	*no response*	LCWX	0
31	follows good CI	follows good CI	LCWX	0

Table 10: Pilot behaviour and risk of collision (ACAS/uneq) – good CI

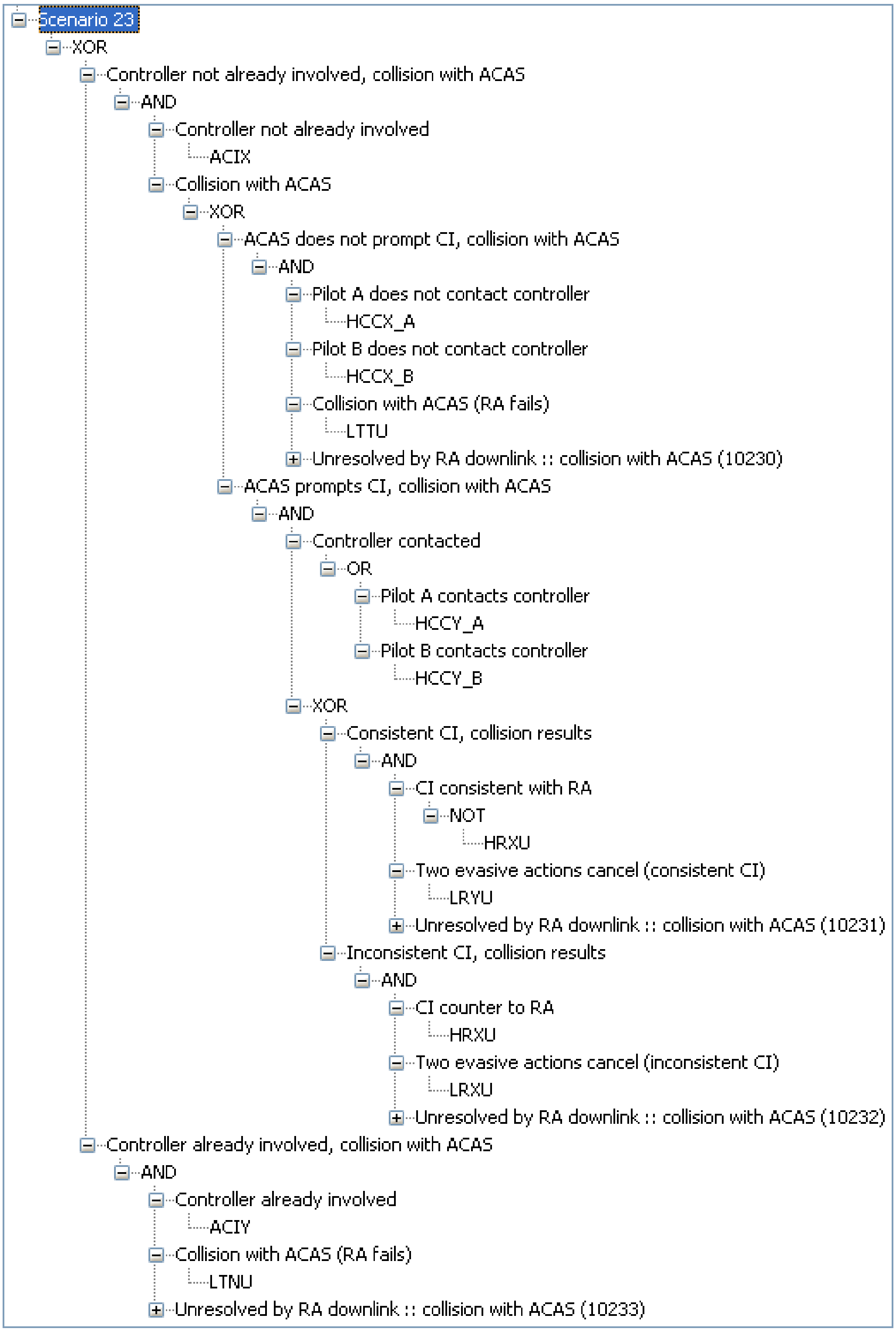

Figure 8: RA downlink tree – '*D*' branch, ACAS/ACAS encounter, scenario 23, risks of collision with ACAS and RA downlink sub-trees

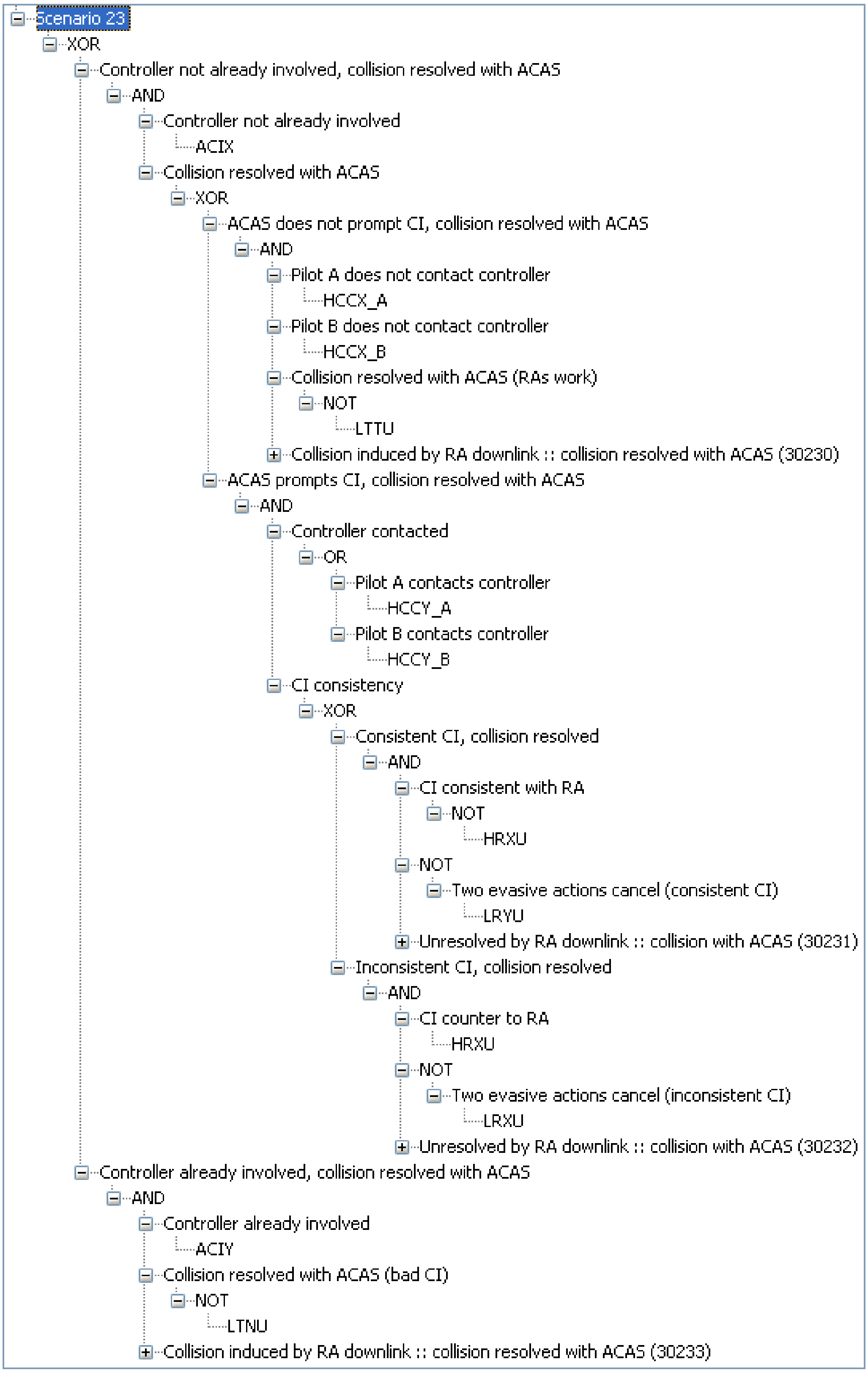

Figure 9: RA downlink tree – '*C*' branch, ACAS/ACAS encounter, scenario 23, risks of collision with ACAS and RA downlink sub-trees

The complementary situations (where there is no risk of collision or ACAS alone resolves the risk of collision) are considered on the *A* and *C* branches. The part of the tree complementary to scenario 23 on branch *D* (ACAS/ACAS) is scenario 23 on branch *C* (ACAS/ACAS) and this is shown in Figure 9. Here we see the probability that the risk of collision is resolved when there is no controller instruction (1 – LTTU) and the sub-tree (30230) which evaluates the probability that RA downlink will induce a collision under such a condition; the probability that the risk of collision is resolved when there is a good controller instruction consistent with the RA (1 – LRYU) and the corresponding sub-tree (30231); the probability that the risk of collision is resolved when there is a good controller instruction that is counter to the RA (1 – LRXU) and the corresponding sub-tree (30232); and the probability that the risk of collision is resolved when there is a bad controller instruction RA (1 – LTNU) and the corresponding sub-tree (30233).

3.5.1 Trivial and redundant sub-trees

A number of the RA downlink sub-trees are trivial to evaluate or do not need to be evaluated at all.

Those pilot predilection scenarios in which both digits in the label are even (*i.e.* scenarios 00, 02, 20, 22), correspond to pilot behaviour in which neither pilot responds to any controller instructions. Consequently, in these scenarios controller communications with the pilots (prompted by RA downlink) will have no effect and the risk of collision will remain unchanged. Therefore on branches *B* and *D* (collision with ACAS alone) the sub-trees will have the value of unity (collision unresolved by RA downlink) and on branches *A* and *C* (no collision with ACAS alone) the sub-trees will have the value of zero (collision not induced by RA downlink).

An examination of Table 5 to Table 10 shows that in a number of scenarios the induced risk is zero, *i.e.* a particular condition cannot occur. Consequently, sub-trees evaluating the performance of RA downlink under these conditions are redundant and need not be considered.

4. RA DOWNLINK SUB-TREES

The conditions under which the performance of RA downlink must be considered, and their representation in the RA downlink contingency tree, have been described in section 3. Each condition is combined with a corresponding RA downlink sub-tree. This section describes the structure of these sub-trees and the factors that are considered by them.

4.1 Controller awareness

The first consideration is whether RA downlink is effective in alerting the controller to the occurrence of an encounter in which an ACAS RA or RAs has been issued to the pilot.

If the controller does not become aware of the downlinked RA then the unresolved risk with RA downlink will be unity, and the induced risk will be zero. That the controller is aware of a downlinked RA is a condition for there to be a risk of collision from the subsequent behaviour of the controller and pilot or pilots.

Three factors determine whether the controller is aware of a downlinked RA:

- Whether RA downlinked is deployed – this is determined by the complementary events DLDY (‘RA downlink deployed’) and DLDX (‘RA downlink not deployed’). This pair of events take the values of zero and unity and act a simple ‘toggle switch’ by which the effect of RA downlink can be turned on or off. When DLDY = 0 there is no RA downlink and the contingency tree returns the risk of collision resulting from the action of ACAS alone (the current situation); when DLDY = 1 RA downlink is included in the calculation and the contingency tree returns the risk of collision resulting from the action of ACAS and RA downlink.

- Whether the alert is downlinked in a timely manner – there is an inevitable delay between the time at which the first RA is generated and the time at which the alert can be displayed at the controller’s working position. This latency can mean that when the alert is displayed to the controller there is insufficient time remaining before the potential collision for the downlink to have any effect on the outcome. The contingency tree includes two pairs of events to represent this probability in ACAS/ACAS encounters (DCTY (‘timely downlink in coordinated encounter’) and its converse, DCTX) and in ACAS/uneq encounters (DUTY (‘timely downlink in uncoordinated encounter’) and its converse, DUTX). As well as a dependency on whether the encounter involves one or two ACAS equipped aircraft this factor will also depend on the airspace in which RA downlink is deployed, the technology used to effect RA downlink, and the manner of display at the CWP (see [6]).

- Whether the controller notices the downlinked RA alert in time to have an effect on the outcome of the encounter – this probability is represented by the event HNDY ('controller notices downlinked alert') and its converse, HNDX. The probability will depend on the controller workload and the manner of display at the CWP.

