

Progress on Joint FAA/Eurocontrol Effort to Develop an ICAO Wake Turbulence Re-Categorization

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Abstract--Planned improvements in Air Traffic Management, as described by NextGen in the US and SESAR in Europe, have a common goal of enhancing capacity and harmonizing separation standards. Wake vortices are a product of lift from aircraft and are one of the major constraints in the reduction of separation standards that are one of the solution avenues that NextGen and SESAR are pursuing in the goal for increased capacity. The existing separation standards based on wake turbulence are significantly different between the US and ICAO. Furthermore, both the ICAO and US categories, and associated separation minima among the categories, represent two very safe systems but are optimized for fleet mixes that existed 15 or more years ago. As an example, the last re-categorization effort in the US was performed in 1994. Better knowledge of wake behavior obtained through research and improved sensors that measure wake turbulence provide an opportunity to develop a new set of common categories that provide the same or increased safety over the existing US and ICAO categories while optimizing for current and future traffic demands in the US and Europe. This paper describes a joint FAA/EUROCONTROL methodology for developing and evaluating new candidate wake turbulence categories. The paper provides examples and rough estimates of capacity gains that some examples show over today's US and ICAO categories. Finally, the paper highlights the key steps yet to be completed in achieving a joint recommendation to ICAO in 2010.

Keywords: Wake turbulence, wake vortex, separation standards, re-categorization

I. INTRODUCTION

Current predictions indicate that by 2025, air traffic will double. If the goal is to move towards NextGen and SESAR, it is obvious that a change to current separation standards is required. One way to affect a change to current separation standards is to address the current wake categories in use today. The ICAO standards today for the three wake categories have been in use for many years. The United States last re-categorized in 1994, while in Europe there are some 17 different variations of wake separations.

Wake vortices are a natural by-product of lift generated by aircraft and are one of the major constraints on separations between aircraft pairs. An aircraft exposed to the wake vortex circulation of another aircraft can experience an aerodynamic upset, which it may or may not be able to correct with its control authority, especially when the aircraft is close to the ground. For this reason, numerous Air Traffic Control (ATC) separation standards include consideration of wake vortex behavior, defining the separation at which operations can be conducted with little or no wake vortex hazard. These separation standards have served us well in that there has never been a fatal accident in the U.S. due to wake vortex when instrument flight rules (IFR) separations are being applied.

Wake vortex behavior is strongly dependent on ambient weather conditions. In certain conditions, such as calm winds without turbulence and with little or no stratification, wake vortices linger and last longer than with stronger atmospheric turbulence or stronger stratification. Separation standards and ATC procedures have been designed for the worst-case conditions within a specific category based on aircraft weight. In the last decade, the FAA and NASA have performed wake vortex studies which have greatly increased our knowledge of wake vortex evolution. This new knowledge will be applied to the proposed methodology for developing new wake turbulence categories and associated separation minima.

II. METHODOLOGY

A wake vortex methodology has been developed which incorporates an encounter hazard model and a wake vortex decay model, which, when used with aircraft control authority, results in separations for each aircraft pair. We calculate the vortex strength of the vortex from the lead aircraft based on current ICAO separations and assume these circulations are acceptably safe in the current NAS. From these circulations, we can re-group aircraft into different groupings to determine the optimum groupings for a given number of aircraft categories.

Fig. 1 shows a block diagram of the methodology used in this study. Relevant characteristics of the aircraft to be used in

the re-categorization are given in a database. These characteristics include physical characteristics, such as Maximum Take-Off Weight (MTOW) and wingspan, as well as performance characteristics, such as approach speed. These aircraft characteristics are used both (i) to determine the strength of the wake vortices with time using the aircraft as a leader and (ii) in an encounter hazard model, such as the NASA 1-degree of freedom (1-DOF) encounter model [1], to determine the worst-case or near worst-case result of the aircraft encountering a wake vortex of a given strength.

