IMPACT OF WAKE TURBULENCE ON DETERMINING RUNWAY CAPACITY

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This article deals with one part of the problem with air traffic control capacity i.e.runway capacity. It is based primarily on the separations required, depending on the category of aircraft, resulting wake turbulence and its negative effects on the aircraft behind it. Based on these parameters, mathematically described is formulation for traffic delays during arrivals, departures or mixed traffic.

K e y w o r d s: separations, wake turbulence, capacity, Dual Threshold Operations, High Approach Landing System

1 INTRODUCTION

In 1960, the FAA in cooperation with the Airborne Instrument Laboratory has developed models to estimate runway capacity. These models worked with the idea of steady states of Queuing theory. In principle, two models have been developed, one for the runway designed only for the arrivals or only for departures and the second one for mixed traffic. The runway model used exclusively for arrivals or departures was simple (Poisson model), the sense of which was to handle aircrafts according to first-come first-served basis. Demand on arrivals and a departure was defined as the Poisson distribution with established average rate for arrivals and departures. Operation on the runway was intended as a general distribution of operating time by operating time and standard deviation. The process of operation is more complicated for the runway with mixed traffic, where runways are used both for arrivals and also for departures that is why model with distribution of arrivals was developed as aprevention. In this model, when the same runway is used for departures and arrivals, arrivals have precedence over departures. Operation process for departures supposes to use Poisson distribution even if the process deals with problem of shifting on the end of runway and it is not in accordance with the Poisson distribution. It is more than a Queuing theory output.

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2 SEPARATIONS BETWEEN THE AIRCRAFTS ON APPROACH

Wake turbulence is the biggest obstacle in the implementation of reduction in separation. It is a kind of mechanical turbulence, the intensity of which depends on the weight of the aircraft. The primary issues are the whirls formed at the ends of the wings that are strong enough to flip the aircraft. The current separation is made for the worst-case scenario. This is restricting the runway capacity even in most of the cases it is not the worst-case scenario, changes in separations are not approved. Air traffic controllers have a tendency to expand separations, which lead to the reduction in runway capacity. Studies have demonstrated that almost 20 percent of the runways are not used because of using incorrect separation. [1]

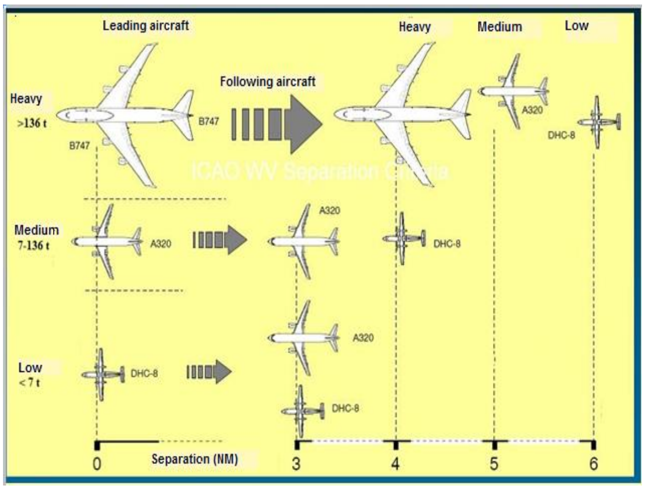

Fig. 1 Separation between aircrafts [6]

Solutions of studies about this problem are predicting changes in wind direction and speed, using ground and airborne radars and laser real-time analysis and display. By studying wind, one can predict the degree of turbulence dispersion. Experiments with laser system (LIDAR) allows us to analyze the swirls and turbulence in real time and develop a model which can be used by pilots and air traffic controllers for warning when wake turbulence is exceeding the safety limit. A new concept for short-term control of turbulence is a program called Wake Protection Zone. This concept creates space around the aircraft where the aircraft must stay on final approach. Air traffic controller and pilot know where exactly the aircraft is located in this area and when next aircraft can be allowed to follow it. The aircraft, which left the area, must repeat the approach procedures. Frankfurt Airport is testing and also implementing a method with displacing a runway threshold on one of the parallel runways, where light aircrafts can land on the higher glide- slope than the heavy aircrafts on the second runway, avoiding the problem with whirls caused by heavy aircraft (Fig. 2). These procedures are called High Approach Landing System (HALS) and Dual Threshold Operations (DTOP). [2]

