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The analysis of collision risk effect among different aircraft combinations by parallel runways spacing

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Abstract. International Civil Aviation Organization (ICAO) has stipulated the spacing of parallel runways, but it hasn't considered different aircraft categories classified by speed. So there is no provision as a reference for the safety runway spacing corresponding to different aircraft speed combinations. This paper studied the safety spacing of parallel runways based on aircraft categories classified by speed in the ICAO regulations with the aim of providing more reasonable planning for the parallel runway configuration suited for different aircraft speed combinations. The improved simulation model is established. The innovations are mainly reflected in the following two aspects. First, based on the established evasion solution to the hazardous scenario in PLB(Parallel Landing Blunder) model, this paper added a new solution that the deviating aircraft (blunderer) corrects its course returning to the designated approach course (i.e., the course correction solution). Second, when adopting the evasion solution, this paper revised the simulated evasion maneuver command according to Doc. 8168 of ICAO, because it could better reflect the pilot's real response. According to the simulation results, it is concluded that when the combinations consists of the same aircraft category, both A-A and B-B combinations can conduct simultaneous independent parallel instrument approaches (SIPIA) to the parallel runways with the spacing of 835m. When the combinations consist of different aircraft categories, the paper emphatically studied the A-E combinations with the largest difference of approach speed. In the case of A-E combinations, with 1035 m runway spacing, the collision risk of SIPIA is relatively high.

1. Introduction

Farbod Farhadi [1] points out that the main factors affecting airport runway capacity are runway configuration, scheduling plans and safety standards. When the scheduling plan is already optimal and the safety standard interval cannot be further reduced, the airport can only increase the amounts of runways to increase its capacity, which concerns the parallel runway safety issues. Ebrahimi [2] from the NASA research center in the United States conducts a preliminary study on parallel runway requirement from the view of approach safety in 1993. J Sun [3] uses monte carlo method to simulate and calculate the collision risk of parallel runway. Z P Lv [4] uses accident tree analysis to study the collision risk of paired approach. X L Niu [5-6] focuses on the galloping distance and collision risk of paired approach. These studies show that the spacing between parallel runways has a great impact on the safety of aircraft.

With the air traffic rising year by year, all countries are exploring effective ways to improve the air transport capacity. The study on increasing runway capacity is included. Now many airports build a second runway or multiple runways in order to expand their capacity, but if the parallel runway



spacing is too large, the aircraft will have to taxi a rather long distance which is less economical. if the parallel runway spacing is too small, it will jeopardize the flight safety [7].

At present, the International Civil Aviation Organization (ICAO) have specific requirement for parallel runway spacing, that is, 1035 m parallel runway spacing is required for SIPIA [8]. Based on the assumption of 278 km/h approach speed, this provision doesn't take different aircraft speed combinations into account, therefore it has large redundancy. Consequently, there will be a waste of space in the practical airport construction. For instance, the airport designed for aircraft of category A, B or C sometimes boasts the runway spacing which can meet the need of the aircraft of category D or E. Another problem of the current provisions is that they are established base on the past flight simulation results. In recent years, several airports have made preliminary attempts to conduct SIPIA, offering some practical operational advice which are useful for improving the simulation model. However none of these advice are reflected in the established PLB model. On this very note, this paper improved the established PLB model by offering a new solution to the hazardous scenario. The established solution is the evasion solution, and the new one is the course correction solution. Taking the operational advice into account, the paper uses the three-degree-of-freedom (3-DOF) motion equation [9] to establish an improved simulation model as a tool for analysing the collision risk effect of approaching aircraft by parallel runway spacing. In this way, the requirement of parallel runway safety spacing corresponding to different aircraft combinations are summarized, which can make the planning and construction of airport more reasonable and economical.

