Application of the CARA HRA Tool to Air Traffic Management Safety Cases

W. Huw Gibson[a*] and Barry Kirwan [b]
The University of Birmingham, Birmingham, UK
[b]Eurocontrol, Bretigny, France

Abstract: Controller Action Reliability Assessment (CARA) is a human reliability assessment technique, which can be used to quantify human performance in the context of Air Traffic Management (ATM). This paper describes the CARA technique, including the data used for quantification, and the types of air traffic controller behaviours it quantifies, and the performance shaping factors it uses to modify task reliability. In order to evaluate CARA, it was applied in three actual ATM safety cases. The three safety cases related to an aircraft landing guidance system, a position/identity display for the air traffic control (ATC) aerodrome environment and an aerodrome procedure for low visibility conditions using future ATC systems. The performance of CARA in these applications is described.

Keywords: Human Reliability Assessment, Air Traffic Control, Safety Case, Human Error Quantification.

1. INTRODUCTION

European air traffic management (ATM) is being underpinned by quantitative safety assurance. This safety assurance aims to assess current and new systems, as well as system changes, against a quantified target level of safety. To support this process there is a need to quantify the most important element in the safety equation, namely human reliability. Controller Action Reliability Assessment (CARA) is a human reliability assessment (HRA) technique, which can be used to quantify human performance in the context of (ATM). This paper describes CARA and its application to safety cases.

2. OVERVIEW OF CARA APPROACH

CARA uses the basic quantification framework of the Human Error Assessment and Reduction Technique (HEART) [1], but tailored to application in ATC safety assessments. HEART has been selected as a model because it has been the subject of validation exercises [2] and the relevance and adaptability to different domains is supported by recent developments of HEART in the Railway [3, 4] and Nuclear Domains [5]. A similar approach in terms of using generic tasks and modification factors can also be seen in the SPAR-H technique [6]. It is recognised that within the HRA research community there is a focus on “Second Generation” techniques [7]. However, CARA is modelled on, and is therefore itself, a “First Generation” approach. The selection of a first generation approach was required because:

- CARA quantification is underpinned by observed and auditable human performance data and therefore it naturally focuses on generic features of human performance of key personnel (e.g. controllers and pilots), rather than the more indirect influence of wider organisational issues or errors of commission.
- There was a pragmatic requirement to contribute human factors knowledge to safety cases and communicate human factors (HF) judgements within a quantified safety framework in the short term.

[*] w.h.gibson@bham.ac.uk

- As with any competent HRA assessment, a CARA assessment should be underpinned by an understanding of context. This context can be modelled to some extent using Error Producing Conditions, but will always be a qualitative component of the assessment.

While the basic framework of the HEART technique is used, the details of CARA are closely tailored to the ATC context. There are three key elements of the HEART approach which are used for CARA:

- **Generic Task Types**. During a Human Reliability Assessment (HRA) analysts will have specific tasks they need to quantify. For the HEART technique, a specific task is compared with Generic Tasks Types (GTTs), of which there are eight. The GTT which best matches the specific task being assessed is selected. The selected GTT is associated with a human error probability, and therefore this provides an initial quantification for the task being assessed. A new set of GTTs have been developed for CARA which are specific to the ATM environment, and have been quantified using human performance data.
- **Error Producing Conditions**. In addition to GTTs, HEART also uses Error Producing Conditions (EPCs). EPCs are factors which are predicted to negatively influence human performance and therefore increase the generic human error probability associated with a GTT. Examples of EPCs are ‘time pressure’ or ‘operator inexperience’. The technique also defines a ‘maximum affect’, which is a numerical value which reflects the maximum impact that an EPC can have on a task. EPCs and maximum affects have been developed for CARA which are specific to the ATC context.
- **Calculation Method**. HEART uses a simple calculation method to combine GTT HEP and EPC values. It also allows modification of the strength of affect of EPCs through a weighting process. The calculation method is not changed for CARA. The formula is:

$$\mathbf{HEP = GTT \times [(EPC_1-1) \times APOA_1 + 1] \times [(EPC_2-1) \times APOA_2 + 1] \times \ldots \times [(EPC_n-1) \times APOA_n + 1]}$$

Where:

- GTT = the human error probability associated with a GTT
- EPC = the maximum affect associated with an EPC
- APOA = is the assessed proportion of affect value between 0.05 and 1, where 0.05 is a very weak effect and 1 is a full affect.

3. KEY CARA ELEMENTS

The following sections describe the CARA approach. CARA is currently under review by EUROCONTROL and the approach as described here is not yet released for use in assessments.