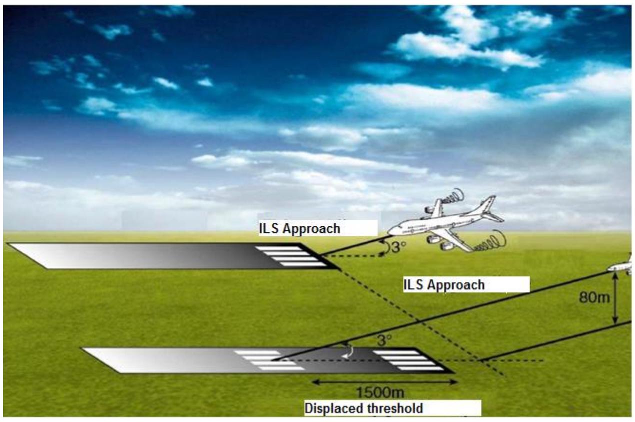

Fig. 2 Displaced runway threshold [6]

The procedures above can also be presented as viewed from horizontal point of separation see Fig. 3.

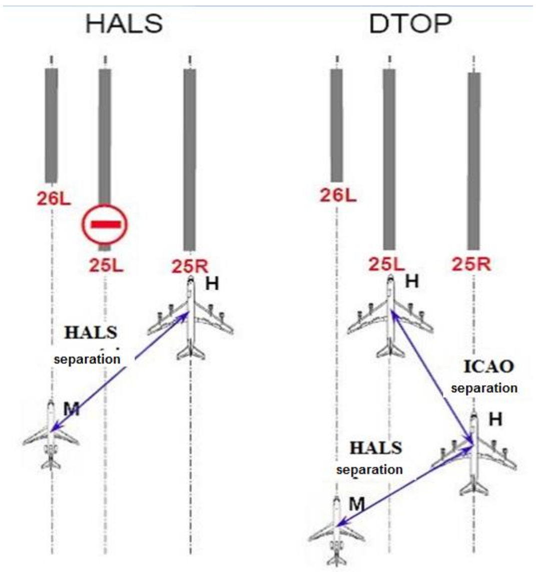

Fig. 3 HALS and DTOP separation [6]

These procedures can be used at the airports with parallel runways, but also at airports, where there is a high percentage of regional flights, what allows tthe use of the shorter runway only for arrivals. Current and future programs dealing with turbulence include separation between aircrafts depending on the weather (Weather-Dependent Aircraft Separation), Air Traffic Control (ATC), the time separation (Time-Based Separation), departure separation dependent on crosswind (Crosswind-Reduced Separations for Departure). The final solution to the relations between the various parts of the programs can lead to the reduction of the distance between aircraft.

Reducing separation below one mile between consecutive aircrafts or indented configuration can increase runway capacity by 20%. Research and development in reduction and control of wake turbulence has a high benefit to increasing runway capacity.

3 MATHEMATICAL FORMULATIONS OF DELAYS

Calculation of delay for runway used only for arrivals:

$$W_a = \frac{\lambda_a(\sigma_a^2 + 1/\mu_a^2)}{2(1-\lambda_a/\mu_a)} \qquad (1)$$

W_a - average delay of arriving aircraft
λ_a - average intensity of arrivals
μ_a - average level of services for arrivals or equivalent time of service
σ_a - standard deviation

Average time of service is understood as the runway occupation time (ROT) or time-based separation in the air directly related to the threshold, depending on which value is higher.

The departure model is identical to the one for the arrival, but there is the difference in labelling:

$$W_d = \frac{\lambda_d(\sigma_d^2 + 1/\mu_d^2)}{2(1-\lambda_d/\mu_d)} \qquad (2)$$

W_d - average delay of departing aircraft
λ_d - average intensity of departures
μ_d - average level of services for departures or equivalent time of service
σ_d - standard deviation of average time of service for departures

Arrivals enjoy priority over departures in mixed traffic and delays are calculated as the arriving traffic.The average time of delays is calculated with the formula:

$$W_d = \frac{\lambda_d(\sigma_j^2 + j^2)}{2(1-\lambda_d^j)} + \frac{g(\sigma_f^2 + f^2)}{2(1-\lambda_a^f)} \qquad (3)$$

W_d - average delay of departing aircraft
λ_a - average intensity of arrivals
λ_d - average intensity of departures
j - average time range between 2 consecutive departures
σ_j - standard deviation of time range between 2 consecutive departures
g - average degree at which the difference between consecutive arrivals occurs
f - average mean time range during which no departure traffice can be realized
σ_f - standard deviation of time range during which no arrival traffic can be realized.

