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Thinking about downlink of resolution advisories from airborne collision avoidance systems

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Abstract

One of the open questions about Airborne Collision Avoidance Systems (ACAS) is whether Resolution Advisory (RA) information should be automatically downlinked to the display of the controller handling the aircraft involved. The aim here is to see if a clear pathway for decision-makers can be derived from rational assessment using general safety principles and Human Factors guidelines, plus readily available data. Situational awareness principles indicate that RA downlink should be as simple as possible, consistent with improving safety, preferably using an existing display type. The proposed method for assessing the potential benefits and disadvantages of RA downlinking uses Airproxes, mainly because they represent occasions in which situational awareness is impaired, and a structured analysis of the effects of downlinking on the various kinds of Airprox, controller action and pilot report.

Introduction

The International Civil Aviation Organisation (ICAO) mandated Airborne Collision Avoidance Systems (ACAS) in 1993. ACAS has proved its worth in preventing mid-air collisions. However, the success of ACAS depends crucially

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on the correct performance by flight crews and air traffic control (ATC) of the necessary operational procedures.

One important issue about operational procedures arose following the publication of an accident investigation report into a near mid-air collision over Japan on 31 January 2001 (ICAO, 2002). This involved two aircraft equipped with ACAS II, and resulted in injuries to passengers and crew. Subsequently, there was the tragedy of the 2002 Überlingen mid-air collision (BFU, 2004) involving two ACAS II equipped aircraft, a B757-200 and a TU154M.

The key ACAS issue was the response by the pilot to a Resolution Advisory (RA), upon which the pilot must act. This aspect has been the subject of considerable international action. There are now several guidelines and instructions in place to clarify the position for aircrew and ATC, e.g. CAA (2003), ICAO (2004), Eurocontrol (2002), IBAC (2002).

One of the open questions is whether RA information should be automatically downlinked to the display of the controller handling the aircraft involved in an ACAS RA. This note explores some of the issues raised. It should be noted immediately that such a downlink might not – if the reconstruction of events in BFU (2004) is accurate – have prevented the Überlingen accident. One reason for this caution is that the controller involved was responsible for two workstations. He was distracted by a time-consuming task on the other workstation, arising from a delayed A320 to Friedrichshafen, with the complication of a failed telephone connection. To quote BFU (2004) 'The controller considered the (B757-200/TU154M) problem solved too early and moved to the adjacent workstation' (p. 105). The controller has to be looking at the display if he or she is to see a downlinked RA symbol. The questions posed are therefore generic, i.e. concerning the whole range of potential future mid-air collisions in which there are RAs.

Technical aspects of such a downlink, e.g. the timings and reliability of RA data, are not covered here – and are already the subject of current research work, eg Eurocontrol (2003) (which includes summaries of previous research work) and Drozdowski (2004) (see also the informative Eurocontrol website: http://www.eurocontrol.int/ra-downlink). The aim here is to see to what extent useful answers can be derived from rational assessment using general safety principles, Human Factors guidelines, and readily available data. (A useful conclusion would include the identification of supplementary research and analysis that would be most helpful to decision-makers.)

The desired RA sequence

ICAO's air traffic management procedures for ACAS (ICAO, 2001) are shown in Figure 1.

15.6.3.2 When a pilot reports a manoeuvre induced by an ACAS resolution advisory (RA), the controller shall not attempt to modify the aircraft flight path until the pilot reports returning to the terms of the current air traffic control instruction or clearance but shall provide traffic information as appropriate.

15.6.3.3 Once an aircraft departs from its clearance in compliance with a resolution advisory, the controller ceases to be responsible for providing separation between that aircraft and any other aircraft affected as a direct consequence of the manoeuvre induced by the resolution advisory. The controller shall resume responsibility for providing separation for all the affected aircraft when:

a) The controller acknowledges a report from the flight crew that the aircraft has resumed the current clearance; or

b) The controller acknowledges a report from the flight crew that the aircraft is resuming the current clearance and issues an alternative clearance which is acknowledged by the flight crew.

Figure 1 Extracts re ACAS from ICAO (2001)

The sequence of actions for a pilot following an RA is set out very clearly in CAA (2003). Figure 2 lists the main points. Note that the ‘current clearance’ would be the instructions prior to any collision avoidance manoeuvre initiated by ATC.

