Risk Assessment of Separation Between Runway and Taxiway Not Meeting Standard During Take-off

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Abstract. In view of the fact that the separation between runway and taxiway of the flying area can't meet the standard separation and the risk of aircraft operation, this paper analyses factors causing aircraft veer off the ground in taking off and uses entropy of information to select 15 factors in the 25 factors combines with the multiple Logistic regression method to set up the accident frequency deviation model. On this basis, combining with accident event model which is based on the history data of the plane veer off the runway, the risk model of the taking off stage is established when separation does not meet the standard requirements of the running slip distance. By running the risk model, this article takes the airport as an example to analyse the collision risk of sliding on the ground in taking off under the existing conditions and put forward the operation method of determining the separation between runway and taxiway and the operation constraints when the separation can't meet the standards, providing a theoretical basis for determining runway operation conditions and designing the separation between runway and taxiway.

1. Introduction

The distance between the runway and taxiways is that between the centerline of the runway and the centerline of the parallel taxiway in the flight area. To ensure the safety of the aircraft running on the runway, there are clear requirements for the distance between runway and taxiway, such as the 4D airport is not less than 176m [1]. With the development of air transport industry, especially the expanding use of civil and military airports, the original standard has not been adapted to modern application needs. Research on such aspect is few, but the determination of the distance between runway and runway is of great significance for reference. Whether the aircraft can operate at such an airport or not, if operating, how risky is the collision with the plane on the taxiway, there is no relevant research in domestic. Nowadays, domestic research on aircraft collision risk assessment and safety distance design is mainly focused on the flight area, including REICH model [2], EVENT model [3]. Document [4] reviewed the different methods of safety assessment for flight intervals. On the aspect of ground safety interval, Wang Yong researches the effects of the slant range and approach glide angles of paired aircrafts and aircraft type combination on runway separation under the dependent parallel approach mode of closely spaced parallel runways [5]. SUN analyze the collision risk under the circumstance of dodge and no-dodge, and determine the safety distance of closely spaced parallel runways on basis of Monte Carlo method [6].

Taking the take-off status of aircraft as the main research object, this paper aims to establish a risk analysis model for collision between runway take-off aircraft and taxiway running aircraft, so as to provide a new method for determining the safety distance between runway and taxiway and restrictive conditions for take-off.

2. The collision risk model during the aircraft take off process

2.1 Analysis of factors affecting take-off deviation

Before takeoff, when running along runway / taxiway, the aircraft may deviate from the centerline of runway or taxiway due to weather, operation and other factors, creating potential risk and injure. In order to ensure the safety of take-off and determine the safety interval, the factors affecting should be analyzed first. In this aspect, different views are adopted at home and abroad, and different literatures show different research angles. In this paper, the risk factors which affect the deviation during ground operation before take-off are classified into 25 factors, based on case analysis and literature review, they are x_1 Temperature (<5) (℃), x_2 Temperature (5~20) (℃), x_3 Temperature (>20) (℃), x_4 Rain (0/1), x_5 Snow (0/1), x_6 Wind (0/1), x_7 Fog (0/1), x_8 Crosswind Speed (Knot), x_9 Tailwind Speed (Knot), x_{10} Frozen Precipitation (0/1), x_{11} Altitude (Km), x_{12} Visibility (Km), x_{13} Aircraft Class (1~5), x_{14} Aircraft Braking System (0/1), x_{15} Flat Tire (0/1), x_{16} Engine Failure (0/1), x_{17} Front Wheel Turn Blocking (0/1), x_{18} Pilot Level (1~4), x_{19} Unreasonable Flight Procedure (0/1), x_{20} Unsuitable Command of Air Traffic Controllers (0/1), x_{21} Failure of Unit Resource Management (0/1), x_{22} Violation of Standard Operating Procedures (0/1), x_{23} Icing Conditions (0/1), x_{24} Log Criticality Factor>0 (0/1), x_{25} No Runway Center Line Light (0/1).