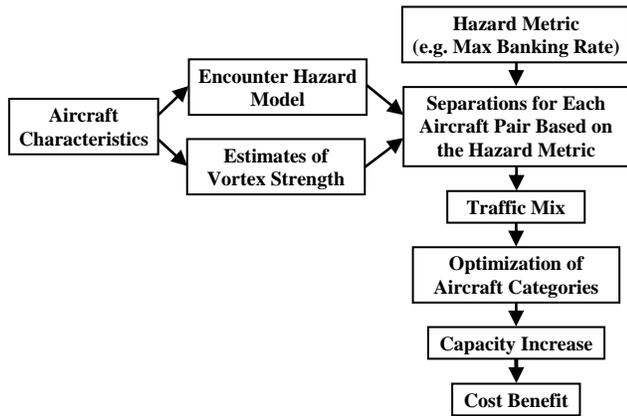


Figure 1. Flow chart showing the re-categorization methodology.

To estimate the strength of the wake vortices with time, we can use either numerical wake vortex models or field measurements of wake vortices behind aircraft. One such plot of field measurements is shown in Fig. 2. This plot shows non-dimensional wake strength on the vertical axis (the vortex strength at a given time after generation divided by the initial vortex strength) and non-dimensional time on the horizontal axis. We use non-dimensional parameters in order to plot many different aircraft on the same graph.

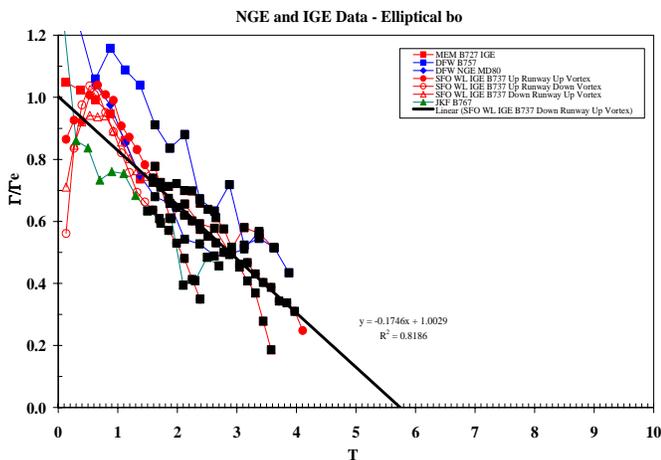


Figure 2. A circulation decay model derived from observed data. The linear decay rate was computed based on vortex data from 5 different aircraft at 4 airports using 2 different wake vortex measurement sensors.

Fig. 2 shows the median circulation strength vs. time for 5 aircraft (ranging from MD80 to B767) from 4 different airports (Memphis, DFW, San Francisco, and JFK). The black squares show the data for non-dimensional times from 1.5 to 4, and the

solid black line is a linear least squares fit to the black squares. In the examples shown in this paper, we use the solid black line in Fig. 2 to estimate vortex strength behind each aircraft as a function of dimensional time. Because the methodology shown in Fig. 1 is modular, we are not constrained to use the linear least squares fit shown in Fig. 2, and we can easily use any circulation decay model or estimate to see the effect on the final re-categorization categories.

Fig. 3 shows comparisons of two 1-DOF models with measurements from Condit and Tracey [2] for a B737-100 following a B747-100. The vertical axis in Fig. 3 is the roll angle (in degrees) times the wingspan (in feet), and the horizontal axis is the vortex induced rolling moment coefficient. The solid curved line is a second order fit to the model predictions using the Condit and Tracey data for the NASA 1-DOF model [1] and the dashed curved line is a second order fit to the model predictions using the Condit and Tracey data for an FAA 1-DOF model [3]. Both 1-DOF models show similar predictions. The NASA 1-DOF model, used for most of the results in this paper, assumes the aircraft is initially centered in the vortex core and that the pilot response time and the vortex encounter time are both user-defined. A value of 0.6 sec was used for both these times. In Fig. 3, we are most interested in the region where the vortex induced rolling moment coefficient is less than 0.05 to 0.07, since, for larger values, the vortex induced rolling moment might exceed the roll control authority of the aircraft.

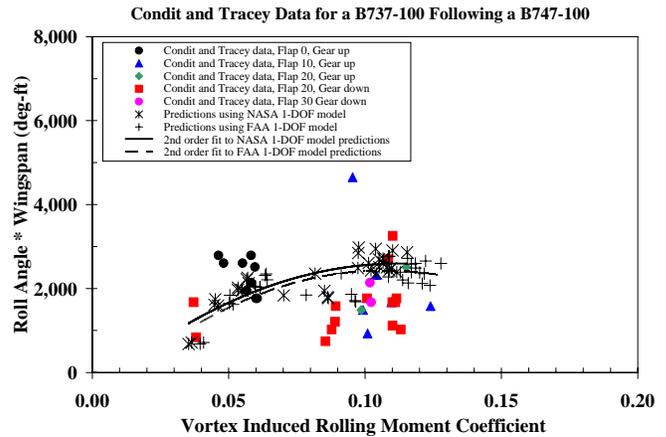


Figure 3. Symbols show data from Condit and Tracey [2] and curved lines show the predictions from two 1-DOF encounter models [1, 3].