3.1. Generic Task Types

The task types for the CARA GTTs were developed based on the following:

- Review of task analyses for controller tasks [8, 9, 10] to ensure that the GTTs, and their structures and descriptions, can be understood within an accepted model of the controller. It should be noted that the key focus for CARA has so far been the controller. Other key areas for which there will be further future developments are maintenance tasks and pilot tasks.
- Review of ATC HRA quantification requirements through a safety case review and consideration of HF aspects of reliability for future systems.
- Review of models of Human Performance.
- Review of Human Reliability Assessment techniques, principally HEART, NARA [5] and CREAM [7, 11].

A key objective for CARA is that there is a clear link between the GTT, the GTT HEP value and the data which have been used to derive that HEP value. This is critical in order to ensure that the actual values used are underpinned by the best available data and that the values used can be objectively reviewed.

Existing human error probability data sources have been reviewed to identify suitable data. They have included the CORE-DATA database [12] and Air Traffic Control research literature accessed through the Ergonomics Information Analysis Centre [13]. The literature search was based on identifying papers which included human error as a performance measure and were related to Air Traffic Control. In addition, actual data have been collected from simulations [12] and where required expert judgement has been undertaken.

The preferred method for combining the study HEPs to provide the single GTT HEP has been through averaging the data. The geometric mean approach has been selected as the preferred averaging approach for dealing with human error probabilities. Human error probability data are often considered on a base 10 Logarithmic scale. The geometric mean provides a measure of central tendency particularly well suited to consideration of the data using this logarithmic scale.

In addition, the variability within the HEPs underpinning the GTT HEP are also described using uncertainty bounds. To this end, the 1-Sample t test has been used to compute a 95% confidence interval for the geometric mean. For this analysis of the data points underlying a geometric mean, the calculated statistics are based on the Log10 values, as it is assumed that this is a more relevant distribution for considering HEP data, and also to be consistent with the use of the geometric mean.

Where there were insufficient data to use the geometric mean, a specific datapoint has been selected, and the rationale for selection of the datapoint is provided in the GTT technical basis report.

The CARA GTTs and their context and associated human error probabilities are presented in Table 1. It should be noted that as CARA is based on underpinning data, there are some GTTs requiring further underpinning data, in particular those noted as ‘holding values’ in the table.

3.2. Error Producing Conditions

The identification of relevant EPCs has been grounded in a review of existing EPC type factors used in other HRA techniques and predicted additional ATC EPC demands. These EPCs have been placed within the broad structure of the HERA [14] contextual conditions, with the aim of ensuring that the CARA EPC structure reflects a classification structure already in use within the ATC context. The following techniques were selected to be reviewed in detail to identify relevant EPCs:

- HEART [1], because the technique is not industry-specific and the technique is based on the EPC approach from which CARA is derived.
- NARA [5], while from the nuclear industry it uses the HEART EPC approach.
- HERA [14], this is seen as the key HRA approach which is focused on ATM. It is not a quantification technique, but an ATM incident HF causal analysis technique.
- SPAR-H [6], a key quantification technique from the nuclear industry, which uses a focussed set of eight PSFs.
- CREAM [7], a generic quantification technique which has a set of nine common performance conditions.

Table 1: CARA GTTs

Task Context	Generic Task Type	HEP	Uncertainty Bounds
A. Offline tasks	A. Offline tasks.	0.03	-
B. Checking	B1. Active search of radar or FPS, assuming some confusable information on display.	0.005	0.002-0.02
	B2. Respond to visual change in display (e.g. aircraft highlighted changes to low-lighted).	0.13	0.05-0.3
	B3. Respond to unique and trusted audible and visual indication.	0.0004	-
C. Monitoring for conflicts or unanticipated changes	C1. Identify routine conflict.	0.01	Holding Value
	C2. Identify unanticipated change in radar display (e.g. change in digital flight level due to aircraft deviation or corruption of datablock).	0.3	0.2-0.5
D. Solving conflicts	D1. Solve conflict which includes some complexity. Note, for very simple conflict resolution consider use of GTT F.	0.01	Holding Value
	D2. Complex and time pressured conflict solution (do not use time pressure EPC).	0.19	0.09-0.39
E. Plan aircraft in/out of sector	E. Plan aircraft in/out of sector.	0.01	Holding Value
F. Manage routine traffic	F. Routine element of sector management (e.g. rule-based selection of routine plan for an aircraft or omission of clearance).	0.003	Holding value
G. Issuing instructions	G1. Verbal slips.	0.002	0.001-0.003
	G2. Physical slips (two simple choices).	0.002	0.0008-0.004
M. Technical and support tasks	M3. Routine maintenance task.	0.004	0.0009-0.01

The identification of maximum affects has been based on a review of maximum affect values or similar constructs used in existing HRA techniques. The review has included:

- HEART and CARA, because the maximum affect approach is the same as that used for CARA.
- SPAR-H uses multipliers for the performance shaping factors and the largest negative multipliers (i.e. which make the error more likely) are considered.
- CREAM includes maximum common performance condition coefficients which have similar multiplying functions.