The manner in which these three events are incorporated into the sub-trees on the *B* and *D* branches is illustrated by sub-tree 10230 in Figure 10.[15] The *A* and *C* branches are concerned only with induced risk and so the 'No prospect of controller message' option is not included on the sub-trees on those branches as illustrated by sub-tree 30230 in Figure 11. In scenario 23 we know that pilot A does not follow any controller instruction (see Table 3) and so the branches labelled 'Change in only pilot A's behaviour, collision results' and 'Change in both pilots' behaviour, collision results' cannot occur and the corresponding probability is set to zero.

[15] The appropriate sub-tree is labelled simply 'No prospect of controller message', meaning that there is no prospect of a controller message which is prompted solely by RA downlink. Whether there is a controller message in the absence of RA downlink is handled at a higher level in the contingency tree. Branch 10320 happens to correspond to the case where there is no controller instruction in the absence of RA downlink; the corresponding cases where there is a controller instruction in the absence of RA downlink are handled on branches 10321 and 10322 (see Figure 8).

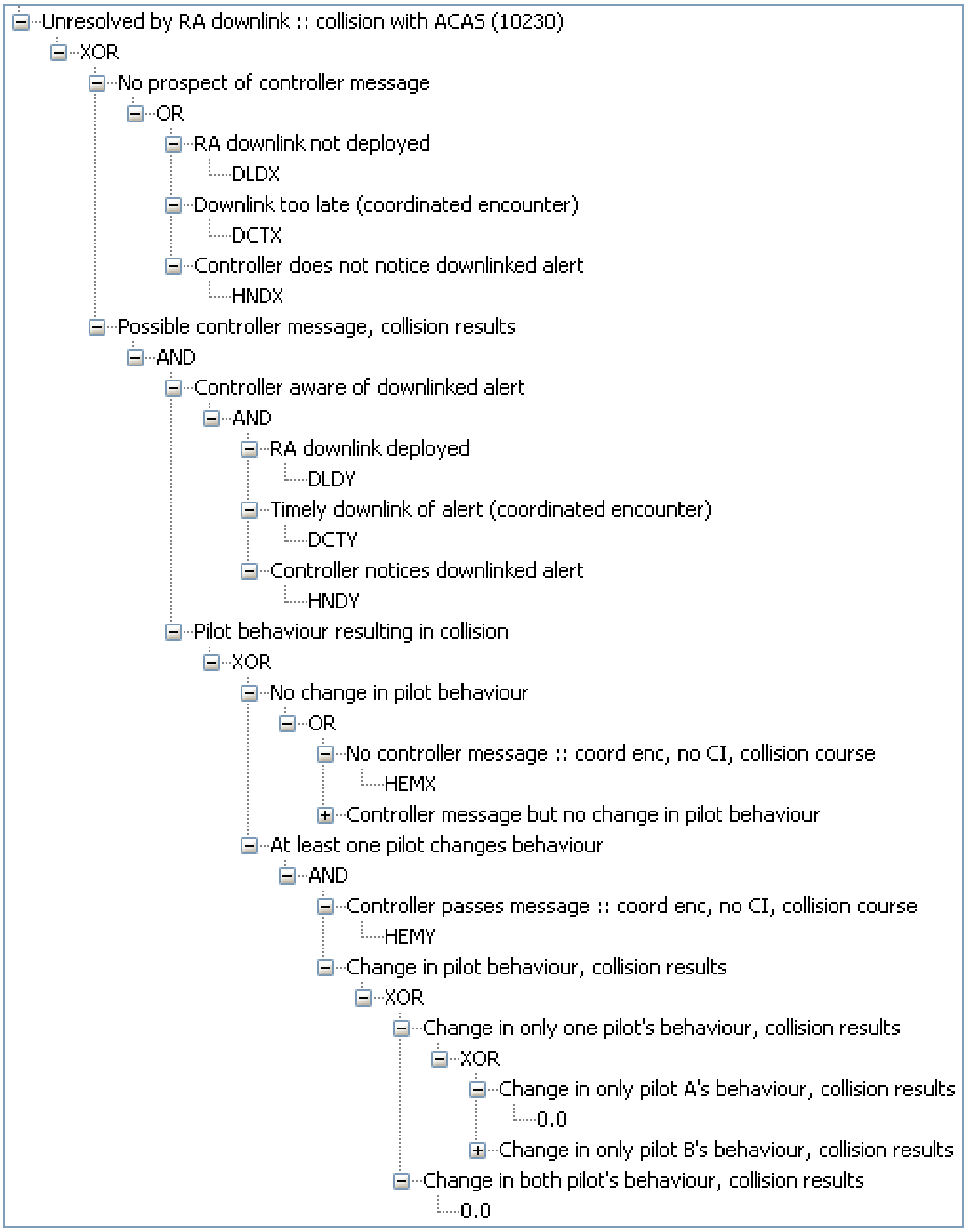

Figure 10: High-level view of sub-tree 10230

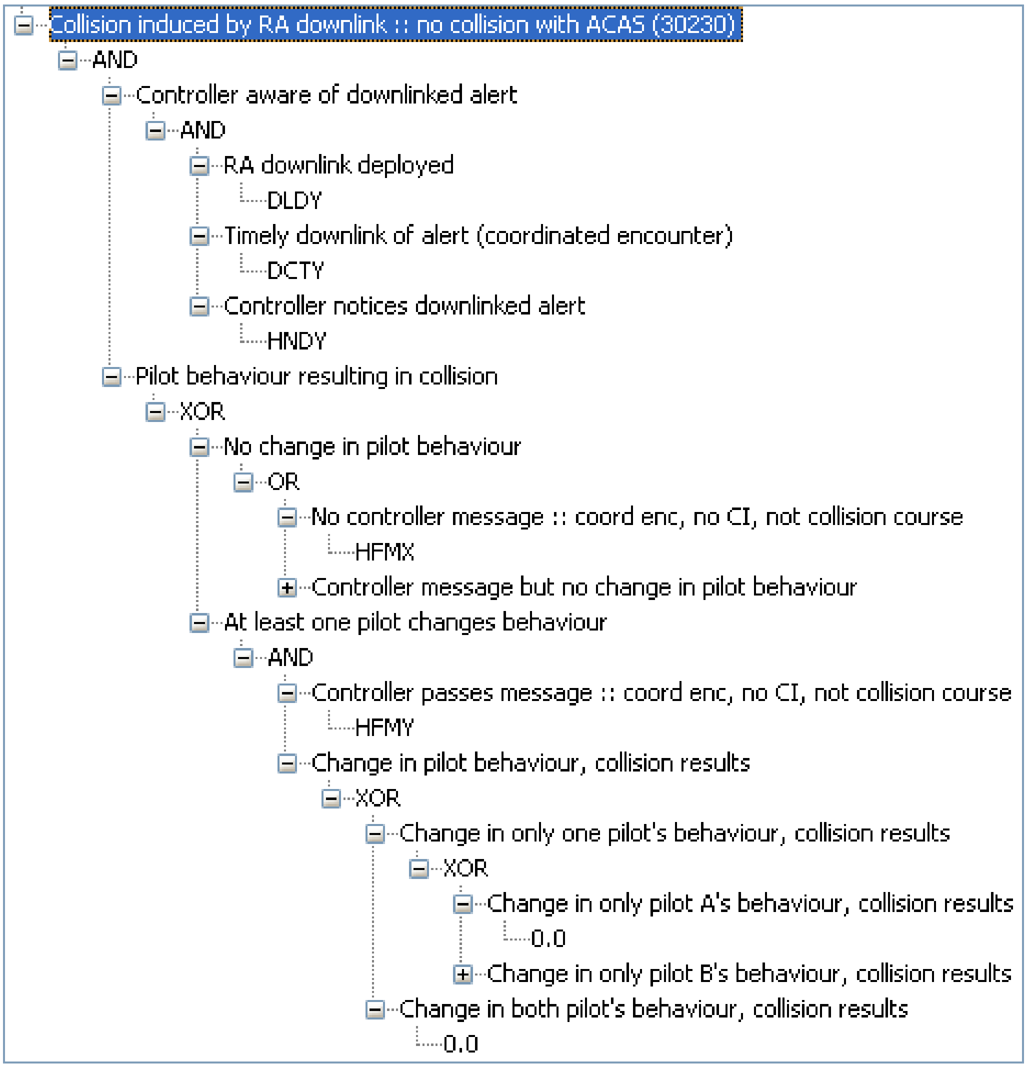

Figure 11: High-level view of sub-tree 30230

4.2 Controller intervention

4.2.1 Controller message

Should the controller become aware of the RA downlink alert (in time for any action by him to have an effect) the controller must then decide whether to intervene in the encounter by passing advice to at least one of the aircraft involved in the encounter. The event that the controller does pass a message is included in the sub-trees in a number of different guises corresponding to different circumstances that will influence the probability:

- Whether the encounter is coordinated – the controller's tendency to intervene in the encounter may depend on whether both aircraft are subject to an ACAS RA or whether only one aircraft is subject to an RA (the other aircraft being unequipped).

- Whether the controller issued an instruction (prompted by contact from a pilot) to the aircraft involved in the encounter – the controller may previously have issued no instruction to the aircraft, he may have issued an instruction that was consistent with the RA or he may have issued an instruction that was counter to the RA.[16] Each of these circumstances might affect the controller's tendency to intervene in the encounter.

- Whether the aircraft are now on a collision course as a result of ACAS (branches *B* and *D*) or whether they are not on a collision course (branches *A* and *C*).

The event 'controller passes a message' is coded as H*n*MY in the contingency tree and comes in twelve different flavours corresponding to the combinations of (coordinated encounter / uncoordinated encounter) × (no CI / consistent CI / inconsistent CI) × (on collision course / not on collision course). Each combination is coded by a different letter as indicated in Table 11. *E.g.* in sub-tree 10230 (see Figure 10) the aircraft in a coordinated encounter receive no controller and are on a collision course (without RA downlink there will be a collision) so the event 'controller passes a message' is represented by HEMY, while in sub-tree 30230 (see Figure 11) the aircraft are not on a collision course so the event is represented by HFMY.

equipage	controller involvement	effect of ACAS alone	*n*
ACAS/ACAS	no CI	on collision course	E
		not on collision course	F
	consistent CI	on collision course	G
		not on collision course	H
	inconsistent CI	on collision course	I
		not on collision course	J
ACAS/unequipped	no CI	on collision course	K
		not on collision course	L
	consistent CI	on collision course	M
		not on collision course	N
	inconsistent CI	on collision course	O
		not on collision course	Q

Table 11: Circumstances of controller behaviour prompted by RA downlink

[16] The contingency tree assumes that a 'bad controller instruction' is inconsistent with the RA.

4.2.2 Controller countermands previous instruction

The contingency tree allows for two possible modes of behaviour by a controller who passes a message, prompted by RA downlink, to the aircraft. A controller may give a new instruction or (in encounters where he previously gave an instruction *i.e.* 'good CI' or 'bad CI' sub-trees) he may countermand the previous instruction thus allowing pilots to follow the RA instead (if their predilection is so to do).[17]

In line with the assumption that original controller instructions are passed to both aircraft involved in the encounter (see 2.5.1) it is assumed that when an instruction is countermanded the controller passes this message to both aircraft. (That is not to say that both pilots will necessarily become aware of the countermanding, as is described in section 4.2.5.)

The event 'controller countermands previous instruction' (subject to the condition that the controller passes a message) is coded as H*n*XY in the contingency tree. There are eight flavours of this event corresponding to those circumstances in the contingency tree where the controller has previously passed an instruction (*n* = G to J, M to Q in Table 11).

The converse event, H*n*XX, (if the controller passes a message but does not countermand a previous instruction) is that the 'controller gives a new instruction', and this is described in more detail in section 4.2.3 below.

4.2.3 Controller gives instruction prompted by RA downlink

Given that the controller, prompted by RA downlink, intervenes in an encounter by passing a message, the contingency tree considers two possibilities: the message might countermand a previous instruction (as described in section 4.2.2); or the message might pass a new instruction (as described in this section).

In encounters where the controller previously gave an instruction ('good CI' or 'bad CI') the probability that a message prompted by RA downlink will be a new instruction is given by the event H*n*XX. In encounters where the controller previously gave no instruction ('no CI') the message can only be an instruction.