Fig. 3 shows that the two 1-DOF models give similar predictions using the data of Condit and Tracey, and that the data is fairly well represented by the model predictions.

The hazard metric in Fig. 1 can be based on maximum bank angle, maximum roll rate, or any other parameter estimated by the hazard model. In this paper, we will use maximum bank angle. Given the aircraft characteristics, an estimate of vortex strength with time, an encounter model, and a hazard metric, we can calculate the separations for each aircraft pair. For N aircraft (e.g., 30 aircraft), there are N^2 (900 for 30 aircraft) combinations of leader-follower pairs, giving an N by N separation matrix (30 by 30 matrix for 30 aircraft). Two examples will be given in Section III.

Both uniform and non-uniform traffic mixes are being evaluated for their respective influence on the resulting optimized set of categories. The similarities and differences in the resulting optimized categories will provide a measure of the robustness of any final recommended wake turbulence separation matrix to changes in fleet mix that may arise from operator and aircraft manufacturer decisions. This effect can be seen in some of the following examples.

Examples of the optimization of aircraft categories are given in the next section. Each grouping into categories gives a capacity increase (or decrease), with only one grouping being the best optimization. Using this best optimization (or any other grouping), a cost benefit can then be determined.

III. EXAMPLES OF RESULTS

In this section, we use the methodology described in Section II in three examples. In the first example, we will illustrate the methodology using 5 aircraft and 3 categories to explain the procedure. Next, we will show the results of using 30 aircraft with a non-uniform traffic mix and 4, 5, and 6 categories to show the increase in capacity due to increasing the number of categories. Finally, we will show the results of using 30 aircraft with a uniform traffic mix to show the effect of traffic mix. The methodology will ultimately be used with 60 or more aircraft comprising more than 80 percent of the current and projected traffic in both the US and Europe.

To illustrate the methodology, we start with 5 aircraft, numbered 1 through 5, and show how we group these aircraft into 3 categories. We assume the traffic mix is uniform for this example. For definition purposes, a "category" means a collection of aircraft (for example, we want to end up with 3 categories). On the other hand, a "group" refers to a selection of individual aircraft that are placed into a category. Therefore, we "group" the aircraft into "categories," then find the optimum grouping.

To begin, we sort the five aircraft either by some characteristic (e.g., MTOW, wingspan, etc.) or based on previous knowledge (see below). For this example, we will assume that the sorting was done by aircraft weight, with aircraft 1 being the heaviest aircraft and aircraft 5 being the lightest aircraft. We then group these (sorted) aircraft into 3 categories, with the requirement that each category contains at least 1 aircraft.

In Fig. 4, each line shows a possible grouping for 5 aircraft and 3 categories. On each line, each color represents a different category. For example, on the first line, the first category is represented by aircraft 1, the second category is represented by aircraft 2, and the third category is represented by aircraft 3, 4, and 5. On the second line, the first category is represented by aircraft 1, the second category is represented by aircraft 2 and 3, and the third category is represented by aircraft 4 and 5. Fig. 4 shows that there are 6 possible groupings of 5 aircraft into 3 categories, with the requirement that we maintain the sorting and that each category has at least 1 aircraft.

1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5

Figure 4. Six possible groupings using 3 categories and 5 aircraft. Each line represents a different grouping and each color represents a different category.

The next step is to optimize the groupings. An example of this procedure is shown in Figs. 5 and 6 for the fourth grouping shown in Fig. 4 (the fourth line in Fig. 4 shows the first category represented by aircraft 1 and 2, the second category represented by aircraft 3, and the third category represented by aircraft 4 and 5).

Follower=>	1	2	3	4	5
Leader 1:	4	5	6	7	8
Leader 2:	4	4	6	6	7
Leader 3:	3	4	6	6	7
Leader 4:	3	4	5	6	6
Leader 5:	3	4	4	5	5

Figure 5. An example of a separation matrix for the fourth grouping shown in Figure 4. Each color represents a different category.

