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Methods of Aircraft Re-categorizations for Reducing Wake Vortex Separations

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Abstract—**The current criteria of wake vortex separation may limit the capacity of the busy airports despite ensuring flight safety. Based on plenty of measured data together with the knowledge of wake vortex behavior, the concept of Re-categorization (RECAT) has been proposed by the international air traffic researchers. This concept has attracted more and more interests, as it can apply to reduce separations with more precision by increasing the amount of aircraft categories. The methods for classifying aircraft categories were studied systematically, and the parameters termed as Required Decay Distance (RDD) and Wake Vortex Impedance (WVI) were proposed by authors to consider the influence of leading aircraft's wake vortex circulation, and the resistant ability of following aircraft when encountering wake vortex. By comparing RECAT-I with RECAT-EU, the standard we proposed called RECAT-NEW can obtain more balanced and reasonable results in safety domain. Furthermore, on the basis of the data in airport peak operation conditions, the RECAT-NEW is expected to increase 2.2% of airport capacity.**

Keywords-wake vortex separation standards; aircraft re-categorization; required decay distance; wake vortex impedance; required actual roll rate

I. INTRODUCTION

The safety of wake vortex between leading and following aircraft all depends on the initial circulation of leading aircraft's induced vortex, the ambient atmosphere parameters and the controllability of following aircraft. The current method of maintaining wake vortex separation is to classify aircraft into four categories based on maximum takeoff weight and to define the separation criteria for different category combinations [1]. These relatively conservative separations, which were defined in 1960s, have worked well in ensuring safe and order flight operations. However, many actual factors such as crosswind, turbulence, temperature, atmospheric characteristics, and ground effect, together with the differences of aircraft in type, weight, span and speed, make the real lasting time and influence of wake vortex less than the criteria above under most flight conditions, which implies that there is a potential to reduce the current separation criteria[2]. With the rapid increase of air traffic in China, these criteria restrict the capacity of big and busy airports such as Peiking, Shanghai, and Guangzhou, resulting in unnecessary flight delays [3].

In 2007, EUROCONTROL raised a concept of RECAT in order to reduce wake vortex separation by re-categorize aircraft scientifically and reasonably, thus to improve air traffic management efficiency [4]. The research on RECAT will be conducted in three stages, RECAT-I, RECAT-II and RECAT-III. And RECAT-I has been completed so far, which involves re-categorizing aircraft into six types depending on their Initial Circulation of Wake Vortex, and re-calculating sufficient separations for different category combinations without sacrificing safety level. In December 2012, FAA and EUROCONTROL submitted the results of RECAT-I as a proposal to ICAO 12th Air Navigation Conference, thus to spread the application of RECAT throughout the world[5].

FAA issued Safety Alert for Operators (SAFO) in October 2012 and announced Memphis Airport become the first airport to conduct RECAT-I operation[6]. Other American airports such as KMIA, KPHL, KSDF, KIAH and KSSO began to conduct RECAT-I operation in 2013[7]. To improve the implement of RECAT-I in Europe, EUROCONTROL started the program of RECAT-EU and aimed to optimize the aircraft categories of RECAT and to reduce vortex separations [8]. Japan initiated the program of CARATS in 2010 and planned to realize RECAT-I operation until 2018[9][10].RECAT is a set of technical methods to reduce vortex separation but not a fixed classification result. There are differences in aircraft categories and separation minima for RECAT-EU, RECAT-I and RECAT1.5. So far, there have been European and American relevant organizations which issued vortex separation criteria but seldom published the method of aircraft re-categorization and calculation of vortex separation.

Generally, mechanisms and models associated with RECAT technology can be divided into several areas, including wake vortex decay & transportation, encountering of wake vortex and safety assessment metrics. Many researchers have been carried out in these areas. The mechanisms of leading aircraft wake vortex have been investigated very thoroughly, and various operational models to predict the position and strength of a wake have been developed and validated. The first wake transport and decay model was developed by NASA's Greene in 1986. This model assumes that the impulse per unit length of a wake is reduced by the sum of viscous drag, buoyancy force, and turbulent decay. From a single equation, circulation, velocity, and vertical position of the wake can be determined [11]. Sarpkaya eliminated the viscous drag in Greene's model and proposed an empirical model for turbulent decay that relies on the eddy dissipation rate instead of turbulent kinetic energy [12][13].