Development of maximum affects using data from existing techniques has been assessed as an adequate approach for the development of CARA as a usable HRA tool in the short term. In the future it is intended that the EPCs will be validated with data from incident data and other approaches and consideration will also be given to basing the maximum affects on data from the existing experimental literature.

The CARA EPCs are presented in Table 2. For the EPCs shaded grey in the maximum affect column, there is limited support and information available from other techniques and therefore they should be treated with caution.

Table 2: CARA EPCs

HERA Element	CARA EPCs	Maximum Affect
Documentation/ Procedures	1. Shortfalls in the quality of information conveyed by procedures	5
Training and Experience	2. Unfamiliarity and adequacy of training/experience	20
	3. On-the job training	8
Workplace Design/HMI	4. A need to unlearn a technique and apply one which requires the application of an opposing philosophy – stereotype violation	24
	5. Time pressure due to inadequate time to complete the task	11
	6. Cognitive overload, particularly one caused by simultaneous presentation of non-redundant information	6
	7. Poor, ambiguous or ill-matched system feedback – general adequacy of the Human-Machine Interface	5
	8. Trust in system	-
	9. Little or no independent checking	3
	10. Unreliable instrumentation	1.6
Environment	11. Environment - controller workplace noise/ lighting issues, cockpit smoke	8
Personal Factor Issues	12. High emotional stress and effects of ill health.	5
	13. Low vigilance	3
Team Factor Issues	14. Difficulties caused by team co-ordination problems or friction between team members.	10
	15. Difficulties caused by poor shift hand-over practices.	10
Pilot-controller Communication	16. Communications quality	-
Traffic and Airspace Issues	17. Traffic Complexity	10
	18. Unavailable equipment/degraded mode	-
Weather Issues	19. Weather	-
Non-HERA: Organisational Culture	20. Low workforce morale or adverse organisational environment.	2
Non-HERA: Cognitive Style	21. Shift from anticipatory to reactive mode	10
	22. Risk taking	4
Pilot actions	Covered as a separate GTT therefore no specific EPCs	-

3. APPLICATION OF CARA TO ATC SAFETY CASES

CARA has been applied to three safety cases. The safety cases have been related to:

1. Aircraft landing guidance system [15]
2. A position/identity display for the air traffic control (ATC) aerodrome environment [16]
3. An aerodrome procedure for low visibility conditions using future ATC systems.

All the safety cases already contained some element of human error quantification and this was a criterion for selection of the safety case. A key feature of human error quantification is that it allows the integration of human error with engineering and contextual factors into a single assessment model. We therefore did not wish to create isolated human performance models or assessments but work within pre-existing integrated safety case frameworks. CARA has been successfully applied in all three safety cases, with a total of 27 assessments being undertaken to generate human error probabilities.

For case study (1) and case study (3) there were existing analyses undertaken using the HEART approach. For case study (2), human error probabilities had been estimated as part of the safety case using expert judgement. In order to apply CARA for case study (2) it was first necessary to develop some more detailed modelling using simple fault trees, as the original expert judgement assessment was at a higher task level than is required to match the CARA GTTs.

Key findings related to the differences between applying CARA and HEART were noted for case study 1. The HEART assessment used only two GTTs (F and G), whereas the CARA assessment used 6 different GTT descriptions. The CARA GTTs were better tailored to the specifics of ATCO and maintenance tasks. In general, the choice of GTT was therefore fairly straight forward. This also meant that fewer EPCs were required to be applied for CARA.

For case study 1, the calculated values for CARA were generally within one order of magnitude of the HEART calculated values (see Figure 1). It should be noted that the results do not reflect on the reliability of either HEART or CARA, they merely compare the quantification outcomes if the CARA approach is applied, with those calculated using HEART. While not a reliability study, this is at least a positive indication of convergence between the two techniques.

For the other two case studies, CARA supplanted analysts' judgement. In some cases this led to increases in the HEP, and in other cases, decreases. One notable result however was that CARA's application led to new insights concerning display features and their impacts on human reliability (e.g. via provision of a dedicated audible and visual alarm). Such insights were based on a sensitivity to human factors not previously evident in the analysis, and would enable the system design team to determine precisely how to maximise human reliability and controller response to an alarm in the control tower. This result in particular showed that CARA can be useful not only for quantification in a safety case, but also for determining how to improve Human Factors in a safety-critical system.

