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108	隋东	副高	072	NEW METHOD FOR SAFETY ASSESSMENT OF PARALLEL ROUTES	TRANSACTIONS OF NANJING UNVERSITY OF AERONAUTICS & ASTRONAUTICS	2009.26.1	
109	张洪海 胡明华 陈世林	中级 正高 硕士	072 072 072	机场终端区容量利用和流量分配协同优化策略	西南交通大学学报	2009.44.1	
110	张洪海 胡明华	中级 正高	072 072	多跑道着陆飞机协同调度多目标优化	西南交通大学学报	2009.44.3	
111	张洪海 胡明华	中级 正高	072 072	CDM GDP飞机着陆时隙多目标优化分配	系统管理学报	2009.18.3	
112	张洪海 胡明华	中级 正高	072 072	多跑道降落飞机协同调度优化	交通运输工程学报	2009.9.3	
113	张洪海 胡明华	中级 正高	072 072	多机场终端区容量利用和流量分配建模与仿真	系统仿真学报	2009.21.18	
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117	张进 胡明华 张晨	博士 正高 博士	072 072 072	空中交通管理中的复杂性研究	航空学报	200930.11	
118	王艳军 胡明华	博士 正高	072 072	基于冲突回避的动态滑行路径算法	西南交通大学学报	2009.44.6	
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123	刘欢 胡明华 瞿英俊	硕士 正高 博士	072 072 072	程序管制条件下基于管制员工作负荷的扇区容量评估	交通运输系统工程与信息	2009.9.1	
124	张钧翔 胡明华	硕士 正高	072 072	基于Agent的多机场终端区空中交通智能仿真系统设计	交通运输工程与信息学报	2009.7.2	
125	薛磊 胡明华 王艳军	硕士 正高 博士	072 072 072	停机坪滑行道运行优化模型研究	第八届全国交通运输领域青年学术会议	2009	
126	殷允楠 胡明华 谢华	硕士 正高 中级	072 072 072	航迹配对在动态流量统计预测中的应用	第八届全国交通运输领域青年学术会议	2009	
127	杨晶姝 胡明华	硕士 正高	072 072	进场飞机动态排序模型与算法研究	第八届全国交通运输领域青年学术会议	2009	
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130	王世锦 隋东	中级 副高	072 072	Aircraft flight safety analysis in low altitude airspace	TRANSACTIONS OF NANJING UNIVERSITY OF AERONAUTICS & ASTRONANTICS	2009.26.2	
131	王世锦	中级	072	fuzzy comprehensive evaluation for atc radar performance	ICCLTP2008会议论文集	2008	
132	王世锦 隋东	中级 副高	072 072	空管雷达保障系统运行性能的模糊综合评判	南京航空航天大学学报	2008.40.6	
133	王世锦 隋东	中级 副高	072 072	空中交通管制员人因可靠性定量分析研究	人类工效学	2009.15.4	

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135	汤新民	副高	072	飞行模拟软件在民航教学实践中的应用	软件导刊•教育技术导刊	2009.0.35	
136	张旭婧 韩松臣 钟育鸣	硕士 正高 硕士	072 072 072	基于区间数判断矩阵的民航空管运行管理风险评估	交通运输工程与信息学报	2009.7.3	
137	王玉婷 韩松臣	硕士 正高	072 072	Research on Airport Surface Modeling and Path Planning Algorithm Based on	IEEE International Conference on Intelligent Computing and Intelligent Systems 会议	2009	
138	姜静逸 韩松臣	硕士 正高	072 072	The Satisfaction Degree Control Mining Method Applied in the airport emergency rescue scale decision-making	IEEE 2009 international Symposium on Computational Intelligence and Design 会议	2009	
139	姜静逸 韩松臣	硕士 正高	072 072	新型组合预测模型在空中交通流量预测中的应用	中国民航大学学报	2009.27.5	
140	姜静逸 韩松臣	硕士 正高	072 072	基于满意控制的机场应急救援决策规则的数据挖掘	应用科学学报	2009.27.6	
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142	周蕊 韩松臣	硕士 正高	072 072	进离场分离条件下的扇区划分模型研究	交通信息与安全	2009.27.6	
143	朱新平	博士	072	Agent-oriented Simulation and Evaluation of Aerodrome Airside	IEEE International Conference on Grey Systems and Intelligent Services 会议	2009	
144	吴薇薇 朱金福	副高 正高	073 073	航线开辟优选方案模型的集对分析研究	工业技术经济	2009.28.7	
145	吴薇薇 朱金福	副高 正高	073 073	Research on Airline Route Scheme Optimization Model	2009 WRI workd congress on software engineering	2009.4.0	
146	吴薇薇 宁宣熙	副高 正高	073 091	城市街道网单行道改造方案的评估	系统工程理论与实践	2009.29.7	