The Probabilistic Two-Phase wake vortex decay and transport model (P2P) has been developed by DLR and is described in details in (Holzapfel 2003, Holzapfel 2004). It is designed to include as much knowledge as possible gained from both experimental and numerical wake vortex research with a focus on operational needs. This model is derived from their own Deterministic 2-Phase (D2P) model. The difference is that P2P is based on the uncertainties of wake vortex evolution found in LES and field experiment data. Uncertainty allowances are modeled by conducting three model runs with different fixed and dynamic uncertainty parameters [14][15]. Proctor reviewed these models, compared the calculated data of these models with what from Denver International Airport's LIDAR wake measurements, then proposed three phase wake vortex decay models[16][17]. These models have been widely used due to their simple format and fast reaction time, although the precision of these models are lower than numerical simulation or LIDAR detections. WEI Zhiqiang and XU Xiaohao established the simulation model for civil aviation wake vortex flow field based on APA and D2P, then applied this model to the development of dynamic wake vortex calculation tools[18].

For many new developments, knowledge of the complete process that is from vortex generation to encounter risk is a prerequisite. In many cases, the strip method (SM) is used to calculate aerodynamic forces and moments that are induced by the wake vortex flow field [19]. HAN Hongrong discussed the responses of aircraft when encountering wake vortex and established the separation calculation model [20]. Wake Vortex Encounters (WVEs) can be investigated in flight simulators safely, under controlled conditions, and with moderate costs. In the 1990s, the FAA equipped a Boeing 737 flight training simulator with WVE simulation [21]. Fast-time flight simulations are another important application of WVE models. The objectives are either sensitivity studies or statistical analyses of traffic scenarios. Loucel and Crouch were the first who investigated WVEs with deformed vortices in offline flight simulations [22]. The encountering aircraft was a Boeing 737-300 flying horizontal in landing configuration with autopilot employed. Based on flight dynamic equations, Han and Li studied the method to calculate the bank angle of aircraft when encountering wake vortex [23]. Airbus developed the WVE (wake vortex encounter) simulation platform VESA to simulate WVEs in fast time by combining wake vortex velocity models with high-fidelity, six degrees-of-freedom flight simulations of different transport aircraft [24]. DLR developed another package called as Wake Scene to predict WVEs in complex air traffic scenarios and allows assessing the encounter probabilities behind different aircraft during arrival and departure [25].

Some metrics were proposed and used to assessment the severity and risk of aircraft encountering wake vortex fields, include wake strength, induced roll moment coefficient (RMC), equivalent roll rate (ERR), and maximum bank angle [26]. In the research of RECAT-I, wake strength was used as the primary hazard metric to categorize aircraft types, except that RMC used to reduce the separation of Category B (the Heaviest of the Heavy category) behind Category B aircraft [4]. Gerben and Lennaert proposed to use ERR as severity metric, which means the roll rate in the equilibrium situation where wake vortex induced rolling moment and aircraft roll rate induced rolling moment (damping) are in balance without pilot intervention [27]. In project of RECAT-EU, the initial categorization of aircraft types was based on aircraft weight and wing span by using clustering analysis methods. Furthermore, RMC and ERR were selected as Primary metrics to assessment the severity of wake encounter [5]. Campos and Marques presented moment models for simulating aircraft roll response due to the wake vortex effects, and calculating Peak roll rate data [28].

In this paper, a wake vortex characteristic behavior model is developed to calculate current ICAO separation criteria in order to find the acceptable minimum separation. The concept of required decay distance (RDD) is proposed to re-categorize aircraft initially, and wake vortex impedance (WVI) is used to do further classification of medium and light aircraft. On the basis of re-categorization, the minimum separation for different type combinations is calculated and RECAT-NEW is presented. Finally, comparisons are made between RECAT-NEW, RECAT-I and RECAT-EU in the aspects of safety and airspace capacity improvement.

II. Modeling and Calculation of Wake Vortex Characteristics

The minimum separation between aircraft depends upon the initial circulation of leading aircraft's wake vortex, vortex decay condition affected by atmospheric parameters, and the response of following aircraft encountering the vortex.

A. Model of Wake Vortex Initial Circulation

In flight, lift is produced by wings which also generate a vortex area following the aircraft. The circulation of the vortex weakens from the initial part, and the initial circulation loop can be found in the way below[2].

$$\Gamma_0 = \frac{m g}{\rho v s B} \tag{1}$$

Where Γ_0 is initial circulation loop (m^2/s), m is aircraft mass (kg), ρ is the air density (kg/m^3), v is airspeed (m/s), s is wing load distribution coefficient, which is usually $\pi/4$, B is wing span (m).

B. Model of Wake Vortex Decay

When wake vortex is generated, the circulation will be dampened with time (i.e. decay), the vortex core will displace down rearward. The influence of vortex on following aircraft is relative to the initial circulation and its decay condition. One objective of the research on new generation ATC automation system is to consider the effect of meteorology on dynamic vortex separation. But restricted by the technologies of detecting meteorological parameters, detecting and predicting vortex, and real-time sharing flight data, it takes years for ATC automation system to find their applications. While the approach of reducing separation minimum by refining aircraft categories is efficient and less difficult, that's why it has become one of the key focuses in recent years [4].

