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A Method of Analysis Integrating HCR and ETA Modeling for Determining Risks Associated with Inadequate Flight Separation Events

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Abstract

This paper proposes an event tree to analyze the risk of inadequate flight separation based on the HCR model. We explore how the consequences of such an event depend on factors such as abilities and mental states of pilots and air traffic controllers, and the efficiency of human-machine interaction. We also discuss possible practical measures to control risks in an effort to improve civil aviation safety.

Keywords: inadequate flight separation, HCR model, event tree analysis (ETA)

Introduction

With the rapid development of the air transportation industry, air traffic is increasing constantly and airspace is becoming more congested. One effective countermeasure is reducing flight separation by implementing Reduced Vertical Separation Minimums (RVSM). While many countries have already begun this process, it creates some challenges for pilots and controllers. If operational errors are made, inadequate flight separation will occur very quickly.

In fact, incidents of traffic conflict happen frequently, and the risk of inadequate flight separation always exists. If the potential collision hazard is not detected and appropriate actions are not taken immediately, a mid-air collision could result, such as the collision between a Boeing 757 and a TU-154 over south Germany on July 1, 2002. In this case, the controller gave incorrect instructions to the pilots, and inadvertently caused an accident that would have been avoided otherwise (Brooker, 2008; De Carvalho, Gomes, Huber, & Vidal, 2009).

Therefore, there is a great need to analyze how the abilities of pilots and air traffic controllers (and their human-machine interfaces) affect the risk analysis results of inadequate flight separation and to effectively assess the safety risk. Based on this, we can implement regulations and measures to decrease the odds of near-misses and mid-air collisions, as well as improve the overall safety of aviation.

Currently, most research on inadequate flight separation occurrences focuses on modeling the near miss and calculating the collision probability. A few works contain an analysis of human factors and human error in these incidents (Xiao-hao, Dong-bin, & Xiong, 2008; Xiao-hao, Dong-bin, Xiong, & Xiu-hui, 2008; Zhao-ning & Ji-min, 2010). Event Tree Analysis (ETA) is a system safety analysis method which is highly effective in determining how various events can result in

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accidents. Human Cognitive Reliability (HCR) is an effective way to quantify the numerical relationship between human and machine interfaces. In this study, the ETA and HCR method were integrated to analyze and calculate risks brought by inadequate flight separation. The event tree of inadequate flight separation is presented and the process of error rate calculation is also illustrated. The case study proved the applicability of this method, and some constructive suggestions are given in conclusion.

Methodology

Safety Risk Analysis

Safety risk analysis (SRA) consists of a variety of methods, e.g., risk matrix analysis, fuzzy comprehensive evaluation, fault tree analysis (FTA), and event tree analysis (ETA) (Global Aviation Information Network, 2003; Johnson, 2003; Kumamoto & Henley, 1996). These methods can all help the air traffic control system identify hazards, assess risks, and investigate accidents.

A risk matrix is the most popular analysis method in the civil aviation industry. It has two factors: risk severity and risk probability. Each factor has several levels, e.g., high, medium, and low. This method is most useful when the risk of an accident is small and the results are mainly subjective. However, it is not applicable to severe-consequence rare events, such as aviation accidents.

The fuzzy comprehensive evaluation method is another widely used method. It applies fuzzy set theory in mathematics to establish an expert system on a given problem. Supported by the Flight Safety Foundation, Hadjimichael and McCarthy (2009) developed the Flight Operations Risk Assessment System (FORAS). This assessment is performed using a mathematical model which synthesizes a variety of inputs, including information on crew, weather, aircraft, and so on. The system will identify those elements that contribute most significantly to the calculated risk. It can be used to reduce the risks caused by controlled flight into terrain, loss of control, runway incursion, etc. It is good for multilevel problems, but is highly subjective (Place, 2005).

FTA is a method of failure analysis in which an undesired state of a system is analyzed using backward logic to combine a series of lower-level events. This analysis method is mainly used in the field of safety engineering, especially for complex and large systems, to quantitatively determine the probability of a safety hazard. However, the required data is hard to collect and the computation has a high degree of complexity.