The pilot should:

- ⇒ Respond immediately by following the RA as indicated, unless doing so would jeopardise the safety of the aeroplane;
- ⇒ Follow the RA even if there is a conflict between the RA and an air traffic control (ATC) instruction to manoeuvre;
- ⇒ As soon as possible, as permitted by flight crew workload, notify the appropriate ATC unit of the RA, including the direction of any deviation from the current air traffic control instruction or clearance;
- ⇒ Promptly comply with any modified RAs;
- ⇒ Limit the alterations of the flight path to the minimum extent necessary to comply with the RAs;
- ⇒ Promptly return to the terms of the ATC instruction or clearance when the conflict is resolved;
- ⇒ Notify ATC when returning to the current clearance.

Figure 2 Pilot actions following an RA – main instructions (CAA, 2003)

Figure 3 shows a picture of this process, even more simplified, but this version shows both the pilot actions etc – above the time line – and the controller events below it. Again, note that this is what *should* happen following an RA if everything proceeds as desired according to the guidance.

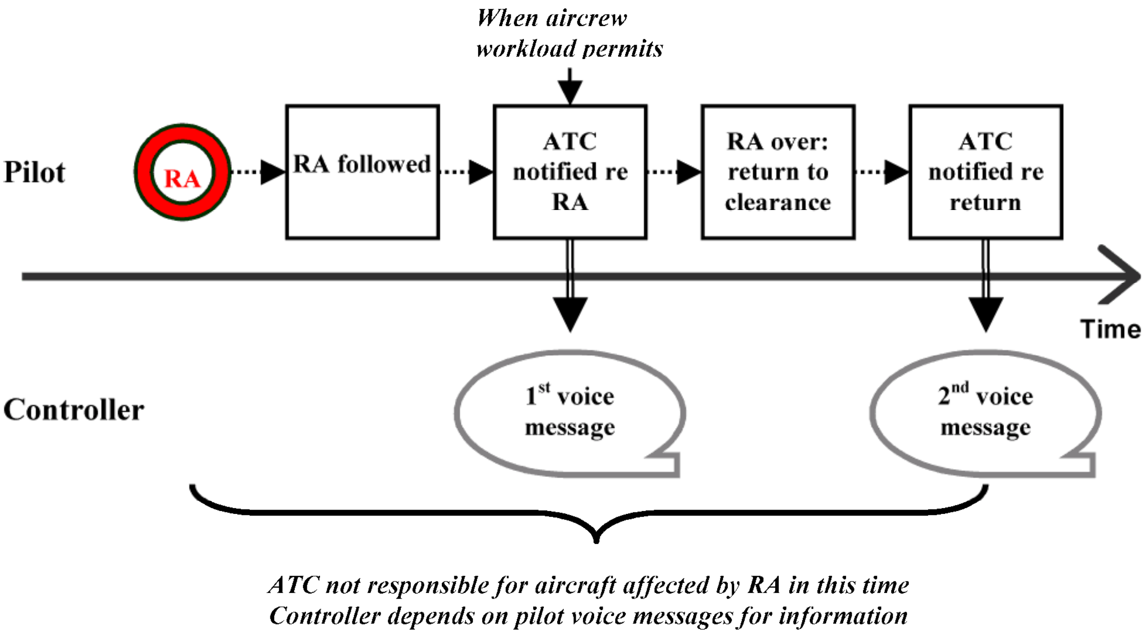

Figure 3 ***Desired*** **sequence following an RA – simplified**

In Figure 3, the start of the RA is shown by the annulus around 'RA'. There are three key points to note about ATC's involvement as sketched in figures 2 and 3. The controller handling the aircraft with the RA:

i. Ceases to be responsible for providing separation from the instant the RA is indicated (because in this ideal version of event the pilot should 'respond immediately' – figure 2) until the pilot notifies that the aircraft has returned to its 'prior to RA' normal clearance;
ii. Does not know about the RA, nor what the aircraft is doing, until the pilot's first voice message;
iii. Does not know that the RA has ended until the second voice message.

It is worth examining the meaning of the word 'responsible' here. The word is being used in the sense of 'being in control' or 'having decision-making authority', as distinct from any kind of legal interpretation. The controller would believe that he or she has control of the aircraft flightpaths until the first voice message is received from the pilot. In the period from the start of the RA to the receipt of the voice message, the controller could therefore issue instructions, perhaps (unknowingly) contrary to ACAS RA indications – but still be doing his/her job correctly. This is why it is crucial that the pilot ignores such instructions and notifies ATC that an RA is being followed.