Where, aircraft type, 1 represents small aircraft， 2 represents midsize aircraft， 3 represents jumbo jet, 4 represents large commuter flight, 5 represents heavy jet aircraft. The driver level rises with the increase of number. 0 means no, 1 means yes.

Considering the fact that there many factors that deviate the aircraft during its take off process, in order to quantify the importance and uncertainties of each factor, this paper firstly adopted the information entropy to select the factors that may deviate the aircraft during its sliding process. Secondly, based on data history, after the elimination of relevant variables, multiple backward stepwise logistic regression was conducted, and the regression coefficient of each factors were fitted after the calculation.

2.2 The initial selection process of influence factors based on information entropy

The main idea of information theory pointed out that the uncertainty of the system is in positive correlation with the value of entropy. Therefore, when judging the deviation process of an aircraft, the bigger difference in entropy an introduced factor can make, the better it can predict the deviation process. Based on the idea above, this paper adopted the factor selection method based on the dependent entropy variables. The specific progress is shown below:

Suppose the event Y represents weather a deviation happen s when the plane takes off, Y=1 means the deviation happens, Y=0 means the deviation is avoided. $X = (x_1, x_2, \ldots, x_{24})$ represents all the factors that affect the deviation, whose meaning is shown in table 1. Then the entropy of Y can be defined as follows:

$$M(\mathrm{Y}) = -(p_1 \log p_1 + p_2 \log p_2) \tag{1}$$

Where p_1, p_2 represent the ratio of Y=0 and Y=1 in all take-off operations respectively. For each x_i, select a partition point m, dividing all take-off operations into two groups based on $x_i > m$ and $x_i \le m$, the entropy of each group is

$$M_{\mathrm{j}}(\mathrm{Y}) = -(p_{1\mathrm{j}} \log p_{1\mathrm{j}} + p_{2\mathrm{j}} \log p_{2\mathrm{j}}) \tag{2}$$

Where $p_{1\mathrm{j}}$ and $p_{2\mathrm{j}}$ represents the ratio of Y=0 and Y=1 in each group and $\mathrm{j} = 1, 2$.

Combine (1) and (2), we know, when x_i is applied, the entropy change of Y is

$$\Delta M(\mathrm{Y}) = M(\mathrm{Y}) - \left[l_1 M_1(\mathrm{Y}) + l_2 M_2(\mathrm{Y}) \right] \quad (3)$$

In which, l_1 and l_2 represents the weight of each group according to sample size after dividing. For x_i, diffident $\Delta M(\mathrm{Y})$ can be obtained if m is changed, when $\Delta M(\mathrm{Y})$ maximizes, m is the optimal segmentation point. $\mathrm{MAX}(\Delta M(\mathrm{Y}))$ of each factor is sorted, the larger ones are reserved, and the reserved factors is analyzed using logistic regression model.

In this paper, 25 factors concerning the deviation are analyzed using information entropy method, the calculation results $|\Delta \mathrm{I}(\mathrm{Y})|$ from x_1 to x_{25} are shown in Table 1.

Table 1. Collision factors and their entropy.

Variable Code	|ΔI(Y)|	Ranking	Variable Code	|ΔI(Y)|	Ranking	Variable Code	|ΔI(Y)|	Ranking
x_1	0.1721	7	x_{10}	0.0534	15	x_{19}	--	--
x_2	0.1004	11	x_{11}	0.0209	19	x_{20}	--	--
x_3	0.1001	12	x_{12}	0.2531	5	x_{21}	--	--
x_4	0.0826	14	x_{13}	0.1233	10	x_{22}	0.0233	17
x_5	0.0923	13	x_{14}	0.0166	21	x_{23}	0.1822	6
x_6	0.0223	18	x_{15}	--	--	x_{24}	0.3482	1
x_7	0.1420	8	x_{16}	0.3263	2	x_{25}	0.0398	16
x_8	0.2533	4	x_{17}	0.0185	20			
x_9	0.2689	3	x_{18}	0.1408	9			

From the results, 21 factors have a certain impact on the occurrence of deviation, but there exists big difference in their influence. Taking the entropy change 0.05 as the standard, 15 factors are picked as the main factors for logistic regression, including temperature (<5, 5~20, >20), rain, snow, fog, crosswind speed, tailwind speed, freezing precipitation, visibility, aircraft type, engine failure, pilot level, icing condition and critical factor logarithm (the ratio between the required runway length and the available runway length).