ETA is an inductive procedure that shows all possible outcomes resulting from an accidental event and takes into account additional events and factors, such as whether or not installed safety barriers are functioning. By studying all relevant accident events, ETA can be used to identify all potential accident scenarios and sequences in a complex system. Design and procedural weaknesses can be identified, and probabilities of various outcomes from an accidental event can be determined. ETA is generally applicable for almost any type of risk assessment application, but used most effectively to model accidents when multiple safeguards are in place as protective features. It is also highly effective in determining how various initiating events can result in accidents of interest.

Human Reliability Analysis (HRA)

HRA was first used for safety analysis of nuclear plants in the 1960s. Swain and Guttmann (1983) developed the technique for human error rate prediction (THERP), based on an HRA event tree model, which decomposed all crew behaviors into different developing processes, identified the path of failure in the event tree, and carried out the appropriate calculations. Later, Kirwan (1994) showed that the main purpose of HRA should be to assess risks caused by human faults and control such human faults. Therefore, he divided HRA into three processes: fault identification, fault frequency determination, and design of fault avoidance methods.

The first generation of HRA methods emphasized analyzing, predicting, and reducing human faults by qualitative and quantitative statistical methods. These methods can be used to design and improve the safety of a system by decreasing the probability of major human faults to an acceptable threshold. HRA is related to the field of human failure theory and human reliability data analysis (including field and simulator data analysis), as well as statistical analysis and forecasting techniques of human failure probability based on experts. The main HRA models are as follows: ASEP, CM, DNE, HCR, MAPPS, MFSM, OAT, PC, SLIM, SHARP, and THERP (Embrey, Humphreys, Rosa, Kirwan, & Rea, 1984; Hall, Fragola, & Wreathall, 1982; Hannaman, Spurgin, & Lukic, 1985; Hannaman, Spurgin, Joksimovich, Wreathall, & Orvis, 1984; Potash, Stewart, Dietz, Lewis, & Dougherty, 1981; Samanta, O'Brien, & Morrison, 1985; Seaver & Stillwell, 984; Siegel, Bartter, Wolf, & Knee, 1984; Swain & Guttmann, 1983).

The second generation of HRA methods further explores human behavior processes. In particular, these methods examine the mechanisms and probabilities of human errors in different stages of cognitive activities including observation, diagnosis, decision and action. Second generation HRA models focus on the integrity of the interaction between people and machine, taking into account the impact of psychological processes and the environment. In addition, the effects of team spirit are often considered. Such models include many human-machine-environment concepts taken from systems engineering. Contemporary popular second-generation HRA models are as follows: CES, IDA, ATHEANA, and CREAM (Cooper, et al., 1996; Hollnagel, 1998; Smidts, Shen & Mosleh, 1997; Woods, Roth, Pople, & Embrey, 1987).

HRA requires different analysis methods for different scenarios and industries. To date, these various reliability models have been applied only rarely to air traffic control.

The Human Cognitive Reliability (HCR) model belongs to the first generation of HRA models. Hannaman et al. (1984) proposed a way to quantify the numerical relationship between non-response probability and response time based on human-machine interfaces, human cognition, and mean response time (Humphreys, 1995). HCR uses cognitive psychology to study dynamic cognitive processes (including inspection, diagnosis, and decision) and to explore the mechanisms of human error. Compared with other models of HRA, HCR has its own advantages. Firstly, the approach explicitly models the time-dependent nature of HRA (Humphreys, 1995). Secondly, it is a fairly quick technique to carry out and is relatively easy to use (Humphreys, 1995). Finally, the three modes of decision-making—knowledge-based, skill-based, and rule-based—are all modeled (Humphreys, 1995). These characteristics are beneficial in the safety analysis of civil aviation. In this paper, we will use HCR and ETA to study the faults of pilots and air traffic controllers (ATCs) in an event of inadequate flight separation.