What happens in practice?

In reality, sometimes the desired RA sequence is not followed. The controller may receive one message or none at all, or just get the information some time after the RA has finished (as a consequence of the increased cockpit workload during the RA). Two aircrews responding to complementary RAs might report on the same radio frequency more or less simultaneously, thus jamming the frequency and producing confusing transmissions.

Conflicts producing RAs can be very complex. This is best illustrated by examining Airprox reports (UKAB, 1999-). Airproxes are the best data on hazardous occurrences – and hence potential accidents – from the reality of operations. Appendix A shows selected summaries of Airproxes involving Civil Air Transport (CAT) aircraft incidents in the year 2000. The selection picks up seven Airproxes with RAs where ATC did not appear to be fully monitoring the potential conflict prior to an STCA and/or ACAS alert. Airproxes are a very valuable data source for this kind of incident because of their thorough investigation and publicly availability of detailed reports. The fact that the work of the UKAB is non-punitive (cases of gross negligence would be dealt with by other means) is particularly helpful, because pilots and controllers are generally very willing to share their thoughts about how the incident developed, and indeed their mental processes and workload.

There are several relevant messages about ATC safety defensive failures from Appendix A.

- Controllers can be coping with high workload.
- Controllers can be distracted by other conflicts.
- Trainees need careful mentoring.
- People can make judgement mistakes in instructions and coordination.

None of these is new: they are the meat-and-drink of Human Factors incident analyses. The simplest point to make is that Airproxes – and consequent RAs – frequently represent some kind of loss of situational awareness in the broadest sense of the phrase. An appropriate definition here would be on the lines of 'being aware of what is happening and understanding what that information means for decisions now and in the future': see Endsley and Jones (1996); Endsley and Rodgers (1994). In such cases, the controller is not aware of an incident until the pilot's voice message(s).

More important, the Airprox data also demonstrates the weakness of relying on conventional simulations and trials of display options. These can be very helpful in many ways in giving a good picture of pilot/controller behaviour, but they do not necessarily reproduce the realities of operational safety in genuinely risky situations. Thus, in conventional simulations, controllers generally do not lose situational awareness – and so do not face the problem of trying to regain it.

For example, in the MITRE Study reported in Eurocontrol (2003) (section 6.20 controllers did not report ever observing any RA events where an evasive manoeuvre was taken without their anticipation. It seems unlikely that this reflects USA controller performance in reality – UK Airprox data certainly provides many examples where an RA surprises a controller.

It is not straightforward to produce particular states of impaired situation awareness in a controller's mind. For example, controllers need to remember to perform activities in the future. Successful completion of an intended action in the future depends on a type of remembering that has been labelled 'prospective memory' (Harris, 1984; Loft et al, 2004). There is evidence that a high percentage of ATC related errors involved failures to execute deferred actions (Freed and Remington, 1999). How could this state of mind consistently be engineered in a simulation?

Note also that Short Term Conflict Alert (STCA) plays a part in ensuring the controller's situation awareness. For example, Hale and Law (1989), albeit with early versions of both STCA and ACAS, shows that in many cases an STCA alert will occur well before an ACAS RA. Thus, the controller should have developed some degree of situational awareness about the possible RA before it actually occurs. This research also showed that there will be circumstances in which the RA to the pilot and the STCA to the controller occur at about the same time.

How can ACAS RA downlink be shown to be a good thing – or not?

Eurocontrol (2003) discusses a wide range of aspects of ACAS RA downlink. It concludes inter alia that: 'There are potential operational safety benefits in providing the ACAS Resolution Advisory to the controller'. What evidence would be required to support such a conclusion if an implementation decision is to be made? There are related questions. Should the controller have particular items of information because this is required by ATC regulations? Should the controller have specific pieces of information because this is needed for him or her to perform ATC competently?

The most important thing to get right is the basis on which such a downlink would be provided. Under the present guidance, the controller has no responsibility for providing separation during the progress of an ACAS RA. As stressed in the points I to III above, all that the controller actually knows about the RA is provided by the pilot, *as information to improve situational awareness*. It is only after the second voice message that the controller resumes responsibility for issuing instructions to the pilot.