Given that the controller decides to give an instruction, prompted by RA downlink, he might decide to give an instruction to both aircraft or to one of the two aircraft only (alternatively there might be only enough time to give an instruction to one of the aircraft). The probability that the controller gives an instruction to both aircraft is given by event H*n*BY, and comes in twelve flavours corresponding to the circumstances *n* = K to Q, detailed in Table 11.

[17] The controller might also pass traffic information in an attempt to help the pilots' situational awareness. The indirect way in which this might influence the outcome of the encounter goes beyond the scope of the current contingency tree.

The converse probability that the controller gives an instruction to one aircraft only is represented by the event H*n*BX.

Given that the controller gives an instruction to only one of the two aircraft in the encounter there arises the question of which aircraft:

- In coordinated encounters between two ACAS aircraft the symmetry of the situation allows us to choose arbitrarily, and the contingency tree assumes that the instruction is given to aircraft A. *E.g.* in pilot predilection scenario 23 we assume that the instruction is given to aircraft A (whose pilot in fact responds to the RA rather than any controller instruction). The situation where the instruction had instead been given to aircraft B (whose pilot responds to the controller instruction) is covered in scenario 32 where the predilections of aircraft A and aircraft B are reversed.

- In uncoordinated encounters where only one of the aircraft is ACAS equipped the situation is not symmetrical. The controller may choose to give an instruction to the ACAS equipped aircraft (event H*n*AY), or to the unequipped aircraft (the converse event H*n*AX). This event comes in six flavours corresponding to the circumstances of uncoordinated encounters detailed in Table 11.

4.2.4 Nature of instruction prompted by RA downlink

When the controller gives an instruction, prompted by RA downlink, the contingency tree must consider the nature of the instruction and its consequent effect on the risk of collision.

As a general principal, the contingency tree assumes that instructions prompted by RA downlink are potentially as effective as similar instructions given as a result of contact from the pilot (which in turn was prompted by an ACAS TA)[18].

All instructions prompted by RA downlink are considered to be 'good' (remember, this does not mean that the instruction, if followed, would necessarily resolve the collision, nor that the instruction ought to have been issued: merely that it is issued in circumstances where there is some prospect of a successful instruction being issued. The actual success, or otherwise, of the instruction is considered further down in the contingency tree). This is the case even if the controller is initially involved in the encounter (see section 2.5.1), since the RA downlink alert is expected to provide additional information to the controller (not least fact that there is an RA, as well as the sense of the RA or RAs) that will influence any instruction that he gives.

The contingency tree must take into account whether the instruction is consistent with the sense of the RA and also whether a new instruction is consistent with a previous instruction (in the case that one pilot follows an

[18] *I.e.* the latter controller instructions being those considered in the full-system contingency trees.

initial controller instruction whereas the other pilot follows a new controller instruction).

The contingency tree allows for the possibilities that an instruction given by the controller is consistent with the sense of the RA indicated by the downlinked alert (event HMNY), or that the instruction is counter to the sense of the RA indicated by the downlinked alert (the converse event HMNX).

That the controller gives an instruction consistent with the sense of the RA indicated by the downlinked alert is no guarantee that the instruction will indeed be consistent with the sense of the RA that is indicated on the flight-deck. This is because ACAS can reverse the sense of an RA when it diagnoses that the initial RA is not working.[19] Any such geometric reversal in the sense of an RA will ultimately be displayed at the CWP via RA downlink but will be subject to the same processes as the display of the initial RA. Consequently there will be latency in the display of RA reversals of the same nature[20] as the latency of the display of initial RAs. This latency in the display of RA reversals can mean that while intending to give an instruction that is consistent with the sense of the RA, the controller might select an instruction that is counter to the RA that is currently displayed on the fight-deck, because the RA sense has invisibly reversed. The probability that an RA will have reversed invisibly is dependent on two factors:

- Whether the aircraft on a collision course with ACAS alone (*i.e.* given the pilots' response to ACAS and any controller instruction prompted by contact from the pilots, rather than whether the aircraft were originally on a collision course) or not – geometric reversals can be expected to be more common when the aircraft are on a collision course;

- Whether the encounter is between two ACAS aircraft (in which case the RAs will be coordinated) or between an ACAS aircraft and an unequipped aircraft – geometric reversals can be suppressed for certain geometries and Mode S address hierarchies in coordinated encounters.

The events representing the possibility of an invisible RA reversal (and its converse) for the four possible combinations of these factors are shown in Table 12.

[19] There can also be reversals to ensure that the RAs in a coordinated encounter have compatible senses. These coordination reversals generally occur very soon after an initial RA is selected and the current study assumes that the sense of the RAs 'agreed' by the ACAS systems in coordinated encounters will be apparent to the controller before he decides on a course of action.

[20] But, due to stochastic effects, not necessarily of the same magnitude in individual cases.

	collision course with ACAS	not on a collision course with ACAS
ACAS/ACAS	DCCY (DCCX)	DCNY (DCNX)
ACAS/uneq	DUCY (DUCX)	DUNY (DUNX)

Table 12: Events representing the probability that an RA has invisibly reversed, or not, depending on ACAS equipage and encounter geometry

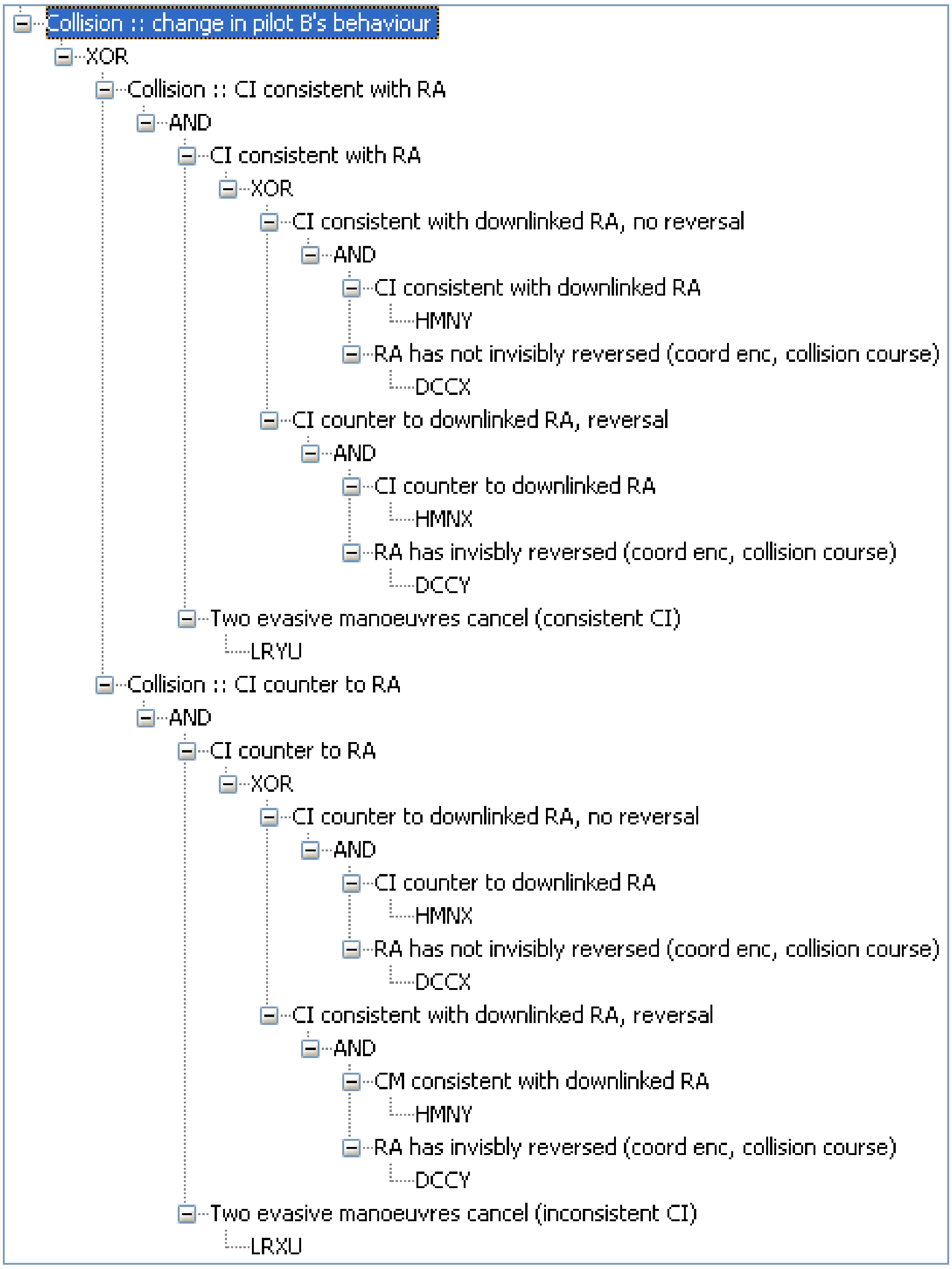

Figure 12: Treatment of potential RA reversals in sub-tree 10230

The controllers selection of an instruction based on the displayed RA downlink alert and the possibility of an invisible RA reversal are handled in the tree in the manner illustrated in Figure 12 (which is a detail from sub-tree 10230). The events representing the risk of collision (LRYU for an instruction consistent with the RA on the flight-deck, LRXU for an instruction counter to RA on the flight-deck) are the same as the events when one aircraft follows a controller instruction prompted by contact from a pilot and the other aircraft responds to the RA, in line with the principle described at the start of this section.

4.2.5 Pilot behaviour

In the full-system contingency tree (and therefore in the corresponding top levels of RA downlink contingency tree) it is assumed that a pilot will notice any message passed by the controller (although according to his predilection the pilot may choose to ignore the instruction in the message).

For controller messages prompted by RA downlink (be they the countermanding of a previous instruction or a new instruction) this assumption is not necessarily valid. The flight-crew of ACAS equipped aircraft will have received an RA and the workload on the flight deck will have increased, consequently a message from the controller may go unnoticed. The probability that a controller message prompted by RA downlink is not noticed by the pilot of an ACAS equipped aircraft is represented by the event HCMX. The converse event (that the pilot of an ACAS equipped aircraft does notice any controller message) is HCMY.

The pilot of an unequipped aircraft will not be dealing with an RA and so the RA downlink contingency tree assumes that the pilot will always notice any controller message as before.

Given that the controller, prompted by RA downlink, passes a message to an aircraft the pilot will comply with the message if:

- for an ACAS equipped aircraft the pilot notices the controller message and his predilection is to follow the instruction;

- for an unequipped aircraft if the pilot's predilection is to follow the instruction.

If neither pilot complies with a controller message prompted by RA downlink then the situation is unchanged and in sub-trees on branches *B* and *D* the collision risk (unresolved by RA downlink) will be unity, while in sub-trees on branches *A* and *C* the collision risk (induced by RA downlink) will be zero.

Otherwise, if either of the pilots does comply with a controller message prompted by RA downlink then that pilot will either revert to the behaviour he would have displayed in the absence of a controller instruction (in the case of a message countermanding an earlier controller instruction prompted by contact with the pilot), or follow a new controller instruction. The possible combinations of the behaviour of the two pilots and the consequent risk of collision (given the conditions relevant to the each sub-tree) are shown in Table 13 and Table 14 for ACAS/ACAS encounters, and in Table 15 and Table 16 for ACAS/unequipped encounters.