Fig. 5 shows the separation matrix for our 5 aircraft. We derive this separation matrix using our aircraft characteristics (e.g., leading aircraft approach speed, weight, etc), an encounter model, an estimate of vortex circulation decay with time, and a hazard metric. We read the matrix in Fig. 5 in the following way. If aircraft 1 (the heaviest aircraft in our example) is both the leader (left-most column) and the follower (top row), the separation is 4 nm. If aircraft 1 is the leader and aircraft 5 (the lightest aircraft) is the follower, the separation is 8 nm.

Since each category can have only 1 separation, we replace the original separations between aircraft pairs in Fig. 5 with the maximum separation within a category. (We must use the maximum separation in each category since smaller separations are not allowed for aircraft with larger original separations.) For example, the upper left category shown in red in Fig. 5 (leader aircraft 1 and 2 and follower aircraft 1 and 2) has separations of both 4 and 5 nm. For this category, we replace all separations with the largest separation, 5 nm in this example. This replacement is shown in Fig. 6. We repeat this procedure for all the categories in Fig. 5, which results in the revised separation matrix shown in Fig. 6. To compute the "cost" of this grouping, we compute the total distance required to accommodate all aircraft pairs for this aircraft grouping combination. In this example, we add up all 25 separations in Fig. 6. For each of the 6 possible groupings in Fig. 4, we get a revised separation matrix like that in Fig. 6, and we can compute a "cost" associated with that grouping. The optimum

grouping, then, is that grouping with the minimum total distance (minimum cost).

Follower=>	1	2	3	4	5
Leader 1:	5	5	6	8	8
Leader 2:	5	5	6	8	8
Leader 3:	4	4	6	7	7
Leader 4:	4	4	5	6	6
Leader 5:	4	4	5	6	6

Figure 6. Revised separation matrix for the 3 categories shown in Fig. 5.

We now look at an example using 30 aircraft rather than just 5 aircraft. We will also use a non-uniform traffic mix determined from observed arrival demand at some capacity constrained airports in the US and Europe. Fig. 7 shows the original sorting for 30 aircraft representative of today's fleet. This sorting could be on wingspan, maximum landing weight, or any other way of sorting, including manual sorting based on expert judgment. Using the circulation decay model shown in Fig. 2 and the NASA 1-DOF model, we can calculate the total distance for all possible groupings for these 30 aircraft. For 6 categories, the results are shown in Fig. 8.

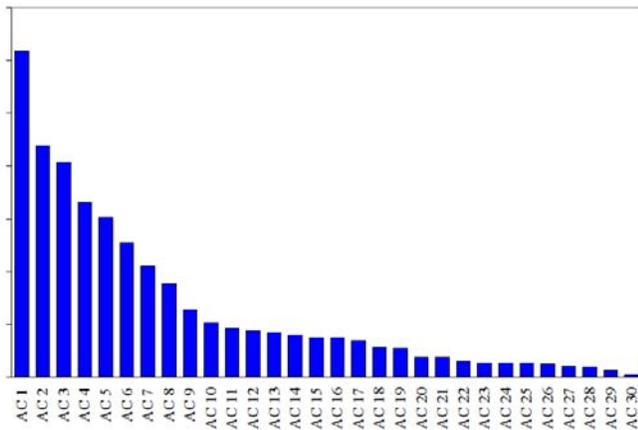


Figure 7. Original sorting for the 30 aircraft example.

In Fig. 8, the red line indicates that we have used 6 categories (right vertical axis). Each grouping gives a total distance, like in the 5 aircraft example, which is plotted using the left vertical axis. From the horizontal axis, we see that there are nearly 120,000 possible groupings for these 30 aircraft and 6 categories. The worst possible grouping happens to be, in this example, the final grouping on the right, where the total distance is around 5,700 nm. In contrast, the best grouping (the minimum total distance) is around the 12,000th grouping, and the total distance for that grouping is around 2,600 nm. The non-uniform traffic mix assumption is used in the computation of these “costs.” The black dot at the first relative grouping and a total distance of 2,500 nm represents dynamic spacing. Thus, for this example, the optimum grouping is not far from dynamic spacing.