The published separation criteria should applies to any possible weather conditions, which means that it's unnecessary to consider specific meteorological parameters including wind, temperature, and turbulence and that the impact of meteorology on vortex dissipation is analyzed in a conservative way. Wake vortex have been measured actually by RECAT researchers in US and Europe, e.g. Laser radar, Pulse Doppler radar and Sonar devices have been used for three years to measure the position and circulation of vortex in the near earth phase at the airports of San Francisco, Memphis, Kennedy, and Heathrow. And the results derived from the detection are shown below [6].

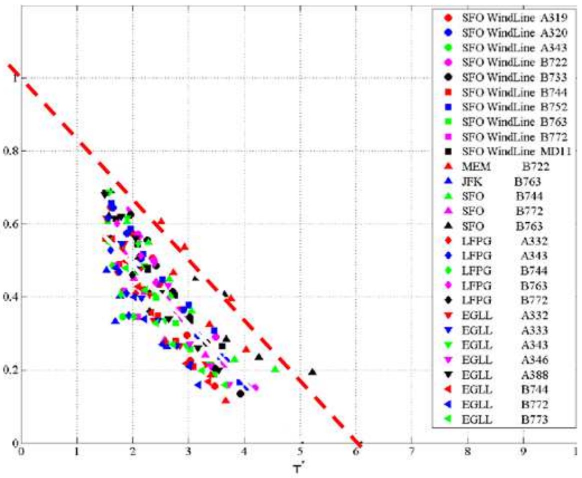

Figure 1. Decay data derived from detection results

In the diagram, the abscissa denotes dimensionless relative time and the ordinate shows the dimensionless relative circulation. Fig. 1 illustrates that the vortex intensity decreases linearly with time. The conservative vortex decay model, which is developed by using linear fitting method, is shown by the red broken line and can be found by the following equation.

$$\Gamma^* = 1 - \frac{1}{6} t^* \tag{2}$$

In the formula, Γ^* is the dimensionless relative circulation (i.e. the ratio of actual vortex circulation to Initial Circulation of Wake Vortex, denoted by the ordinate of Fig.1), t^* is dimensionless relative time (i.e. the ratio of vortex decay time to reference time, denoted by the abscissa of Fig.1). And,

$$t^* = t / t_0 = t \frac{\Gamma_0 / 2\pi s B}{sB} \tag{3}$$

Where t is vortex decay time (s). And the relationship of vortex intensity during decay and flight distance can be found by substituting (1) and (3) into (2).

$$\Gamma(d) = \frac{mg}{\rho v s B}\left(1 - \frac{mg}{12\rho\pi v^2 s^3 B^3} d\right) \tag{4}$$

Here d is flight distance (i.e. the distance after the aircraft, and the unit is m).

C. Model for Calcultating Induced Roll Moment Coefficient

In the safety analysis of encountering wake vortex, it was assumed an aircraft flies just into the center of vortex causing the most severe roll moment. With the influence of induced upwash and downwash airflow, lift varies as following: [18]

$$\Delta L = \frac{1}{2}\rho_\infty V_\infty^2 \int_{-\frac{B}{2}}^{\frac{B}{2}} C_L'(y) C(y) dy \tag{5}$$

$$C_L'(y) = C_L^\alpha \arctan\left(\frac{V_Z(y)}{V_\infty}\right) \approx C_L^\alpha \frac{V_Z(y)}{V_\infty} \tag{6}$$

In the equations, ΔL is the variation of lift, $C(y)$ is length of wing chord, B is wing span, y is the coordinate of wing chord along the spanwise direction, $C_L'(y)$ is the variation of lift which is related to change of angle of attack and lift coefficient slope, C_L^α is lift coefficient slope, $V_Z(y)$ is the induced velocity of vortex flow field on the airfoil, and $\Delta\alpha(y)$ is the change of following aircraft's angle of attack caused by vortex induced velocity. Substituting (6) into (5), the integral along the spanwise direction can be found and C_{RV}, i.e. induced roll moment coefficient, can be obtained.

$$C_{Rv} = \frac{\Gamma C_L^\alpha}{\pi V B^3 (1+\lambda)} \int_{-\frac{B}{2}}^{\frac{B}{2}} \frac{y^2 \left[B - 2|y|(1-\lambda)\right]}{(y^2 + r_c^2)} dy \tag{7}$$

In the equation, λ is the taper ratio of wing, r_c is vortex core radius. Induced roll moment coefficient (IRMC) is one of the indices of safety with wake vortex [9]. But it can not reflect the actual safety without considering the influence of aircraft damping and handling characteristics.