ACAS/ACAS encounters

In coordinated encounters both aircraft are ACAS equipped and the possible combinations when pilot behaviour reverts to a combination that might occur without RA downlink (because the controller countermands a previous instruction) are shown in Table 13, together with the risk of collision that arises. The grouping of the risks by columns depends on whether the aircraft were originally on a collision course (branches C and D) or not originally not on a collision course (branches A and B). These cases (in which neither pilot follows a new controller instruction) repeat cases shown in Table 5, Table 7, and Table 9, and described in sections 3.4.1, 3.4.2, and 3.4.3.

behaviour of one pilot	behaviour of other pilot	risk branches *C* & *D*	risk branches *A* & *B*
no response	*no response*	1	0
follows bad CI	*no response*	1	0
follows bad CI	*follows bad CI*	1	0
follows good CI	*no response*	LCWX	0
follows good CI	follows good CI	LCWX	0
responds to RA	*no response*	LTNU	LTNI
responds to RA	*follows bad CI*	LTNU	LTNI
responds to RA	follows good CI	LRYU/LRXU	LRYI/LRXI
responds to RA	responds to RA	LTTU	LTTI

Table 13: Pilot behaviour reverts to a previous combination – risk of collision with RA downlink (ACAS/ACAS)

behaviour of one pilot	behaviour of other pilot	unresolved risk branches *B* & *D*	induced risk branches *A* & *C*
follows new CI	*no response*	LCWX	0
follows new CI	*follows bad CI*	LCWX	0
follows new CI	follows good CI	LRYU/LRXU	LRYI/LRXI
follows new CI	follows new CI	LCWX	0
follows new CI	responds to RA	LRYU/LRXU	LRYI/LRXI

Table 14: Pilot behaviour involves new combination – risk of collision with RA downlink (ACAS/ACAS)

Those cases in which at least one of the pilots follows a new controller instruction (*i.e.* one prompted by RA downlink) are shown in Table 14. The grouping of the risks in the columns depends on whether the aircraft are on a collision course with ACAS (branches *B* and *D*), or not on a collision course with ACAS (branches *A* and *C*). These cases have not previously been considered and are described below:

- **'follows new CI / no response'** – one pilot follows a new controller instruction while the other pilot neither responds to any controller instruction nor follows the RA. A new controller instruction prompted by RA downlink is assumed (all other things being equal) to be as effective as a good controller instruction prompted by contact from a pilot. The consequence of this behaviour is therefore this the same as **'follows CI / no response'** described in section 3.4.3 and shown in Table 13:

- unresolved collision risk = LCWX
- induced collision risk = 0

- **'follows new CI / follows bad CI'** [21] – one pilot follows a new controller instruction while the other pilot follows a previous bad controller instruction. A bad controller instruction alone, has no prospect of resolving an encounter and following such an instruction is effectively the same as not responding at all. The consequence of this behaviour is therefore the same as **'follows new CI / no response'** described above:
  - unresolved collision risk = LCWX
  - induced collision risk = 0
- **'follows new CI / follows good CI'** – one pilot follows a new controller instruction while the other pilot follows a previous good controller instruction. The two instructions are separate and are treated in the same way as a good controller instruction and an RA.[22] When the two separate controller instructions are consistent with one another (both consistent with the RA or both counter to the RA) we have:
  - unresolved collision risk = LRYU
  - induced collision risk = LRYI

  When the two separate controller instructions are counter to one another (one consistent with the RA and the other counter to the RA) we have:
  - unresolved collision risk = LRXU
  - induced collision risk = LRXI
- **'follows new CI / follows new CI'** – both pilots follow a new controller instruction. A new controller instruction prompted by RA downlink is assumed (all other things being equal) to be as effective as a good controller instruction prompted by contact from a pilot. The

[21] Applicable only to branches C and D.

[22] Even though the two separate controller instructions may be consistent, they are not as tightly connected as when both pilots follow a good controller instruction or both pilots follow a new controller instruction. Under those circumstances the instructions followed by the two pilots are effectively two halves of the same instruction and the risks described elsewhere in this section are applicable.

consequence of this behaviour is therefore the same as **'follows CI / follows CI'** described in section 3.4.3 and shown in Table 13:

- o unresolved collision risk = LCWX
- o induced collision risk = 0

- **'follows new CI / responds to RA'** – one pilot follows a new controller instruction while the other responds to the RA. A new controller instruction prompted by RA downlink is assumed (all other things being equal) to be as effective as a good controller instruction prompted by contact from a pilot. The consequence of this behaviour is therefore the same as **'follows CI / responds to RA'** described in section 3.4.3 and shown in Table 13:

  When the new controller instruction is consistent with the RA we have:

  - o unresolved collision risk = LRYU
  - o induced collision risk = LRYI

  When the new controller instruction is counter to RA we have:

  - o unresolved collision risk = LRXU
  - o induced collision risk = LRXI

<u>ACAS/unequipped encounters</u>

In uncoordinated encounters only one of the aircraft is ACAS equipped and the possible combinations when pilot behaviour reverts to a combination that might occur without RA downlink (because the controller countermands a previous instruction) are shown in Table 15, together with the risk of collision that arises. As before, the grouping of the risks by columns depends on whether the aircraft were originally on a collision course (branches *C* and *D*), or not originally not on a collision course (branches *A* and *B*). These cases (in which neither pilot follows a new controller instruction) repeat cases shown in Table 6, Table 8, and Table 10, and described in sections 3.4.1, 3.4.2, and 3.4.3.

behaviour of ACAS pilot	behaviour of uneq pilot	risk branches *C* & *D*	risk branches *A* & *B*
no response	*no response*	1	0
no response	*follows bad CI*	1	0
no response	follows good CI	LCWX	0
follows bad CI	*no response*	1	0
follows bad CI	*follows bad CI*	1	0
follows good CI	*no response*	LCWX	0
follows good CI	follows good CI	LCWX	0
responds to RA	*no response*	LTSU	LTSI
responds to RA	*follows bad CI*	LTSU	LTSI
responds to RA	follows good CI	LRYU/LRXU	LRYI/LRXI

Table 15: Pilot behaviour reverts to a previous combination – risk of collision with RA downlink (ACAS/uneq)

behaviour of ACAS pilot	behaviour of uneq pilot	unresolved risk branches *B* & *D*	induced risk branches *A* & *C*
no response	follows new CI	LCWX	0
follows bad CI	follows new CI	LCWX	0
follows good CI	follows new CI	LRYU/LRXU	LRYI/LRXI
follows new CI	*no response*	LCWX	0
follows new CI	*follows bad CI*	LCWX	0
follows new CI	follows good CI	LRYU/LRXU	LRYI/LRXI
follows new CI	follows new CI	LCWX	0
responds to RA	follows new CI	LRYU/LRXU	LRYI/LRXI

Table 16: Pilot behaviour involves new combination – risk of collision with RA downlink (ACAS/uneq)

Those cases in which at least one of the pilots follows a new controller instruction (*i.e.* one prompted by RA downlink) are shown in Table 16. Again, the grouping of the risks in the columns depends on whether the aircraft are on a collision course with ACAS (branches *B* and *D*), or not on a collision course with ACAS (branches *A* and *C*). These cases have not previously been considered and are described below:

- **'follows new CI / no response'** – one pilot follows a new controller instruction while the other pilot neither responds to any controller instruction nor follows the RA. The consequence of this behaviour is the same as with **'follows new CI / no response'** in ACAS/ACAS encounters described above:

- o unresolved collision risk = LCWX
- o induced collision risk = 0

- **'follows new CI / follows bad CI'** [23] – one pilot follows a new controller instruction while the other pilot follows a previous bad controller instruction. The consequence of this behaviour is the same as with **'follows new CI / follows bad CI'** in ACAS/ACAS encounters described above:
  - o unresolved collision risk = LCWX
  - o induced collision risk = 0

- **'follows new CI / follows good CI'** – one pilot follows a new controller instruction while the other pilot follows a previous good controller instruction. The consequence of this behaviour is the same as with **'follows new CI / follows good CI'** in ACAS/ACAS encounters described above. When the two separate controller instructions are consistent we have:
  - o unresolved collision risk = LRYU
  - o induced collision risk = LRYI

  When the two separate controller instructions are counter to one another we have:
  - o unresolved collision risk = LRXU
  - o induced collision risk = LRXI

- **'follows new CI / follows new CI'** – both pilots follow a new controller instruction. The consequence of this behaviour is the same as with **'follows new CI / follows new CI'** in ACAS/ACAS encounters described above:
  - o unresolved collision risk = LCWX
  - o induced collision risk = 0

- **'responds to RA / follows new CI'** – the ACAS pilot responds to the RA while the pilot of the unequipped aircraft follows a new controller instruction. The consequence of this behaviour is the same as with **'follows new CI / responds to RA'** in ACAS/ACAS encounters described above:

[23] Applicable only to branches C and D.

When the new controller instruction is consistent with the RA we have:

- o unresolved collision risk = LRYU
- o induced collision risk = LRYI

When the new controller instruction is counter to RA we have:

- o unresolved collision risk = LRXU
- o induced collision risk = LRXI

5. EVENTS IN RA DOWNLINK CONTINGENCY TREE

This section describes the full set of events whose probabilities are required to evaluate the risk of collision. The code for each event is given together with a paragraph describing the context in which the event occurs. This is important because many events (particularly the new controller related events described in section 5.2.2) are superficially similar to other events but have different probabilities because the circumstances in which they occur influence the probability of the event occurring.

Events inherited from the full-system contingency tree (see [16]) are described in section 5.1. New events, derived for the RA downlink contingency tree, are described in section 5.2.

5.1 Events inherited from full-system contingency tree

5.1.1 Geometry events

GCCY – aircraft are on a collision course.

The probability, in a close encounter between two aircraft (at least one of which is ACAS equipped) in the airspace of interest, that if neither pilot changes his trajectory a midair collision will occur. The converse event is *GCCX (aircraft are not on a collision course)*.

5.1.2 Equipment events

EAEX_B – second aircraft is not ACAS equipped

One of the aircraft in the encounters considered (close encounters in the airspace of interest) is by definition ACAS equipped. The probability that the other aircraft is not ACAS equipped is equal to the proportion of unequipped aircraft in the airspace. The converse event is *EAEY_B (second aircraft is ACAS equipped)*.

5.1.3 ATC events

ACIY – controller already involved

A controller is 'involved' if he is aware of, and unconcerned by, the encounter even though the aircraft are on a collision course – the collision course might be a direct consequence of a recent (incorrect) controller instruction, or the controller may have observed the aircraft flight-paths and (incorrectly) judging the situation to be safe refrained from giving an instruction to resolve the conflict. The converse event is *ACIX (controller is not already involved)* in which circumstance a controller instruction prompted by contact from the pilot has some prospect of resolving the encounter.

Collision course

HRXU – controller instruction is counter to RA (on collision course)

The probability that when the aircraft are on a collision course an instruction, given by a controller who is not already involved, will be in the opposite vertical sense to the initial RA.[24]

Not collision course

HRXI – controller instruction is counter to RA (not on collision course)

The probability that when the aircraft are not on a collision course an instruction, given by a controller who is not already involved, will be in the opposite vertical sense to the initial RA.

5.1.4 Pilot events

HCCY_A – ACAS pilot contacts controller

The probability that the pilot of an ACAS equipped aircraft will, when he receives an ACAS traffic alert, contact the controller for guidance. The converse event is *HCCX_A (ACAS pilot does not contact controller)*

HFCX_A – pilot ignores controller instruction

The probability that a pilot will ignore an instruction from the controller in the absence of any other advice (*i.e.* when there is no ACAS RA). This action may be wilful or due to an oversight (*e.g.* the pilot mishears the callsign). The converse event is *HFCY_A (pilot notes/follows controller instruction)*.

HFRX_A – ACAS pilot ignores RA

The probability that an ACAS pilot will ignore an RA in the absence of any other advice (*i.e.* when there is no controller instruction). The converse event is *HFRY_A (ACAS pilot notes/follows RA)*.[25]

HPRY_A – ACAS pilot prefers RA to controller instruction

The probability that an ACAS pilot who receives a controller instruction at about the same time as an ACAS RA is generated and who ignores neither will respond to the RA in preference to following the controller instruction. The converse event is *HPRX_A (ACAS pilot prefers controller instruction to RA)*.

[24] Allowing for any coordination reversals that might occur within the first few cycles of a coordinated RA in an encounter between two ACAS aircraft.

[25] *N.B.* This is not the same as the probability that the pilot does not follow the RA. The latter probability was determined from on-board recordings in the ASARP study and found to have a value of 0.1. However, (as explained in [17]) this also includes the case that a pilot notes the RA but nevertheless does not follow it because he prefers a controller instruction. The current event will consequently have a lower probability than the probability that the pilot does not follow the RA.

The full-system contingency tree included two versions of each of the above events: one set for the pilot of aircraft A with the suffix *'_A'* (as above); and another set for the pilot of aircraft B with the suffix *'_B'*. The distinction is not required in the RA downlink contingency tree and so the events *HCCY_B*, *HFCX_B* are assigned the same probabilities as the events *HCCY_A* and *HFCX_A* respectively, and the events *HFRX_B* and *HPRY_B* (when aircraft B is ACAS equipped) are assigned the same probability as *HFRX_A* and *HPRY_A* respectively.