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148	白杨 朱金福	中级 正高	073 073	航空物流系统的概念模型与结构分析	企业经济	2009.0.1	
149	杨文东 朱金福	中级 正高	073 073	新时期民航运输管理专业需求分析	南京航空航天大学学报（社会科学版）	2009.11.2	
150	杨文东 朱金福	中级 正高	073 073	Economic analysis of spider web airline networks	Academic of Xi' an Jiaotong University	2009.21.1	
151	杨文东 王文芳	中级 硕士	073 073	有时间窗的多式联运问题分析与建模	南京航空航天大学学报（自然科学版）	2009.41.1	
152	杨文东 姜静逸	中级 硕士	073 073	基于VBA的飞机配载平衡的教学仿真系统的构建	南京航空航天大学学报（社科版）	2008.10.1	
153	唐小卫 朱金福	中级 正高	073 073	Optimaization Model and Algorithm of Unblanced Aircraft Recovery	International Conference on Transportation Engineering 2009	2009	
154	唐小卫 朱金福	中级 正高	073 073	基于SCPN的机场航班进离港流程建模与仿真	系统仿真学报	2009.21.22	
155	唐小卫 朱金福	中级 正高	073 073	繁忙机场飞机推出程序研究	第八届全国交通领域青年学术会议	2009	
156	高强	硕士	073	航空收益管理中等待表制度研究	第八届全国交通领域青年学术会议	2009.0.10	
157	高强	硕士	073	停机区推出共用停止点设计优化.	交通信息与安全	2009.27.6	
158	高强	硕士	073	Research on Greedy Simulated Annealing Algorithm for Irregular Flight Schedule Recovery Model.	IEEE 灰色系统与智能服务国际会议 (IEEE GSIS 2009)	2009	
159	刘明 李云	硕士 硕士	073 073	基于MAS的多航段的航空货运路径选择	第八届全国交通领域青年学术会议	2009	

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161	高荣环 许俐	硕士 副高	073 073	基于动态规划的团队舱位控制模型	第八届全国交通领域青年学术会议	2009	
162	杨玉兰 罗亮生	硕士 博士	073 073	基于航空公司顾客资产驱动因素的忠诚层次分析	空运商务	2009.0.15	
163	杨玉兰 罗亮生	硕士 博士	073 073	航空公司的交叉销售管理策略研究	第八届全国交通运输领域青年学术会议	2009	
164	李雯 许俐	硕士 副高	073 073	我国枢纽机场航班时刻优化方法研究	科技信息	2009.0.35	
165	王文芳 罗亮生	硕士 博士	073 073	我国民航初始飞行人才培养中存在的问题及对策	空运商务	2009.0.9	
166	李云 刘明 朱金福	硕士 硕士 正高	073 073 073	约束编程与线性规划混合技术在机组排班中的应用	第八届全国交通领域青年学术会议	2009	
167	戴军 朱金福	硕士 正高	073 073	空港综合交通枢纽评价指标体系	科技信息	2009.0.33	
168	鲁悦 朱金福	硕士 正高	073 073	航空公司航线效益分析实证研究	科学决策	2009.0.11	
169	叶纪 朱金福	博士 正高	073 073	不定期机票销售数量的优化控制方法研究	系统工程学报	2009.24.5	
170	陆宏兰 朱金福	硕士 正高	073 073	不正常航班恢复中旅客流恢复问题的研究	第八届全国交通运输领域青年学术会议	2009	
171	陆宏兰 朱金福	硕士 正高	073 073	多机型不正常航班一体化恢复	第八届全国交通运输领域青年学术会议	2009	
172	覃义 朱金福	博士 正高	073 073	Airline Network Design With Variable Hub Number	The 2nd Conference on Power Electronics and Intelligent Transportation System (PEITS 2009)	2009	

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174	黄勇辉 朱金福	博士 正高	073 073	基于加速遗传算法的投影寻踪聚类评价模型研究与应用	系统工程	2009.27.11	
175	黄勇辉 朱金福	博士 正高	073 073	政府绩效评估的成本分析与研究	金融与经济	2009.0.10	
176	屈云茜 朱金福	硕士 正高	073 073	Hub Characteristics Evaluation in Domestic Airline Network	国际应用统计学术研讨会	2009	
177	屈云茜 朱金福	硕士 正高	073 073	中国城市航空运输发展的潜力研究	统计与决策	2009.0.13	
178	陶婧婧 朱金福	硕士 正高	073 073	航班计划编排系统设计	第八届全国交通运输领域青年学术会议	2009	
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181	张 璟 朱金福	博士 正高	073 073	Logistics Amount Forecasting Based on Combined ARIMA and ANN Model	IEEE 灰色系统与智能服务国际会议 (IEEE GSIS 2009)	2009	
182	张 玮 朱金福	博士 正高	073 073	Passsenger traffic forecast based on gray-Markove method	IEEE 灰色系统与智能服务国际会议 (IEEE GSIS 2009)	2009	
183	陆迅 朱金福	博士 正高	073 073	航站楼车道边容量评估与优化	哈尔滨工业大学学报	2009.41.9	
184	陆迅 朱金福	博士 正高	073 073	航站楼旅客行李提取转盘指派问题	南京航空航天大学学报	2009.41.2	
185	陆迅 唐小卫	博士 中级	073 073	航站楼旅客离港流程仿真研究	西南交通大学学报	2009.44.1	