D. Model for Calcultating Required Actual Roll Rate

Required Actual Roll Rate (RARR) is the required minimum roll rate to balance damping moment and induced moment regardless of handling moment. In the process of disturbed motion caused by vortex, the resultant roll moment includes induced, damping and handling moments. Then we have:

$$M_X = \frac{1}{2}\rho V^2 S_W B \left(C_{Rv} - C_{Rp}\frac{B}{2V} p - C_{Rc}\right) \tag{8}$$

Where M_x is resultant roll moment, C_{RP} is damping moment index, P is Roll Rate, C_{RV} is handling moment index. According to (8), we can obtain Required Actual Roll Rate as below:

$$p = \frac{2\Gamma C_L^\alpha \int_{-\frac{B}{2}}^{\frac{B}{2}} \frac{y^2\left[B - 2|y|(1-\lambda)\right]}{(y^2 + r_c^2)} dy}{\pi C_{Rp} B^4 (1+\lambda)} \tag{9}$$

In the equation, P is Required Actual Roll Rate. It is easy to see that RARR is mainly affected by the residual circulation of leading aircraft (Γ) and design parameters of following aircraft. Relatively speaking, RARR can reflect the severity and safety of wake vortex more objectively and accurately.

E. Calculation and Analysis of Current Separation Safety

In the paper, IRMC and RARR of ICAO current separation criteria are calculated for different combinations of aircraft categories. To gain more conservative results, traversal search method is used, i.e. for a given combination of aircraft categories, all the types of the leading aircraft category are computed, and the same for following aircraft category. Then find the maximum value among all the combinations. And the specific method as shown below.

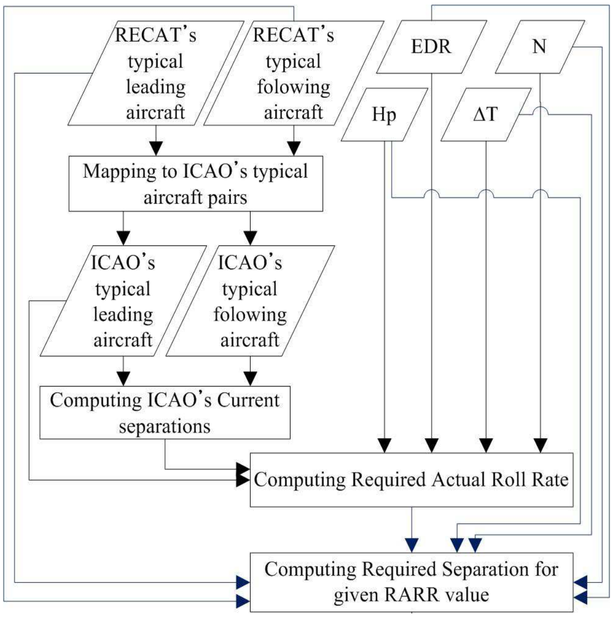

Figure 2. Flow chart for calculating RARR

There are other computational conditions including International Standard Atmosphere, flight height which is less than 300m above ground, aircraft weight which is 85% of Maximum landing weight, and default approach landing speeds.

To satisfy the needs of research, basic data of 60 types of commonly used aircraft are collected, including aircraft type, certificated weight, size of wings, wing aerodynamic coefficient, approach speed, roll moment of inertia, etc.. With the help of the wake vortex separation safety auxiliary computing tool developed by us, IRMC and RARR of ICAO current separation criteria are calculated, and the results are as shown in Fig. 3 and 4.