So, the first question is whether or not ACAS RA downlinking would change the concept of responsibility sketched in figure 3. It is certainly possible that this might be changed – but this does not seem to be an obviously prudent thing to do. The present guidance makes it clear that the pilot has complete responsibility for the changes to the aircraft's flightpath that take place during the duration of the RA. Complicating responsibilities in a time critical (the duration of an RA would typically be 15-40 seconds) and potentially safety critical situation should not be contemplated unless there are tangible benefits. It is certainly not obvious that an intervention by the controller would be assured of delivering such safety benefits. Moreover, it is not difficult to construct reasonable RA scenarios – based on actual Airproxes – in which such an intervention would actually increase risk. This is an instance where the best advice probably comes from Hippocrates, the famous Greek physician: 'Make a habit of two things – to help, or at least to do no harm'. A general safety principle might be that when there is a choice to be made, choose the option that makes the minimum changes necessary to achieve safety gains.

Thus, if this argument is accepted, the downlinking of RA information should not change responsibilities on pilots and controllers from those in the current guidance. The controller does not acquire additional responsibilities for the duration of the RA. There is thus no issue about additional legal liability on the controller; to reiterate, the controller *must* take *no* action during the RA.

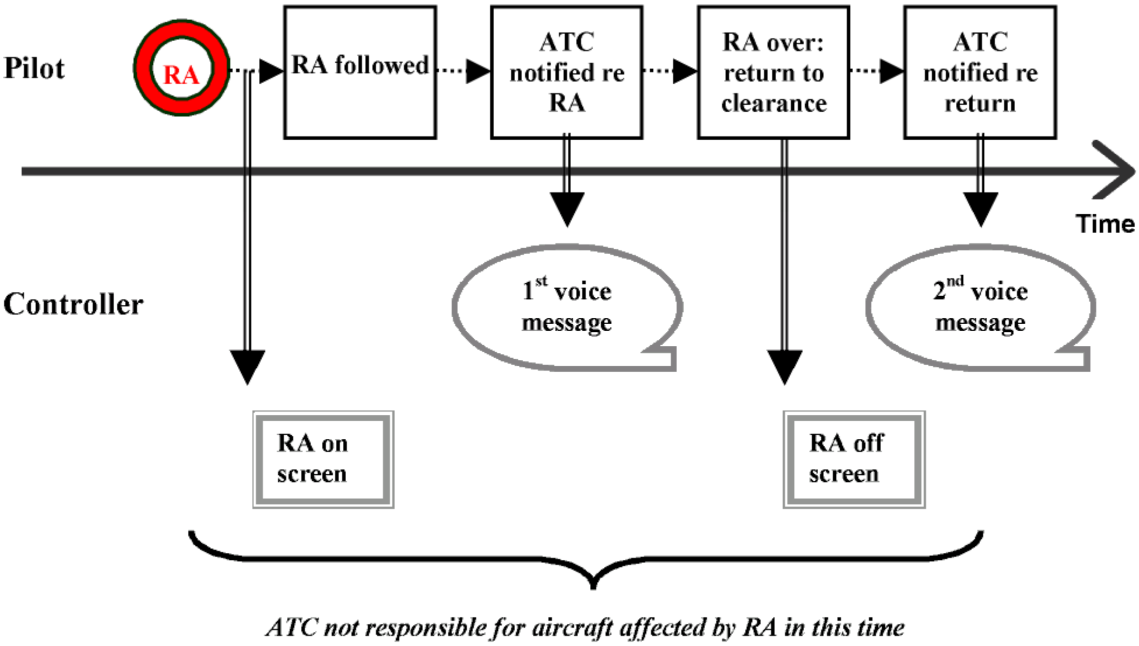

Figure 4 Simplified sequence following an RA plus Downlink

The simplest way of displaying information about the RA would just be to replace a STCA block symbol by a similar 'RA' display block (which has the advantage that the display of the RA symbol would tell the controller to cease any actions arising from the STCA alert). This would be shown from the onset of the RA to its end, but note that the end time of the display would actually be the ‘switch-off’ of the RA (plus the various system processing delays), *not* the notification to ATC that the aircraft was returning to its earlier clearance (figure 4). The figure makes it obvious that the two voice messages generally occur at different times – and indicate different events – from the downlink messages on the display screen.