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187	司海青 王同光	副高 正高	074 012	Calculation of the Unsteady Airloads on Wind Turbine Blades under Yawed Flow	Modern Physics Letters B	2009.23.3	
188	司海青 王同光	副高 正高	074 012	基于全隐式无分裂算法求解三维N-S方程	计算力学学报	2009.26.2	
189	张明 韩松臣	中级 正高	074 072	基于变精度粗集的动态扇区数规划	西南交通大学学报	2009.44.3	
190	张明 韩松臣	中级 正高	074 072	基于双重力模型和人工神经网络的空中交通流量组合预测	西南交通大学学报	2009.44.5	
191	张明	中级	074	空中交通管制员工作负荷的模糊综合评价	人类工效学	2009.15.2	
192	桑保华 姜长生	中级 正高	074 031	Integrated Guidance and Control for a Missile in the Pitch Plane Based upon Subspace Stabilization	2009 Chinese Control and Decision Conference 会议	2009	
193	桑保华	中级	074	基于状态反馈的导弹非线性H2/H∞鲁棒制导律	弹道学报	2009.21.4	
194	李桂芳 黄圣国	中级 正高	074 071	马尔科夫使用模型在仿真系统测试中的应用	南京航空航天大学学报	2009.41.6	
195	李桂芳 黄圣国 刘星	中级 正高 副高	074 071 074	Delay-dependent output feedback robust passivity controller design for uncertain delayed systems	Proceedings - International Conference on Advanced Computer Control, ICACC 2009 会议	2009	
196	李桂芳 黄圣国	中级 正高	074 071	Delay-dependent output feedback passive control for time-delayed system	2009 International Conference on Measuring Technology and Mechatronics Automation会议	2009	

NEW METHOD FOR SAFETY ASSESSMENT OF PARALLEL ROUTES

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Abstract: A new safety assessment method for parallel routes is presented. From the aspects of safety guard system of air traffic control (ATC) and considering the flight conflict as causing event of air collision accidents, this paper fosters a four-layer safety guard of controller command, short-term conflict alerts (STCAs), pilot visual avoidance, and traffic alert collision avoidance system (TCAS). Then, the problem of parallel routes collision risk is divided into two parts: the calculation of potential flight conflict and the analysis of failure probability of the four-layer safety guard. A calculation model for controller interference times is induced. By using cognitive reliability and error analysis method (CREAM), the calculation problem to failure probability of controller sequencing flight conflicts is solved and a fault tree model of guard failure of STCA and TCAS is established. Finally, the Beijing-Shanghai parallel routes are taken as an example to be calculated and the collision risk of the parallel routes is obtained under the condition of radar control. Results show that the parallel routes can satisfy the safety demands.

Key words: air traffic control; human factors; safety assessment; short-term conflict alerts; traffic alert collision avoidance system

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INTRODUCTION

Parallel routes are one of the most commonly used route structures. By using them, the capacity of the routes can be effectively broadened. With the development of area navigation (RNAV) and the required navigation performance (RNP) technologies, the plan of the routes now is no longer strictly constrained by the position of navigation facilities, thus promoting the use of parallel routes in turn. During the planning of parallel routes, one key point is that the airspace planning department should focus on the separation. If the separation is too small, the flight safety would be undetermined. If the separation is too large, the resource of airspace would be wasted. The evidence for determining the separation is the safety of parallel routes. The studies on collision risks of parallel routes began in the 1960's. Refs. [1-3] comprehensively considered the navigation error, aircraft size and traffic flow amounts, and established a collision risk model.

This model is successfully used in the separation safety assessment of North Atlantic parallel routes. Ref. [4] analyzed in detail all the reasons which caused lateral navigation error and introduced weighted analysis method for the lateral navigation error, thus improving the Reich model. Ref. [5] borrowed from the collision absorbing boundary theory and introduced an aircraft collision risk calculation model based on Markov process. Refs. [6-7] summarized the traditional analysis model and discussed the key problems focused on the safety assessment of routes, such as human factors, alert system and so on. Refs. [8-9] also studied the effects that the radar precision error would have the risks of the air collision.

