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PROBABILISTIC MODEL FOR AIRPORT RUNWAY SAFETY AREAS

Summary. The Laboratory of Aviation Safety and Security at CTU in Prague has recently started a project aimed at runway protection zones. The probability of exceeding by a certain distance from the runway in common incident/accident scenarios (take-off/landing overrun/veer-off, landing undershoot) is being identified relative to the runway for any airport. As a result, the size and position of safety areas around runways are defined for the chosen probability.

The basis for probability calculation is a probabilistic model using statistics from more than 1400 real-world cases where jet airplanes have been involved over the last few decades. Other scientific studies have contributed to understanding the issue and supported the model's application to different conditions.

1. INTRODUCTION

Take-off and landing are the most critical phases of flight. Statistics show that between years 1959 and 2012 57% of all accidents happened in these two phases, and 41% belong to the final approach and landing alone, as can be seen in Fig. 1 [1]. However, this study does not deal with the whole 57%, but only with events that happen in close proximity to the runway (RWY) during take-off and landing.

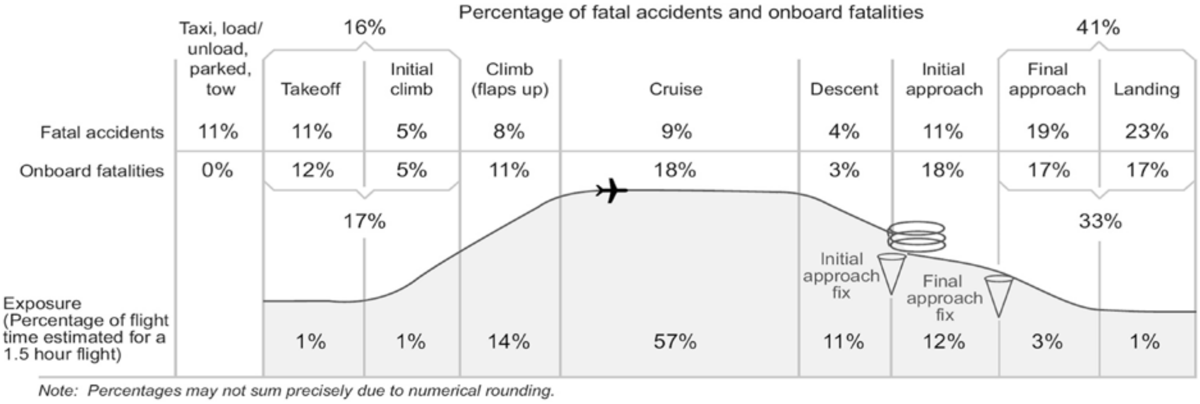

Fig. 1. Statistical summary of commercial jet airplane accidents, Worldwide operations 1959 – 2012 [1]

For the needs of emergency planning and airports infrastructure [2] growth, it is necessary to know areas around the runway where an airplane might end up in the event of a runway excursion or a landing undershoot. The goal of this study is to define these areas around RWY (their dimensions) of Czech airports depending on historical data and operation experiences. Five scenarios were identified: Take-off overrun, Take-off veer-off, Landing overrun, Landing veer-off and Landing undershoot.

2. SCENARIOS

The position of an airplane after it stops is defined by two distances. The first one is “x” – the distance of the nose wheels from the end of TODR/LDR (Take-off Distance Required/Landing Distance Required) or from the end of RWY. The second one is the distance “y” of the airplane’s nose wheel from the RWY’s centreline (extended centreline) or from the runway edge.

1. *Landing overrun* – is an excessive use of the runway after touch down, when an airplane stops at certain “x” distance beyond the LDR and “y” distance from the runway centreline.
2. *Landing undershoot* – in this case the first contact with the ground takes place before the runway threshold. Distances “x” and “y” of this first contact are reported. During normal operations airplanes touch down at various distances from the runway end, but due to the impossibility of modelling this fact, distance “x” is measured from the runway’s end.
3. *Take-off overrun* – has the same position determination as the Landing overrun, but LDR is replaced with TODR.
4. *Landing veer-off* – is an event when an airplane veers-off from the runway in the time between touch down and runway exiting, but does not exceed the length of the RWY. Distance “y” is measured from the runway edge.
5. *Take-off veer-off* – is similar to Landing veer-off.