An additional level of information would somehow be to indicate the nature of the RA, i.e. equivalent to the first voice message content that states the direction of deviations from the current ATC instruction or clearance. A more complex display option would be to have the RA data displayed separately from any STCA data block – but what reasons could be put forward to support a case that this would this add some degree of safety value?

The major change from a Hunan Factors viewpoint is that a voice message from a pilot would have been replaced by a visual message on a controller display position, i.e. broadly similar data presented in different sensory channels (see Wickens and Hollands, 2000, for research results on human information processing abilities). Thus, the controller might hear voice messages from the pilot, *or* see the RA information displayed upon the screen, *or* get both of these inputs at about the same time. In passing, this explains why an automatic voice message generated by an RA downlink would not be a good idea – as it potentially doubles and near-duplicates the air/ground RT transmissions to the controller.

Structured analysis

How can some kind of structure be introduced into the analysis of the effects of downlinking? The range of potential incidents has to be broken down into distinct incident categories each grouping incidents having similar characteristics. One way is to start by enumerating the different categories of incident according to the controller’s appreciation of potential conflicts, the actions that he or she is taking, and the information supplied by the aircrew. As well as indicating where there would be safety benefits, this enables a check to be made against potential problems, e.g. the kinds of questions posed in Drozdowski (2004).

- Excessive information for the controller?
- Controller distracted?
- Misleads controller to expect aircraft manoeuvres?

Figure 5 is a simple version of such a structure breakdown. The questions posed in sequence are:

- Is the controller ‘situation aware’ (coded as SA)? In other words, does he or she believe or judge that an RA is about to take place.
- If the answer is ‘Yes’ to SA, then is the controller issuing some kind of instruction to an aircraft to manoeuvre away from the conflict – Controller

Acting (CA)? (If the answer is 'No' to SA i.e. 'NSA', then the controller cannot be issuing a conflict-avoidance instruction because there is no reason to – although the controller might by chance be issuing an unrelated instruction.)

- Does the controller receive a pilot report about the RA? Three possibilities are offered: None – i.e. no message to the controller, Partial information – e.g. only one voice message or incomplete information about manoeuvres, or Full information, i.e. as set out in the guidance material. These are marked by dotted, normal and thick arrows in the diagram, and by the identifiers N, P and F in the coding.

With this structure, it is possible to ask a variety of 'what if' questions for the different end states – the 'codings' – at the right hand side of the Figure. Some examples illustrate the kind of analysis that could be carried out by an expert controller/Human Factors team who has been briefed about the various kinds of Airprox with RAs.

The top box on the right of the Figure is coded NSA/NA/N, i.e. the controller is not situationally aware, is therefore not acting to resolve this particular incident, and no information is supplied by the pilot. This would seem to be a case where the controller *should* get RA downlink information, because otherwise he or she will not know that the aircraft may have deviated markedly from its specified clearance. If the RA downlink data is presented in the same format as an STCA data block, then it is presumably hardly any more distracting that STCA, which is an accepted type of conflict display.

But note that the pilot may well not pass a message to the controller for particular kinds of RA, where the pilot may well judge that no immediate danger exists and there was no deviation from the controller's clearance, for example:

An RA can reinforce an ATC clearance, e.g. 'Limit Vertical Speed' or 'Adjust Vertical Speed' where the aircraft is already levelling off. These RAs would not be interpreted as indicating 'immediate danger'.

Not all RAs require a deviation from the clearance. A corrective RA might say 'Limit Climb 2000ft/min' and a preventative RAs could say 'Do not Climb'. Such RAs imply that the aircraft would reach its cleared level at a different time from that planned by the controller.

Consider the code SA/A/N – the controller situationally aware, acting to prevent a conflict, and getting no information from the pilot (NB: refer back to the earlier discussion on controller responsibility). Given that the controller has decided to act, perhaps because of an STCA warning, he or she will want to know that the manoeuvre instruction is not being executed. The controller will therefore want as much information possible about the duration of the RA – so downlinking is worthwhile because it compensates for the lack of information from the pilot. Distraction should not be an issue, because the controller has already decided that there is a conflict needing attention. The RA downlink would be expected to decrease the likelihood of a contradictory ATC clearance. The controller's situational awareness would be changed; it would be associated with a better understanding – a new 'state of mind' – about his/her responsibility for action to prevent a collision.