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Ref. [10] presented a method for the protection zone. The method considers aircraft turbulence wake and dynamics characteristics. Based on that people can establish aircraft protection zone and determine the minimal safety separation between aircraft. The researches mentioned above are either mainly tuning to the safety assessment in the circumstance of non-controller interference, or qualitative researches on the effects of human factors and the alert system on the safety. Therefore, there is no mature methodology yet to make the safety assessment for controller interference. This paper analyzes in detail the safety protection system for air traffic control, and modifies the traditional collision risk model. Combined with the human reliability analysis technology, such as cognitive reliability and error analysis method (CREAM), and human cognitive reliability (HCR), this paper introduces a quantitative safety assessment methodology for the parallel routes with controller interference.

1 SAFETY ASSESSMENTS OF NON-CONTROLLER INTERFERECE PARALLEL ROUTES

By analyzing collision risk of non-controller interference parallel routes, the Reich model is the most widely used one. The key of the model is that each aircraft is considered as a rectangle box, which has the mean sizes of λ_x, λ_y, λ_z. These sizes represent the mean length, the width and the height of each aircraft group, respectively. The collision risk between two boxes is equal to the collision risk between a point and a box having the sizes of $2\lambda_x$, $2\lambda_y$ and $2\lambda_z$ in mathematics. According to Ref. [11], the lateral collision risk can be shown as

$$C = P_y(S_y)P_z(0)\frac{\lambda_x}{\widetilde{S}_x}\left\{E_y(\text{same})\left[\frac{|\bar{x}_s|}{2\lambda_x}+\frac{|\bar{y}|}{2\lambda_y}+\frac{|\bar{z}|}{2\lambda_z}\right]+E_y(\text{opp})\left[\frac{|\bar{x}_o|}{2\lambda_x}+\frac{|\bar{y}|}{2\lambda_y}+\frac{|\bar{z}|}{2\lambda_z}\right]\right\} \tag{1}$$

where C is the amount of estimated fatal accidents of aircraft in each flight hour; $\widetilde{S}_x$ the longitudinal separation; S_y the lateral separation; $P_y(S_y)$ the lateral overlapping probability, i. e., every two aircraft are assigned to be correct lateral separation, actually they do not have the possibility to be laterally separated. $P_z(0)$ is the vertical overlapping probability, called the vertical overlapping possibility of two aircraft at the same level. E_y(same) and E_y(opp) are the same direction and opposite direction occupation rates, respectively; $|\bar{x}_s|$ and $|\bar{x}_o|$ the relative speeds in same longitudinal direction and opposite longitudinal direction; $|\bar{y}|$ is the mean relative speed in lateral direction when an aircraft loses its lateral separation standard; and $|\bar{z}|$ the mean vertically relative speed of the aircraft at the same level.

2 SAFETY ASSESSMENTS OF CONTROLLER INTERFERENCE PARALLEL ROUTES

Under the condition of radar control, controllers may interfere when an aircraft deviates from the route, so the focus of safety assessment is the controller error. Besides, multiple guard mechanism taken by modern air traffic control (ATC) system can improve the safety level. In the typical radar control scenario, in order to avoid the collision, the used methods can be grouped into four layers, i. e., controller command, short-term conflict alerts (STCAs), pilot visual avoidance, and traffic alert collision avoidance system (TCAS). As shown in Fig. 1, every layer has its disadvantage. When the disadvantage of each layer happened at the same time, accidents take place. Thus the potential flight conflict is the causal factor of the air collision. No collision accidents will happen without a potential conflict. However, the main purpose of the four layer guard is to prevent as much as possible the potential flight conflict from becoming an air collision accident. Hence, based on the mechanics of the safety guard, the problem of aircraft collision risk can be divided into calculation of potential flight conflict and failure probability analysis of

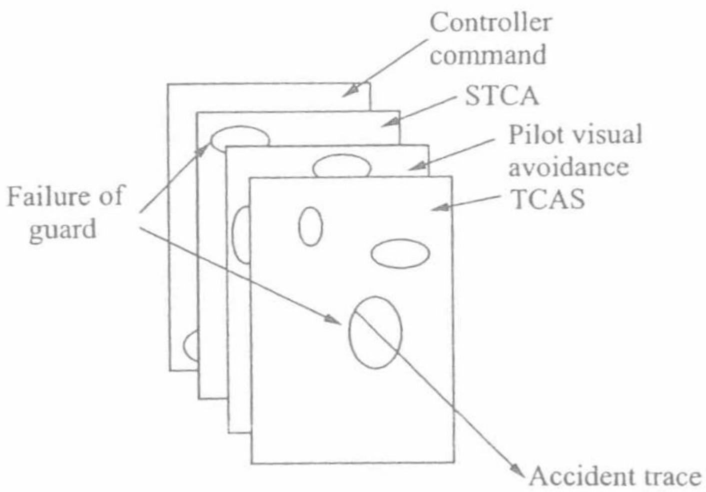


Fig. 1 Typical safety guard of ATC system

each layer. Based on logical relationship of safety layers, the safety assessment of controller interference parallel routes can be realized after the human reliability is thoroughly considered.