It is obvious that the distance an airplane travels after going off-runway depends on the velocity at which it leaves the runway and on the characteristics of the Runway Strip and Runway End Safety Area (RESA). However, covering these factors is not a subject of this study, because it would require determining area dimensions separately for each airplane as well as its velocity. Therefore, it would be impossible to define the general dimensions of areas around runways that are the outcomes of the probabilistic model.

3. DEFINITION OF RELEVANT AREAS AROUND THE RWY

The International standard (ICAO Annex 14 [3]) addresses areas around the runway related to the scenarios described above. Their purpose is to prevent damage to the airplane and injury or death of people in the airplane. Nevertheless, operating consequences of the expansion of a runway system, and the fact that air transport needs to be environmentally responsible [4, 5], require determination of areas that would not only protect the airplane and the airport’s infrastructure but would also provide proper materials for land use and compatibility planning. For this reason, this study proposes to expand the areas defined above, so that they would reflect information and data obtained from accident and incident investigations.

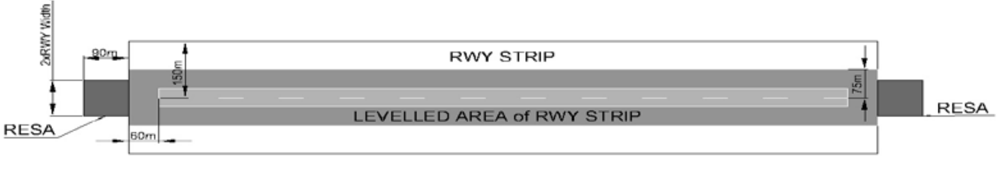

Fig. 2. Two areas defined by the international standards. They are the Runway strip and RESA. Dimensions of these areas in Fig. 2 are the minimums for airports with code number 3 and 4 set by the ICAO Annex 14. A full description of the Runway strip and RESA is in the ICAO Annex 14 [3] and in the ICAO Aerodrome Design Manual, Part 1 [6]

4. MATHEMATICAL MODEL

In order to define the size of areas around the runway where an airplane would end up in case of one of the five scenarios, a mathematical model is needed. For this purpose, data from the ACRP Report 50 [7] were utilized. It contains a database of accidents and incidents with the above-mentioned five scenarios. The data indicate that the probability of exceeding by a certain distance from the runway decreases with the increase of this distance, suggesting that the probability distribution is likely exponential. Wong, Pitfield, Caves and Appleyard confirmed this suggestion before [8].

The probability density function of this distribution is:

$$f(x) = \begin{cases} 0, & x < 0 \\ \lambda e^{-\lambda x}, & x \geq 0 \end{cases} \tag{1}$$

and its graph is shown in Fig. 3.

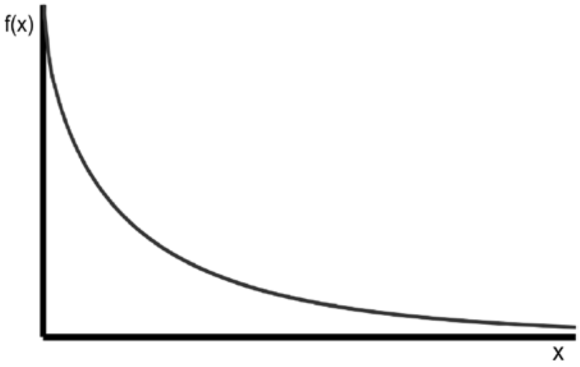

Fig. 3. Probability density function graph

This study used a modified formula that allows accurate determination of probability. The probability that the length of running off the runway will be greater than "x" is:

$$P(Location > x) = e^{-ax^{n}} \tag{2}$$

where a, n are coefficients.