2. Simulation

2.1 Design of simulation

In 1993. Y.s. Ebrahimi[2] established PLB model to analyse the requirements of parallel runways for independent instrument approach under the most adverse circumstances. The hazardous scenario of PLB can be described as follow: when two aircraft conduct SIPIA to parallel runways, one aircraft (blunderer) deviates from its designated course toward the other aircraft (threatened aircraft) on the adjacent approach. In this hazardous scenario, PLB model adopts the evasion solution, that is, the threatened aircraft (evader) on the adjacent course will evade in order to avoid the blunderer, as shown in Figure 1. In this context, this paper introduces another solution, the course correction solution, i.e., the blunderer will take corrective action to return to the designated approach course, as shown in Figure 2.

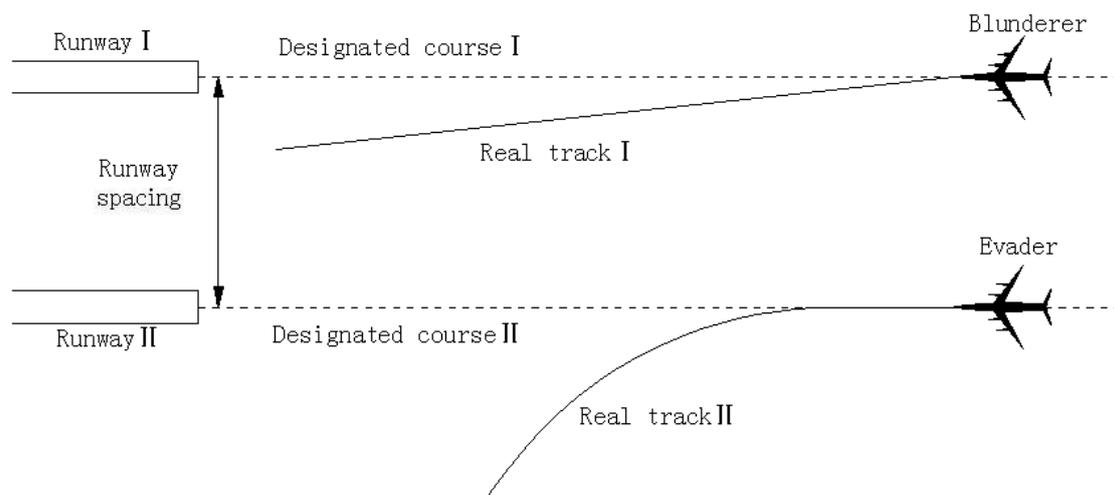


Figure 1. Evasion solution.

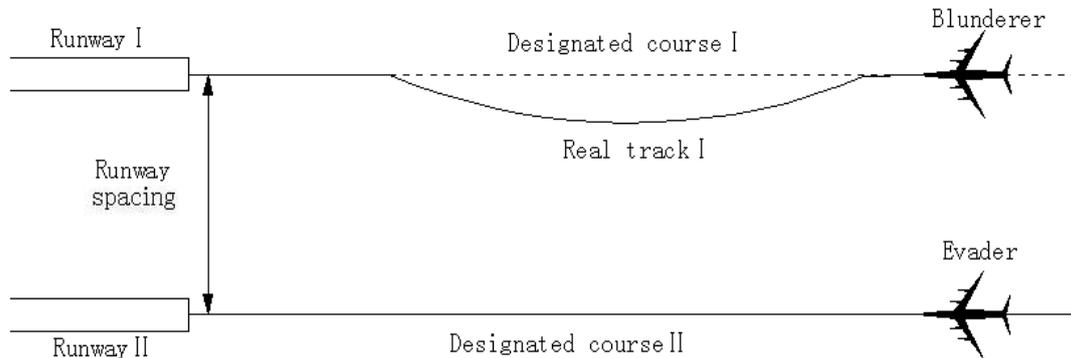


Figure 2. Course correction solution.

2.2 Assumptions of simulation conditions

According to the characteristics of simulation, the following assumptions and simulation conditions are proposed in this paper:

1. The approach aircraft doesn't need to maintain a radar safety interval and doesn't take into account the influence of wake.

2. The approach parameters adopt the values recommended by ICAO [8]: the approach distance is 18.5km, the height is 600m, and the descending Angle is 3 degrees.

