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DYNAMIC WAKE VORTEX SEPARATION COMBINING WITH TRAFFIC OPTIMIZATION

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Abstract

Current wake vortex separation minima are a major impediment to increasing air traffic capacity since they are greater than radar separation minima. The concept of dynamic wake vortex separation, which allows reduced separations in favorable weather conditions when wake durations on flight paths become shorter, would allow an increase in capacity. To realize dynamic wake vortex separation, the Japan Aerospace Exploration Agency (JAXA) is developing a wake vortex advisory system (WVAS) that calculates reduced separations that have equal safety to current separations. In addition, JAXA is developing a traffic pattern optimization system (TPOS) that optimizes runway allocation and take-off/landing sequences to maximize airport capacity. An airport terminal traffic simulation indicates that 4.5% and 3.4% airport capacity gains can be achieved by introducing WVAS and TPOS individually.

1 Introduction

The demand for air travel continues to grow, and there is a strong demand to reduce aircraft separations to increase traffic capacity. Wake vortex separation minima are a major impediment to this since they require 4–8 nm separations, which are greater than the radar separation minima of 2.5–3 nm that apply to aircraft under radar surveillance (table 1). The current wake vortex separation minima were established in the 1970s when knowledge of wake vortices was limited, and might therefore be overly conservative, assuming the worst case. However, during the past few decades our knowledge of wake vortices has greatly increased thanks to advances in lidar measurement and CFD analysis techniques [1], [2], and based on these advances the concept of dynamic wake vortex separation, which allows reduced separations in favorable weather conditions when wake durations on flight paths become shorter, has been studied intensively [3]-[6]. In this concept, the current wake vortex separation minima are considered to be adequately safe, and the wake vortex encounter (WVE) risks at reduced separations must be equal to or lower than the risks at current separations. WVE risk means the probability that a following aircraft encounters a leading aircraft's wake vortex which is strong enough to be hazardous to flight. However, there are still only a limited number of researches that have discussed how to control WVE risk at reduced separations, apart from a few studies that mainly discuss wake vortex advection due to crosswinds and so are applicable only to crosswind conditions [5], [6]. In addition, the sum total of wake vortex separations can be reduced by optimizing an airport's traffic pattern (runway allocation and sequencing) because wake vortex separation depends on the combination of leading and following aircraft (table 1).

The Japan Aerospace Exploration Agency (JAXA) is developing two technologies to realize dynamic wake vortex separation and

Table 1. ICAO wake vortex separation minima

Leading aircraft	Following aircraft			
	A380	Heavy	Medium	Light
A380	–	6 nm	7 nm	8 nm
Heavy	–	4 nm	5 nm	6 nm
Medium	–	–	–	5 nm
Light	–	–	–	–

increase airport capacity: a Wake Vortex Advisory System (WVAS) and a Traffic Pattern Optimization System (TPOS). WVAS calculates reduced separations that have equal safety to current separations; that is, it probabilistically assures that the WVE risks at reduced separations do not exceed those at current separations for a wide range of weather conditions by using a probabilistic wake vortex prediction model which can consider more complicated wake decay and advection processes than crosswind advection. TPOS optimizes runway allocation and take-off and landing sequences to maximize airport capacity.

This paper first introduces the WVAS and the TPOS architectures. We then describe airport terminal traffic simulation studies to demonstrate separation reduction and capacity gains expected by introducing these systems.

2 Wake Vortex Advisory System

2.1 Concept of Dynamic Wake Vortex Separation

Wake durations on flight paths vary greatly according to weather conditions such as wind, turbulence intensity and atmospheric stability. Consequently, although current separation rules prescribe fixed minimum wake vortex separations, the actual WVE risk varies with the weather (Fig. 1), but based on a long history of safe aircraft operations the risks at current separations are considered to be practically safe for all weather conditions. If we determine a target risk level within these current separation risks, and reduce separation until the expected risk at the reduced separation reaches the target risk level, the WVE risk at the reduced separation would be acceptably safe since the maximum risk at the reduced separation, equal to the target risk level, is within the level of risk admitted by current separations (Fig. 1). Other constraints such as radar separation minima remain in force during this separation reduction process. This concept of dynamic wake vortex separation according to weather conditions is proposed as a candidate for the next separation standard in ICAO's global air navigation capacity and efficiency plan (GANP, [7]).