The probability that the length of running off to the side of the RWY will be greater than “y” is:

$$P(Location > y) = e^{-by^{m}} \tag{3}$$

where b, m are coefficients.

An important note is the necessity of appointing feet instead of meters into these two formulas.

The values of the coefficients (Table 1) were adopted from a study modelling the location and consequences of aircraft accidents [9], which identified 1,414 incidents and accidents since 1980, from a database of more than 260,000 aviation incidents and accidents, and is therefore considered statistically significant. There is some bias introduced due to technology evolution over the last few decades, but in 1980 the level of automation and technology reached some maturity; thus, the final effect of the bias is unlikely to be significant. Take-off and landing overruns accounted for 44%, veer-off for 48% and landing undershoot only for 8%. Landing was linked to 83% of the events.

Table 1

Coefficients

Scenario	**Coefficients "a"**	**Coefficients "n"**	**R^2**
For distance "x"			
Landing overrun	0.00321	0.98494	0.998
Landing undershoot	0.01481	0.7515	0.987
Take-off overrun	0.00109	1.06764	0.992
	Coefficients "b"	**Coefficients "m"**	
For distance "y"			
Landing overrun	0.20983	0.4862	0.939
Landing undershoot	0.02159	0.7739	0.986
Landing veer-off	0.02568	0.80395	0.915
Take-off overrun	0.04282	0.65957	0.987
Take-off veer-off	0.01639	0.86346	0.942

Operational experience and statistical data showed that the probability of an airplane stopping within the currently defined ICAO areas is approximately 55%. This is not satisfactory and, as a result, we favoured dimensions that would assure much higher probability, namely 95%. It is a high enough value for the needs of prospective planning; the remaining odds of 5% are left for rare events and to account for statistical error. Obviously, 100% would be the most desirable from the safety point of view, but it could lead to unacceptable costs due to significant changes to existing infrastructure. For different scenarios, the size of new areas varies and to assure the same level of safety for all of them, the one putting the greatest dimensional requirements was chosen, specifically Take-off overruns area. Figure 4 shows the runway strip and RESA together with the proposed layout and dimensions of the area, which aims to increase the protection of airplanes, protect airport infrastructure and provide a basis for land use and compatibility planning.

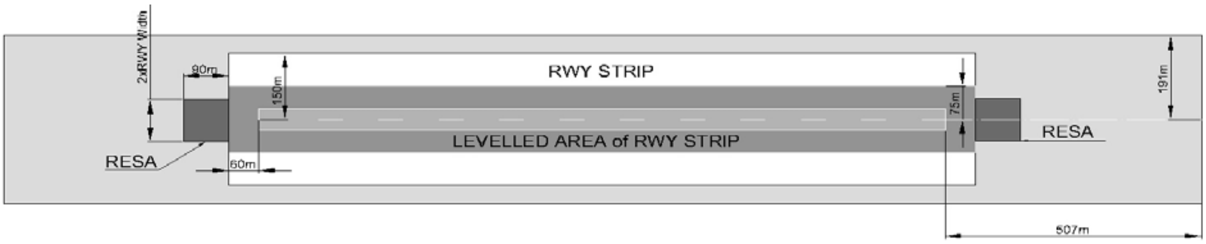

Fig. 4. Depiction of Runway, Runway strip and RESA + an area proposed by this study (light grey)

5. CORRECTION OF DIMENSIONS OF SAFETY AREAS FOR THE REMAINING RUNWAY LENGTH

Each plane has different operating characteristics and other airport infrastructure needs. Two of them are the Take-off Distance Required (TODR) and Landing Distance Required (LDR) already mentioned above. It does not make sense that two airports with similar operations and with different runway lengths (e.g. 2,000m and 4,000m) should have placed the proposed areas at the runway ends. If the airport has a runway longer than TODR and (or) LDR, then it can be argued that the aircraft has a longer safety area (LSA) remaining than just the RWY Strip and RESA (Fig. 5), which is for such a length as the length of the unused runway during take-off or landing. This idea was already addressed in Kirkland et al. [10] and Valdes et al. [11].