During periods of heavy traffic, we can expect zero result in calculation of delays of departures when the aircraft are holding at the end of the runway, ready for departure and cleared for take off. It should be noted that these equations are valid when the intensity of arrivals and departures is lower than the speed of service, which is a condition for derived equations. Use of these models in practice been illustrated by following example.

The calculation of delay for runway system used only for arrivals, where the average value of service is 60 seconds for each aircraft with standard deviation 12 second and the intensity of arrivals 45 aircrafts per hour. The level of services for arrivals is equal to 1 minute on each aircraft, meaning 60 aircrafts per hour.

$$W_a = \frac{45\left[\left(12/3600\right)^2 + 1/60^2\right]}{2\left(1 - 45/60\right)} = 0.026\,\mathrm{h} = 1.6\,\mathrm{min} \qquad (4)$$

It is the reason why the average delay of arriving aircraft is 1.6 minute.

The relationship between the capacity and delay can be determined by the speed of operation, which is in accordance with the 4 minutes delay using equation mentioned above. Let us suppose that the standard deviation is the same then we get:

$$\frac{4}{60} = \frac{45\left[\left(12/3600\right)^2 + 1/\mu_a^2\right]}{2(1 - 45/\mu_a)} \qquad (5)$$

or μa is equal to 52 arrivals per hour. If the criterion for the delay was maximum 4 minutes, it means that the capacity of runway is determined by the the delay of 52 landings per hour.

To increase runway capacity by 15%, or from 52 to 60 arrivals, delays must be reduceed by 40%, i.e. 2.4 minutes. The procedure is typical at the airports that are close to their capacity saturation. Small increase in runway capacity leads to a significant decrease of delays.

4 FORMULATION OF RUNWAY CAPACITY BY TIME- SPACED CONCEPT

Time-spaced concepts are very useful utilities to understand the order of operations on the runway and the surrounding airspace. The basic rules for determining the order of aircraft operation are:

- Two aircraft cannot use the same runway at the same time
- Arriving aircraft have priority over the departing one when they use the same runway
- Departures may be cleared for take off only if the next arrival is far enough from the runway threshold.

Time-space diagram for the three arrivals and three departures (Fig 4) shows us that the average interval of departures *j* is the average times between consecutive departures *Jpq* a *Jqr*. Also the average time range between the arrivals, the difference (gap) between the arrivals *Ig*, where the departures *g* can be done, is the average of the amount *Glm* and *Gmn*. The final value of the interval when no departures can be done *f* is the average amount of *Fm* and *Fn*.

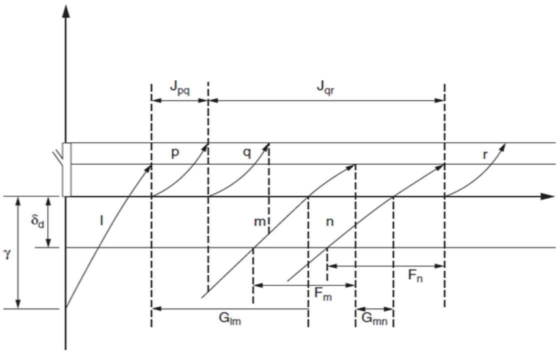

Fig. 4 Time - spaced diagram of the runway system for mixed traffic [5]

Then, we can present a description of order of operations shown on the time-spaced diagram. The first departure *p* can be allowed until the first arrival *l* reaches the distance *δd* from the runway threshold. The second departure *q* can be allowed after the first departure *p* released the runway and the *m* arrival is at the greater distance than the *δd* distance from the runway threshold at that time. The third departure *r* cannot be allowed because the arriving aircraft *m* was closer than the *δd* distance from the runway threshold.