This paper chooses the working scenario of ATC in China when constructing the model, and the typical working scenario is shown in Table 1.

Table 1 Scenario of model construction

Scenario	Reason
Radar control	In the busy airspace, our country has basically realized radar control.
ATC automatic system has the ability of STCA	The automatic systems used by our country control center mainly are Eurocat, Raytheon and Alenia. Eurocat and Raytheon have STCA function. The control center using Alenia system now has STCA function after transformed.
Aircraft equipped with TCAS	The used large and medium aircraft now in civil aviation in China are mainly Boeing and Airbus series, which have advanced airborne equipments. From 2003, the authority announced by TCAS was compulsory on aircraft.
Aircraft flying under IFR rules	All airspace in China is controlled. Aircraft usually follow instrument flight rule (IFR) except in the airspace around the aerodrome.

This paper only considers controller command, STCA and TCAS. Pilot visual avoidance can be ignored, because an aircraft flies en-route by instrument flight rule(IFR) and is not visual flight rule(VFR) in most time.

The parameters are defined as follows: C_R is air collision risk of aircraft; N_C the potential flight conflict times; P_{HE} the failure probability of controller sequencing flight conflicts; P_S the failure probability of STCA guard and P_T the failure probability of TCAS guard.

Assuming that controller command, STCA and TCAS are not related to each other, only when these three guards all fail the air collision will take place. Therefore, it is be shown as

$$C_R = N_C \times P_{HE} \times P_S \times P_T \tag{2}$$

In this model, the calculation of N_C, P_{HE}, P_S, and P_T is difficult and is also the key to decide whether the model is applicable. In the following parts, how to calculate N_C, P_{HE}, P_S, and P_T is introduced.

2.1 Calculation model of potential flight conflict times

Under the condition of the radar control, the definition of the conflict mode is that on the parallel routes, when two aircraft separation is lower than minimal radar separation, the controller will interfere. In our country, the regulated minimal radar separation S_{radar} equals to 10 km. The model of interference times of the controller can be expanded by the Reich model[11]. If the lateral and longitudinal separations can be expanded into a rectangular box with a radar separation value S_{radar}, then the interference times of the controller under the radar separation condition can be considered as the adding number of n collision times of the same flight level. Using Eq. (1), a new equation can be deduced as

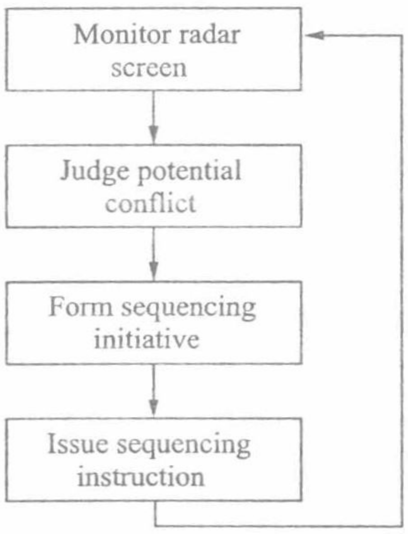
$$G_Y = nP_y(S_y)P_z(0)\frac{S_{radar}}{\bar{S}_x} \cdot \left\{E_{same}\left[\frac{|\bar{\dot{x}}_s|}{2S_{rader}} + \frac{|\bar{\dot{y}}|}{2S_{radar}} + \frac{|\bar{\dot{z}}|}{2\lambda_z}\right] + E_{opp}\left[\frac{|\bar{\dot{x}}_o|}{2S_{radar}} + \frac{|\bar{\dot{y}}|}{2S_{radar}} + \frac{|\bar{\dot{z}}|}{2\lambda_z}\right]\right\} \tag{3}$$

where G_Y is the interference times of controller. Actually, most of the potential flight conflicts can be solved by the controller interference. Hence, the controller interference times can be considered to be equal to the potential flight conflict times, i. e., $G_Y = N_C$.

2.2 Failure probability of controller sequencing flight conflicts

The controller basic obligation is to handle potential flight conflicts to ensure flight safety. The wrong command from the controller can directly lead to the aircraft separation lower than regulated minimal separation. How to objectively evaluate controller errors is diffcult in safety assessment. The development of human reliability analysis offers a new method for evaluating controller errors.