Analysis of an Inadequate Flight Separation Event

How to Build an Event Tree

An event tree describes the process of people's behavior and activities in the form of a two-state event and time-sequence, based on task analysis. Generally, when analyzing human failure through an event tree, each branch node only has two probabilities (success or failure). Using the following scenario as an example, an event tree will be constructed based on this principle.

In 2008, a B737-800 received a TCAS alert upon reaching 30,000 feet. A voice warning of "TRAFFIC" and a visual warning of "TA" on the display panel suggested that there was an approaching aircraft at the same altitude (about 6 nautical miles ahead), and that these two aircraft would collide in 20 seconds if they maintained their current directions and speeds. After effective communication and some collaborative work between the air traffic controller and the pilots, this hazard was avoided (Aviation Safety Office, 2007). A scenario was designed based on this event; i.e., if the air traffic controller discovers the conflict, he or she will correct the error, and if the air traffic controller doesn't discover the conflict, TCAS warns, the pilot will take action. Using this logic, we can construct the event tree in Figure 1.

Analysis Model of Human Error Rate

In this scenario, the pilot and air traffic controller are working with a specific human-machine interface and are under time pressure, which fits the parameters of the HCR model. Therefore, we will adopt HCR to study the possible errors of the pilot and the ATC. The formula of the HCR model (Tiemin, Xingkai, Gongzhi, 2005) is given by