4. CONCLUSION

One of the key drivers for human reliability assessment since its inception, has been the need to build a link between the predicted reliability of engineering systems and the predicted reliability of the people who are at the core of that system. Air traffic control is highly dependent on human reliability to achieve safety objectives. Even for future systems, the Air Traffic Controller will have a crucial role. There is therefore a need to link engineering and human reliability in the context of ATM so that we can understand system reliability. To take a simplistic argument, if a system engineer can identify that a system component will fail with a certain frequency, the human factors community need to be able to state whether the human component will in fact be more or less reliable. We need to know whether effort should be focused on the reliability of the human or the engineered component. Arguments also need to be made as to how the human and engineered system component can improve reliability. Human and engineering reliability have a common language through quantification. That common language or link cannot be so easily articulated through qualitative arguments in a predictive context.

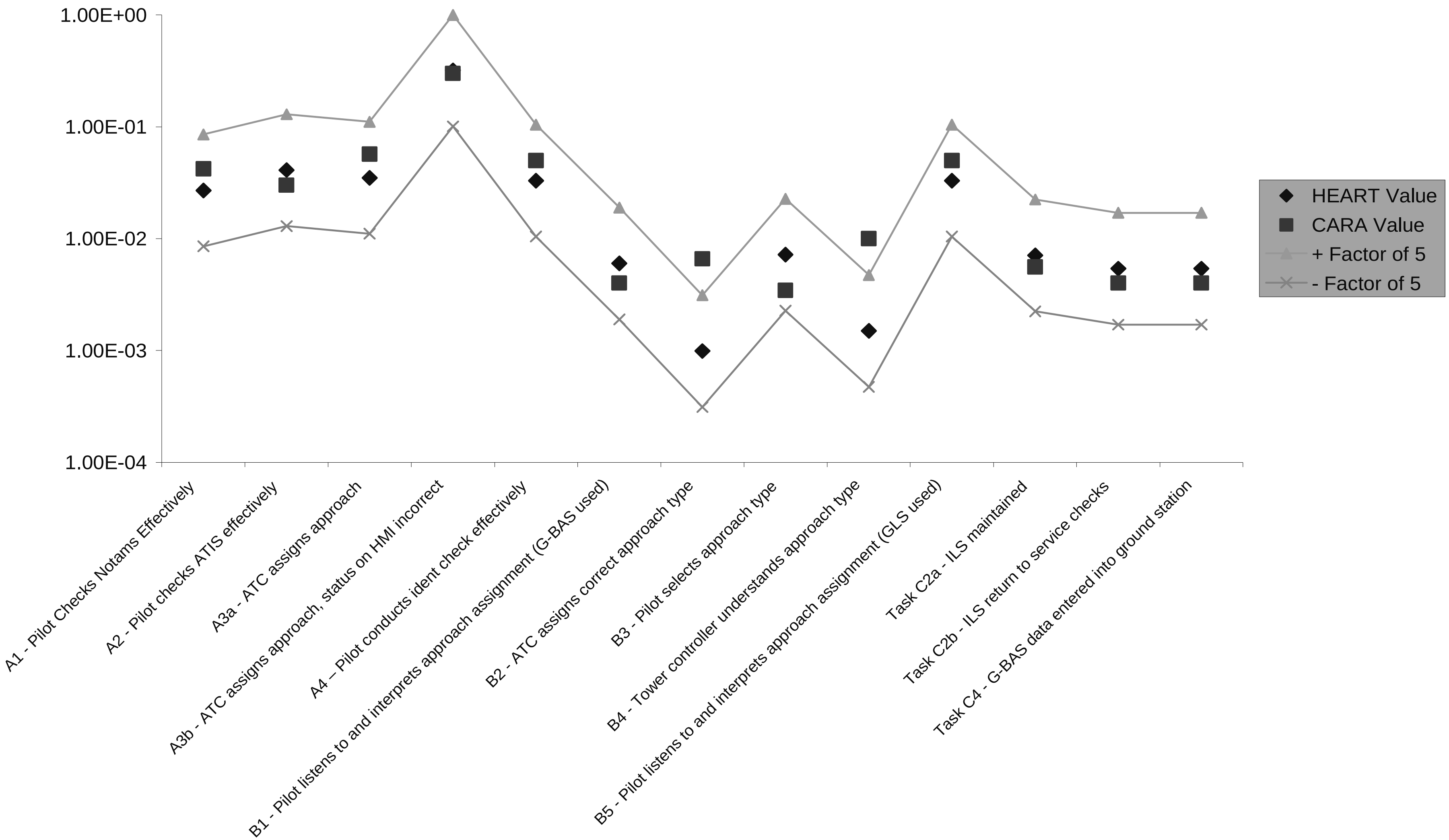
CARA responds to an immediate need for there to be a technique which allows human factors and human reliability to be considered within ATM safety cases alongside engineering elements. There may be an argument within the HRA community that human performance does not fit within fault and event trees which can be found in the current context of safety cases. However, there is a pragmatic requirement for human factors to enter into the safety case dialogue, and for that dialogue to be meaningful it is required to be in a quantified context.