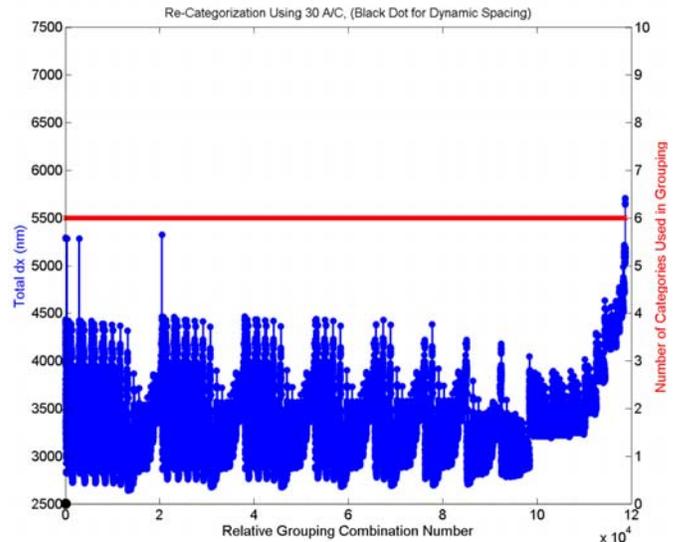


Figure 8. All possible groupings for 6 categories with 30 aircraft and their total separations.

The optimum grouping shown in Fig. 8 is displayed in Fig. 9. In this figure, bars with the same color represent the same category. Thus, the red bar is one aircraft in one category, and the seven blue bars represent seven aircraft in the next category. Note in Fig. 8 that there are several groupings with a total distance nearly as small as that of the optimum grouping. These groupings represent small modifications to the optimum grouping, such as shifting a single aircraft from one category to an adjoining category.

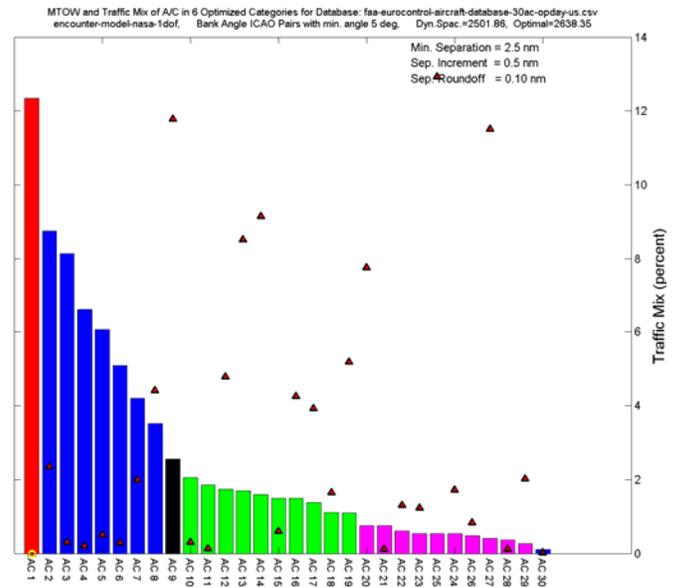


Figure 9. Example of 6 optimized categories with 30 aircraft. Bars with the same color represent the same categories. The traffic mix is shown for each aircraft with red triangles (right vertical axis).

The traffic mix we used for this 30-aircraft example was a non-uniform traffic mix shown in Fig. 9 by the triangles, which go with the scale on the right vertical axis. Note from the traffic mix that several aircraft are very frequent, such as aircraft 9, while other aircraft are very rare, such as aircraft 10 and 11.

Fig. 10 shows the 6 optimized categories for the same 30 aircraft using a uniform traffic mix. Most of the boundaries between the categories remain the same as those for the non-uniform traffic mix. However Aircraft 8 is added to Aircraft 9 in the third category (black bars in Figs. 9 and 10) for the uniform traffic mix, instead of just a single aircraft (Aircraft 9) for the non-uniform traffic mix. This example illustrates that traffic mix has some effect in the re-categorization.