$$E = e^{-\left[\frac{(t/T_{0.5})-B}{A}\right]^{C}} \quad (1)$$

where *t* represents the available time to choose and execute

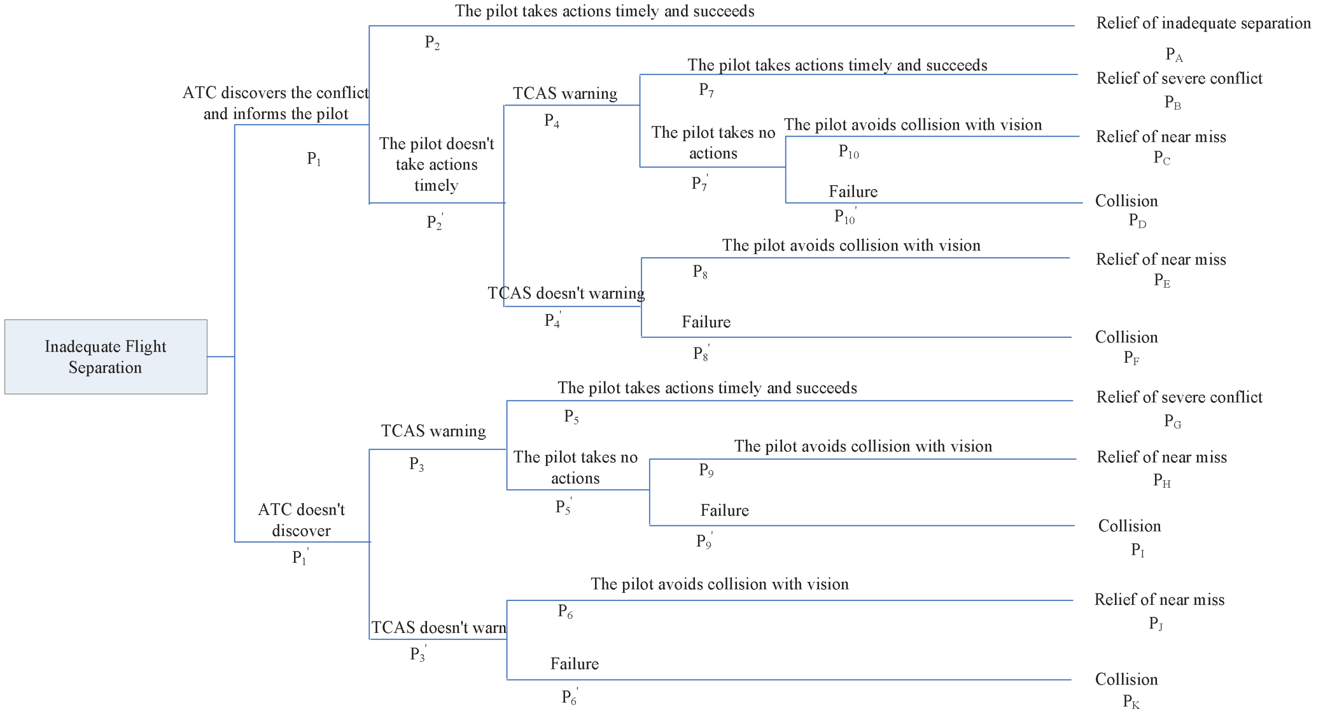

Figure 1. Event tree of inadequate flight separation.

Table 1
HCR Model Coefficients

Behavioral Level	*A*	*B*	*C*
Skill-based	0.407	0.7	1.2
Rule-based	0.601	0.6	0.9
Knowledge-based	0.791	0.5	0.8

appropriate actions, $T_{0.5}$ is the average time necessary to choose and execute appropriate actions, and *A*, *B*, and *C* are coefficients representing the type of behavior used by the pilot or controller (see Table 1).

The more abstract and novel the behavior, the higher the probability of error. Skill based behaviors are the most routine, consisting simply of stored patterns. Rule based behaviors are slightly more complex, using "if-then" logic. Knowledge based behaviors are the most abstract.

This model considers only cases where $t/T_{0.5} \geqslant B$; when $t/T_{0.5} < \text{B}$, the probability of error is considered to be 1. With regard to the values for the coefficients *A*, *B* and *C*, due to differences in crew abilities, human-machine interfaces, and regulations across countries, parameters obtained from experiments in airplane flight simulators may differ drastically. Experiment data provided by IAEA was used in this research, since studies have shown that this data are generally applicable for ordinary rule-based jobs (Xuhong, & Xiangrui, 2007).

The pilots' operations are mostly skill-based, while those of the air traffic controllers are rule-based. According to Table 1, $A = 0.407$, $B = 0.7$, $C = 1.2$ will be used for pilots' operations, while $A = 0.601$, $B = 0.6$, $C = 0.9$ should be used for air traffic control operations. The time available to choose and execute appropriate actions, *t*, can be obtained by simulated experiments and analysis. $T_{0.5}$ can be determined using the following equation (Tiemin et al., 2005):

$$T_{0.5} = \overline{T_{0.5}}(1 + k_1)(1 + k_2)(1 + k_3) \tag{2}$$

where

$\overline{T_{0.5}}$ = Average time necessary to choose and execute appropriate actions under standard conditions;

k_1 = coefficient for operators' abilities; (see Table 2; values from Hongde, & Wei, 2006);

k_2 = coefficient for operators' nervousness;

k_3 = coefficient for efficiency of human-machine interaction.

Calculation of Human Error Rate

In the scenario given above (see Figure 1), the cruising speed of each aircraft is about 500 knots. The two airplanes are flying in opposite directions, so their relative speed is about 1000 knots. When this scenario occurs, the distance between the two airplanes is 6 nautical miles, leaving only 21.6 seconds for the air traffic controller and pilot recognize the situation and respond appropriately.

Once ATC discovers two airplanes with inadequate flight separation, immediate action is taken to increase the separation: the air traffic controller discovers the conflict → the air traffic controller decides how to adjust the separation → the air traffic controller informs the pilot and sends instructions → the pilot answers and reads back the instructions → the pilot moves the flight controls → the airplane's flight path changes.

According to repeated measurements, it takes 2 seconds for an air traffic controller to identify a conflict and decide how to adjust its flight path, 1.5 seconds for the air traffic controller to inform the pilot and send instructions; 1.5 seconds for the pilot to answer and repeat the clearance; 0.4 seconds for the pilot to move the flight controls; and 2 seconds for the airplane to change its flight path (Qinggui, 2005). The average total time for the entire conflict resolution procedure is 7.4 seconds.

The total available time to choose and execute appropriate actions, *t*, is 21.6 seconds. We then analyze *t*, $\overline{T_{0.5}}$ and the human error rate for the four basic events in this event tree.