5.1.5 Logic events

<u>Collision course</u>

LTTU – collision unresolved by ACAS, coordinated encounter, both pilots typical response

The probability that when two aircraft are on a collision course in a coordinated encounter, and each of the pilots responds to the RA with a typical response, that a collision will still occur.

LTNU – collision unresolved by ACAS, coordinated encounter, one pilot typical response, other pilot no response

The probability that when two aircraft are on a collision course in a coordinated encounter, and one of the pilots responds to the RA with a typical response while the other does not respond to the RA, that a collision will still occur.

LTSU – collision unresolved by ACAS, uncoordinated encounter, ACAS pilot typical response

The probability that when two aircraft are on a collision course in an uncoordinated encounter (the non-ACAS aircraft having a Mode S transponder), and the ACAS pilot responds to the RA with a typical response while the unequipped aircraft does not follow a controller instruction, that a collision will still occur.

LCWX – collision unresolved by good controller instruction

The probability that when two aircraft are on a collision course that an instruction from a controller who is not already involved, if followed (when neither aircraft responds to an ACAS RA), will fail to resolve the encounter. The converse event is *LCWY (collision resolved by good controller instruction)*.

LRXU – two evasive manoeuvres fail to resolve collision

The probability that when two aircraft are on a collision course when one pilot responds to the RA while the other pilot follows an instruction from a controller who is not already involved, which is counter to the RA, that a collision will occur.

Not collision course

LTTI – ACAS induced collision, coordinated encounter, both pilots typical response

The probability that when two aircraft are not on a collision course in a coordinated encounter, and each of the pilots responds to the RA with a typical response, that a collision will be induced.

LTNI – ACAS induced collision, coordinated encounter, one pilot typical response, other pilot no response

The probability that when two aircraft are not on a collision course in a coordinated encounter, and one of the pilots responds to the RA with a typical response while the other does not respond to the RA, that a collision will be induced.

LTSI – ACAS induced collision, uncoordinated encounter, ACAS pilot typical response

The probability that when two aircraft are not on a collision course in an uncoordinated encounter (the non-ACAS aircraft having a Mode S transponder), and the ACAS pilot responds to the RA with a typical response while the unequipped aircraft does not follow a controller instruction, that a collision will still occur.

LRXI – two evasive manoeuvres induce collision

The probability that when two aircraft are not on a collision course when one pilot responds to the RA while the other pilot follows an instruction from a controller who is not already involved, which is counter to the RA, that a collision will be induced.

5.2 New events in RA downlink contingency tree

5.2.1 RA downlink events

DLDY – RA downlink is deployed

An event that enables the contingency tree to evaluate the current risk of collision (without RA downlink) by setting DLDY = 0, and compare this with the risk collision with RA downlink by setting DLDY = 1. The converse event is *DLDX (RA downlink is not deployed)*.

DCTX – downlink too late in coordinated encounter

The probability that in an encounter between two ACAS equipped aircraft, when RA downlink is deployed, the delay in the display of the alert to the controller is too long to allow any effective intervention by the controller. The converse event is *DCTY (timely downlink in coordinated encounter)*.

DCUX – downlink too late in uncoordinated encounter

The probability that in an encounter between an ACAS equipped aircraft and an unequipped aircraft, when RA downlink is deployed, the delay in the display of the alert to the controller is too long to allow any effective intervention by the controller. The converse event is *DCUY (timely downlink in uncoordinated encounter)*.

<u>Coordinated encounter, aircraft on collision course with ACAS</u>

DCCY – RA has invisibly reversed

The probability in a coordinated encounter, given that a collision would occur without RA downlink, that a geometric reversal in the RA sense would occur but not be displayed at the CWP before the controller could effectively intervene in the encounter. The converse event is *DCCX (RA has not invisibly reversed)*.

<u>Coordinated encounter, aircraft not on collision course with ACAS</u>

DCNY – RA has invisibly reversed

The probability in a coordinated encounter, given that a collision would not occur without RA downlink, that a geometric reversal in the RA sense would occur but not be displayed at the CWP before the controller could effectively intervene in the encounter. The converse event is *DCNX (RA has not invisibly reversed)*.

<u>Uncoordinated encounter, aircraft on collision course with ACAS</u>

DUCY – RA has invisibly reversed

The probability in an uncoordinated encounter, given that a collision would occur without RA downlink, that a geometric reversal in the RA sense would occur but not be displayed at the CWP before the controller could effectively intervene in the encounter. The converse event is *DUCX (RA has not invisibly reversed)*.

<u>Uncoordinated encounter, aircraft not on collision course with ACAS</u>

DUNY – RA has invisibly reversed

The probability in an uncoordinated encounter, given that a collision would not occur without RA downlink, that a geometric reversal in the RA sense would occur but not be displayed at the CWP before the controller could effectively intervene in the encounter. The converse event is DUNX (RA has not invisibly reversed).

5.2.2 Controller events

HNDY – controller notices downlinked alert

The probability, given that an RA alert has been downlinked in a timely manner, that the controller will notice the alert sufficiently early to effectively intervene in the encounter. The converse event is *HNDX (controller does not notice downlinked alert)*.

HMNX – new controller instruction is counter to downlinked RA

The probability, given that a controller issues an instruction prompted by RA downlink, the instruction will be counter to the sense of the downlinked RA. The converse event is *HMNY (new controller instruction is consistent with downlinked RA)*.

<u>Coordinated encounter, no CI, collision course with ACAS</u>

HEMY – controller gives instruction prompted by RA downlink

The probability in a coordinated encounter in which a collision would occur without RA downlink, given that the controller is not already involved and has not issued an instruction prompted by contact from a pilot, that the controller issues an instruction prompted by RA downlink. The converse event is *HEMX (controller does not give instruction prompted by RA downlink)*.

HEBY – controller gives instruction to both aircraft

The probability in a coordinated encounter in which a collision would occur without RA downlink, given that the controller is not already involved and has not issued an instruction prompted by contact from a pilot but decides to issue an instruction prompted by RA downlink, that the controller gives an instruction to both aircraft. The converse event is *HEBX (controller gives instruction to only one aircraft)*.

<u>Coordinated encounter, no CI, not collision course with ACAS</u>

HFMY – controller gives instruction prompted by RA downlink

The probability in a coordinated encounter in which a collision would not occur without RA downlink, given that the controller is not already involved and has not issued an instruction prompted by contact from a pilot, that the controller issues an instruction prompted by RA downlink. The converse event is *HFMX (controller does not give instruction prompted by RA downlink)*.

HFBY – controller gives instruction to both aircraft

The probability in a coordinated encounter in which a collision would not occur without RA downlink, given that the controller is not already involved and has not issued an instruction prompted by contact from a pilot but decides to issue an instruction prompted by RA downlink, that the controller gives an instruction to both aircraft. The converse event is *HFBX (controller gives instruction to only one aircraft)*.

Coordinated encounter, consistent CI, collision course with ACAS

HGMY – controller passes message prompted by RA downlink

The probability in a coordinated encounter in which a collision would occur without RA downlink, given that the controller has already given an instruction consistent with the sense of the downlinked RA, that the controller passes a message prompted by RA downlink. The converse event is *HGMX (controller does not pass message prompted by RA downlink)*.

HGXY – controller countermands previous instruction

The probability in a coordinated encounter in which a collision would occur without RA downlink, given that the controller has already given an instruction consistent with the sense of the downlinked RA and decides to pass a message, that the message will countermand the previous instruction. The converse event is *HGXX (controller gives new instruction)* – that instead of countermanding the previous instruction, the controller gives a new instruction.

HGBY – controller gives instruction to both aircraft

The probability in a coordinated encounter in which a collision would occur without RA downlink, given that the controller has already given an instruction consistent with the sense of the downlinked RA but decides to issue a new instruction, that the controller gives the instruction to both aircraft. The converse event is *HGBX (controller gives instruction to only one aircraft)*.

Coordinated encounter, consistent CI, not collision course with ACAS

HHMY – controller passes message prompted by RA downlink

The probability in a coordinated encounter in which a collision would not occur without RA downlink, given that the controller has already given an instruction consistent with the sense of the downlinked RA, that the controller passes a message prompted by RA downlink. The converse event is *HHMX (controller does not pass message prompted by RA downlink)*.

HHXY – controller countermands previous instruction

The probability in a coordinated encounter in which a collision would occur without RA downlink, given that the controller has already given an instruction counter to the sense of the downlinked RA and decides to pass a message, that the message will countermand the previous instruction. The converse event is *HHXX (controller gives new instruction)* – that instead of countermanding the previous instruction, the controller gives a new instruction.

HHBY – controller gives instruction to both aircraft

The probability in a coordinated encounter in which a collision would not occur without RA downlink, given that the controller has already given an instruction consistent with the sense of the downlinked RA but decides to issue a new instruction, that the controller gives the instruction to both aircraft. The converse event is *HHBX (controller gives instruction to only one aircraft)*.

<u>Coordinated encounter, inconsistent CI, collision course with ACAS</u>

HIMY – controller passes message prompted by RA downlink

The probability in a coordinated encounter in which a collision would occur without RA downlink, given that the controller has already given an instruction counter to the sense of the downlinked RA, that the controller passes a message prompted by RA downlink. The converse event is *HIMX (controller does not pass message prompted by RA downlink)*.

HIXY – controller countermands previous instruction

The probability in a coordinated encounter in which a collision would occur without RA downlink, given that the controller has already given an instruction counter to the sense of the downlinked RA and decides to pass a message, that the message will countermand the previous instruction. The converse event is *HIXX (controller gives new instruction)* – that instead of countermanding the previous instruction, the controller gives a new instruction.

HIBY – controller gives instruction to both aircraft

The probability in a coordinated encounter in which a collision would occur without RA downlink, given that the controller has already given an instruction counter to the sense of the downlinked RA but decides to issue a new instruction, that the controller gives the instruction to both aircraft. The converse event is *HIBX (controller gives instruction to only one aircraft)*.

<u>Coordinated encounter, inconsistent CI, not collision course with ACAS</u>

HJMY – controller passes message prompted by RA downlink

The probability in a coordinated encounter in which a collision would not occur without RA downlink, given that the controller has already given an instruction counter to the sense of the downlinked RA, that the controller passes a message prompted by RA downlink. The converse event is *HJMX (controller does not pass message prompted by RA downlink)*.

HJXY – controller countermands previous instruction

The probability in a coordinated encounter in which a collision would not occur without RA downlink, given that the controller has already given an instruction counter to the sense of the downlinked RA and decides to pass a message, that the message will countermand the previous instruction. The converse event is *HJXX (controller gives new instruction)* – that instead of countermanding the previous instruction, the controller gives a new instruction.

HJBY – controller gives instruction to both aircraft

The probability in a coordinated encounter in which a collision would not occur without RA downlink, given that the controller has already given an instruction counter to the sense of the downlinked RA but decides to issue a new instruction, that the controller gives the instruction to both aircraft. The converse event is *HJBX (controller gives instruction to only one aircraft)*.

<u>Uncoordinated encounter, no CI, collision course with ACAS</u>

HKMY – controller gives instruction prompted by RA downlink

The probability in an uncoordinated encounter in which a collision would occur without RA downlink, given that the controller is not already involved and has not issued an instruction prompted by contact from a pilot, that the controller issues an instruction prompted by RA downlink. The converse event is *HKMX (controller does not give instruction prompted by RA downlink)*.

HKBY – controller gives instruction to both aircraft

The probability in an uncoordinated encounter in which a collision would occur without RA downlink, given that the controller is not already involved and has not issued an instruction prompted by contact from a pilot but decides to issue an instruction prompted by RA downlink, that the controller gives an instruction to both aircraft. The converse event is *HKBX (controller gives instruction to only one aircraft)*.

HKAY – controller give instruction to ACAS aircraft only

The probability in an uncoordinated encounter in which a collision would occur without RA downlink, given that the controller is not already involved and has not issued an instruction prompted by contact from a pilot but decides to issue an instruction (prompted by RA downlink) to one aircraft only, that the controller gives the instruction to the ACAS equipped aircraft. The converse event is *HKAX (controller gives instruction to unequipped aircraft only)*.