CARA has been successfully applied to three safety cases, and provides an initial indication that human reliability assessment can be used to underpin human factors arguments in a quantified ATM safety case context.

Acknowledgements

The authors would like to acknowledge the support of Chris Machin (EUROCONTROL), Derek Fowler (EUROCONTROL), Ed Smith (DNV) and Eric Perrin (EUROCONTROL) for the safety case assessments in which CARA was trialled.

Figure 1 – CARA & HEART HEPs for Case Study 1



References

[1] J.C. Williams. *"HEART – a proposed method for assessing and reducing human error"*, Proceedings of the 9th Advances in Reliability Technology Symposium, 1986, University of Bradford.
[2] B. Kirwan, R. Kennedy, S. Taylor-Adams, et al. *"The Validation of Three Human Reliability Quantification Techniques - THERP, HEART and JHEDI: Part II - Results of Validation Exercise"*, Applied Ergonomics, 28, pp. 17 – 25, (1997).
[3] L. Cullen and S. Smith *"Rail-specific human reliability assessment technique for driving tasks"*, T270 Rail Safety and Standards Board, 2004, London
[4] J.W. Kim, W. Jung, S.C. Jang, and J.B. Wang *"A Case Study for the Selection of a Railway Human Reliability Analysis Method"* International Railway Safety Conference, 22-27 October 2006, Belfast.
[5] B. Kirwan, W.H. Gibson, R. Kennedy, J. Edmunds, G. Cooksley, and I. Umbers *"Nuclear Action Reliability Assessment (NARA): A data-based HRA tool"*, C. Spitzer, U. Schmocker, and V.N. Dang (Eds.) Probabilistic Safety Assessment and Management, pp. 1206 – 1211 Springer, 2004, London,.
[6] D. Gertman, H. Blackman, J. Marble, J. Byers and C. Smith *"The SPAR-H Human Reliability Analysis Method"*, NUREG/CR-6883, U.S. Nuclear Regulatory Commission, 2005, Washington, D.C..
[7] E. Hollnagel *"Cognitive Reliability and Error Analysis Method: CREAM"* Elsevier,1998, Oxford.
[8] K.W. Kallus, D. Van Damme, and A. Dittman *"Integrated Task and Job Analysis of Air Traffic Controllers - Phase 2: Task Analysis of En-route Controllers"*, HUM.ET1.ST01.1000-REP-04, EUROCONTROL, 2000, Brussels, Belgium.
[9] A. Dittmann, K.W. Kallus, and D. Van Damme *"Integrated Task and Job Analysis of Air Traffic Controllers - Phase 3: Baseline Reference of Air Traffic Controller Tasks and Cognitive Processes in the ECAC Area"*, HUM.ET1.ST01.1000-REP-05, EUROCONTROL, 2000, Brussels, Belgium.
[10] EUROCONTROL *"Working Draft First ATC Support Tools Implementation (FASTI) – Cognitive Task Analysis"*, EUROCONTROL, 2007, Brussels, Belgium.
[11] M.C. Kim, P.H. Seong and E. Hollnagel *"A Probabilistic Approach for Determining the Control Mode in CREAM"*, Reliability Engineering and Systems Safety, 91, pp. 191-199, (2006).
[12] W.H. Gibson, B. Hickling and B. Kirwan *"Feasibility Study Into The Collection Of Human Error Probability Data"*, EEC Note No. 02/06, EUROCONTROL, 2006, Bretigny-Sur-Orge, France.
[13] http://www.tandf.co.uk/ergo-abs/.
[14] A. Isaac, O. Straeter and D. Van Damme *"A Method for Predicting Human Error in ATM (HERA-PREDICT)"*, HRS/HSP-002-REP-07, EUROCONTROL, 2004, Bretigny-Sur-Orge, France.
[15] http://www.eurocontrol.fr/Newsletter/2002/November/GBAS/GBASv0.32.htm
[16] EUROCONTROL *"A-SMGCS Levels 1 & 2 Preliminary Safety Case"* EUROCONTROL, 2005, Brussels, Belgium.