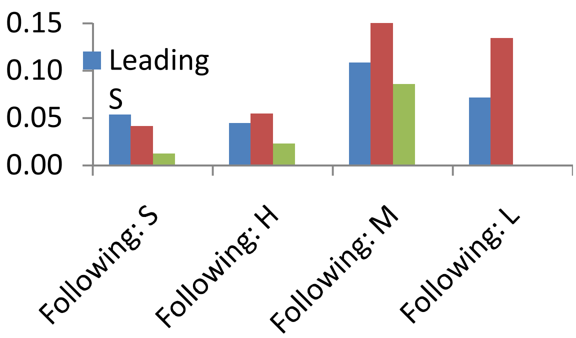

Figure 3. IRMC for different combinations

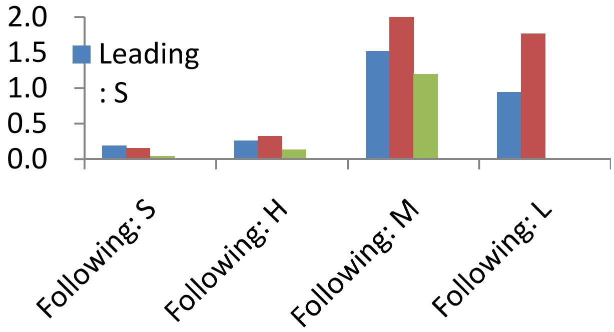

Figure 4. RARR for different combinations

From above, the variations of IRMC and RARR for different combinations have the similar tendency. The results are significantly large in the cases with a Super leading aircraft and a Middle following one, or the cases with a Heavy leading aircraft and a Middle following one, or the cases with a Heavy leading aircraft and a Light following one. This means the current separation is slightly smaller. On the other hand, when the combinations are M-S, M-L, L-H, L-M, M-L and L-L, the IRMC is obviously smaller, which means there is possibility to reduce the separation.

III. AIRCRAFT CATEGORIZATION METHODS

A. Categorization Method Based on Maximum Takeoff Weight

Aircraft can be classified into four categories based on their Maximum Takeoff Weight, then separation criteria for different combinations are defined as shown below.

TABLE I. CALSSIFICATION BASIS OF CURRENT SEPARATION CRITERIA

Categories	***Super***	***Heavy***	***Middle***	***Light***
Weight	Only A380	>=136t	136T>m>7t	<=7t

B. Categorization Method Based on Initial Circulation of Wake Vortex

For RECAT-I and RECAT-EU, categories are defined based on wingspan and weight, which is essentially on the basis of Initial Circulation of Wake Vortex (ICWV). Although this method is more reasonable than the former one, vortex decay and the resistant ability of following aircraft are still not considered.

For RECAT, Heavy aircraft are subdivided into B and C types, and Middle aircraft are subdivided into D, E and F types, the last one of which includes Light aircraft. It is found by NASA that most vortex encounters occur during the phases of final approach and landing[7]. Thus final approach speed and landing weight are chosen to calculate initial circulation for RECAT. Equation (1) is used to find ICWV of commonly used aircraft as shown in Fig. 5.

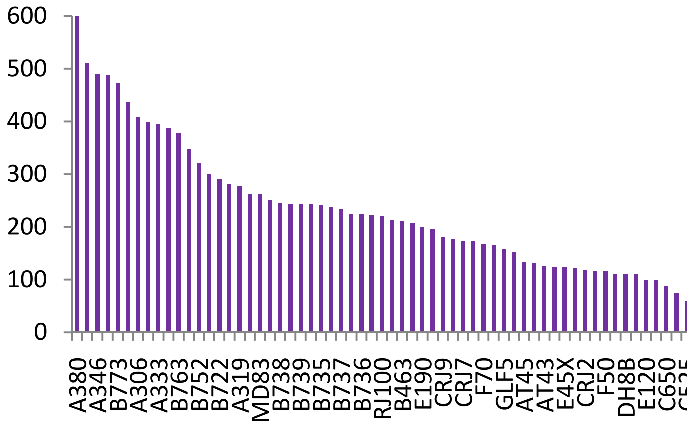

Figure 5. ICWV for different aircraft type

The differences of vortex decays for different aircraft are not discussed in ICWV calculations, neither the response of following aircraft. Therefore, the results are different from actual flight situations. Vortex circulations are calculated by using (4), which decrease in intensity with the increase of distance, and the results are illustrated in Fig. 6 where the abscissa denotes flight distance and the ordinate shows the circulation of wake vortex (m^2/s).

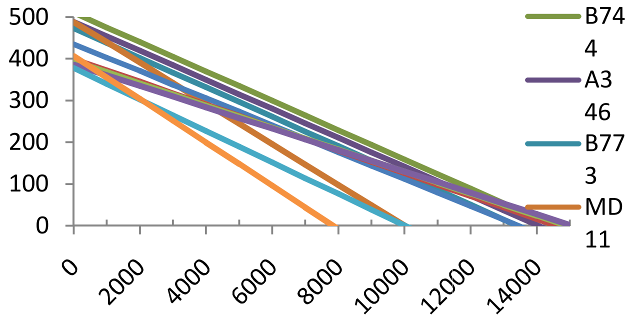

Figure 6. Relationship between circulation and distance

As shown in Fig. 6, circulation of wake vortex decays vary greatly for different aircraft, e.g. ICWV of MD-11 is greater than that of A340-300, but the circulation of MD-11 decays more rapidly, so the circulation is greater than that of A340-300 at the location of 5000 meters away or farther.