2.3 The logistic regression frequency model of aircraft deviation during the take-off process

This paper established the frequency model of aircraft deviation during the take-off process on the basis of Logistic regression. However, as has been stated in section 2.1, there are so many factors to influence the deviation process that each dependent variable may result in multiple collinear problem. Therefore, this paper brought up an improved method as follows: firstly, the relevant variables are eliminated via the Pearson's relevant variable method. Secondly, the incident frequency was modeled through the Logistic regression. Finally, insignificant variables are excluded through the multiple backward stepwise logistic regression and the regression index of each factors are updated. Therefore, the quantified frequency model of aircraft deviation during the take-off process is established.

2.3.1 The mechanism analysis of Logistic regression model

The probability of deviation incidents is a nonlinear function consisted of a series of explanatory variables, which can be described as follows:

$$P(y=1) = \frac{\exp(\alpha + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n)}{1 + \exp(\alpha + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n)} \quad (4)$$

Where, dependent variable P represents the probability of a plane deviating from the center-line of a runway or a taxiway, x_1, x_2, x_3, …, x_n are independent variables, representing the factors affecting the deviation, α, β_1, β_2, …, β_n are logistic regression coefficients.

Apply the logarithmic transformation into (4), and the nonlinear model is transformed into a linear model, and a logistic regression model can be obtained as follows

$$\ln(\frac{P}{1-P}) = \alpha + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n \quad (5)$$

2.3.2 The test of correlation

Since the chosen factors in section 2.1 possess the interconnection multiple collinear problem with each other, which present great influence on the accuracy of the model, the Pearson relevance index r was calculated to eliminate relevant variables, as is shown in equation 6:

$$r = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{x_i - \bar{x}}{s_x}\right)\left(\frac{y_i - \bar{y}}{s_y}\right) \quad (6)$$

Where, n is the sample number, x, y is the influence factors under correlation test, $\bar{x}$, $\bar{y}$ is the average value of the factor, s_x, s_y is the variance.

After calculation, we know, the correlation between visibility and fog is 0.723, considering entropy change sorting, the factor fog is eliminated. The multivariable correlation of the remaining 14 factors is tested using tolerance index, the result is shown in figure 1. In the figure TOL means the tolerance value, R represents the re-determination coefficient of the regression when each index is the dependent variable relative to other indexes.

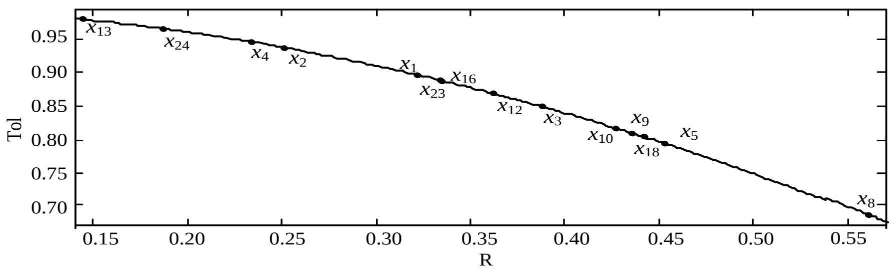

Fig 1. Chart of Correlation test based on tolerance

From Figure 2, the tolerance of each factor is higher than 0.5, we can consider the multivariate collinearity of the remaining 14 factors is weak and all 14 factors reserved can be applied in logistic model.