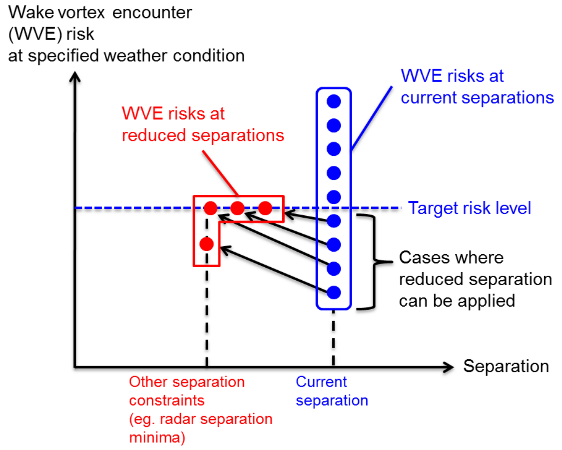


Fig. 1. Concept of dynamic wake vortex separation

2.2 WVAS Architecture

In order to calculate dynamic wake vortex separations that have equal safety to current separations, WVAS has two functions: probabilistic wake vortex prediction and WVE risk evaluation.

2.2.1 Probabilistic Wake Vortex Prediction

There are a number of parametric wake vortex prediction models such as D2P/P2P/S2P developed by DLR [8]-[10], DVM/PVM developed by UCL [11], and the AVOSS model developed by NASA/NWRA [12]. These models output a wake vortex's circulation intensity (the product of wake-induced wind velocity and distance from wake vortex's core) and position considering its generation, decay and advection processes. The initial vortex intensity depends on aircraft parameters such as lift (which is equal to weight in level flight) and airspeed. Ambient atmospheric parameters such as wind speed/direction, turbulence intensity and stratification govern the decay and advection processes. The ground effect is also modeled as a function of the wake vortex's circulation intensity, its height above the ground and the time elapsed since its generation.

WVAS employs the S2P model since it is capable of providing probability density distributions (PDDs) of wake vortex circulation intensity and vertical/lateral positions in real-time. Considering wake decay and advection processes, the S2P model predicts the uncertainty bounds (the upper and lower limits) of wake vortex parameters, and then applies the prescribed PDDs normalized by the calculated uncertainty bounds to express wake vortex random behaviors (Fig. 2). Since the uncertainty bounds account for wake vortex deterministic behaviors influenced by flight conditions and local weather conditions, the PDDs are independent of these. We therefore require only a single PDD for each wake vortex parameter derived from a wake vortex observation database. At present, the WVAS uses PDDs based on about 2,400 wake vortex observation data [9].

2.2.2 WVE Risk Evaluation Considering Wake Vortex Prediction Errors

WVE risk is defined as the probability that a following aircraft enters the hazard area of the wake vortex generated by a leading aircraft. The hazard area is the area within which wake-induced turbulence can be hazardous to flight. To calculate the WVE risk, we need the hazard area size and the PDDs of leading/following aircraft position, wake vortex circulation intensity and position. In our method, the hazard area size is described as a function of wake vortex circulation intensity and the flight characteristics of the following aircraft [13]. The PDDs of wake vortex parameters are calculated by the S2P model, and the PDDs of aircraft position are considered as prescribed distributions based on flight procedure standards. Once all these parameters have been established, we can calculate WVE risk [13].

However, we have to be aware that the WVE risk calculation process may have errors, mainly due to wake vortex prediction errors. If we underestimate the WVE risks at reduced separations, the true WVE risks at reduced separations might exceed the target risk level. Likewise, if we overestimate the WVE risks at current separations, the target risk level based on those overestimated WVE risks might exceed the true WVE risks at current separations. Therefore, errors in the WVE risk calculation at either current separations or reduced separations may lead to the WVE risks at reduced separations becoming greater than those at the current separations.

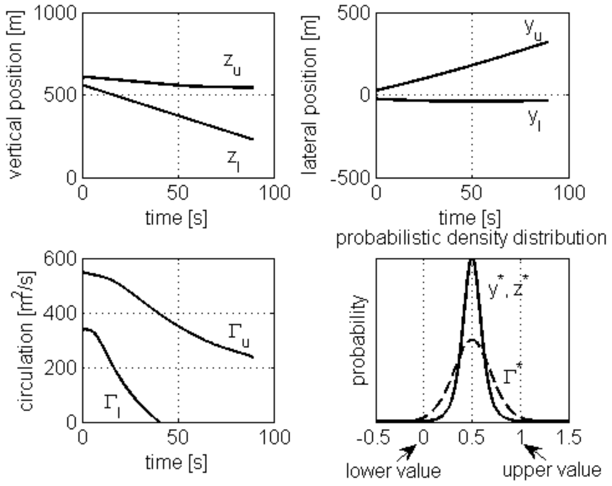


Fig. 2. Example of S2P wake vortex prediction $X = X^* (X_u - X_l) + X_l$, $X = y, z, \Gamma$; where X^* is a normalized value, X_u is a upper limit, X_l is a lower limit.