<u>Uncoordinated encounter, no CI, not collision course with ACAS</u>

HLMY – controller gives instruction prompted by RA downlink

The probability in an uncoordinated encounter in which a collision would not occur without RA downlink, given that the controller is not already involved and has not issued an instruction prompted by contact from a pilot, that the controller issues an instruction prompted by RA downlink. The converse event is *HLMX (controller does not give instruction prompted by RA downlink)*.

HLBY – controller gives instruction to both aircraft

The probability in an uncoordinated encounter in which a collision would not occur without RA downlink, given that the controller is not already involved and has not issued an instruction prompted by contact from a pilot but decides to issue an instruction prompted by RA downlink, that the controller gives an instruction to both aircraft. The converse event is *HLBX (controller gives instruction to only one aircraft)*.

HLAY – controller give instruction to ACAS aircraft only

The probability in an uncoordinated encounter in which a collision would not occur without RA downlink, given that the controller is not already involved and has not issued an instruction prompted by contact from a pilot but decides to issue an instruction (prompted by RA downlink) to one aircraft only, that the controller gives the instruction to the ACAS equipped aircraft. The converse event is *HLAX (controller gives instruction to unequipped aircraft only)*.

Uncoordinated encounter, consistent CI, collision course with ACAS

HMMY – controller passes message prompted by RA downlink

The probability in an uncoordinated encounter in which a collision would occur without RA downlink, given that the controller has already given an instruction consistent with the sense of the downlinked RA, that the controller passes a message prompted by RA downlink. The converse event is *HMMX (controller does not pass message prompted by RA downlink)*.

HMXY – controller countermands previous instruction

The probability in an uncoordinated encounter in which a collision would occur without RA downlink, given that the controller has already given an instruction consistent with the sense of the downlinked RA and decides to pass a message, that the message will countermand the previous instruction. The converse event is *HMXX (controller gives new instruction)* – that instead of countermanding the previous instruction, the controller gives a new instruction.

HMBY – controller gives instruction to both aircraft

The probability in an uncoordinated encounter in which a collision would occur without RA downlink, given that the controller has already given an instruction consistent with the sense of the downlinked RA but decides to issue a new instruction, that the controller gives the instruction to both aircraft. The converse event is *HMBX (controller gives instruction to only one aircraft)*.

HMAY – controller give instruction to ACAS aircraft only

The probability in an uncoordinated encounter in which a collision would occur without RA downlink, given that the controller has already given an instruction consistent with the sense of the downlinked RA but decides to issue a new instruction (prompted by RA downlink) to one aircraft only, that the controller gives the instruction to the ACAS equipped aircraft. The converse event is *HMAX (controller gives instruction to unequipped aircraft only)*.

Uncoordinated encounter, consistent CI, not collision course with ACAS

HNMY – controller passes message prompted by RA downlink

The probability in an uncoordinated encounter in which a collision would not occur without RA downlink, given that the controller has already given an instruction consistent with the sense of the downlinked RA, that the controller passes a message prompted by RA downlink. The converse event is *HNMX (controller does not pass message prompted by RA downlink)*.

HNXY – controller countermands previous instruction

The probability in an uncoordinated encounter in which a collision would occur without RA downlink, given that the controller has already given an instruction counter to the sense of the downlinked RA and decides to pass a message, that the message will countermand the previous instruction. The converse event is *HNXX (controller gives new instruction)* – that instead of countermanding the previous instruction, the controller gives a new instruction.

HNBY – controller gives instruction to both aircraft

The probability in an uncoordinated encounter in which a collision would not occur without RA downlink, given that the controller has already given an instruction consistent with the sense of the downlinked RA but decides to issue a new instruction, that the controller gives the instruction to both aircraft. The converse event is *HNBX (controller gives instruction to only one aircraft)*.

HNAY – controller give instruction to ACAS aircraft only

The probability in an uncoordinated encounter in which a collision would not occur without RA downlink, given that the controller has already given an instruction consistent with the sense of the downlinked RA but decides to issue a new instruction (prompted by RA downlink) to one aircraft only, that the controller gives the instruction to the ACAS equipped aircraft. The converse event is *HNAX (controller gives instruction to unequipped aircraft only)*.

Uncoordinated encounter, inconsistent CI, collision course with ACAS

HOMY – controller passes message prompted by RA downlink

The probability in an uncoordinated encounter in which a collision would occur without RA downlink, given that the controller has already given an instruction counter to the sense of the downlinked RA, that the controller passes a message prompted by RA downlink. The converse event is *HOMX (controller does not pass message prompted by RA downlink)*.

HOXY – controller countermands previous instruction

The probability in an uncoordinated encounter in which a collision would occur without RA downlink, given that the controller has already given an instruction counter to the sense of the downlinked RA and decides to pass a message, that the message will countermand the previous instruction. The converse event is *HOXX (controller gives new instruction)* – that instead of countermanding the previous instruction, the controller gives a new instruction.

HOBY – controller gives instruction to both aircraft

The probability in an uncoordinated encounter in which a collision would occur without RA downlink, given that the controller has already given an instruction counter to the sense of the downlinked RA but decides to issue a new instruction, that the controller gives the instruction to both aircraft. The converse event is *HOBX (controller gives instruction to only one aircraft)*.

HOAY – controller give instruction to ACAS aircraft only

The probability in an uncoordinated encounter in which a collision would occur without RA downlink, given that the controller has already given an instruction counter to the sense of the downlinked RA but decides to issue a new instruction (prompted by RA downlink) to one aircraft only, that the controller gives the instruction to the ACAS equipped aircraft. The converse event is *HOAX (controller gives instruction to unequipped aircraft only)*.

Uncoordinated encounter, inconsistent CI, not collision course with ACAS

HQMY – controller passes message prompted by RA downlink

The probability in an uncoordinated encounter in which a collision would not occur without RA downlink, given that the controller has already given an instruction counter to the sense of the downlinked RA, that the controller passes a message prompted by RA downlink. The converse event is *HQMX (controller does not pass message prompted by RA downlink)*.

HQXY – controller countermands previous instruction

The probability in an uncoordinated encounter in which a collision would not occur without RA downlink, given that the controller has already given an instruction counter to the sense of the downlinked RA and decides to pass a message, that the message will countermand the previous instruction. The converse event is *HQXX (controller gives new instruction)* – that instead of countermanding the previous instruction, the controller gives a new instruction.

HQBY – controller gives instruction to both aircraft

The probability in an uncoordinated encounter in which a collision would not occur without RA downlink, given that the controller has already given an instruction counter to the sense of the downlinked RA but decides to issue a new instruction, that the controller gives the instruction to both aircraft. The converse event is *HQBX (controller gives instruction to only one aircraft)*.

HQAY – controller give instruction to ACAS aircraft only

The probability in an uncoordinated encounter in which a collision would not occur without RA downlink, given that the controller has already given an instruction counter to the sense of the downlinked RA but decides to issue a new instruction (prompted by RA downlink) to one aircraft only, that the controller gives the instruction to the ACAS equipped aircraft. The converse event is *HQAX (controller gives instruction to unequipped aircraft only)*.

5.2.3 Pilot events

HCMX – ACAS pilot not notice controller message

The probability that the pilot of an ACAS equipped aircraft (who will have already received an RA) will not notice a message from the controller. The converse event is *HCMY (ACAS pilot does notice controller message)*.

5.2.4 Logic events

Two logic events might be expected to be covered by the events inherited from the full-system contingency tree: the probability that an ACAS RA and a consistent controller instruction will result in a collision. However, in the full-system study it was implicitly assumed that in these cases a collision never resulted. That assumption has been relaxed in the RA downlink contingency tree and so the events are described here.

<u>Collision course</u>

LRYU – two evasive manoeuvres fail to resolve collision

The probability that when two aircraft are on a collision course when one pilot responds to the RA while the other pilot follows an instruction from a controller who is not already involved, which is consistent with the RA, that a collision will occur.

<u>Not collision course</u>

LRYI – two evasive manoeuvres induce collision

The probability that when two aircraft are not on a collision course when one pilot responds to the RA while the other pilot follows an instruction from a controller who is not already involved, which is consistent with the RA, that a collision will be induced.

5.3 Tuning probabilities to specific RA downlink implementations

5.3.1 RA downlink implementation

RA downlink might be deployed in a number of different circumstances, which potentially will affect its performance:

- downlink technology employed – there are two viable candidates for an RA downlink technology: Mode S reports downlinked through an existing Mode S radar network; or extended squitter downlinked through a dedicated ground station network. The chosen downlink technology will affect the latency of downlinked alerts.

- radar coverage and (for extended squitter) the ground station coverage – the number and the characteristics of Mode S radars and (for extended squitter) the number of ground stations will affect the latency of downlinked alerts.

- immediately or synchronised display of downlinked alerts – downlinked alerts might be displayed immediately they are available at the CWP or they might be delayed to be displayed at the next routine update of the display. This will directly affect the latency of downlinked alerts.

- airspace in which RA downlink is deployed – RA downlink might be deployed to aid controllers of terminal airspace or en-route controllers. Differences in radar coverage, the way in which airspace is managed, the aircraft using the airspace, and the characteristics of ACAS alerts at different altitudes will all affect the performance of RA downlink (both the latency of downlinked alerts and the circumstances in which it is hoped they will aid the controller).

The RA downlink contingency tree structure, described here, can be used to evaluate the risk of collision with any combination of the factors described above, by using suitable values of the event probabilities to reflect the particular implementation of RA downlink.

The principal means of determining the probabilities for those events that vary with the RA downlink implementation are through the use of a suitable encounter model (described in section 5.3.2) and through the use of a model of downlink latencies (described in section 5.3.3).

5.3.2 Event probabilities determined by encounter models

The effectiveness of the ACAS collision avoidance algorithms are determined by computer simulations of ACAS RAs, including models of pilot response and altimetry error (see *e.g.* [3]). Such simulations enable the logic event probabilities to be determined (LTTU, LTNU, LTSU, LTTI, LTNI, and LTSI: see section 5.1.5), together with the probability that the aircraft are originally on a collision course (GCCY: see section 5.1.1).

The simulations can be tailored to reproduce the behaviour of ACAS in a particular airspace by using encounters generated by an encounter model. The encounter model reproduces the characteristics of the airspace by employing distributions of relevant parameters that in turn were derived from the observation of real encounters in airspace of the type under consideration. This was the approach adopted in the ACASA and ASARP studies. Knowing the airspace which the encounter model reproduces also enables the proportion of ACAS equipped aircraft to be determined (EAEY_B: see section 5.1.2).

The encounter models in the ACASA and ASARP studies used separate distributions of parameters for each of several altitude layers. By using only encounters from appropriate altitudes layers event probabilities relevant to either terminal or en-route airspace can be determined.

While the primary latency of RA downlink (*i.e.* the time delay between an RA on the flight-deck and the presentation of a downlinked alert at the CWP) does not depend on the individual encounters, the timing of the presentation of a downlinked alert relative to the latest time at which a controller intervention can affect the outcome of an encounter does depend on nature of the encounters. This is because the time thresholds of ACAS alerts (and therefore the nominal warning times) depend on altitude (ACAS is more sensitive at high altitudes were RA warning times can be up to 35s compared to as little 15s close to the surface). This altitude dependence therefore affects the downlink event probabilities and is incorporated into the latency modelling tool which is discussed in the next section.

5.3.3 Event probabilities determined by latency models

The RA downlink events in the contingency tree (other than the simple ‘switch’ of whether RA downlink is deployed or not) are connected with the latency of RA downlink (see section 5.2.1) Their probabilities can be calculated using a model of RA downlink latencies such as the ‘Kairos’ model whose development and use is reported in [6].

The Kairos model allows each of the factors described in section 5.3.1 to be varied so as to reflect the particular RA downlink implementation that is of interest.

The timeliness of RA downlink alerts (events DCTY and DUTY) can be determined directly from the outputs of the Kairos tool. The probabilities that the RA has invisibly reversed (events DCCY, DCNY, DUCY, and DUNY) can be determined from the outputs of the Kairos tool (to determine the latency of any reversal) combined with probabilities derived from ACAS simulations using the encounter model (to determine the probabilities of such reversals).