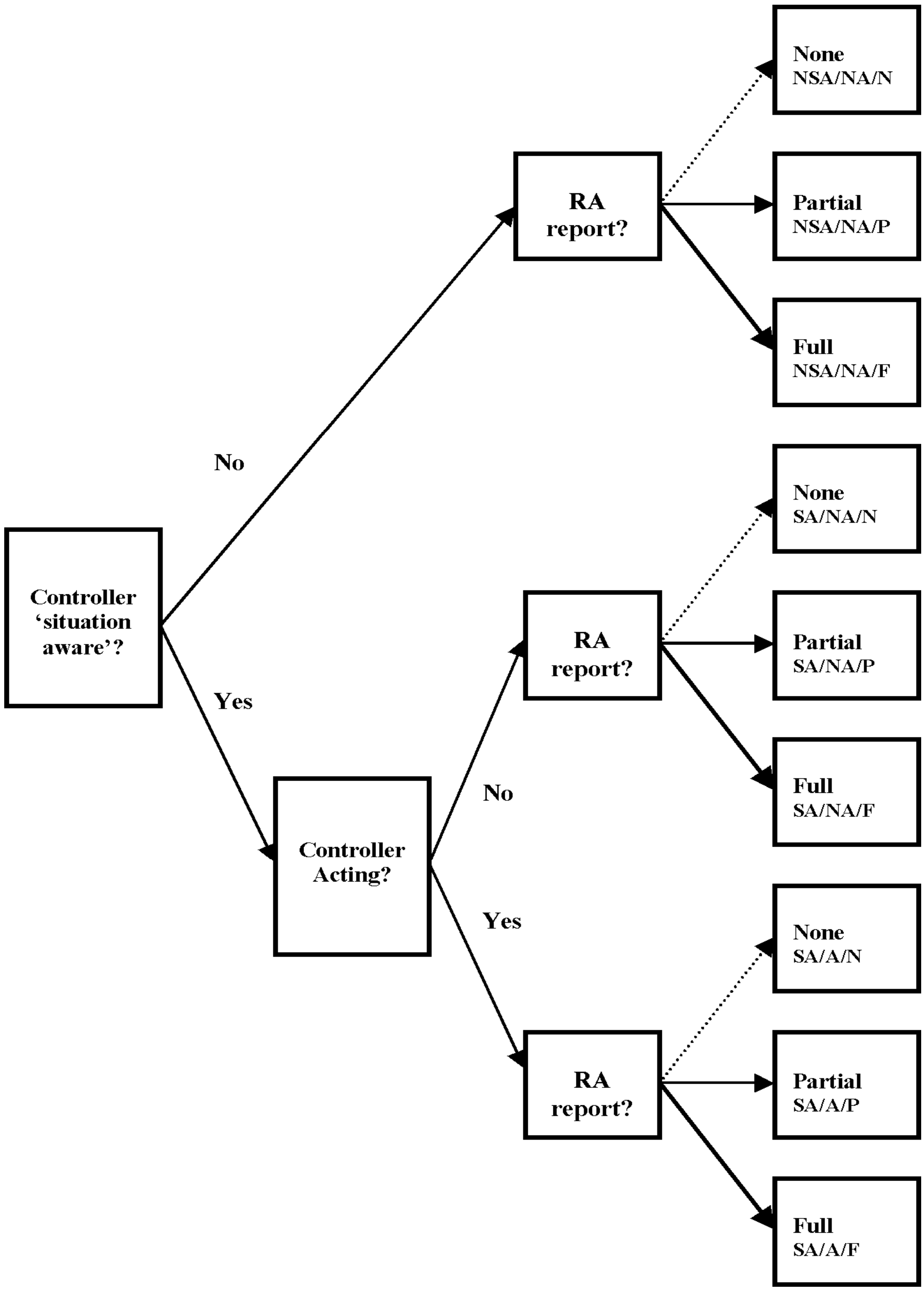

Figure 5 Different kinds of RA event – controller viewpoint

In contrast, the code SA/NA/N means situationally aware, no action, and no pilot information. Why is the controller not acting? There are several possibilities, for example: the forthcoming RA may be being judged as of a nuisance variety – i.e. an overcautious response because of limited data available to the ACAS software; or other problems in the controller's sector may be judged as more urgent; or the controller is a trainee and waiting for guidance from a mentor. Thus, in some circumstances, the RA downlink would be a distraction to SA/NA/N, but in others, particularly the trainee case, it might add to safety.