The flowchart of controller sequencing flight conflicts is shown in Fig. 2. It has the following characteristics: (1)Sequencing process is dynamic and the process is continuous and repetitive according to the flight dynamics; (2)The process is greatly affected by the context.



ig. 2 Flow chart of controller sequencing flight conflicts

Considering controller working characteristics, the CREAM method can perfectly satisfy the basic demand of controller reliability analysis. The evidences are as follows: (1)The CREAM method is based on a context relied cognitive model. It emphasizes the important context effects on human behavior. It summaries environmental factors as common performance condition (CPC)and gives CPC level effect on human reliability[12]; (2) CREAM method offers a unique cognitive model and a structure. It has double-direction functions with recursion and forecast. Thus the quantitative analysis of human errors can be make; (3)The CREAM method is based on cognitive psychology; (4) The CREAM method offers the data of basic cognitive function failure probability.

2.3 STCA guard failure probability

After the STCA warning, controllers can solve flight conflict in time according to the flight performance and air traffic situation. If the conflict is not solved in time, TCAS warning or aircraft collision will happen.

Based on the characteristics of STCA, a STCA guard fault tree can be established, as shown in Fig. 3, so that the STCA guard failure probability can be calculated.

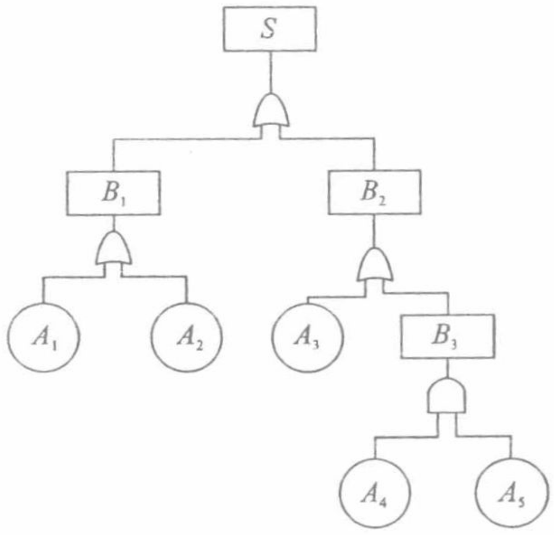


Fig. 3 STCA guard fault tree

In Fig. 3, S is STCA guard failure; B_1 is the pilot in not getting the conflict avoidance instruction; B_2 is the pilot for executing wrong instruction; B_3 is the pilot for misunderstanding instruction; A_1 is the controller not responding in time; A_2 is the communication failure; A_3 is wrong instruction given by controller; A_4 is the wrong understanding by pilot; and A_5 is the controller not finding the mistake from pilot read back.

The probability of the top event can be shown as

$$P_S = P(A_1 + A_2 + A_3 + A_4A_5) = P(A_1 + A_2 + A_3) + P(A_4A_5) - P(A_1 + A_2 + A_3)P(A_4A_5) \qquad (4)$$

The probability estimations of basic events A_1, A_2, A_3, A_4, and A_5 consider the event characteristics and select different methods. (1)The essence of controller not responding in time(A_1) is that the staff does not respond to abnormal signal in the regulated time. Its probability estimation can be realized through HCR model and its model parameters can be determined by experiments. (2)The probability of communication failure(A_2) can be received through the reliability data estimation of communication system. (3) The probability of A_3, A_4 and A_5 can be estimated by using CREAM method.

The key of HCR model is that the relationship between human cognitive behaviors (regulation, technique, and knowledge) failure probability $P(t)$ and time t falls in the three-parameter Weibull distribution[13]. Therefore, the non-responding probability $P(t)$ in the regulated time t can use this distribution, and the equation is shown as

$$P(t) = \exp\left\{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}\right\}, t \geqslant \gamma$$
$$P(t) = 1.0, t < \gamma \tag{5}$$

where γ is the initial position of distribution curve, called the position parameter (at minimal response); η the coordination scale, called the scale parameter (at particular response); and β the distribution curve shape, called the shape parameter. When responding time equals to middle time value ($T_{1/2}$), $P(t)=0.5$. Then

$$T_{1/2} = \gamma + \eta(\ln 2)^{1/\beta} \tag{6}$$

$T_{1/2}$ is standardized, then

$$P(t) = \exp - \left\{\frac{(t/T_{1/2} - C_\gamma)}{C_\eta}\right\}^{\beta}, t/T_{1/2} \geqslant C_\gamma$$
$$P(t) = 1.0, \quad t/T_{1/2} < C_\gamma \tag{7}$$
$$C_\gamma = \gamma/T_{1/2}, C_\eta = \eta/T_{1/2}$$

where C_γ, C_η, β are three standardized parameters of the Weibull distribution.

In the actual work, the frequency of STCA warning is rather low. It is impossible to collect real data. However, one of the prominent advantages of HCR model is that it can collect related data by the simulator.

2.4 TCAS guard failure probability

Based on the working characteristics of TCAS, this paper constructs a TCAS guard fault tree.

In Fig. 4, T is TCAS guard failure; C_1 the pilot not responding in time; C_2 the wrong operation of the pilot; D_1 the pilot A not responding in time; D_2 the pilot B not responding in time; D_3 the wrong operation of Pilot A; D_4 the wrong operation of Pilot B; and D_5 the TCAS system failure.