3. It is assumed that the blunderer penetrates the no transgression zone (NTZ) at a 30-degree angle [10] and proceeds on this track toward the aircraft on the adjacent approach. The threatened aircraft (evader) is vectored away to achieve separation, and the simulation ends when the evader has achieved a 30-degree track change to parallel the blunderer's track. Or the blunderer correct its course returning to its designated course.

4. Other underlying assumptions:

Aircraft turn rate: 3 degree per second.

Delay time: 8 seconds which corresponds to 300 m assuming a dedicated radar monitoring controller with a frequency override broadcast capability.

Guidance: a front-course instrument landing system (ILS) and navigation accuracy of 46m (one sigma) at 18.5km.[10]

2.3 Characteristics analysis of pilot's operation during the approach

The aircraft's approach flight is a kind of flight mode under the guidance of the navigation equipment and the controller. The navigation equipment applied in this paper's improved simulation model is the most widely used instrument landing system (ILS) [11], remaining consistent with the equipment used in the PLB model. In the PLB model, the evader initiates maneuver after receiving the instruction given by the controller. So the total response time in the PLB model consists of the controller's response time and the pilot's response time. However, according to the data of test flights and simulated test flights conducted by a certain country (with reference to doc.8168 [8]), when command terms of the Air Traffic Service (ATS) are consistent with the stipulations of independent parallel approaches in PANS-ATM [12], the pilot always arrests the decent first and then makes a climbing turn following the instructions of ATS. That is to say, when the pilot received the instructions issued by the controller, his reaction is to arrest the descent first and then initiate a climbing turn, instead of directly flying sideways to evade. According to the actual response of the pilot, this paper improved the PLB model by adding the time for pilot to adjust the aircraft attitude.

But there is no real flight data as a reference for the added time of adjusting the aircraft attitude. Since the evasion solution depicted above is very similar to a missed approach, for in either scenario, the aircraft needs to arrest the descent first and immediately initiate a climbing turn. According to the relevant ICAO regulations concerning missed approach, the climb establishment time is defined as the

sum of the pilot’s response time, the aircraft’s response time and the time of adjusting the aircraft attitude from descent to climb (adjusting time).

Since there is no consideration of adjusting time in PLB model, the improved simulation model compliments a 6-second additional time of adjusting the aircraft attitude from descent to climb and retains the response time set by the PLB model.

2.4 Operation model of aircraft

The three-degree-of-freedom (3-DOF) dynamic model can be built in the flight-path coordinate system:

$$\begin{cases} \dot{V} = g(c_x - \sin \theta) \\ \dot{\psi}_s = -\frac{g}{V \cos \theta} c_y \sin \gamma_s \\ \dot{\theta} = \frac{g}{V} (c_y \cos \gamma_s - \cos \theta) \end{cases} \quad (1)$$

Where V is the speed of the aircraft; g is the gravitational acceleration, ψ_s is the yaw angle; γ_s is the roll angle; c_x, c_y are the control parameters of aircraft speed and pitching respectively. Once we get the initial values of ψ_s, V, θ and the changes of γ_s, c_x, c_y in the simulation, we can obtain the changes of ψ_s, V, θ by calculating the integral of formula (1). And the aircraft's real position in the three-dimensional space at any time can be obtained based on formula (2).

$$\begin{cases} \dot{x} = V \cos \psi_s \cos \theta \\ \dot{y} = V \sin \theta \\ \dot{z} = -\sin \psi_s \cos \theta \end{cases} \quad (2)$$

2.5 Independent instrument approach simulation

The aircraft's horizontal and lateral movement is realized by controlling the changes of γ_s , the aircraft's pitching movement is mainly controlled by c_y , and c_x is the maneuvering command to control the aircraft's flight speed. In the presented model, all of the pilot’s operations during the approach process can be simulated by adjusting the three maneuver parameters. Once the parameters change, the aircraft attitude will shift correspondingly, enabling the aircraft to fly along the ILS course or initiate maneuvers to avoid collision.

This paper adopts the aircraft categorization raised by ICAO[8], taking the indicated airspeed as the classification criterion. Same aircraft categorization is applied to the flight procedure design.