It is also possible, by reviewing a representative sample of Airproxes, to associate each coding with an approximate probability of occurrence.

Discussion and summary

The analyses above have tended to focus on situational awareness aspects. This is because it has been assumed that RA downlink would not be used in ways that changed the existing pilot/controller responsibilities during a potentially serious conflict. Situational awareness has been the subject of considerable research, and there appears to be good understanding of the key issues. Endsley et al (2003) provides some well-argued and clearly stated principles to achieve good situational awareness:

- 'Just say no to feature creep.'
- 'Group information to reduce complexity.'
- 'Ensure logical consistency across modes and features.'
- 'Operators must be able to ascertain at a glance the status of the entire system.'
- 'Minimize alarm disruptions to ongoing activities'; etc.

These kinds of principles can be very tough to apply in practice, but they certainly provide a checklist against which designs can be assessed.

It is important to *use* the Endsley et al situational awareness principles in this context. They indicate that RA downlink should be as simple as possible, consistent of course with improving safety. This would seem to favour a system in which an RA is displayed on the STCA data block; thus using an existing display type and emphasising to the controller that he or she should take no actions in respect of an earlier or simultaneous STCA alert. A more complex display might indeed persuade a controller to issue instructions rather than communicating with the aircrew.

The display should therefore be no more complex than this basic version, unless it can be demonstrated that there would be significant safety benefits from something subtler. The controller should not be making any decisions based solely on downlinked data, because, as stressed earlier, this data is not equivalent to the voice message information from the pilot: they are *part*-substitutes. Telling the controller about what the pilot is seeing on the ACAS display is *not* the same as the pilot's voice messages informing the controller.

The display of downlinked RA data is thus to inform the controller of the situation that has arisen between two aircraft. It warns the controller of potential problems if instructions are issued during the (short) duration of the RA. It helps the controller to assess the situation and to decide on the appropriate decisions about communicating with the pilots involved.

But are there significant safety benefits from downlinking the basic RA data? Arguments are put forward here to demonstrate that simulations trials are not a sufficient way of assessing the safety benefits from RA downlinking. Simulations do not necessarily reproduce the realities of operational safety in genuinely risky situations. Controllers In simulations, generally do not lose situational awareness – and therefore not face the problem of trying to regain it.

The data source proposed for assessing the potential benefits and disadvantages of RA downlinking is Airproxes. Airproxes are very valuable because the publicly available reports provide details of thorough investigations. The non-punitive nature of Airprox reporting means that pilots and controllers are generally very willing to share their thoughts about how the incident developed, and indeed their mental processes, workload and situational awareness.

The next step is to introduce a structure into the analysis of the effects of downlinking on the various kinds of Airprox. One way is to start by enumerating the different categories of incident according to the controller's appreciation of potential conflicts, the actions that he or she is taking, and the information supplied from the aircrew. A simple version of such a structure breakdown poses questions: Is the controller 'situation aware'; is the controller issuing some kind of instruction to an aircraft to manoeuvre away from the conflict; and does the pilot report the RA? This structure makes it possible for a formal analysis by an expert controller/Human Factors team (familiar with the various kinds of Airprox that involve an RA), asking 'what if' safety questions for the different end states.

At the very least, it would have to be demonstrated from this structured breakdown that the safety benefits from 'positive codings' are markedly greater than any disadvantages from 'negative' ones. A more sophisticated analysis would use the estimated probabilities of each coding, so the frequency and effects on controller workload and situational awareness could be weighed appropriately.

To summarise, the benefits of the pathway developed here are that:

- There is clarity about the possible uses of RA downlink, the most useful information sources, and the ways of analysing safety benefits.
- The focus is on situational awareness – for which there are some very useful guidelines based on extensive research.
- Airproxes are shown to be a better guide to risk-bearing incidents involving RAs, because they provide information on impairments of situational awareness, whereas conventional simulations/trials cannot be assured of doing this.
- An example is given of structured analysis of the effects of downlinking on the various kinds of Airprox, controller action and pilot report; this breakdown makes it much easier to ask well-defined 'what if' questions.