To probabilistically assure the safety of reduced separations considering wake vortex prediction errors, we propose using the confidence intervals of the PDDs of wake vortex parameters in the WVE risk evaluations [13], [14]. The wake vortex prediction errors are quantified by the confidence intervals of the PDDs. In WVE risk evaluations, the WVE risk at reduced separation should be intentionally

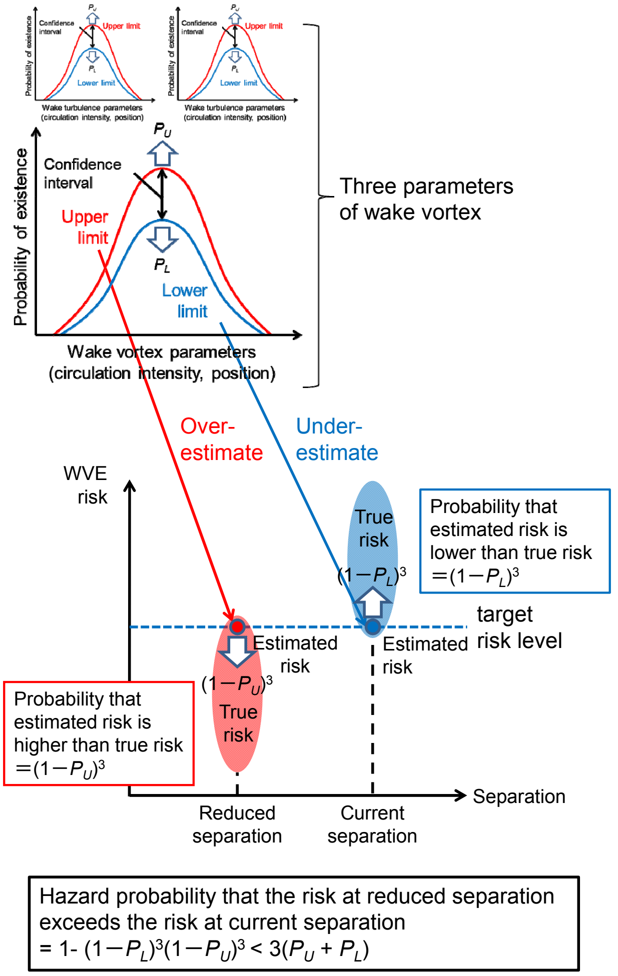


Fig. 3. WVE risk evaluation method

overestimated using the upper confidence interval of the PDDs, and the risk at current separation intentionally underestimated by using the lower confidence interval (Fig. 3). Finally, WVAS outputs the reduced separation for which the overestimated WVE risk is equal to the target risk level based on the underestimated WVE risk at the current separation. By employing this WVE risk evaluation method, we can control the hazard probability that the WVE risk at reduced separation exceeds that at current separation to be equal to or lower than a threshold value [13], [14]. This threshold value is a user-defined parameter and indicates the safety level of the reduced separations.

3 Traffic Pattern Optimization System

3.1 Concept of Traffic Pattern Optimization

The TPOS optimizes runway allocations and take-off/landing sequences to maximize airport capacity. These two factors are related to airport capacity as follows.

(1) Runway allocation: At airports with multiple runways, it may not be possible to operate each runway independently; for example, landing traffic on one runway might interfere with departing traffic on another. Airport capacity is increased as interferences between runways are reduced.

(2) Take-off/landing sequence: The sum total of wake vortex separations can be reduced by increasing the opportunities of successive take-offs/landings of aircraft belonging to the same wake vortex separation category, since wake vortex separations are minimized when both leading and following aircraft belong to the same category (table 1).

3.2 TPOS Architecture

TPOS employs two-stage optimization to obtain within a practical time a solution that gives high airport capacity while satisfying complex runway operation constraints.

3.2.1 Runway Allocation Optimization (first stage)

In the first stage, TPOS optimizes the runway allocations of take-off/landing aircraft. Input parameters to this stage are the ratio of take-off to landing aircraft, the ratios of traffic wake vortex separation categories, the usage of each runway (take-off only, landing only, or both take-off and landing), and simplified runway operation constraints. The take-off/landing sequence is assumed to be random at this stage. This optimization problem is solved by the non-linear programming (NLP) method. The outputs of this stage are optimized ratios of take-off/landing aircraft and aircraft wake vortex separation categories for each runway, and the predicted airport capacity based on those optimized ratios.