C. Categorization Method Based on Required Decay Distance

The method of Initial Circulation of Wake Vortex can not reflect the real impact of vortex on following aircraft, so Required Decay Distance (d_r) derived from (4) can be used to find out the actual influence of wake vortex after a certain decay.

$$d_r = \frac{12\rho\pi v^2 s^3 B^3}{mg}\left(\frac{mg}{\rho v s B} - \Gamma_{\min}\right) \tag{10}$$

Here, d_r is Required Decay Distance (m), Γ_{min} is acceptable minimum wake vortex circulation (m^2/s). Required Decay Distances of some aircraft are calculated and shown in Fig. 7.

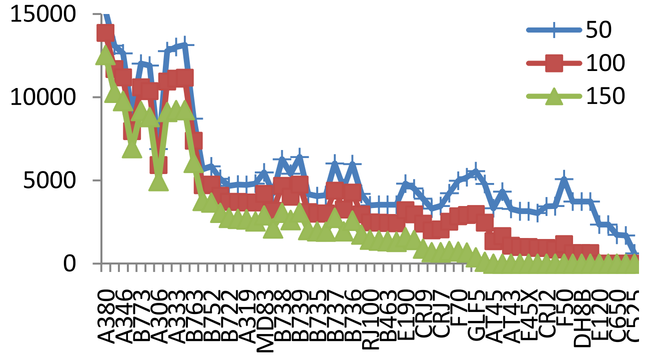

Figure 7. RDD for some aircraft

The same as Fig. 5, the abscissa denotes aircraft types and the ordinate shows RDD. Three curves are corresponding to three minimum wake vortex circulation respectively (i.e. 50 m^2/s, 100 m^2/s and 150 m^2/s). Analyzing RDD data computed and the published separation criteria of ICAO, RECAT-I and RECAT-EU, a new category system is proposed.

TABLE II. BASIC DATA RANGE OF DR FOR RECAT ANALYSIS

Required Decay Distance	***Categories***
dr >=12000m	A
12000m > dr >=10000m	B
10000m > dr >=5000m	C
dr <5000m	D, E, F

According to the resulted *dr* of different aircraft and the reference of Table 2, aircraft can be re-categorized as Fig. 8. In the diagram, Type A is shown in yellow, Type B in purple, Type C in blue, and other types in red.

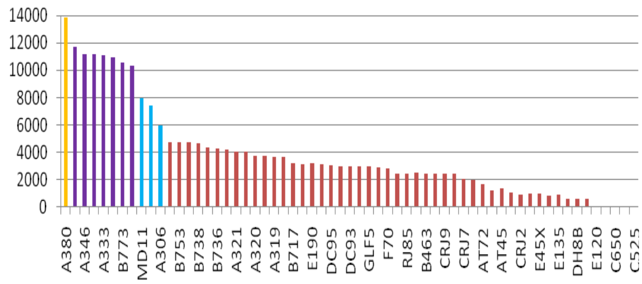

Figure 8. Aircraft's initial categorization based on RDD data

D. Categorization Method Based on Wake Vortex Impedance

Middle and Light aircraft (i.e. Type D, E and F) generate relatively small vortex circulations, thus seldom affect the separation minimum with following aircraft. But the restriction of ATC surveillance system resolution shall be considered. Because of small span, slow speed and less moment of inertia, these aircraft are easily affected by the leading aircraft's wake vortex. Therefore, Middle and Light aircraft shall be categorized based on their resistant ability of Wake Vortex.

To facilitate categorization of Middle and Light aircraft, the concept of Wake Vortex Impedance (WVI) is defined, which means the allowed maximum wake vortex circulation when the damping moment can balance induced moment regardless of handling moment. The following is deduced from (7) and (8).

$$\mu = \frac{\pi C_{Rp} B^4 (1+\lambda)}{2C_L^{\alpha} \int_{-\frac{B}{2}}^{\frac{B}{2}} \frac{y^2 \left[B - 2|y|(1-\lambda) \right]}{(y^2 + r_c^2)} \mathrm{d}y} \qquad (11)$$

Here, μ is Wake Vortex Impedance. Equation (11) is simplified into (12) when neglecting the influence of vortex core.

$$\mu \approx \frac{\pi C_{Rp} B^2 (1+\lambda)}{2C_L^{\alpha} \lambda} \qquad (12)$$

It is shown that Wake Vortex Impedance is related to the aircraft design parameters such as handling moment index, span, taper ratio and lift coefficient slope. By analyzing the results of WVI and the criteria of ICAO, RECAT-I and RECAT-EU, a new classification is proposed.