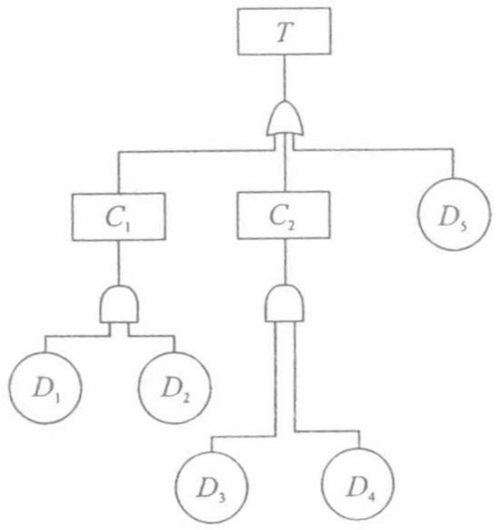


Fig. 4 TCAS guard fault tree

The probability of top event can be calculated as

$$P_T = P(D_1D_2 + D_3D_4 + D_5) =$$
$$P(D_5) + P(D_1D_2 + D_3D_4) -$$
$$P(D_5)P(D_1D_2 + D_3D_4) \tag{8}$$

Basic event probability estimating is as follows: (1) Pilot A is not responding in time (D_1) and Pilot B is not responding in time (D_2). Their probabilities can be estimated by HCR model; (2) Pilot A wrong operation (D_3) probability and Pilot B wrong operation (D_4) probability can be estimated by CREAM method; (3) TCAS system failure probability (D_5) can be estimated by TCAS system reliability data.

3 CASE STUDY

The following safety assessment is based on Beijing-Shanghai parallel routes. The settled conditions are as follows: 100% RNP4 aircraft; 185 km parallel routes; 6 flight levels; aircraft fly in the same direction at the same flight level; 30 aircraft/h in one direction of parallel routes.

3.1 Interference times

Using Eq. (3), when the route separation is 30 km, $N_C = G_Y = 9.0 \times 10^{-3}$/h.

3.2 Failure probability of sequencing flight conflict

CREAM method is used to identify the cognitive activities needed in each step and determine the cognitive functions of each cognitive activity in each step, see Table 2.

Table 2 Cognitive function and activity controller needed in sequencing

No.	Subtask	Cognitive activity	Observation	Interpretation	Planning	Execution
1	Monitor radar screen	Monitor	◆	◆		
2	Judge conflict	Evaluate		◆	◆	
3	Form sequencing initiative	Plan			◆	
4	Issue sequencing instruction	Communicate				◆

As cognitive activity may be related to a number of function failures, work must be in ATC situation, so as to identify the most likely function failure and make each cognitive activity correspond to the most likely function failure. The most probable cognitive function failure mode can be determined, as shown in Table 3.

Table 3 Function failure in process of controller sequencing flight conflict

Serial No.	Subtask	Cognitive activity	Failure mode
1	Monitor radar screen	Observe	O_2
2	Judge conflict	Evaluate	P_2
3	Form sequencing initiative	Plan	P_2
4	Issue sequencing instruction	Communicate	E_3

By the field study, controller interviews and questionnaire investigation, CPCs can be assessed and the value of CPCs can be determined, as shown in Table 4.

Table 4 CPC Level and weighing factors

CPC name	Level	O_2	P_2	E_3
Adequacy of organization	Efficient	1.0	1.0	1.0
Working conditions	Compatible	1.0	1.0	1.0
Adequacy of MMI and operational support	Tolerable	1.0	1.0	1.0
Availability of procedures/plans	Appropriate	0.8	0.5	0.8
Number of simultaneous goals	Matching current capacity	1.0	1.0	1.0
Available time	Temporarily inadequate	1.0	1.0	1.0
Time of day (circadian rhythm)	Day-time (adjusted)	1.0	1.0	1.0
Adequacy of training and experience	Adequate, limited experience	1.0	1.0	1.0
Crew collaboration quality	efficient	1.0	1.0	1.0
Overall effects of CPC		0.8	0.5	0.8

Basic CFP can be consulted from Ref. [12]. According to CPCs, The revised CFP is determined, as shown in Table 5.

Table 5 Revised CFP

Serial No.	Subtask	Failure mode	Basic CFP	Weighing factor	Revised CFP
1	Monitor radar screen	O_2	7.0E−2	0.8	5.6E−2
2	Judge conflict	P_2	1.0E−2	0.5	5.0E−3
3	Form sequencing initiative	P_2	1.0E−2	0.5	5.0E−3
4	Issue sequencing instruction	E_3	5.0E−4	0.8	4.0 E−4

Based on controller sequencing flight conflict event serial, P_{TP}, the failure probability of finishing single sequencing flow can be calculated, $P_{TP}=6.9\times10^{-2}$.