Table 2
Coefficients k_1, k_2, k_3

	Condition	*Value*	*Meanings*
k_1	Proficient	−0.15	Competent at the activity
	Average	0.00	Ordinary level of competency
	Beginner	0.40	Little operating experience
k_2	Urgent	0.60	Emergency; personnel have been threatened Stressful; accidents may occur
	Fairly nervous	0.28	Optimal nervousness; appropriate load
	Optimal	0.00	Without any alert sign; low stress
	Relaxed	0.20	
k_3	Excellent	−0.22	Own emergent support in an emergency
	Good	0.00	Display has comprehensive information
	Average	0.51	Display lacks comprehensive information
	Inferior	0.78	Operator has an awkward display; not ergonomically correct
	Very poor	0.92	The operator cannot see a direct display

Event Tree

In the best case scenario, ATC spots the lack of separation, informs the pilot, and the pilot corrects the aircraft's flight path. This scenario includes two of the four events.

Event 1: ATC discovers the conflict and informs the pilot

This includes two basic actions: air traffic control discovers the conflict and decides how to adjust the separation, then sends instructions to the pilot. $\overline{T_{0.5}} = 2$ seconds + 1.5 seconds = 3.5 seconds. The corresponding value of t is 21.6s.

Event 2: Pilot takes timely action, follows ATC commands, and resolves the conflict

This includes three basic actions: 1) the pilot answers and repeats air traffic control instructions; 2) the pilot moves the flight controls; and 3) the airplane changes its flight path. $\overline{T_{0.5}} = 1.5$ seconds + 0.4 seconds + 2 seconds = 3.9 seconds; the corresponding value of t should then be the actual time of Event 1 subtracted from the total available time (21.6s). However, the actual time of Event 1 is unknown. We therefore assume that the actual time for a former event can be approximated as a percentage of the total available time. That percentage can be expressed by the time to complete the basic actions which the former event includes divided by the average time necessary to relieve the conflict (under standard conditions). Then for Event 2, $t = 21.6 - 21.6*3.5/ (3.5+3.9) = 11.384$s.

Event 3: Pilot takes timely action and resolves the conflict after a TCAS warning

If air traffic control doesn't discover the situation or informs the pilot but the pilot fails to respond, TCAS will still alert the pilot. If the pilot takes actions and corrects the situation after a TCAS warning, the progression is: the pilot hears and judges the TCAS warning → the pilot informs the air traffic controller (2 seconds) → the air traffic controller assesses the situation (2 seconds) → the controller responds with instructions (1.5 seconds) → the pilot answers and repeats instructions (1.5 seconds) → the pilot moves flight controls (0.4 seconds) → the airplane changes its flight path (2 seconds). Therefore, the whole procedure takes 9.4s on average. $\overline{T_{0.5}} = 9.4$ seconds; $t = 21.6$s, equal to the total available time.

Event 4: A pilot sees and avoids the conflict

If both ATC and TCAS fail, a pilot can still avoid a collision by looking outside and seeing an oncoming aircraft. In visual meteorological conditions, a pilot can see another coming aircraft within an efficient distance of no more than 5 nautical miles. The total time available for a pilot to choose and execute appropriate actions to avoid a collision is at most 18 seconds (Potash et al., 1981).

On average, it takes 2.35 seconds (Potash et al., 1981) for a pilot to shift his or her vision from outside the cockpit to the display panel inside the cockpit and back outside the cockpit again (see Table 3; values from Qinggui, 2005). Generally, it takes about 2 to 5 seconds for a pilot to decide the best course of action and begin to manipulate the flight controls. The actual time of completion depends on individual abilities, with some needing as few as 2 to 3 seconds while others need at least 4 to 5 seconds (Boling, 1999). The current study adopts the average value of 4 seconds. Therefore, the average necessary time for a pilot to finish Event 4 is $\overline{T_{0.5}} = 2.35$ seconds + 4 seconds = 6.35 seconds. The total available time is $t = 18$ seconds (see Table 4; values from Qinggui, 2005).