Table 1. Aircraft categories classified by speeds in kilometers per hour.

Aircraft category	Speed at threshold of runway (km/h)	Range of speeds for initial approach (km/h)	Range of final approach speeds (km/h)
A	<169	165/280	130/185
B	169/223	220/335	155/240
C	224/260	295/445	215/295
D	261/306	345/465	240/345
E	307/390	345/467	285/425

This paper introduces the concept of acceptable closest distance (ACD). When the spacing between two approaching aircraft is less than ACD, we consider that a collision has occurred. The simulation model can be used to calculate the collision risk under a given ACD. The simulation conditions are shown in Table 2.

Table 2. Basic conditions of the simulation.

parameter	value
NTZ width	60% of runway spacing

Adjusting time (from descent to climb)	6(s)
Response time mean/standard deviation	8.0/9.8
Longitudinal distance	0
Blunderer start	blunder at 18.5(km) to 1(km) (from runway threshold)
Average speed	varies according to aircraft type (in Table 1)
Blunder angle	30 (deg)
Evader bank angle	22 (deg)
Evader turn heading	55 (deg)
Evader climb rate	7 (m/s)

3. Conclusion and analysis

3.1 Aircraft combinations of same category

3.1.1 The evasion solution. When the evasion solution is adopted in a hazardous scenario, we studied the collision risk effect among same category combinations by parallel runway spacing. Take the final approach speed in Table.1 as the simulation parameter and set the ACD value at 160 m. Figure 3 and Figure 4 show the collision risk effect among same category combinations by parallel runway spacing with the speed set at the upper and lower limit (the speed range is shown in Table.1), respectively.

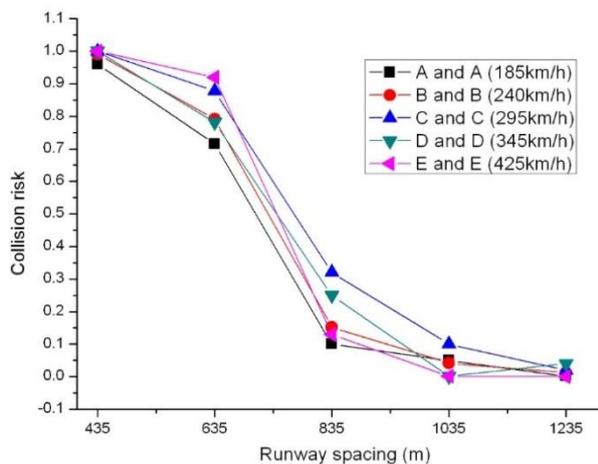


Figure 3. Collision risk and runway spacing (upper limit speed and evasion solution).

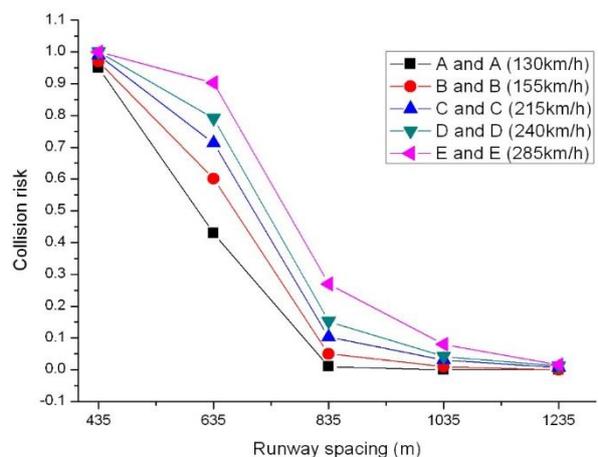


Figure 4. Collision risk and runway spacing (lower limit speed and evasion solution).