6. PRELIMINARY CALCULATION OF RA DOWNLINK RISK RATIO

The RA downlink contingency tree has been used to perform a preliminary calculation of the efficacy (in terms of the effect on the risk of mid-air collision) of RA downlink. At this stage of the study there are many events whose probability is not known with any accuracy (principally the human factors events describing the controllers' reaction to downlinked alerts). Consequently this calculation can only give the broadest indication of the performance of RA downlink and serves rather as a demonstration of the use of the contingency tree.

6.1 Events inherited from the full-system contingency tree

Probabilities for events in the full-system contingency tree have been derived in the ASARP study (see [17]), which calculated the full-system risk ratio for ACAS deployed in the RVSM altitude layer. These values have been used here for the probabilities of events inherited from the full-system contingency tree (see section 5.1), and are shown in Table 17.

The assumption, implicit in the ASARP study, that when one aircraft responds to the RA and the other aircraft follows a consistent controller instruction that a collision will not result has been repeated here (*i.e.* LRYU = 0, and LRYI = 0).

description	code	value
not on an collision course	GCCY	0.054797
on an collision course	GCCX	0.945203
controller is already involved	ACIY	0.5
controller is not already involved	ACIX	0.5
proportion of ACAS equipped aircraft	EAEY_B	0.976854
proportion of unequipped aircraft	EAEX_B	0.023146
pilot contacts controller in response to an ACAS TA	HCCY	0.005
pilot does not contact controller in response to an ACAS TA	HCCX	0.995
pilot notes/follows controller instruction	HFCY	0.99
pilot ignores controller instruction	HFCX	0.01
pilot notes/responds to RA	HFRY	0.986218
pilot ignores RA	HFRX	0.013782
pilot prefers RA to controller instruction	HPRY	0.911695
pilot prefers controller instruction to RA	HPRX	0.088305
controller instruction counter to RA (not on a collision course)	HRXI	0.072500
controller instruction counter to RA (on a collision course)	HRXU	0.093200
coordinated RAs fail (typical response, on CC)	LTTU	0.000425
coordinated RA fails (no response by intruder, on CC)	LTNU	0.002021
RA against uneq threat fails (typical response, on CC)	LTSU	0.003297
two inconsistent evasive manoeuvres fail to resolve collision	LRXU	0.046000
two consistent evasive manoeuvres fail to resolve collision	LRYU	0.0
controller instruction resolves collision	LCWY	0.9
controller instruction fails to resolve collision	LCWX	0.1
coordinated RAs fail (typical response, not on CC)	LTTI	0.000148
coordinated RA fails (no response by intruder, not on CC)	LTNI	0.002448
RA against uneq threat fails (typical response, not on CC)	LTSI	0.001767
two inconsistent evasive manoeuvres induce an collision	LRXI	0.035340
two consistent evasive manoeuvres induce an collision	LRYI	0.0

Table 17: Event probabilities from ASARP full-system contingency tree

6.2 Events new to the RA downlink contingency tree

The probabilities used in the ASARP study are applicable to RVSM altitude layers. Consequently the remaining probabilities that depend on the downlinking environment have been chosen to reflect deployment in en-route airspace. Furthermore, the use of the Mode S report method of downlinking alerts, a typical radar coverage pattern (see [6]), and the immediate display of alerts at the CWP have been assumed.

6.2.1 Downlink event probabilities

The timeliness of alerts can be determined from a model of the latencies involved in the RA downlink process, and an assessment of what constitutes timeliness. Here it has been assumed that at least 20s is required for the controller to notice the alert, pass any message to the pilot, and for the subsequent pilot reaction to have an effect.

Using the Kairos model described in [6] it was found (in the en-route environment using Mode S reports, typical radar coverage and the immediate display of alerts at the CWP) that 65.3% of alerts could be displayed to the controller with more than 20s remaining until the potential collision of the two aircraft. This value corresponds to a mixed equipage environment in line with the ACAS mandate (22.6% of encounters are between an ACAS aircraft and an unequipped aircraft, 77.4% of encounters are between two ACAS equipped aircraft). Adjustment of the Kairos tool will be required to obtain values purely for coordinated encounters or for uncoordinated encounters, but for the preliminary calculation and knowing that downlink will be more timely in coordinated encounter (since there are two aircraft from which the RA might be downlinked) a value of 0.7 is adopted for the timely downlink in a coordinated encounter (DCTY), and a value of 0.6 for the timely downlink in an uncoordinated encounter (DUTY).

The probabilities that an RA will have invisibly reversed depend on the likelihood of a reversal and whether this reversal is hidden by latency of downlink. Given that a collision occurs (in the absence of RA downlink) between two ACAS aircraft, a naïve ‘back-of-an-envelope’ calculation suggestions that it is virtually certain that the RA (which is not working) will have reversed at some point. While this may overstate the case it emphasises that the likelihood of a reversal is much greater than the proportion of operational RAs that reverse (when there is in fact no risk of collision) might suggest. Uncoordinated RAs can be expected to be more likely to reverse (since ACAS is not constrained by the need to coordinate with the other aircraft) and any reversal is more likely to be hidden (since there is only one aircraft from which the alert can be downlinked). Bearing these factors in mind a value of 0.25 has been adopted for the probability of a hidden reversal in a coordinated encounter (in which a collision would occur without RA downlink) (DCCY) and a value of 0.5 in an uncoordinated encounter (DUCY).

In encounters in which a collision would not occur without RA downlink the proportion of encounters in which the RA reverses can be expected to be more in line with operational experience (*i.e.* a few percent). A value of 0.01 has been adopted for the probability of a hidden reversal in a coordinated encounter (in which a collision would not occur without RA downlink) (DCNY) and a value of 0.05 in an uncoordinated encounter (DUNY).

These probabilities are summarised in Table 18.

description	code	value
timely downlink in coordinated encounter	DCTY	0.7
downlink too late in coordinated encounter	DCTX	0.3
timely downlink in uncoordinated encounter	DUTY	0.6
downlink too late in uncoordinated encounter	DUTX	0.4
RA has invisibly reversed :: coordinated encounter, on collision course with ACAS	DCCY	0.25
RA has not invisibly reversed :: coordinated encounter, on collision course with ACAS	DCCX	0.75
RA has invisibly reversed :: coordinated encounter, not on collision course with ACAS	DCNY	0.01
RA has not invisibly reversed :: coordinated encounter, not on collision course with ACAS	DCNX	0.99
RA has invisibly reversed :: uncoordinated encounter, on collision course with ACAS	DUCY	0.5
RA has not invisibly reversed :: uncoordinated encounter, on collision course with ACAS	DUCX	0.5
RA has invisibly reversed :: uncoordinated encounter, not on collision course with ACAS	DUNY	0.05
RA has not invisibly reversed :: uncoordinated encounter, not on collision course with ACAS	DUNX	0.95
controller notices downlinked RA	HNDY	0.99
controller does not notice downlinked RA	HNDX	0.01
ACAS pilot notices controller intervention	HCMY	0.9
ACAS pilot does not notice controller intervention	HCMX	0.1
New controller instruction is consistent with downlinked RA	HMNY	0.95
New controller instruction counter to downlinked RA	HMNX	0.05

Table 18: Event probabilities for downlink events and controller intervention

6.2.2 Human factors event probabilities

Event HNDY corresponds to whether the controller notices the downlinked RA alert at the CWP. Generally the controller can be expected to notice an alert and a failure rate of 1% has been assumed. Consequently HNDY = 0.99.

Event HCMY corresponds to whether the pilot notices a message from the controller (given that the controller passes a message). The pilot will be in a stressful situation because he is dealing with an ACAS RA. Therefore a higher failure rate of 10% has been assumed. Consequently HCMY = 0.9.

If, as a result of a downlinked alert, the controller chooses to give an instruction to either of the aircraft, the event HMNX determines whether the instruction is counter to the downlinked RA. This event is similar to the events HRXU and HRXI where the controller gives an instruction (prompted by contact from the pilot) that is counter to the RA (see Table 17). There, the only cue to the likely sense of an RA being the geometry of the encounter as displayed on the CWP, the probabilities are 7% and 9% respectively. Following a downlinked alert the controller will have more information as the sense of the RAs will be displayed – it is therefore assumed that the controller will be less likely to give an instruction counter to the sense of the downlinked RA, and a value of 5% has been adopted.

The events described above are summarised in Table 18.

A large number of events describing the controller's behaviour, following a downlinked alert, are ostensibly similar but depend on the circumstances:

- is the encounter a coordinated encounter (between two ACAS aircraft), or an uncoordinated encounter (between an ACAS aircraft and an unequipped aircraft);
- are the aircraft on a collision course (given the pilots' response to ACAS and any controller instructions prompted by contact from the pilots), or not;
- has the controller given an instruction prompted by contact from the pilots, and if so was the instruction counter to the RA, or not.

Events of the form H*n*MY[26] correspond to whether the controller intervenes in the encounter. When the aircraft are on a collision course it has been assumed that there is a 50% chance that the controller will intervene; when the aircraft are not on a collision course it has been assumed that there is only a 10% chance that the controller will intervene.

Given that the controller does intervene he may countermand a previous instruction when one was given (events of the form H*n*XY). It is assumed that there is a 90% chance that a controller who intervenes, having previously

[26] The letter *n* can take any of the values indicated in Table 11.

given an instruction, will do so to countermand that instruction (otherwise he will issue a new instruction).

A controller who is prompted by RA downlink to give an instruction may give the instruction to one aircraft only or to both aircraft (events of the form H*n*BY). It is assumed that in coordinated encounters the controller will give any instruction to both aircraft in 90% of cases; in an uncoordinated encounter it is assumed that the controller will give an instruction to only one aircraft in 90% of cases.

In an uncoordinated encounter in which the controller gives an instruction prompted by RA downlink to only one of the aircraft, it is assumed that in 90% of cases the instruction will be given to the unequipped aircraft (events of the form H*n*AX).

The events described above are summarised in Table 19.

description	code	value
controller intervenes :: on collision course with ACAS	HEMY, HGMY, HIMY, HKMY, HMMY, HOMY	0.5
controller does not intervene :: on collision course with ACAS	HEMX, HGMX, HIMX, HKMX, HMMX, HOMX	0.5
controller intervenes :: not on collision course with ACAS	HFMY, HHMY, HJMY, HLMY, HNMY, HQMY	0.1
controller does not intervene :: not on collision course with ACAS	HFMX, HHMX, HJMX, HLMX, HNMX, HQMX	0.9
intervention countermands previous instruction	HGXY, HHXY, HIXY, HJXY, HMXY, HNXY, HOXY, HQXY	0.9
intervention gives new instruction	HGXX, HHXX, HIXX, HJXX, HMXX, HNXX, HOXX, HQXX	0.1
new instruction is to both aircraft :: coordinated encounter	HEBY, HFBY, HGBY, HHBY, HIBY, HJBY	0.9
new instruction is to one aircraft only :: coordinated encounter	HEBX, HFBX, HGBX, HHBX, HIBX, HJBX	0.1
new instruction is to both aircraft :: uncoordinated encounter	HKBY, HLBY, HMBY, HNBY, HOBY, HQBY	0.1
new instruction is to one aircraft only :: uncoordinated encounter	HKBX, HLBX, HMBX, HNBX, HOBX, HQBX	0.9
new instruction is to ACAS aircraft :: uncoordinated encounter	HKAY, HLAY, HMAY, HNAY, HOAY, HQAY	0.1
new instruction is to unequipped aircraft :: uncoordinated encounter	HKAX, HLAX, HMAX, HNAX, HOAX, HQAX	0.9

Table 19: Event probabilities for controller behaviour following RA downlink

6.3 Use of Quercus

The event probabilities summarised in Table 17, Table 18, and Table 19 have been used to perform a preliminary calculation of the risk of collision with RA downlink.

The contingency tree tool Quercus version 4.0 was used with the contingency tree structure in the file “tradlct_26.tree” and the probabilities in file “pradlct_26.prob”.

The specific assumptions of section 3.1.3 where also implemented with the full-system contingency tree developed in the ASARP project, so that the ACAS risk ratios for the conditions under which RA downlink is being considered could also be calculated.

The results are described in the next section.

6.4 Results

6.4.1 ACAS full-system risk ratio

The ASARP full-system contingency tree has been used to evaluate the risk of mid-air collision in encounters satisfying the following conditions:

- at least one aircraft is ACAS equipped;
- all aircraft are equipped with Mode S transponders and report altitude;
- ACAS units always track any collision threat;
- there is a controller; and
- visual acquisition plays no part in preventing an RA.