If the time available for the pilot to recognize the situation and take appropriate actions is less than the average necessary time for proper operations (6.35 seconds), a mid-air collision will result no matter what actions are taken.

Suppose that, at the beginning, the air traffic controller and the pilot are both at the optimal level of nervousness; i.e., in Events 1 and 2, $k_2 = 0.00$. Considering that the nervousness of the pilot will increase after he hears a TCAS warning or sees the oncoming aircraft, $k_2 = 0.28$ in Events 3 and 4. By calculating the human error rate using different combinations of k_1 and k_3 (see Tables 5 through 8), different hypothetical situations can be constructed. For example, if the operator is a beginner and the human-machine interaction is extremely poor, $t/T_{0.5} < 0.7$ for Event 3, and the chance of collision is considered to be 1.

Equipment Reliability

The key equipment in this instance is TCAS, so only the reliability of TCAS will be considered in this paper. Assuming that the aircraft has two independent TCAS systems, the probability of TCAS failure in normal operation is 0.02 (Yunfei, 2011).

Risk Analysis

According to civil aviation statistics in China, there were 61 events of inadequate flight separation from 1998 to

Table 3
Time for Looking from Outside of Cockpit to Instruments and Then Looking Back

Action	*Time(s)*
Turn head and eyes toward the flight instruments	0.23
Align sight with instruments	0.07
Focus on an instrument	0.50
Read figures	0.80
Turn head and eyes to outside of the cockpit	0.23
Look at the oncoming aircraft	0.50
Total	2.35

Table 4
Time Parameters for Single Event

No.	*Event*	*t(s)*	$\overline{T_{0.5}}$[32] (s)
1	ATC discovers the conflict and informs the pilot	21.6	3.5
2	The pilot takes timely action, follows ATC commands, and resolves conflict	11.4	3.9
3	The pilot takes timely action and resolves conflict after TCAS warning	21.6	9.4
4	The pilot avoids collision visually	18.0	6.4

Table 5
Rate of Human Errors for Event 1

k_1k_3	−0.15	0.00	0.40
−0.22	1.53×10^{-5}	7.67×10^{-5}	1.12×10^{-3}
0.00	1.64×10^{-4}	5.99×10^{-4}	5.15×10^{-3}
0.51	4.83×10^{-2}	7.70×10^{-3}	3.43×10^{-2}
0.78	7.78×10^{-3}	1.69×10^{-2}	6.16×10^{-2}
0.92	1.13×10^{-2}	2.34×10^{-2}	7.86×10^{-2}

Table 6
Rate of Human Errors for Event 2

k_1k_3	−0.15	0.00	0.40
−0.22	7.17×10^{-7}	1.40×10^{-5}	1.30×10^{-3}
0.00	5.37×10^{-5}	4.743×10^{-4}	1.29×10^{-2}
0.51	6.27×10^{-3}	2.28×10^{-2}	0.16
0.78	2.31×10^{-2}	6.52×10^{-2}	0.30
0.92	3.85×10^{-2}	9.84×10^{-2}	0.39

Table 7
Rate of Human Errors for Event 3

k_1k_3	−0.15	0.00	0.40
−0.22	1.13×10^{-3}	5.65×10^{-3}	6.43×10^{-2}
0.00	1.17×10^{-2}	3.76×10^{-2}	0.22
0.51	0.15	0.29	0.74
0.78	0.29	0.49	0.97
0.92	0.38	0.60	1

Table 8
Rate of Human Errors for Event 4

k_1 k_3	−0.15	0.00	0.40
−0.22	8.04×10^{-5}	6.59×10^{-4}	1.60×10^{-2}
0.00	1.70×10^{-3}	7.91×10^{-3}	7.97×10^{-2}
0.51	4.83×10^{-2}	0.12	0.44
0.78	0.12	0.24	0.67
0.92	0.17	0.32	0.79

2007. Total flight time was 21.801 million flight hours (Yun, Yunxiao, & Xiaochun, 2004), so the odds of inadequate flight separation are 61/21,801,000 = 2.80×10^{-6} per flight hour.