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Appendix 1 Examples of CAT Airproxes with RAs

Below are listed selected summaries of Airproxes involving Civil Air Transport (CAT) aircraft incidents in the year 2000. The selection picks up Airproxes with RAs where ATC did not appear to be fully monitoring the potential conflict prior to an STCA and/or ACAS alert. It is stressed that this is a selection for illustrative purposes not a statistical sample. The analysis focuses on defensive safety barriers:

- *Human monitoring and intervention* Did the pilots see the other aircraft (prior to any ACAS alert or ATC instruction)? Was the controller aware of the conflict prior to any alarms?
- *Warnings* Did ACAS alert in the aircraft – Traffic Advisory (TA) or Resolution Alert (RA)? Did the controller get a STCA alert?
- *Context and issues* Were there special factors, e.g. extreme weather? Were there procedural problems or confusions? Did equipment fail? Were there human factors issues, etc?

All Airproxes in the A, B and C categories are included – there were 35 in total in 2000. The number is the Airprox Board reference. The 'Cause' shown in the summarised information against each numbered incident is taken directly from the Airprox Board Report. Aircraft – 'A' and 'B' – and controllers have been de-identified. The information in this appendix is not 'official Airprox Board' data. It may contain errors of interpretation and omissions, particularly in the third category above.

18/00	**Cause** Distracted by the handover process, the Heathrow Final Director did not ensure standard separation between A and B.	
Context and issues	**Warnings**	**Monitoring and intervention**
Very strong wind, high workload, ATC distraction	ACAS RA to B only No STCA alert	Pilot of A saw B conflicting and heard ATC instruct B to avoid. Pilot of B saw A intermittently in cloud. ATC detected that the wrong aircraft had been instructed to turn.

29/00	**Cause** B descended below its cleared level.	
Context and issues	**Warnings**	**Monitoring and intervention**
Flight deck procedure error, fatigue	ACAS RA both to A and B. STCA activated before ACAS passed to ATC	Neither pilot saw the other aircraft. ATC occupied with other traffic, did not spot high descent rate. NB: Board agreed that any separation was to a large degree fortuitous…with different geometry …could have been considerably more serious.

32/00	**Cause** ATC descended B into the path of A	
Context and issues	**Warnings**	**Monitoring and intervention**
Error by ATC in descending A, lack of ATC coordination	ACAS RA to both A and B No STCA	Pilots saw other aircraft after ACAS RA. ATC first aware of problem following ACAS reports

55/00	**Cause** The B crew climbed about their cleared level whilst responding to an ACAS RA.	
Context and issues	**Warnings**	**Monitoring and intervention**
Possible ACAS malfunction	No ACAS alert to A NB: ACAS fitted but not operational, ACAS RA to B. No STCA	Pilot A saw B. Pilot B did not sight A. ATC were advised of the ACAS-induced climb. NB: the RA to aircraft B related to another aircraft, not aircraft A. Response to this RA by aircraft B caused this Airprox as stated in Cause.

85/00	**Cause** The ATC mentor did not monitor adequately his trainee's instructions which put B into conflict with A.	
Context and issues	**Warnings**	**Monitoring and intervention**
Trainee, RT equipment confusion	ACAS RA for both aircraft No STCA	Pilot of A saw B, but pilot of B did not see A. ATC monitoring situation, but mentor dealing with other problem.

111/00	**Cause** Controller a did not provide the appropriate separation between A and B, compounded by actions not carried out by controller b.	
Context and issues	**Warnings**	**Monitoring and intervention**
Controller distraction, sector split, change of controller	ACAS RA for A, pilot B saw A on ACAS display but no alert. STCA alerted	Pilot A did not see B. Pilot B saw A after ACAS alert. ATC was aware that aircraft head on at about time of STCA.

145/00	**Cause** ATC did not maintain standard separation between A and B.	
Context and issues	**Warnings**	**Monitoring and intervention**
Previous military fighter formation in neighbourhood, severe weather, ATC preoccupied with other conflict, workload	ACAS RA to A only ATC at airport not STCA equipped. LATCC STCA alert	Pilot A, because of weather, saw B only after the ACAS alert. Pilot B heard the ACAS alert on RT and saw A subsequently. ATC was not aware of conflict until advised of ACAS alert.