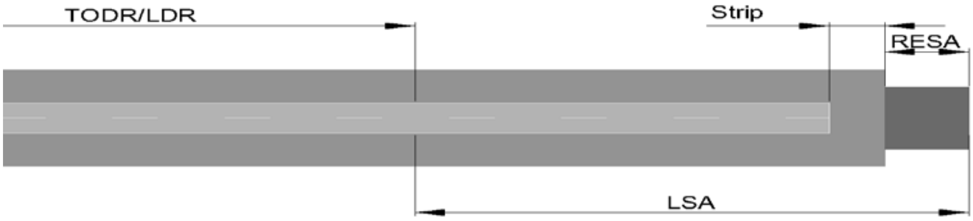

Fig. 5. LSA depiction

Another factor is the altitude of the airport, which increases the TODR and LDR. It is required that the declared distances were extended by 7% for every 300 meters of altitude. The same methodology can be applied to recalculate the lengths of TODR and LDR [5].

$$TODR = TODR_{SL} + \left(altitude \times \frac{0.07}{300}\right) \times TODR_{SL} \tag{4}$$

$$LDR = LDR_{SL} + \left(altitude \times \frac{0.07}{300}\right) \times LDR_{SL} \tag{5}$$

Formulas (4) and (5) are using units in meters. TODRSL and LDRSL are the Take-off Distance Required and Landing Distance Required at sea level at conditions corresponding with the International Standard Atmosphere (ISA).

It is not a goal of this article to provide extremely accurate dimensions of safety zones and therefore the correction for temperature and slope of runway is not used. Average temperature at Czech airports is not too different from the temperature of the ISA. Other influencing factors could be identified, but this article aims to present only the generalized size of safety areas.

6. PRESENTATION OF OUTCOMES

A probability of 0.95 was chosen to define the dimensions of proposed areas surrounding the runway. This means that 95% of the aircraft, which realize one of the above-mentioned five scenarios, will remain within these areas. As an example, in Table 2 are shown dimensions for Take-off overrun and Landing undershoot scenarios whose dimensions are the greatest. Using the aforementioned coefficients, the areas' dimensions are as follows:

Table 2

Dimensions

Distance "x":						
Landing undershoot	x =	1170.7	ft	=	356.8	m
Take-off overrun	x =	1664.2	ft	=	507.2	m

Distance "y" from RWY centerline:						
Landing undershoot	y =	586.3	ft	=	178.7	m
Take-off overrun	y =	626.7	ft	=	191.0	m

Probability density functions of these two scenarios are (Figs. 6, 7, 8 and 9):

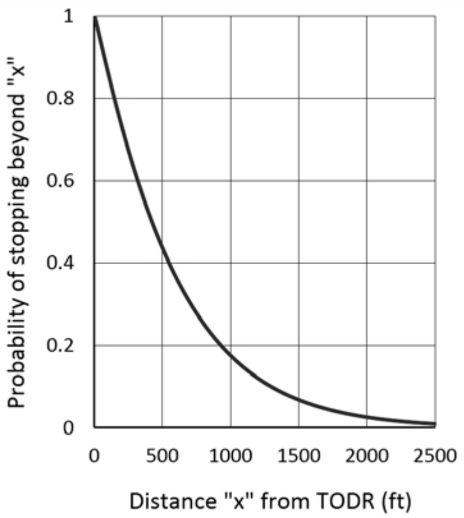

Fig. 6. Probability density function graph for Take-off overrun distance "x"