Based on the human error rates calculated using the HCR model, the probabilities of each branch on the event tree can be constructed. According to Civil Aviation Administration of China (CAAC) accident and incident standard (GB14648-93, MH/T 2001–2008), the consequences of inadequate flight separation are broken into four categories: lack of adequate flight separation, serious lack of flight separation (incident), near-miss (serious incident), and collision (accident). Using different combinations of coefficients for operators' abilities, operators' nervousness, the efficiency of human-machine interaction, and the four basic events, more than 100 analytical results from the event tree can be created. To limit the scope of the article, the probabilities of consequent events will be discussed: 1) when $k_1 = 0.00$ and the values of coefficients for efficiency of human-machine interaction are manipulated; and 2) when $k_3 = 0.00$ and the values of coefficients for operators' abilities are manipulated (see Figures 2 and 3).

When human-machine interaction is efficient, the accident odds are acceptable even when the operators are beginners. As the skill of the operators grows, the probability of an accident (or an incident) will decrease; when the operators are highly skillful, every curve becomes flat. As the operators' abilities change from "beginner" to "average", the probability of serious incident decreases even faster than that of incident (see Figure 2).

The efficiency of the human-machine interaction has an enormous impact on the risk of inadequate separation events. Improving it can effectively decrease incident probability and increase the probability of surviving a conflict. If the design of the human-machine interfaces follow principles of human factors, the display equipment and warning system are efficient, and if both the pilot and air traffic controller have emergency support available, the chances of recognizing and correcting for a loss of separation are very good. For an average operator, when there is a comprehensive display and good human-machine interaction, accident probability can decrease from unacceptable to acceptable (see Figure 3).

Risk Control

Three recommendations for the future have been developed in order to limit the amount of risk involved in air traffic control. First, airlines should design scenario training for air traffic controllers and pilots together in order to prepare them for a real inadequate flight separation event. In training, special attention should be paid to the efficiency of communication between air traffic controllers and pilots so that the urgency of the situation may be communicated in minimum time with no loss of information. Air traffic control should have a normal amount of traffic to simulate working conditions during the entire

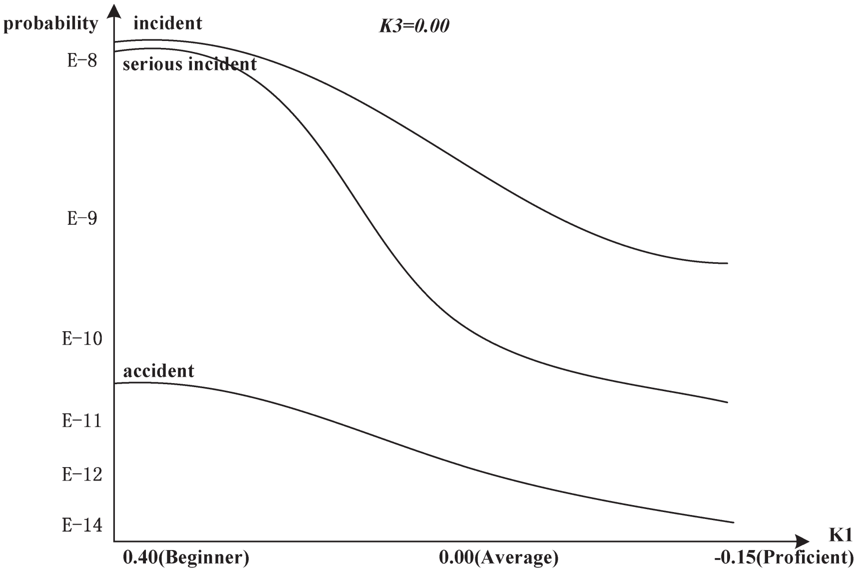

Figure 2. The influence of operators' ability.