TABLE III. BASIC DATA RANGE OF μ FOR RECAT ANALYSIS

Wake Vortex Impedance	***Categories***
μ >=800	D
800m > μ >=350	E
μ <350	F

According to the WVI and the criteria above, Middle and Light aircraft can be re-classified as shown in Fig. 9. In the diagram, Type D is illustrated in blue, Type E in red, and Type F in green.

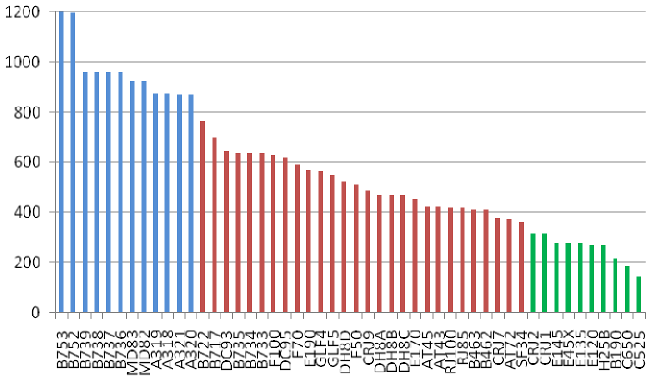

Figure 9. Aircraft's categorization based on WVI

On the basis of Required Decay Distance, Wake Vortex Impedance, and the classification criteria shown in Table 2 and 3, aircraft on service nowadays can be re-categorized as illustrated in Fig. 8 and 9. And the methods above can be used to re-classify the future aircraft.

IV. EFFECTS OF WAKE VORTEX REDUCTION

A. Method of Calculating Separation for Different Aircraft Combinations

For a given leading and following aircraft combination, the required separation minima are affected by many factors such as turbulence, temperature, wind speed, flight altitude, airspeed, and aircraft weight. In order to ensure the applicability of calculated results, eight key parameters are chosen as shown in Table 4. Then based on the wake vortex flow field established and the model for calculating safety indices, the required separation minimum for a given set of parameters can be found for a given leading and following aircraft combination.

TABLE IV. COMPUTING CONDITIONS FOR SEPARATION ANALYSIS

Parameters	***Range***	***Calculation Step***
Temperature	ISA-20 C ~ISA+30 C	10C
Flight Altitude	300m~1800m	300m
Airspeed Increment of Leading Aircraft	10knots~20konts	5konts
Weight Ratio of Leading Aircraft	0.80~0.95	0.05
Airspeed Increment of Following Aircraft	-10knots~20konts	5konts
Weight Ratio of Following Aircraft	0.80~0.95	0.05

To obtain the separation minimum for a given leading and following aircraft category combination, different aircraft types in each category should be defined first, then the required separation for each aircraft type group is calculated, and the maximum value rounded to 1km is selected as the separation minimum for this combination. The comparison between the separation minima of RECAT-NEW, RECAT-I and RECAT-EU are shown in Fig. 10, where the abscissa denotes aircraft category combination and the ordinate shows the separation (km).

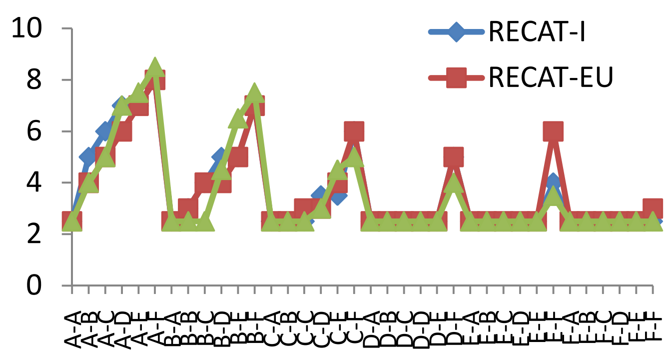

Figure 10. Comparasion of separation minima for different RECATs

According to the diagram, we can conclude that some separation minima of RECAE-NEW are slightly greater than those of RECAT-I or RECAI-EU for some aircraft combinations, e.g. A-E, A-F, B-E and B-F. Therefore, a higher safety level can be maintained when Middle and Light aircraft fly following Heavy or Super aircraft. Meantime, the new separation minima are reduced for some Middle aircraft combinations to improve operation efficiency at airports.

B. Analysis of Required Actual Roll Rate

In order to study the safety of different separation minima in RECAE-NEW, RECAT-I and RECAT-EU, Required Actual Roll Rates (RARRs) for each aircraft combination are calculated and analyzed, as shown in Fig. 11, 12 and 13.