3.2.2 Take-off/landing Sequence Optimization (second stage)

In the second stage, TPOS optimizes the runway allocation and the take-off/landing sequence. Input parameters to this stage are an initial sequence of take-off/landing aircraft, runway usage and full (not simplified) runway operation constraints. A maximum number of allowable changes during optimization can be set to avoid excessive changes to the initial sequence. We employ a constraint programming (CP) method for this optimization because it can find an executable solution within a short time even with complex constraints. However, the parameter search spaces for the optimization of both runway allocation and sequences are too large even for the CP method to obtain a good performance solution in a short time. Therefore, the CP method is used mainly to optimize the take-off/landing sequences. For runway allocation, the CP method tries to realize the optimal solution obtained by the NLP method. As a result, the CP's solution is executable, satisfying all the constraints, and shows a reasonably high capacity throughput based on the NLP's optimal solution.

3.2.3 Example of Traffic Pattern Optimization

Figure 4 exemplifies traffic pattern optimization for an airport with four runways. Runways (RWY) 16L and 16R are used for departures and runways 22 and 23 are used for arrivals. Take-offs from runway 16L and landings on runway 23 are dependent. In this case, we assume that the ratio of take-off to landing aircraft is 1:1 and the ratio of heavy to medium category aircraft is 53:47.

To increase the airport's capacity, the first stage of TPOS optimizes the runway allocation as follows: (1) increase the opportunities for successive take-offs/landings of same-category aircraft for runways 16R and 22, which operate independently; (2) minimize the number of heavy category aircraft taking-off from runway 16L which require excessive wake vortex separations with landing aircraft on runway 23. The second stage optimizes the sequences to increase successive take-offs/landings of same-category aircraft while realizing the optimized runway allocation obtained from the first stage. The expected capacity of the second stage result slightly degrades compared to the first stage result since the second stage result must satisfy all runway operational constraints.

4 Expected Capacity Gain of WVAS

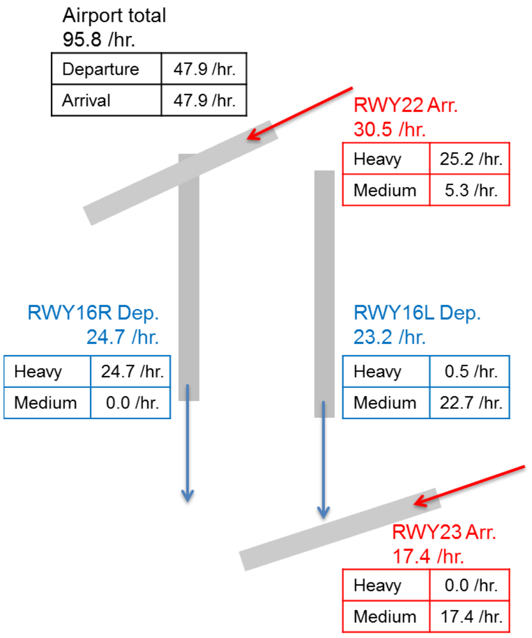
4.1 Simulation Environment

4.1.1 Target Airport

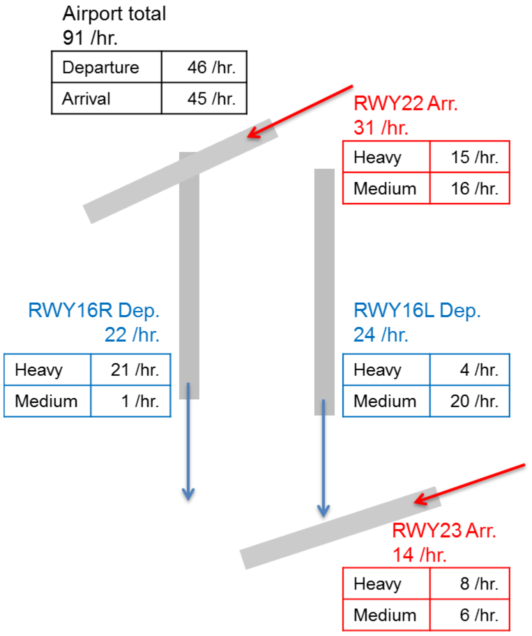
We selected Tokyo International airport as the target for a simulation study since wake vortex separation is a major capacity constraint at this airport, especially when southerly winds prevail. As shown in fig. 5, runways 16L and 16R are used for departures and runways 22 and 23 are used for arrivals when southerly winds prevail. In this configuration, there are three situations where wake vortex separation limits aircraft separations: (1) between successive landings on runway 22; (2) between successive take-offs from runways 16L and 16R; (3) between take-offs from runway 16L and landings on runway 23. Table 2 shows current minimum separations with and without wake vortex separation for these situations. The required separations without wake vortex separation are mainly due to radar separation minima and runway occupation time constraints. In particular, the separation between a take-off from runway 16L and a landing on runway 23 varies greatly according to wake vortex separation constraints. In such a case, we can expect a large capacity gain by introducing WVAS.