The regression model is used to fit the historical data, and the regression coefficient of each factor is determined as (7).

$$P(y=1) = \frac{\exp(-9.066 - 0.514x_1 + 0.543x_2 - 0.284x_3 + 1.24x_4 + 1.130x_5 + 0.121x_8 + 0.381x_9 - 0.103x_{10} - 3.848x_{12})}{1 + \exp(-9.066 - 0.514x_1 + 0.543x_2 - 0.284x_3 + 1.24x_4 + 1.130x_5 + 0.121x_8 + 0.381x_9 - 0.103x_{10} - 3.848x_{12})} \quad (7)$$

2.3.3 The test of significance

After the elimination process of relevant variables, the Wald's test method was adopted to check the significance in regression index of each influence factor and their final frequency model was determined. In the calculation process, if the significant level of the variable is greater than 0.05 and is the highest, the factor is eliminated. Repeat this step, until all the independent variables meet the set level 0.05. After 3 steps, two factors freezing precipitation and temperature (5~20 C) are removed, and the final model retained 12 variables. The test results are shown in Table 2.

In final test, the Wald test results of all the influencing factors are significant, which proves that the 12 factors are closely related to the occurrence of the deviations.

Apply the 12 factors into the model, and the event frequency model can be obtained as follows:

$$\ln\frac{P}{1-P} = -9.078 - 0.155x_1 - 0.286x_3 + 1.27x_4 + 1.132x_5 + 0.124x_8 + 0.384x_9 - 3.849x_{12} + 1.594x_{13} - 3.517x_{16} - 5.684x_{18} + 2.673x_{23} - 4.309x_{24} \quad (8)$$

Convert the model into a nonlinear form:

$$P=\frac{1}{1+e^{-(-9.078-0.155x_1-0.286x_3+1.27x_4+1.132x_5+0.124x_8+0.384x_9-3.849x_{12}+1.594x_{13}-3.517x_{16}-5.684x_{18}+2.673x_{23}-4.309x_{24})}} \quad (9)$$

Table 2. Wald stepwise test results.

Variable	Coefficient	Standard Deviation	Wald	Freedom	Significant Level
x_1	-0.155	0.233	6.921	1	0.009
x_3	-0.286	0.436	5.008	1	0.020
x_4	1.270	0.307	8.749	1	0.003
x_5	1.132	0.258	9.543	1	0.002
x_8	0.124	0.687	5.079	1	0.024
x_9	0.384	0.434	6.963	1	0.008
x_{12}	-3.849	0.671	4.618	1	0.032
x_{13}	1.594	0.412	6.921	1	0.009
x_{16}	-3.517	0.509	5.218	1	0.022
x_{18}	-5.684	0.421	4.532	1	0.033
x_{23}	2.673	0.302	16.085	1	0.000
x_{24}	-4.309	0.409	21.903	1	0.000

2.4 A risk model for the collision of an aircraft running on a runway

2.4.1 The event location model

The event location model is mainly used to estimate the mathematical relationship between the deviations of the front wheel from the runway edge and the probability of accident under the condition of landing or take-off.

In this paper, a similar function formula for the event location model given in reference [7] is used for reference and combines the model coefficient given in reference [8], then determines the final model formula (10):

$$P\{\text{Location}>\text{y}\}=\text{e}^{-0.01639(y/0.3048)^{0.863461}} \quad (10)$$

Where, $P\{\text{Location}>\text{y}\}$ is the probability that the veer-off distance from the runway edge is greater than the specified distance y; y is a given location or distance from the runway edge, the unit is m.