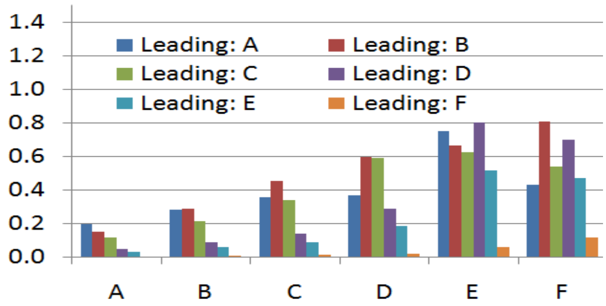

Figure 11. RARR for different combinations (RECAT NEW)

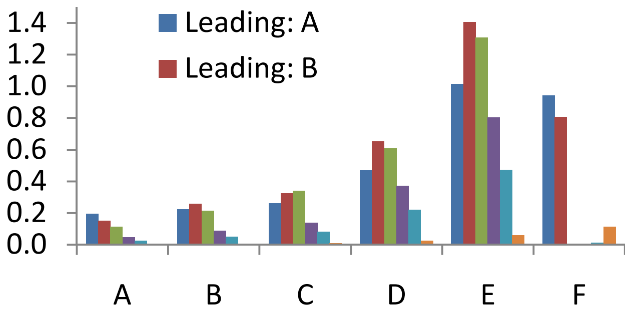

Figure 12. RARR for different combinations (RECAT-I)

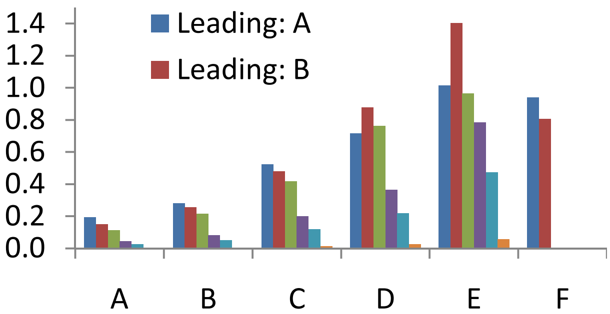

Figure 13. RARR for different combinations (RECAT-EU)

As shown above, compared with the separation criteria of RECAT-I and RECAT-EU, the new separation minima vary slightly in RARRs for different combinations. This means the separation minima are more reasonable and safer.

So as to better analyze the difference of RARRs for differed combinations, the average RARRs and mean square deviations are computed as below.

TABLE V. STATISTICAL DATA FOR DIFFERENT STANDARDS

Statistical data	***Separation Criteria***			
	ICAO	***RECAT-I***	***RECAT-EU***	***RECAT-NEW***
Average	0.540	0.318	0.334	0.315
mean square deviation	0.696	0.385	0.389	0.252

C. Analysis of Weighted Calculation of Separation Criteria

To study the effect of the new separation criteria on airport capacity improvement, takeoff and landing data of 60 types of commonly used aircraft at a certain airport are collected, and the weight coefficients of aircraft combinations are obtained. Then the weighted separation is computed to assist the analysis of capacity improvement. The equation is as below.

$$d_w = \sum_{i=1}^{60} \sum_{j=1}^{60} p_i p_j d_{ij} \tag{13}$$

In the equation, d_w is the weighted separation (m), i is the type number of leading aircraft, j is the type number of following aircraft, p_i is the weight coefficient of leading type, p_j is the weight coefficient of following type, d_{ij} is the separation derived from the leading and following aircraft types.

TABLE VI. BENEFIT VALUES OF DIFFERENT SEPARATION CRITERIA

Parameters	***Separation Criteria***			
	ICAO	***RECAT-I***	***RECAT-EU***	***RECAT-NEW***
Weighted separation	5136	5026	4995	5023
Improvement of capacity	0.00%	2.14%	2.74%	2.20%

V. CONCLUSION

The methods of aircraft re-categorization, the way to determine the minimum acceptable level of safety, and the calculations of required wake vortex separation minima are studied systematically in this paper. It is concluded that:

a. An appropriate increase of aircraft categories can reduce wake vortex separation and improve airport operation efficiency without decreasing safety level.

b. The terms of required decay distance and wake vortex impedance proposed in this paper can reflect the influence of wake vortex circulation of leading aircraft and the responses of following aircraft, which helps to approve the reasonability of the new categorization above.

c. The proposed wake vortex separation criteria can ensure the flight safety of Middle and Light aircraft following Super or Heavy aircraft. While for the combination of Middle aircraft, the separation minima are reduced to increase the airport operation efficiency.

d. The comparisons between RECAT NEW RECAT-I and RECAT-EU show that the required actual roll rates are more balanced and reasonable for different aircraft combinations. And the improvement of airport capacity is approximately same as that of RECAT-I and RECAT-EU.

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