By investigation, it can be found that when potential conflict appears in the time segment of STCA warning, it can support the controller to finish 2—3 sequencing flows. The relationship among these sequencing flows is parallel connection. For conservative consideration, only two sequencing flows are adopted, then $P_{HE}=4.76\times10^{-3}$.

3.3 STCA guard failure probability

When HCR model is used to calculate the probability of controller in not responding in time (A_1), Weibull distribution parameters can be determined by the experiment. The experiment can be conducted on the radar simulator and 50 groups of data are collected. By using nonlinear regression fitting module of SPSS, the data can be processed and analyzed under Weibull distribution fitting[13-14], and the data result is as follows: $\gamma=1.048$, $\eta=0.545$, $\beta=1.048$.

According to Eq. (6), $T_{1/2\text{nominal}}$ can be calculated, $T_{1/2\text{nominal}}=1.5$ s. Eq. (7) is standard, $C_\gamma=0.69$, $C_\eta=0.36$, $\beta=1.885$.

As the actual working environment is different with that of the simulator experiment, the result is revised by operator experience (K_1), psychology pressure (K_2) and human-machine interface (K_3). Based on working experience and the data from nuclear industry, $K_1=0$, $K_2=0.44$, $K_3=0.44$. Then $T_{1/2}=T_{1/2,\text{nominal}}\times(1+K_1)\times(1+K_2)\times(1+K_3)=3.11$ s. According to working experience, the time t is 5 s, $P(t)=3\times10^{-3}$, i. e., $P(A_1)=3\times10^{-3}$. Controller wrong instruction (A_3), pilot misunderstanding instruction (A_4) and controller not finding mistake from the read back (A_5) can also use CREAM method to estimate the probability, then $P(A_3)=4\times10^{-4}$, $P(A_4)=4\times10^{-4}$, $P(A_5)=2\times10^{-1}$.

Communication failure (A_2) probability can be estimated through communication system reliability data. Substituting $P(A_2)=1\times10^{-7}$ into Eq. (4), then $P_S=3.48\times10^{-3}$.

3.4 Estimating TCAS guard failure probability

The pilot not responding to time probability (D_1, D_2) can be estimated through HCR model and HCR model parameter can be determined through experiment on simple flight simulator. C_γ, C_η, β are equal to 0.71, 0.39 and 1.28.

Considering operator experience (K_1), psychology pressure (K_2) and human-machine interface (K_3), then $T_{1/2}=2.43$ s, $P(D_1)=P(D_2)=7.5\times10^{-3}$. By using CREAM method, the probability of D_3 and D_4 can be achieved, $P(D_3)=P(D_4)=4.1\times10^{-2}$. TCAS system failure probability (D_5) can be estimated through TCAS system reliability data, $P(D_5)=1\times10^{-7}$. Substituting it into Eq. (8), $P_T=1.7\times10^{-3}$.

3.5 Collision risk of Beijing-Shanghai parallel routes on radar control

Substituting N_C, P_{HE}, P_S and P_T into Eq. (3), $C_R=2.46\times10^{-10}$. On the radar control, the lateral collision risk is lower than 5.0×10^{-9}, which is the safety standard. Therefore, the routes can satisfy the safety requirement.

4 CONCLUSION

This paper studies the safety problem of parallel routes and introduces a new safety assessment method. The collision risk problem of parallel routes is divided into potential flight conflict calculation and failure probability analysis of each guard layer. Based on all these, it deduces the calculation model of interference times of the controller, and uses CREAM method to solve the problem of calculating the failure probability of controller sequencing flight conflict, and establishes a fault tree model of STCA and TCAS guard failure. Finally, Beijing-Shanghai parallel routes are used as an example and the collision risk of the routes under radar control is calculated. The result shows that the routes can satisfy the safety requirement and offer a good guidance and a reference for the airspace management department to reasonably plan parallel routes.

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平行航路安全评估新方法

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摘要:首先提出了一种平行航路安全评估新方法,即从空中交通管制的安全防护体系入手,将潜在飞行冲突看作空中相撞事故的初因事件,提炼出管制员指挥、短期冲突告警、飞行员目视避让及机载防撞系统告警四层安全防护,进而将平行航路碰撞风险问题分解为潜在飞行冲突计算和各防护层的失效概率分析。然后,推导了管制员干预次数计算模型,采用CREAM方法解决了管制员调配飞行冲突失误概率计算问题,建立了STCA防护失效和TCAS防护失效故障树模型。最后,以京沪平行航路为例进行计算,得出了雷达管制环境下的京沪平行航路碰撞风险。结果表明该航路满足安全要求。

关键词:空中交通管制;人为因素;安全评估;短期冲突告警;机载防撞系统
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