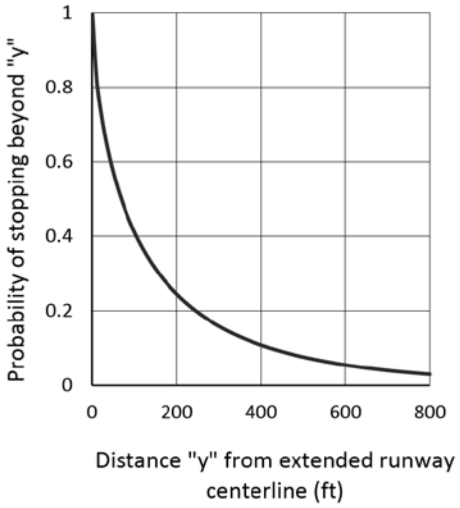

Fig. 7. Probability density function graph for Take-off overrun distance "y"

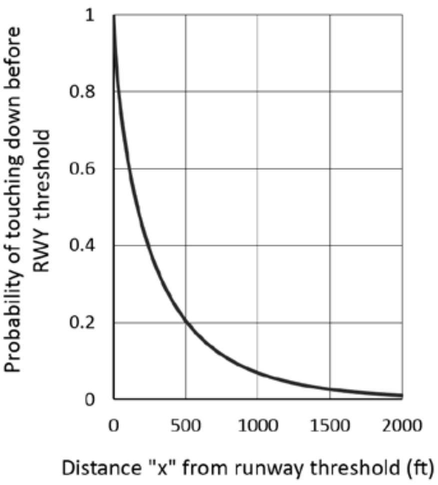

Fig. 8. Probability density function graph for Landing undershoot distance "x"

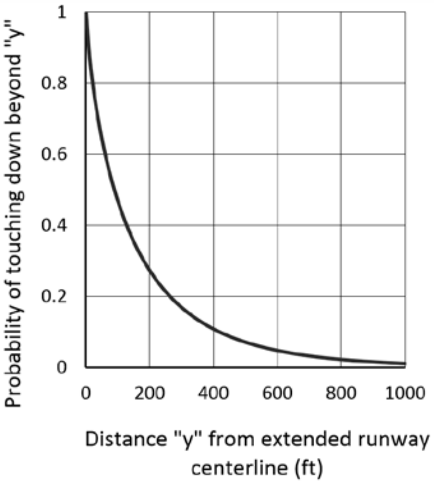

Fig. 9. Probability density function graph for Landing undershoot distance "y"

The figures demonstrate functions for lateral and longitudinal distances "x" and "y" travelled from the runway threshold and extended runway centreline, respectively, for all aircraft comprising the selected data sample. The dimensions from Tab. 2 were obtained as equivalent to 5% probability, i.e., only 5% of cases ended up with an aircraft travelling a larger distance when undershooting or overrunning a runway. To show the use of this paper in the real world environment, the runway at the Leos Janacek Ostrava Airport was chosen as an example. Boeing 747-400 and 777-300ER were chosen, because their TODR are challenging for Ostrava airport's 3,500m long runway. Table 3 shows the values of TODR of these aircraft in terms of the ISA and then corrected for elevation, which is 257 meters.

Table 3

TODR$_{SL}$ and TODR for Boeing 777-300ER [13]
and 747-400 [14]

	TODR$_{SL}$ [m]	TODR [m]
Boeing 777-300ER	3215	3408
Boeing 747-400	3320	3519

The following figures (Figs. 10 and 11) demonstrate the layout of the Take-off overrun and Landing undershoot areas at both runway ends at the Leos Janacek Ostrava Airport. The areas were constructed as generic (averaged) in dimensions due to data sample, which used all aircraft types to compute the probability density functions for these scenarios. They were then adjusted in their position on the runway because different aircraft have different performances, as already mentioned in chapter 5. For instance, ATR 72 is unlikely to ever overrun a runway longer than 3 000 meters under normal conditions if it commences take-off using the entire runway length. The heavier the aircraft, the more runway length is needed and the farther will the computed zones be placed. In extreme cases, the runway may be shorter than the aircraft needs when fully loaded (normally addressed by reducing the load to fit the take-off run to the runway length) and in those cases the zones are simply placed at the end of the runway.