2.4.2 The collision risk model

The probability of the estimation of the event location model is multiplied by the frequency of veer-off to obtain the final collision probability. See formula (11):

$$p=\frac{e^{-0.01639(y/0.3048)^{0.863461}}}{1+e^{-(-9.078-0.155x_1-0.286x_3+1.27x_4+1.132x_5+0.124x_8+0.384x_9-3.849x_{12}+1.594x_{13}-3.517x_{16}-5.684x_{18}+2.673x_{23}-4.309x_{24})}} \quad (11)$$

According to the formula (11), it is possible to quantify the probability of accident that veer-off distance from runway edge is larger than the specified distance, then get collision risk to provide basis for determining the distance between runway and taxiway.

3. Risk assessment of the distance between runway and taxiway in aircraft taking off stage

The risk assessment of separation between runway and taxiway refers to the assessment of whether the risk corresponding to the separation between runway and taxiway is in accordance with the prescribed safety target level.

3.1 Security target level establishment based on risk matrix method

In this paper, the risk matrix method is used to determine whether the accident risk reaches the level of safety goal, which is based on the possibility of accident and the seriousness of the accident. Referring to reference [8], the possibility of the occurrence of the accident is divided into frequent, probable, remote, extremely remote, and extremely improbable, the corresponding probability is greater than 1.0×10^{-3} , 1.0×10^{-3}~1.0×10^{-5} , 1.0×10^{-5}~1.0×10^{-7} , 1.0×10^{-7}~1.0×10^{-9} and less than 1.0×10^{-9} , as shown in Figure 2. The process of evaluating risk of separation between runway and taxiway before take-off is first to determine the severity of deviating from runway, then calculate the allowable possibility of deviation according to the risk matrix and compare with the final collision probability which is calculated by the risk matrix to judge whether the event risk can be accepted (low risk is accepted, medium risk needs to give measures which reduce the risk, high risk is not acceptable).

Severity / Likelihood	No Safety Effect	Minor	Major	Hazardous	Catastrophic
Frequent	Low Risk	Medium Risk	High Risk	High Risk	High Risk
Probable	Low Risk	Medium Risk	High Risk	High Risk	High Risk
Remote	Low Risk	Low Risk	Medium Risk	High Risk	High Risk
Extremely Remote	Low Risk	Low Risk	Low Risk	Medium Risk	High Risk
Extremely Improbable	Low Risk	Low Risk	Low Risk	Low Risk	Medium Risk

Fig 2. Chart of matrix of risk

3.2 Examples of risk analysis
Taking an airport for example, the risk assessment of the separation between the runway and taxiway when planes take off is carried out. The width of airport runway is 30m and of parallel taxiway is 15m, the airport operation type is large aircraft and the types of aircrafts operating on the runway / taxiway are same. The minimum wingtip separation is 31.120m and the separation between runway and taxiway is 64m. The airport is taken as an example to carry out a risk analysis of its existing spacing.

According to the operating conditions of the airport, the 12 influencing factors' values are determined according to the most unfavorable conditions: $x_1=-15$(the temperature is -15°C), $x_3=0$ (not within this temperature range), $x_4=1$(rain), $x_5=1$ (snow), $x_8=30$ (the wind speed of crosswind is 30 Knot), $x_9=5.8$ (the wind speed of tailwind is 5.8 Knot), $x_{12}=0.8$ (the visibility is 0.8 Km), $x_{13}=3$ (aircraft types are large aircraft), $x_{16}=1$(engine failure), $x_{18}=3$ (the pilot level is medium), $x_{23}=1$(freeze), $x_{24}=0$ (the length of the runway meets the needs of the aircraft operation and the logarithm of the critical factor is less than zero). Putting the center of the takeoff plane on the edge of the runway and the wingtip separation between planes running on the runway and taxiway is 15.880m. The values corresponding to the 12 factors and *WD* (calculating the probability of a location model beyond *WD*) both are plugged into the formula (11) to obtain the final collision probability which is $P=2.783\times10^{-7}$.

In this case, due to the lack of separation between runway and taxiway, the collision accidents occur frequently at the stage of take-off, causing serious damage to aircraft, ground facilities and serious injuries. Therefore, the severity of accidents is a potential danger. It is known from the risk matrix that the accident risk is high risk under the collision probability which is $P=2.783\times10^{-7}$. Therefore, in order to ensure the safety of the aircraft, the collision probability of the event needs to be less than 1.0×10^{-7}, at a moderate or low risk state.