Figure 3 shows that the collision risk effect among the same category combinations by parallel runway spacing with the final approach speed set at the upper limit. “A and A” represents A-A combinations, namely the combinations of two category A aircraft. Likewise, other plots represent B-B, C-C, D-D and E-E combinations, respectively. The plots indicate that as the runway spacing increases, the collision risk of each aircraft combinations decreases. When the runway spacing is less than 635 m, the collision risks of all combinations are rather high. When the runway spacing is set at 835 m, the collision risks of A-A, B-B and E-E combinations are reduced evidently, much lower than the collision risks of C-C and D-D combinations. Through analysis, we think probably it is because the aircraft of category A and B have relatively low approach speed, with the 835 m runway spacing, the time that the blunderer penetrates the NTZ will be long enough for the evader to achieve the safe lateral separation between the aircraft so that the collision is more likely to be avoided. On the contrary, the aircraft of category E has the highest approach speed, and the time it needs to penetrate the NTZ is rather short. The reason why the collision risk of E-E combinations is also significantly reduced probably lies in the high descent rate caused by high approach speed. Because of the high

descent rate of category E, even for a relatively short time that the blunderer penetrates the NTZ, there will be enough for the evader to achieve the altitude difference to guarantee safety resulting in the reduction of the collision risk. In summary, when the approach speed is low, the safety separation between the aircraft is mainly affected by the lateral separation; and when the approach speed is high, the safety separation between the aircraft is mainly affected by the altitude difference.

Figure 4 shows the collision risk effect among the same category combinations by parallel runway spacing with the final approach speed set at the lower limit. As we can see from the plots, as the runway spacing increases, the collision risk of each aircraft combinations decreases. When the runway spacing is 1035 m and 1235 m, the collision risks of all combinations stabilize at the minimum value. When the runway spacing is 835 m, the collision risk of E-E combinations with the approach speed of 285 km/h is 0.272. The reason why E-E combinations has a relatively high collision risk is that when the approach speed is around 300 km/h, the time that the blunderer penetrates the NTZ won't be long enough for the evader to maneuver and achieve the safe lateral separation between the two aircraft; besides the descent rate is not high enough to achieve a relatively safe altitude difference. In Figure 3, same conclusion can be validated by C-C and D-D combinations whose collision risk is 0.4 and 0.24 with the approach speed of 295 km/h and 345 km/h (both around 300 km/h), which are similar to the case of E-E combinations in Figure 4.

The plots in Figure 3 and Figure 4 indicate that the runway spacing of 1035 m can be suitable for any aircraft combinations of same category. This finding is in consistent with the research conclusion of Ebrahimi Y. S. (1994) [10], who conducted the research regarding the collision risk effect by runway spacing from 1035 m to 1737 m in 1994. But based on the practical need of that time, no research was carried out to study the collision risk effect by smaller runway spacing. According to the simulation results of this paper, it can be concluded that due to the relatively high collision risk, the runway spacing of 835 m can't satisfy the operation requirements for C-C, D-D and E-E combinations. However, it is relatively safe for A-A and B-B combinations to conduct SIPIA to parallel runways with the spacing of 835m.

3.1.2 The course correction solution. In the improved simulation model, the hazardous scenario can be addressed not only by evasion solution, but also by the course correction solution, i.e., the blunderer takes action to correct its course and return to the designated approach course. Similarly, we took final approach speed (the speed range is shown in Table.1) as the simulation parameter, set the ACD at 160 m, but changed evasion solution to the course correction solution. Figure 5 and Figure 6 show the collision risk effect among the same category combinations by parallel runway spacing with the speed set at the upper and lower limit, respectively.

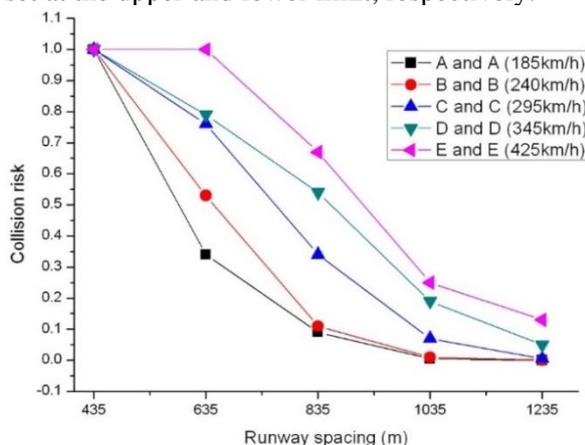


Figure 5. Collision risk and runway spacing (upper limit speed and course correction solution)