An evaluation of the deployment of RA downlink in an en-route controlling environment was undertaken, so that the event probabilities (notably the logic risks) calculated for RVSM airspace in the ASARP study [17] could be used – probabilities from the ACASA study are average values for an airspace including both terminal and en-route controlling environments.

The ACAS risk ratio is calculated to be 1.18% with an induced risk ratio of 0.48%.[27] This indicates that in these circumstances, ACAS substantially reduces the risk of mid-air collision but in the event that a collision does occur there is about a 40% chance that the collision was induced by ACAS.

[27] Because of the specific conditions considered here, these values are not directly comparable with any published in the ASARP study report [9].

6.4.2 RA downlink risk ratio

The collisions that occur when ACAS is deployed form the baseline against which the performance of RA downlink is compared. The risks derived from the branches of the RA downlink contingency tree are shown as percentages of this risk in Table 20.

Shown on the left-hand side of Table 20 are the risks evaluated when RA downlink is not deployed (DLDY = 0). Here we see that induced risk forms just over 40% of the total risk with ACAS, as was reported in section 6.4.1.

On the right-hand side of Table 20 we see the risks evaluated when RA downlink is deployed (DLDY = 1). The results from this preliminary assessment indicate that RA downlink reduces the risk of collision to 95.1% of the risk with ACAS alone. The induced risk is 9.5% of the risk with ACAS alone.

ACAS alone	risk	ACAS and RA downlink	risk	
unresolved by ACAS (D)	59.3%	unresolved by ACAS and not resolved by RA downlink (D_1)	50.9%	85.6%
induced by ACAS (B)	40.7%	induced by ACAS, not resolved by RA downlink (B_1)	34.7%	
		resolved by ACAS, resolution thwarted by RA downlink (C_1)	7.1%	9.5%
		no collision with or without ACAS, collision induced by RA downlink (A_1)	2.4%	
total	100%	total	95.1%	

Table 20: Event probabilities for controller behaviour following RA downlink

Within the terms of this preliminary assessment, for every 1,000 collisions with ACAS the deployment of RA downlink could be expected to resolve 144 of them. However, RA downlink might induce 95 collisions that would not have occurred had ACAS been operating alone. So RA downlink could reduce the number of collisions from 1,000 to 951, but of those 951 collisions 95 would have been induced by RA downlink: in the event that a collision occurred despite equipage with ACAS and the deployment of RA downlink, there would be a 1 in 10 chance that the collision was induced by RA downlink.

Recall that all RA downlink equipment is assumed to work to specification. The induced risk does not arise from errors in the performance of the RA downlink system but rather from the combination of controllers' responses to downlinked RAs and pilots' responses to any controller messages.

6.4.3 Discussion

As was stressed before, definitive values for the event probabilities in the RA downlink contingency tree are not yet available, and consequently the results presented in section 6.4.2 cannot be relied upon as an accurate evaluation of the performance of RA downlink.

Rather the results, which show a risk ratio for the deployment of RA downlink marginally less than 100%, should be taken as indicative of the fact that at this stage the effectiveness of RA downlink is not clear cut: the results suggest that RA downlink will not produce an additional factor of protection as effective as ACAS alone (where risk ratios are typically 10% or lower); nor do they suggest that RA downlink is so obviously deleterious that a risk ratio greatly in excess of 100% is indicated.

Further work, principally to produce accurate values for the event probabilities, will enable more reliable estimates of RA downlink risk ratios to be derived, so that its efficacy in various environments can be judged.

6.5 Deriving definitive event probabilities

The derivation of a definitive set of event probabilities for the RA downlink contingency tree requires work in three main areas: ACAS simulations based on encounter generated by an encounter; latency calculations using the mathematical model developed in FARADS; and appropriate effort to determine the large number of human factors probabilities corresponding to the behaviour of controllers and pilots in a variety of circumstances.

6.5.1 ACAS simulations

ACAS simulations using encounters generated by a safety encounter model were used to produce the logic risks that defined the logic event probabilities in previous full-system contingency trees.

The logic event probabilities required to characterise either terminal airspace or en-route airspace in the full-system contingency tree can be derived from simulations on encounters sets generated by an encounter model (such as that derived in the ASARP study) and restricted to encounters from the altitude range of interest (nominally 1,000ft AGL to FL135 for terminal airspace, and FL135 to FL415 for en-route airspace).

ACAS simulations will also be needed to derive probabilities for the events that described hidden reversals in RA sense. The ACAS simulations will enable the proportion of RAs that reverse to be determined together with the distribution in time (relative to the original RA) at which such reversals occur. Knowing these factors a model of RA downlink latencies, such as the Kairos model developed in FARADS, can be used to determine the probability that a reversal is hidden by latency.

6.5.2 Latency calculations

The use of a latency model in the derivation of the probabilities of hidden RA sense reversals has been mentioned in the preceding section.

The latency model can also be used to derive the probability of timely downlink of alerts. The current implementation of the Kairos model produces latency statistics that are averaged over both coordinated and uncoordinated encounter. By suitable adjustment of the source code it should be possible to obtain separate values for coordinated encounters and for uncoordinated encounters as are required by the RA downlink contingency tree.

6.5.3 Human factors

A large number of events relate to the behaviour of the pilots and controllers (particularly the latter) in a variety of circumstances. The probabilities corresponding to these events will need to be derived using appropriate human factors analysis techniques. These might consist of operational monitoring, interviews and surveys, real-time simulations, mathematical models, or the informed opinions of human factors experts.

6.6 Further work

6.6.1 Populating the event probabilities

The current document reports the first stage of a study: the development of a contingency tree structure that will facilitate the assessment of the safety of RA downlink. A second, optional, stage of the study would use simulations, operational monitoring, and data gathering to provide authoritative values for the event probabilities needed as inputs to the contingency tree (as described above). This would enable the contingency tree to be exercised and the efficacy of RA downlink to be assessed.

6.6.2 Sensitivity analysis

The second stage of the study also allows for the conduct of a sensitivity analysis.

The event probabilities, which form the inputs to the contingency tree, will not be known with absolute precision. Naturally, the more precisely probabilities are known, the more accurately the contingency tree can determine the effectiveness of RA downlink. However, determining probabilities more precisely requires effort and with limited resources it is prudent to concentrate the efforts on those probabilities that have the greatest influence on the overall calculation.

Determining which probabilities have the greatest influence on the overall calculation would constitute a sensitivity analysis. The effective on the output of the contingency tree of varying the values of individual event probabilities within the range of their known precision would be noted. This would enable further effort in refining the contingency tree calculations to be directed to those areas in which it would be most beneficial.

6.6.3 Short-term conflict alert

It was explained in section 2.5.2 that short-term conflict alert (STCA) has not been included as a factor in the contingency tree whose development is described in the current report.

If RA downlink on its own is determined to be effective it may be desirable to extend the scope of the contingency tree to include the interaction of the controller and STCA, and determine whether RA downlink is similarly effective in the STCA environment.

The complex nature of the interaction between STCA and ACAS alerts (see, *e.g.* [12] and [18]) means that the incorporation of STCA alerts would require the contingency tree to be restructured with the introduction of further events to account for the occurrence of STCA alerts, and the controllers' response to these alerts.

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8. ACRONYMS AND GLOSSARY

ACAS — Airborne Collision Avoidance System – The carriage of ACAS II, by civil aircraft with a maximum take-off mass in excess of 5,700kg or a maximum approved passenger configuration of more than 19, is mandated in ECAC airspace.

ACASA — ACAS Analysis – A EUROCONTROL project consisting of a wide range of studies of ACAS performance in European airspace. WP1 studied the safety of ACAS and developed a contingency tree to evaluate the full-system safety performance of ACAS.

AGAS — European Action Group on ATM Safety

ASARP — ACAS Safety Analysis post-RVSM Project – A EUROCONTROL project reprising the safety studies performed in ACASA but using operational RVSM data.

close encounter — For the purposes of this study, an encounter between two aircraft in which the horizontal separation is less than 500ft, and the vertical separation is sufficiently small that an ACAS RA or a controller instruction might cause the aircraft to manoeuvre in the vertical plane. Since horizontal separation is small, if the vertical manoeuvres result in a vertical separation of less than 100ft an NMAC occurs.

contingency tree — A branching structure that allows the evaluation of a complex probability calculation. Probabilities are combined through the use of 'gates'. Used here to calculate the overall risk of a midair collision, it is essential the same as a fault tree but the current term is preferred as not all the states leading to an undesirable outcome are faults in the system.

controller instruction — An message from the controller to a pilot directing him to follow a particular vertical profile. A controller instruction may or may not require a change to the intended vertical profile.

controller message — A message from the controller to the pilot that may constitute a controller instruction (*q.v.*), or may remind the pilot that an ACAS RA takes precedence over a controller instruction (effectively countermanding any previous controller instruction).

CWP — controller's working position

downlink — The process by which an ACAS alert declared on the flight-deck can be passed, via the aircraft transponder, to a ground network and ultimately displayed to the controller.

FARADS	Feasibility of RA Downlink Study – a EUROCONTROL programme addressing the feasibility and desirability of downlinking ACAS RAs from aircraft to the controller in real-time.
full-system	The totality of specific equipment or procedures and the ATM system in which they are embedded. A full-system safety study aims to determine the actual safety benefit that will be achieved when the specific equipment or procedures are in operation.
hidden reversal	An RA reversal that has occurred on the aircraft but which, due to latency, has not yet been presented to the controller.
induced risk	Risk caused by the system that would not exist without the system. If the induced risk is less than the resolved risk there can still be an overall reduction in risk.
Kairos	A PC-based application (developed by QinetiQ for EUROCONTROL) that enables statistical distributions of the latency of RA downlink to be computed.
NMAC	near mid-air collision – a situation in which the separation between two aircraft is less than 500ft horizontally and simultaneously less than 100ft vertically. NMACs are often used as a substitute for collisions when calculating risk ratio.
predilection	A pilot’s predisposition to comply or ignore ACAS RAs, to follow or ignore controller messages, and his preference to comply with an RA or follow a controller message when he ignores neither.
preference	A pilot’s predisposition to comply with an ACAS RA, or to follow a controller messages, when he receives both and ignores neither.
Quercus	A PC-based application (developed by QinetiQ) that enables contingency trees for ACAS and RA downlink to be constructed and evaluated.
RA	resolution advisory – an ACAS alert issued if a diagnosed risk of collision becomes urgent. An RA provides the pilot with advice on how to regulate or adjust his vertical speed so as to avoid a collision. RAs can be displayed in a number of different ways depending on the specific installation (*e.g.* red and green arcs on a vertical speed indicator, or pitch cues on the primary flight display) and are accompanied by an aural annunciation reinforcing the advice provided by the RA display.
reversal	A reversal in the sense of an ACAS RA (*i.e.* a climb sense RA that reverses to a descend sense RA, or *vice versa*).

risk ratio	A measure of the safety performance of a system. The risk ratio is the ratio of the risk of collision with the system deployed, to the risk without the system. Often expressed as a percentage: a risk ratio of 0% would indicate a perfect system (the risk of collision is eliminated by the system); a risk ratio of 100% indicates an ineffective system (the risk is unaffected by the system); a risk between 0% and 100% indicates an effective system (the risk system decreases the risk); risk ratio greater than 100% would indicate a positively deleterious system (the system increases the risk).
RVSM	reduced vertical separation minima – the regime of vertical separation that introduced 1,000ft spacing between standard cruising levels up to FL410.
STCA	short-term conflict alert – a class of ground-based systems that use radar data to warn controllers of potential traffic conflicts.
TA	traffic alert – an ACAS alert indicating the presence of another aircraft that might constitute a collision threat in the near future. TAs alert the pilot to the presence of an intruder that may become a threat to his own aircraft. They are accompanied by an aural annunciation and a change of symbol on a cockpit display of traffic information intended to aid visual acquisition.
TCAS	Traffic alert and Collision Avoidance System – A specific implementation of the ACAS concept. TCAS II Version 7 is currently the only system that is compliant with the ACAS specification.
unresolved risk	Risk that exists whether the system is deployed or not.