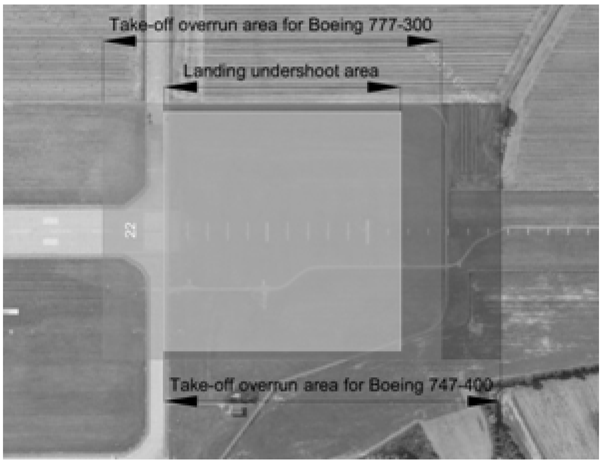

Fig. 10. Proposed safety areas for Boeing 777-300ER and 747-400 at Ostrava airport, RWY 22

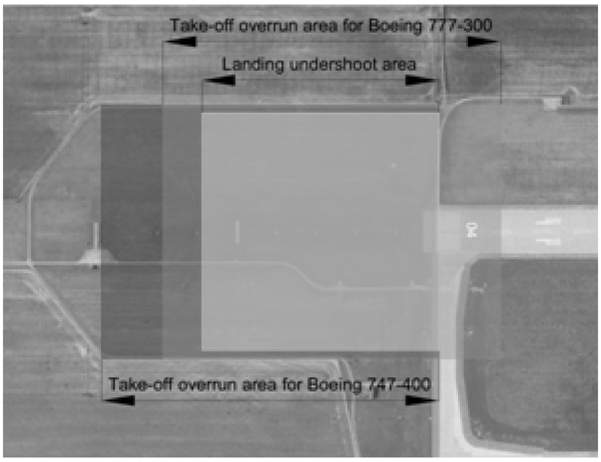

Fig. 11. Proposed safety areas for Boeing 777-300ER and 747-400 at Ostrava airport, RWY 04

With this logic, the take-off overrun area for the Boeing 777-300ER at Ostrava airport begins before the end of the runway, because the TODR of this airplane in the conditions of Ostrava airport is 3408 meters, which is a shorter distance than the runway length (3 500m). TODR for type 747-400 is greater than the length of the runway and therefore its area begins at the end of the runway.

7. CONCLUSION

With regard to experience, the ICAO standards can be considered satisfactory for the current situation, but in the scope of airport expansion it is desirable to consider larger safety areas than only those defined by regulations.

Emergency planning, airport infrastructure expansion planning and land use and compatibility planning require defining areas in close proximity to the runway, which are exposed to an increased risk for accidents. The United Kingdom Civil Aviation Authority determines zones in order to protect people around the airport, so called Public Safety Zones. They ensure safety by restricting the residence and workplace of people there. According to Evans et al. [14] the basic proposed dimension is 300 meters from the runway end in the direction of the extended centreline. It is the area that requires the strictest supervision. This area is also sufficient for containing 90% of Take-off overrun, Landing Overrun and Landing Undershoot cases.

Grant No. VG20132015130 of the Ministry of the Interior of the Czech Republic Laboratory of Aviation Safety and Security at CTU in Prague deals with the current needs of airports in the Czech Republic that have a potential for growth. This study offers the general size of safety areas around the RWY for possible future needs based on operational data. Interactive maps defining these areas will be published at the end of the year. This outcome will be one of the important arguments in planning the new parallel runway 24L/06R at the Vaclav Havel Airport Prague. Possible future research may lead to the application of advanced methodologies that enable the study of basic contributing factors and behavioural patterns [15] [16] present in scenarios such as runway excursion or landing undershoot discussed in this paper.

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