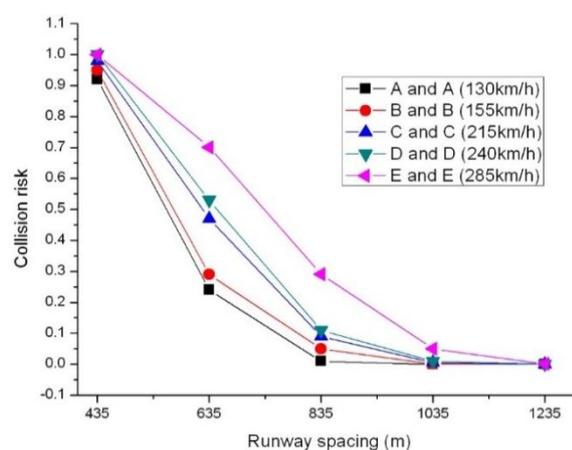


Figure 6. Collision risk and runway spacing (lower limit speed and course correction solution)

On condition of the course correction solution, Figure 5 shows the collision risk effect among the same category combinations by parallel runway spacing with the final approach speed set at the upper

limit. As we can see from the plots, as the runway spacing increases, the collision risk of each aircraft combinations decreases. Compared with Figure 3 (the evasion solution), when the runway spacing is 1035 m and 1235m, only the collision risks of A-A combinations and B-B combinations stabilize at the minimum value, whereas the collision risk of D-D combinations and E-E combinations remains relatively high. Other than that, with the 835 m runway spacing, only the collision risks of A-A combinations and B-B combinations are similar, and the collision risks of C-C, D-D and E-E combinations in Figure 3 are much lower than that in Figure 5. And with the 1035 m runway spacing, the similar results are got. Therefore, we can come to a conclusion that with the same runway spacing, for A-A and B-B combinations, both the evasion and the course correction solution have low collision risks; for C-C, D-D and E-E combinations, adopting the course correction solution can lead to higher collision risks than adopting the evasion solution.

So all in all, on condition of runway spacing ranging from 835 m to 1235 m, if the approach speed is above 240 km/h, the best way to recover from the hazardous scenario is the evasion solution; if the approach speed is below 240 km/h, the course correction solution is recommended, which is because the evasion solution would compromise the original approach process and needs a second-time approach, probably causing flight delay.

On condition of the course correction solution, Figure 6 shows the collision risk effect among the same category combinations by parallel runway spacing with the approach speed set at the lower limit. As we can see from the plots, as the runway spacing increases, the collision risk of each aircraft combinations decreases. When the runway spacing is 835 m, only E-E combinations has a relatively high collision risk. When the runway spacing is set at 1035 m and 1235 m, the collision risks of all combinations stabilize at the minimum value.

In summary, with the runway spacing of 435 m and 635 m, both solutions to the hazardous scenario have relatively high collision risks. When the runway spacing is 835 m, 1035 m and 1235 m, and the approach speed is less than 240 km/h, on matter which solution we adopt (the evasion solution or course correction solution), the collision risk corresponding to each runway spacing is relatively low. If the approach speed is more than 240 km/h, the collision risk of evasion solution is much lower than that of the course correction solution. In general, the evasion solution is superior to the course correction solution. As for A-A and B-B combinations, when the runway spacing is 835 m, either solution proves to have a relatively low collision risk.

3.2 Aircraft combinations of different categories

According to the above analysis, the evasion solution proves to be superior, therefore we decide to adopt evasion solution in our research on aircraft combinations of different categories. And since there are many possible combinations, here we only focus on representative case as follows: the collision risk effect among A-E combinations (the largest difference of approach speed) by parallel runway spacing when evasion solution is adopted.

Figure 7 shows the collision risk effect among A-E combinations by parallel runway spacing when evasion solution is adopted. In this context, we subdivide the A-E combinations into the A^b-E^e combinations and the A^e-E^b combinations: the first combinations consider the aircraft of category E as the evader; the second combinations considers the aircraft of category A as the evader.