4.1.2 Weather Condition

Weather information around the target airport is necessary to simulate wake vortex behaviors. In this simulation, JAXA's non-hydrostatic meso-scale weather forecasting model [13] was used to produce realistic weather data around the airport such as winds, turbulence intensity and atmospheric stability. A domain size of 164 × 164 km^2 with a grid distance of 2 km was used, which covers the whole of the airport's terminal airspace. Using this model, one year of weather data around the airport were generated and



(1) First stage optimization



(2) Second stage optimization

Fig.4 Example of traffic pattern optimization approximately 1,000 cases in which southerly winds prevailed were chosen for the simulation.

Wake vortex behavior depends heavily on the weather parameters listed in table 3. The eddy dissipation rate (EDR) indicates atmospheric turbulence intensity and the Brunt-Väisälä frequency indicates atmospheric stability. These parameters mainly affect the wake vortex decay process, while the wake vortex advection process is mainly determined by wind conditions. The accuracy of wake vortex prediction therefore depends on the accuracy of available weather information. For this study, we assumed two different accuracy levels of available weather information in the WVAS wake vortex prediction. The first case in table 3 assumes the accuracy of current weather forecasts commonly available in Japan. The second case assumes a near-future weather forecast accuracy with errors half of the first case. Figure 6 exemplifies the calculated confidence intervals of the PDD of the wake vortex horizontal position. The vertical axis shows the probability of existence and the horizontal axis shows the actual horizontal position normalized by the predicted horizontal position. The value of 0.5 on the horizontal axis means that the predicted position matches the actual position perfectly. The envelope of the PDD becomes larger as weather information accuracy degrades, so the WVE risks would be further overestimated and the expected separation reduction would become smaller. We can therefore obtain an appropriately safe separation margin that takes into account the accuracy of the available weather information.

4.1.3 Aircraft Type and Trajectory Model

The aircraft types considered in the simulation are heavy and medium category aircraft as defined by current wake vortex separation rules. These two categories are dominant at the target airport.

The nominal routes of departure/arrival traffic were based on the Aeronautical Information Publication and flight procedure standards published by the Japan Civil Aviation Bureau. The PDDs of aircraft positions around the nominal paths were produced based on radar surveillance data and a probabilistic trajectory model used in the risk collision model for ILS landing [15]. In our simulation, the PDDs of aircraft position remain constant regardless of weather conditions and aircraft types.

Table 2. Required separations with/without wake vortex separation

Situation	Wake vortex separation	
	without	with
Successive landings on RWY22	115 sec.	120 sec.
Successive take-offs from RWY16L/R	95 sec.	120 sec.
Take-off from RWY16L and landing on RWY23	47 sec.	102 sec.

Table 3. Accuracy levels of available weather information

Parameter	Errors (1σ)	
	Case 1	Case 2
EDR [$m^{2/3}/s$]	0.05	0.025
Brunt–Väisälä frequency [1/s]	0.005	0.0025
Wind [m/s]	3.0	1.5