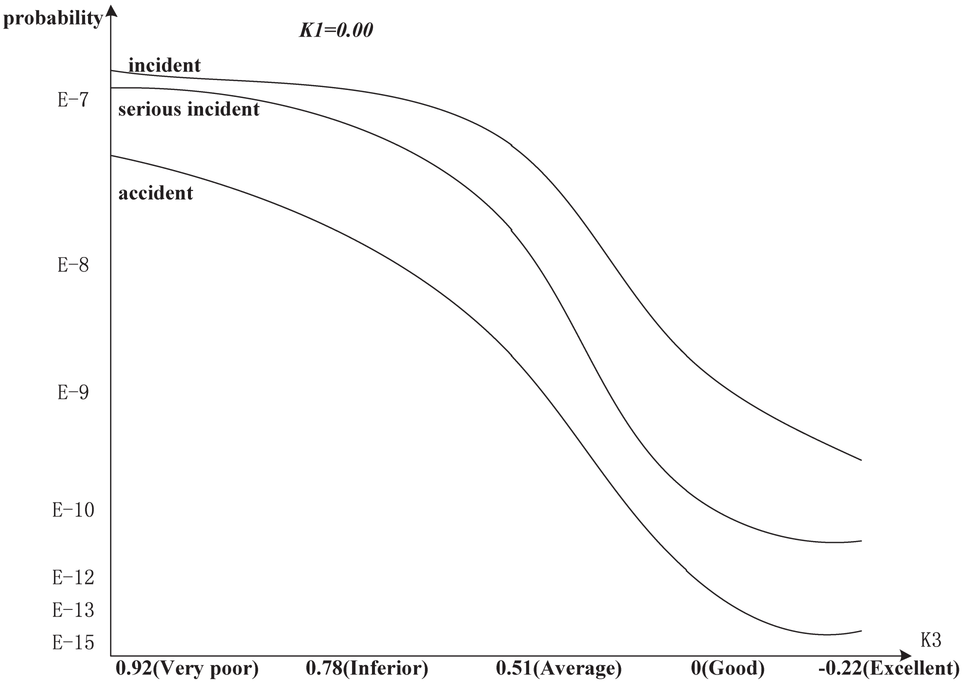

Figure 3. The influence of human-machine interaction.

process, and pilots should follow standard operating procedures. This will help air traffic controllers and pilots better understand the priority level between controllers' instructions and TCAS advisories, preventing further accidents such as the one mentioned in the introduction.

Secondly, air traffic controllers and pilots need to be able to respond quickly and with maximum efficiency in the event of an emergency situation. Their mental status should be stable. Both controllers and pilots need to avoid negative moods such as self-satisfaction, complacency, impulsive, and fear. In particular, controllers need to be quick and alert to unexpected aircraft movement; pilots need to be ready to respond, clear-minded, and in full control of the airplane all the times.

Lastly, the efficiency of the human-machine interaction is imperative to safety. The design of air traffic control devices and airplane control systems should be improved, utilizing the principals of human factors. Such designs should be optimized to maximize the operators' physical and mental comfort, display necessary and sufficient information in a timely manner, reduce the probability of illusions, and provide effective emergency support.

Conclusions

A safety risk analysis method which applies HCR to ETA has been developed in this paper and is applied to the risk analysis of inadequate flight separation.

HCR, a straightforward analytical tool based on an SRA framework and taking into account the person's cognitive processes and the interaction of human-machine interface, can describe and predict human errors. This study demonstrates the ease of application of HCR and ETA to the analysis of the complex human-machine environment.

This method can be difficult to apply, however, if there is inadequate or incomplete information. In order to develop it into an effective risk analysis method, future research should be directed in three areas. Firstly, the event tree construction rules that take into account human behavior should be researched. Secondly, $\overline{T_{0.5}}$ in HCR is a key parameter, but its calculation is sometimes difficult. Accordingly, optimal methods for calculating $\overline{T_{0.5}}$ should be researched and developed. Thirdly, alternatives which are more appropriate for human behavior analysis and reliability analysis should be researched when HCR parameters can't be obtained or the method is limited by some conditions.

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