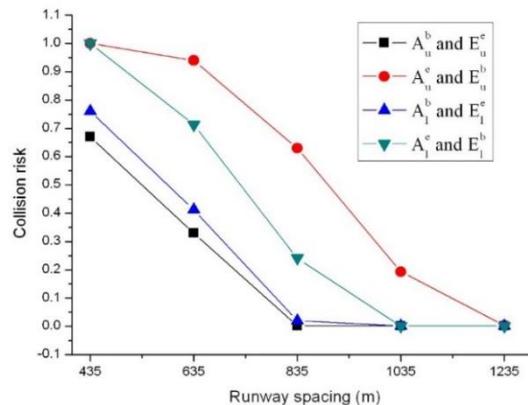


Figure 7. Collision risk and runway spacing (A-E combinations).

In Figure 7, A_u^b is taken as an example, A represents the category of the aircraft, u represents the upper limit of the approach speed, b represents that the aircraft is considered as the blunderer. As for A_l^e , l represents the lower limit of the approach speed, e represents that the aircraft is considered as the evader.

The plots indicate that as the runway spacing increases, the collision risk of each combinations decreases. When the runway spacing is 835 m, the collision risks of $A_u^b-E_u^e$, $A_l^b-E_l^e$ combinations first stabilize at the minimum value. When the runway spacing is 1035 m and 1235 m, the collision risks of all combinations except $A_u^e-E_u^b$ combinations stabilize at the minimum value. Given that both $A_u^b-E_u^e$ and $A_l^b-E_l^e$ combinations consider the aircraft of category A as the blunderer, with a relatively low speed, the blunderer of category A will take a relatively long time to penetrate the NTZ. And the aircraft of category E, as the evader, has high approach speed, which means it will have enough time to take maneuver and avoid collision. In conclusion, whatever the approach speed value is, the upper limit or the lower limit, the collision risks of $A_u^b-E_u^e$ and $A_l^b-E_l^e$ combinations with 835 m runway spacing are relatively low. This is similar to the conclusion drawn by Steven Landry and Amy R Pritchett [13] in the research of the safe zone for paired closely spaced parallel approaches. On the contrary, when the aircraft of category E is considered as the blunderer, it will use less time to penetrate the NTZ due to its fast approach speed. While the aircraft of category A, considered as the evader, has rather low approach speed. As a result, before the evader could complete its evasion maneuver, the two aircraft will collide. Even with the 1035 m runway spacing, the collision risk of $A_u^e-E_u^b$ combinations is relatively high.

4. Conclusion

This paper mainly explored the possibility of reducing the safety spacing of parallel runways to satisfy the needs of different aircraft combinations. On this very note, the configuration of parallel runways designed for different aircraft combinations can be more scientific and reasonable. We have made two innovative improvements to the established simulation model (the PLB model), a tool for analysing the parallel runway requirement. Firstly, given that there is only one solution (the evasion solution) in the PLB model to avoid collision in the hazardous scenario, a new solution (i.e., the course correction solution) was introduced in the hazardous scenario. Secondly, we revised the simulated evasion maneuver command according to the operational advice from Doc. 8168 of ICAO. Based on the aircraft categories of the ICAO regulations, the improved blunder simulation model was applied to the different aircraft combinations. Then the collision risk effect among different aircraft combinations by parallel runway spacing is analysed. According to the simulation results, the main conclusions are listed as follows:

1. When the blunderer belongs to category E (the maximum approach speed is 425 km/h) and the evader belongs to category A (the maximum approach speed is 185 km/h), even with the 1035 m spacing runway, the approaches will face a relatively high collision risk. Hence, on condition of $A_u^e-E_u^b$ combinations, the runway spacing should be increased.

2. When the parallel runway spacing is 435 m or 635 m, the current two solutions (i.e. the course correction solution and the evasion solution) to the hazardous scenario both have relatively high collision risks.

3. When the runway spacing is more than 835 m and the approach speed is above 240 km/h, the

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