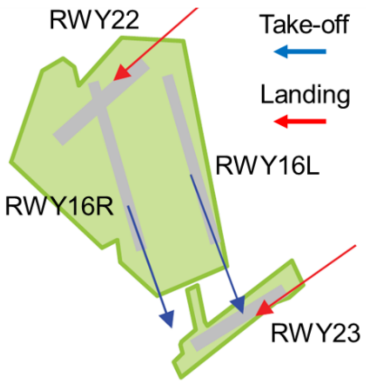


Fig. 5. Runway operations for southerly winds at Tokyo International airport

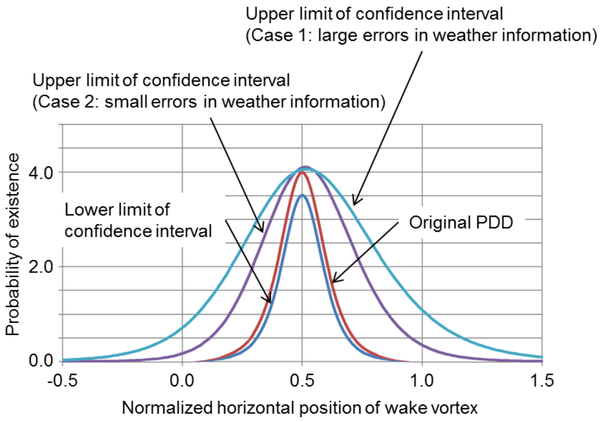


Fig. 6. PDD confidence intervals of wake vortex horizontal position

4.2 Simulation Results

4.2.1 Separation Reduction

Table 4 shows the separation reductions expected by introducing WVAS for the three situations shown in table 2. The reduction shown is averaged over one year of southerly wind operations (about 1,000 different weather conditions). We employed three different target WVE risk levels: 50%/70%/90% cumulative values of the WVE risks at current separations. For example, if we employ the 50% cumulative values as the target risk level, we can reduce separations of all take-off/landing operations by up to 50% unless overridden by other constraints. Major factors affecting separation reduction are as follows.

(1) Target Risk Level: The separation reduction depends heavily on the target risk level. The highest target risk level of 90% cumulative value leads to over 10 seconds of separation reduction in two situations. On the other hand, the lowest target risk level of 50% cumulative value reduces separations by only a few seconds. A higher target risk level brings a larger separation reduction as a natural consequence since it gives more chances to reduce separations, but the total amount of the WVE risks increases. Although the safety of the reduced separations remains acceptable so long as the target risk level is set at or below the risk at current separations, it must be realized that the selection of the target risk level is a trade-off between separation reduction and WVE risk.

(2) Accuracy of Available Weather Information: Poor weather information accuracy decreases the amount of separation reduction. In particular, the separation reduction between runway 16L take-offs and runway 23 landings is largely affected by the weather information accuracy. In this case, leading and following traffic follow different paths, and the flight paths of following traffic are located at the tails of the PDDs of the wake vortex positions in most weather conditions except for strong crosswinds. Meanwhile, the prediction results of wake vortex position are widely spread when the weather information accuracy is poor. In such cases, the probability of wake vortex existence at the tail of the PDD increases as shown in Fig. 6, and the WVE risk therefore increases.

4.2.2 Airport Capacity Gain

The airport capacity gain expected from the achievable separation reduction depends on operating conditions such as aircraft types and take-off/landing sequences. Figure 7 shows the expected capacity gains when we assumed the airport operating conditions for the most congested time period (8–9 a.m.) of the target airport. We obtained a maximum 4.5% capacity gain by WVAS when we employed the 90% cumulative values of WVE risks as the target risk level.

Table 4. Simulated separation reduction by introducing WVAS
(averaged over approximately 1,000 different weather conditions; leading/following aircraft are heavy category aircraft)

Situation	Errors in weather information	Target risk level (cumulative risk value at current separations)		
		50%	70%	90%
Successive landings on RWY22	case 1	0sec.	0sec.	2sec.
	case 2	0sec.	1sec.	3sec.
Successive take-offs from RWY16L/R	case 1	3sec.	5sec.	10sec.
	case 2	4sec.	7sec.	13sec.
Take-off from RWY16L and landing on RWY23	case 1	0sec.	1sec.	7sec.
	case 2	1sec.	7sec.	16sec.

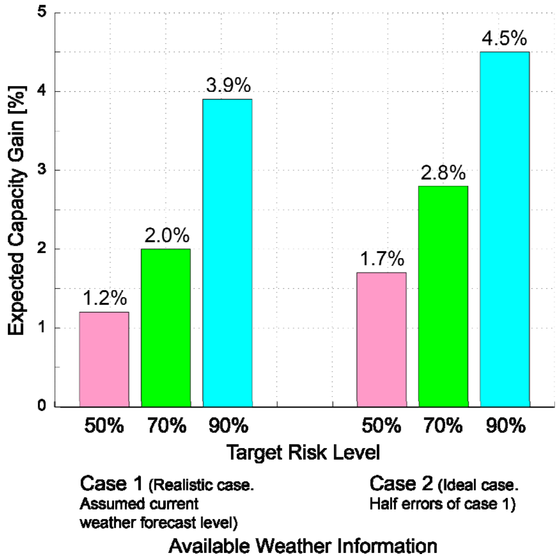


Fig. 7. Expected capacity gain by introducing WVAS.