That was the reason why departure *r* was not allowed until the last arrival *n* vacated the runway. Delays that may occur on this picture are caused because of not respecting the sequence of the operations described above. The same runway is used for arrivals and also the departures. For all aircrafts a common, 7 miles long glide path is used. Only 2 types of aircrafts, type *A* with 120 miles per hour approaching speed and type *B* which approaching speed is 90 miles per hour, can use the runway during the special period. Each arriving aircraft is using the runway for 40 seconds before vacating it. Separations between the aircraft are listed in Table 1. During this period, five aircrafts will be analyzed, arriving consecutively in the the order B, A, A, B, A and also the same number of departing aircrafts will be analyzed.

Table 1 Applicable separations of the time- spaced diagram [5]

The sequence of the aircrafts	**Separations**
Arrival - Departure	Runway vacated
Departure - Arrival	Arrival at least 2 miles from the runway threshold
Departure - Departure	At least 120 seconds
Arrival - Arrival	In miles: Leading aircraft $\begin{array}{ccc} & A & B \\ \text{Following aircraft } A & 4 & 3 \\ B & 5 & 3 \end{array}$

Aircrafts in the time diagram will be displayed so that the first arrival enters the approaching area at the time zero. The arrivals have a priority over the departures. Time-spaced diagram for departures will be displayed after the first arriving aircraft because the priority of arrivals over the departures. The dashed lines show the points, where the separation between the aircrafts is used for maintenance of safety. Numbers in the parentheses indicate the time of aircraft at the indicated point.

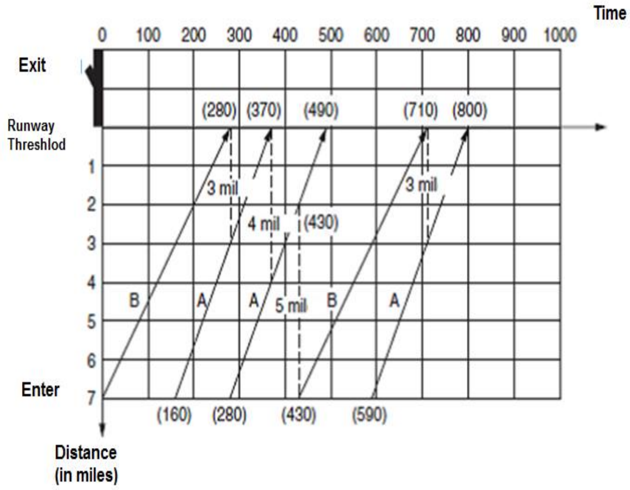

Fig. 5 Time - spaced diagram for arrivals [5]

In Fig. 5, we can see that it took 280 seconds for B-type aircraft from the point of entry to flying over the runway threshold. Immediately after that the first arriving A-type aircraft is approaching at the speed of 120 miles per hour. In this case, the following A- type aircraft is faster than the leading B- type aircraft, i.e it is gradually approaching the leading aircraft. These two aircrafts are closest when the leading aircraft is passing the threshold at the time 280 seconds. At the same time, the following aircraft must be separated at least 3 miles from the leading aircraft or must be passing at a 3 miles distance. If the aircraft is approaching by 1 mile per second speed, then the aircraft will pass the runway threshold 90 seconds later, or at the 370 seconds time. The aircraft will reach the entry-point 210 seconds earlier or at the 160 seconds time.

This process of recording of information continues until all the aircrafts have been recorded. It is necessary to monitor the situations when the B- type aircraft is followed by the A-type aircraft or when the aircraft B is slower than the aircraft A. It is also important to monitor the compliance with the requested separation. The landing processes for both aircraft takes 800 seconds. Time related to runway threshold is 800 - 280 = 520 seconds. In this time frame, there are four pairs of arrivals.Therefore, the average time between arrivals is divided by four, 520/4 = 130 seconds for 1 arrival. Thus, runway capacity is calculated as:

$$C_a = \frac{3600}{130} = 28 \quad \text{Aircraft / hour} \qquad (6)$$

Time-spaced diagram on Fig. 6, based on diagram from Fig. 5, is used to identify aircrafts departing in time spaces between arrivals. Each arriving aircraft spends 40 seconds on runway before vacate the runway.