3.3 Measures to control risk
According to the calculation model, risk reduction measures mainly include two aspects, one is to maintain the existing operating conditions to calculate the safe separation between runway and

taxiway; the other is to keep the existing separation, by limiting the flight conditions such as weather and changing the level of risk to ensure that the separation value meets the safety requirements.

3.3.1 The establishment of separation between runway and taxiway
Aimed at example of 3.2 portion, the corresponding values of 12 factors are plugged into the deviation frequency model to obtain the final deviation frequency value which is $P_1 = 4.578\times10^{-7}$.

Because the collision probability of the event needs less than 1.0×10^{-7}, it is necessary to use $1.0\times10^{-7}/P_1$ to obtain the estimation probability of the accident location model which is $P_2 = 0.128$ in the take-off stage of the aircraft, as indicated by the formula (11). The specified distance *y* of the runway deviation from the edge of the runway is calculated by the formula (10), and the *y* is 57.912 m.

Without changing the operating conditions of the airport, the final required separation between runway and taxiway before the take-off is the sum of the original separation value and the Y, so the value of required separation is 121.912 m. Therefore, it is necessary to increase the existing separation by 57.912 m.

3.3.2 Separation remains unchanged and values of factors to change risk
Aimed at example of 3.2 portion, the separation between runway and taxiway of 64 m is kept unchanged and the final collision probability is reduced to less than 1.0×10^{-7}. By adjusting the influence factors in the deviation frequency model, the final collision probability is reduced and the purpose of reducing the event risk is achieved.

According to the deviation frequency model, we can see that to reduce the estimated probability of the deviation frequency model, the sum of the 12 factors should be reduced until the final collision probability is reduced to less than 1.0×10^{-7}. We analyze the random combination of 12 factors in the deviation frequency model and select the typical combination as follows: $x_1 = -15$ (the temperature is -15°C), $x_3 = 0$ (not within this temperature range), $x_4 = 1$ (rain), $x_5 = 0$ (no snow), $x_8 = 30$ (the wind speed of crosswind is 30 Knot), $x_9 = 5.8$ (the wind speed of tailwind is 5.8 Knot), $x_{12} = 0.8$ (the visibility is 0.8 Km), $x_{13} = 3$ (aircraft types are large aircraft), $x_{16} = 1$ (engine failure), $x_{18} = 4$ (the pilot level is good), $x_{23} = 0$ (no possibility of icing on the road surface), $x_{24} = 0$ (the length of the runway meets the needs of the aircraft operation and the logarithm of the critical factor is less than zero). The values corresponding to the 12 factors are plugged into the deviation frequency model, calculating a new estimation probability of the deviation frequency model ,which is $p_3 = 3.464\times10^{-11}$.

The probability that $p_4 = 0.608$ is estimated by the accident location model. According to the formula (11), the final probability of collision risk is $p_5 = p_3 \times p_4 = 2.106\times10^{-11} < 1.0\times10^{-7} < 1.0\times10^{-9}$, so the level of risk is low and the result can be accepted. Thus, the operational conditions of aircraft can be determined.

4. Conclusions
In recent years, with the development of the air transport industry, the scale of the airport has been expanding and because of the limited terrain, the original small airport cannot expand the separation between runway and taxiway. This paper analyzes the factors affecting the deviation of the aircraft during take-off and based on information entropy and multivariate Logistic regression, a deviation frequency model is established, which is combined with accident location model based on aircraft deviation from the runway accident history data to establish the collision probability model that realizes the risk assessment of the existing separation between runway and taxiway and puts forward measures to reduce the risk. The research results of the paper can provide reference for the determination of runways' operational conditions and the formulation of the standard separation between runway and taxiway in the flight area.

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