5 Expected Capacity Gain of TPOS

5.1 Simulation Environment

5.1.1 Target Airport

We again selected Tokyo International airport as the target of this simulation study. As described previously, this airport's capacity is heavily limited by wake vortex separation when southerly winds prevail (Fig. 5, table 2).

5.1.2 Modeling of Runway Operation

We modeled the runway operations of the target airport by considering runway occupancy times, radar separation minima, wake vortex separation and other separation constraints listed in table 5. These reflect the current ICAO separation rules and some local rules. Separations of #5-11 are resulting from its intersecting runways layout.

5.1.3 Traffic Condition

The aircraft types considered in the simulation are heavy and medium category aircraft as defined by current wake vortex separation rules. These two categories are dominant at the target airport. The ratio of heavy to medium category aircraft is 53:47, reflecting a typical traffic mix of the target airport.

We assumed three ratios of take-off to landing aircraft, 1:1, 2:1 and 1:2, because such ratios change according to time of day. Take-off traffic increases in the morning and landing traffic increases in the evening.

5.2 Simulation Results

Figure 8 shows the expected capacity gain by introducing TPOS. Since the capacity gain realized by TPOS depends on the initial sequence, we conducted the optimization for ten random initial sequences and took the average of these ten results. We obtained a capacity gain of 0.2-3.4%, depending on the ratio of take-offs to landings. It decreases when take-off or landing traffics are dominant because the excessive take-off or landing traffics make it difficult to realize the optimized runway allocation for reducing interferences between runways. The minimum capacity gain was observed when landing traffic is dominant because runway occupancy time of successive landings (115 sec) is almost the same as the wake vortex separation (120 sec, table 5). In other words, we can expect more capacity gains for landing traffic by TPOS if we can reduce the runway occupancy time of successive landings.

Table 5. Separation constraints to simulate runway operations at Tokyo International airport (southerly wind condition)

Separation	Separation minimum	Reason for separation
1) between successive take-offs from the same runway	95sec.	runway occupancy time
2) between successive take-offs from the same runway (when a leading aircraft belongs to heavy category)	120 sec.	wake vortex separation
3) between successive landings on the same runway	115 sec.	runway occupancy time
4) between successive landings on the same runway (when a leading aircraft belongs to heavy category)	120 sec.	wake vortex separation
5) From: take-off clearance from RWY16L To: a take-off aircraft from RWY16L flies over RWY23	95 sec.	runway occupancy time
6) From: a take-off aircraft from RWY16L flies over RWY23 To: a landing aircraft on RWY23flies over RWY23 threshold	47 sec.	radar separation minimum
7) From: a take-off aircraft from RWY16L flies over RWY23 (when a take-off aircraft belongs to heavy category) To: a landing aircraft on RWY23flies over RWY23 threshold	117 sec.	wake vortex separation
8) From: take-off clearance from RWY16R To: a take-off aircraft from RWY16R flies over RWY23	100 sec.	runway occupancy time
9) From: a take-off aircraft from RWY16R flies over RWY23 To: a landing aircraft on RWY23flies over RWY23 threshold	29 sec.	radar separation minimum
10) From: a landing aircraft on RWY23flies over RWY23 threshold To: take-off clearance from RWY16R/L	25 sec.	landing confirmation
11) From: a landing aircraft on RWY22flies over RWY23 threshold To: take-off clearance from RWY16R	23 sec.	engine blast avoidance

6 Conclusion

This paper describes the JAXA's research activities towards dynamic wake vortex separations: the Wake Vortex Advisory System (WVAS) and the Traffic Pattern Optimization System (TPOS). WVAS calculates reduced separations that have equal safety to current separations, while TPOS optimizes runway allocation and take-off/landing sequence to maximize airport capacity. An airport terminal traffic simulation indicated that 4.5% and 3.4% airport capacity gains could be achieved by introducing WVAS and TPOS individually. We expect that a capacity gain of greater than 10% can be achieved by combining these two systems, and plan to conduct additional traffic simulations to demonstrate this. Our simulation results show that WVAS and TPOS would greatly help to realize dynamic wake vortex separation and increase airport capacity. However, both systems are still in development and many aspects have to be validated before they can be used operationally. The probabilistic wake vortex prediction is one such aspect, and JAXA is therefore conducting a wake vortex observation campaign at Narita International airport during 2013–2014 to improve the PDDs of wake vortex parameters used by WVAS.