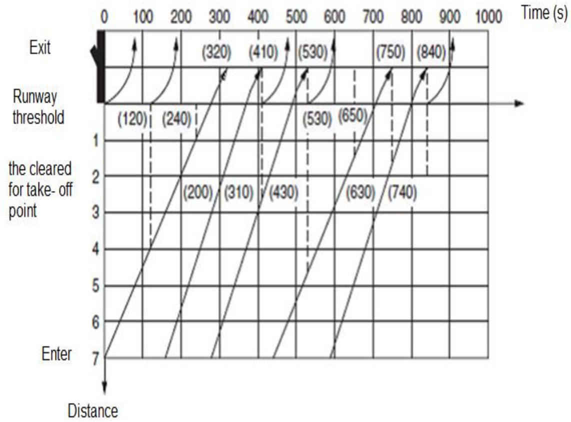

Fig. 6 Time- spaced diagram for departures [5]

That is why the time is firstly assigned when the aircraft vacating the runway. The result is displayed on Fig. 6. At the time when the runway is free, departures can be allowed if the arriving aircraft is at least 2 miles from the runway threshold or there is a 120 seconds separation between the departures.

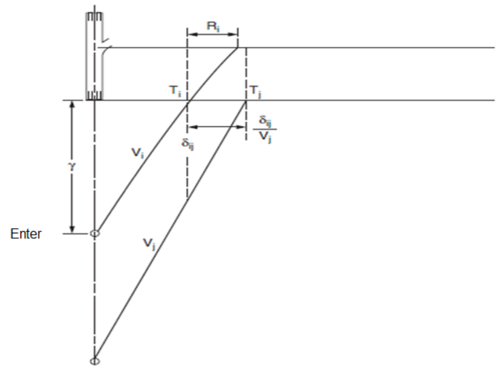

Fig. 7 Time- based diagram for approaching aircrafts (Closing case), Vi <Vj [5]

The dashed lines on Fig. 7 represent the points where the rules for separations between aircrafts are applied and numbers in parentheses indicate the time at the given point. In this case it is ensured that the separtion between aircrafts were observed.

As we can see in Fig. 6, it takes 840 seconds (measured to the threshold) for all aircrafts to land or take off. As we read it, in two cases departures were allowed in the time spaces between two arrivals. So the probability of inserting departures between arrivals in this case is 2:4, it means 0, 5. Runway capacity, for mixed traffic is calculated by the following formula:

$$C_m = \frac{3600}{130}(1.0+0.50) = 42 \quad \text{aircraft / hour} \qquad (7)$$

where, 1.0 represents the probability of arrivals touching the runway threshold every 130 seconds and 0.5 represents insertion of departures between arrivals. Runway capacity for departures is calculated as follows:

$$C_d = \frac{3600}{120} = 30 \text{ aircraft / hour} \quad (8)$$

5 CONCLUSIONS

As the article indicates, runway capacity is the key limiting factor to the capacity of air traffic control system. It is also important in achieving the expected profit and in performing the expectations of passengers, maintaining constant improvement of services quality. Firstly, it is important to develop systems and processes, which make use of the already existing facilities, their capacities and capabilities to prevent further expansion of airport infrastructure. Runway capacity is not considered to be unambigous characteristics only of part of an airport; rather, it is a sum of operations and services of all parts of the airport. That´s why it is important to view it globally and take into account the contribution of every part of the airport.

BIBLIOGRAPHY

[1] BAZARGAN, Massoud: Airline Operations and Scheduling, Embry-Riddle Aeronautical University, Burlington, Ashgate, 2010. 279 s.: il. ISBN: 978-0-7546-7900-4
[2] BUBALO, Branko: Capacity crunch, Draft paper 2010
[3] CODA Digest, Delay to Air Transport in Europe, Eurocontrol, Annual 2011
[4] CHEN, Y.T.: A Modeling Framework to Estimate Airport Runway Capacity in the National Airspace System, Blacksburg, VA, 2006
[5] HORONJEFF, R., a kol: Planning and Design of Airports, McGrawHill, 2010.689 s.: ISBN: 978-0-07-164255-2
[6] BUTLER, W.: Increasing Airport Capacity Without Increasing Airport Size. Reason Foundation, 2008

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