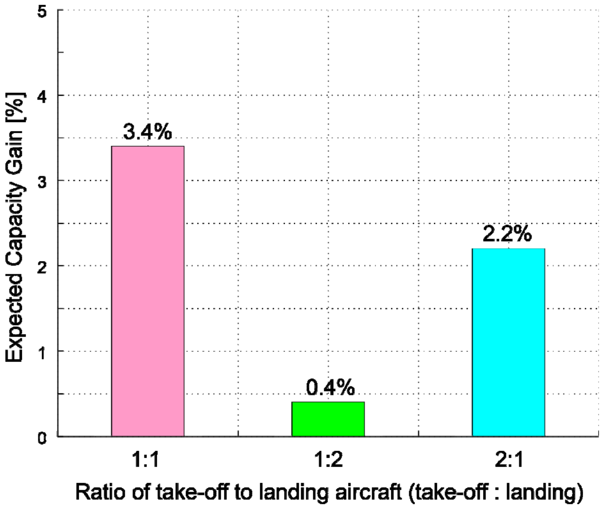


Fig. 8. Expected capacity gain by introducing TPOS

References

[1] Gerz, T., Holzäpfel, F. and Darracq, D. Aircraft Wake Vortices: A Position Paper. *Wakenet*, 2001.

[2] WakeNet2-Europe. Wake Vortex Research Needs for 'Improved Wake Vortex Separation Ruling' and 'Reduced Wake Signatures'. *Final Report of the Thematic Network 'WakeNet2-Europe'*, 6th Framework Program, National Aerospace Laboratory, NLR-CR-2006-171, Amsterdam, 2006.

[3] Holzäpfel, F., Gerz, T., Frech, M., Tafferner, A., Kopp, F., Smalikho, I., Rahm, S., Hahn, K.-U., and Schwarz, C. The Wake Vortex Prediction and Monitoring System WSVBS – Part I: Design. *1st CEAS European Air and Space Conference*, Berlin, Germany, 2007.

[4] Gerz, T., Holzäpfel, F., Gerling, W., Scharnweber, A., Frech, M., Wiegele, A., Kober, K., Dengler, K. and Rahm, S. The Wake Vortex Prediction and Monitoring System WSVBS – Part II: Performance and ATC Integration at Frankfurt Airport. *1st CEAS European Air and Space Conference*, Berlin, Germany, 2007.

[5] Lang, S. Wake Turbulence Mitigation for Departures (WTMD) and Wake Turbulence Mitigation for Arrivals (WTMA). *Global wake conference*, Brussels, Belgium, 2009.

[6] Treve, V. Crosswind dependent separations (CROPS). *Wakenet 3 Specific Workshop 'WV Concepts & Capacity'*, London, UK, 2011.

[7] Anonymous. Global Air Navigation Capacity & Efficiency Plan 2013-2028. *ICAO Doc 9750 Draft 2014-2016 Triennium Edition*, 2012.

[8] Holzäpfel, F. Probabilistic Two-Phase Wake Vortex Decay and Transport Model. *Journal of Aircraft*, Vol. 40, No. 2, 2003.

[9] Holzäpfel, F. Probabilistic Two-Phase Aircraft Wake-Vortex Model: Further Development and Assessment. *Journal of Aircraft*, Vol. 43, No. 3, 2006.

[10] Holzäpfel, F. and Steen, M. Aircraft Wake–Vortex Evolution in Ground Proximity: Analysis and Parameterization. *AIAA Journal*, Vol. 45, No. 1, 2007.

[11] Jackson, W., Yaras, M., Harvey, J., Winckelmans, G., Fournier, G. and Belotserkovsky, A. Wake Vortex Prediction - An Overview. *Phase 6 and Project Final Report*, Transport Canada and its Transportation Development Center, TP 13629e.pdf, 2001, www.tc.gc.ca/tdc/summary/13600/13629e. htm.

[12] Robins, R. E., and Delisi, D. P. NWRA AVOSS Wake Vortex Prediction Algorithm Version 3.1.1. *NASA/CR-2002-211746*, 2002.

[13] Matayoshi, N. Dynamic Wake Vortex Separation according to Weather Conditions. *2013 ATIO Conference*, Los Angeles, USA, August, 2013 (AIAA 2013-4425)

[14] Sugiura, M. and Matayoshi, N. Accuracy Estimation of Probabilistic Wake Vortex Prediction Considering Weather Information Errors. *3rd AIAA Atmospheric Space Environments Conference*, Honolulu, USA, June, 2011 (AIAA 2011-3195)

[15] Anonymous, Manual on the Use of the Collision Risk Model (CRM) for ILS Operations. *ICAO Doc 9274*, 1980.

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