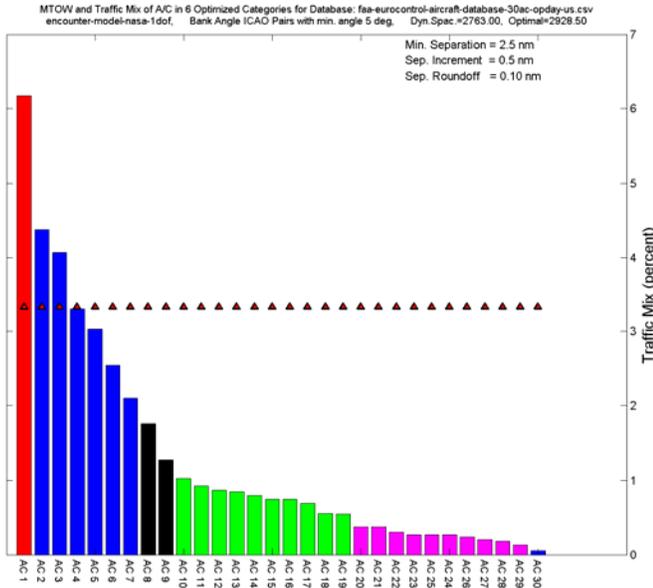


Figure 10. Example of 6 optimized categories with 30 aircraft using a uniform traffic mix. Bars with the same colors represent the same categories. The traffic mix is shown for each aircraft with red triangles (right vertical axis).

The software tools discussed above can be used to easily evaluate different scenarios. For example, we can use the 30-aircraft database above and determine the increase in capacity due to a variety of reasons. Under current ICAO separations, if the following aircraft in an aircraft pair is far enough behind the lead aircraft, the circulation decay curve shown in Fig. 2 would predict that the circulation is zero or low, resulting in a zero or near-zero bank angle following a vortex encounter. If we arbitrarily raise the minimum bank angle to 3 degrees and calculate the increase in capacity using 4, 5, or 6 aircraft categories, the result is the blue curve in Fig. 11. Similarly, if we raise the minimum bank angle to 5 degrees, the result is the red curve in Fig. 11. These results show that capacity increases of 3 to 8 percent are achievable using non-zero worst-case bank angles and current ICAO separations. Other scenarios are currently being explored, along with increasing the database to over 60 aircraft.

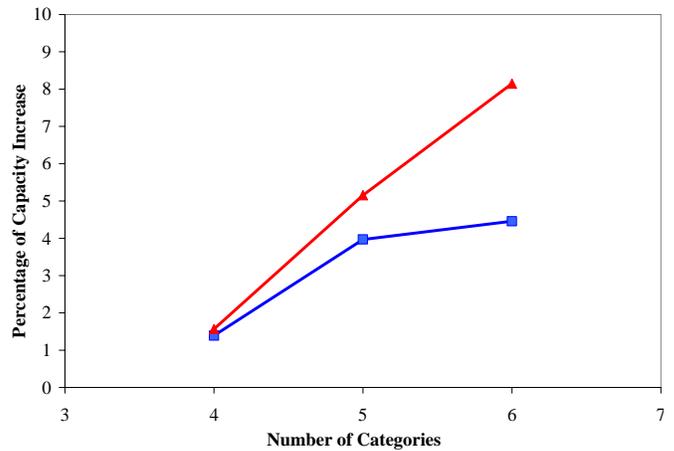


Figure 11. Percentage of capacity increase over the current ICAO separations for minimum bank angles of 3 (blue) and 5 (red) degrees, respectively.

IV. DISCUSSION

High level observations can be made from the examples provided earlier. In particular, while optimized categories are somewhat sensitive to differences in peak demand in the US versus those in Europe, a common wake category matrix and associated separation minima appear to be achievable. This matrix will provide measurable capacity gains at constrained airports in the US and Europe.

The re-categorization effort is ongoing and has a tentative schedule reflected in Fig. 12. The next steps critical to successful re-categorization are listed below:

- Complete the analysis for all 60+ aircraft,
- Perform all tradeoff analyses for multiple wake encounter models,
- Perform all tradeoff analyses for multiple wake decay models,
- Develop the business case for the resulting proposed recommendations to ICAO,
- Evaluate existing controller decision support tools for suitability in supporting implementation of the recommendations to ICAO, and
- Complete the safety case and other supporting documentation.

This effort to develop a new static set of aircraft wake categories and associated separation minima is an early evolutionary step towards NextGen and SESAR. The final step, dynamic pair-wise separation supported by Trajectory Based Operations, envisioned in the far term, is common to both NextGen and SESAR. An intermediate evolutionary step is envisioned that will provide airport-specific optimized static wake turbulence categories. This step will take into account the airport-specific fleet mix and provide further capacity by optimizing for the aircraft that constitute the local arrival and departure demand.

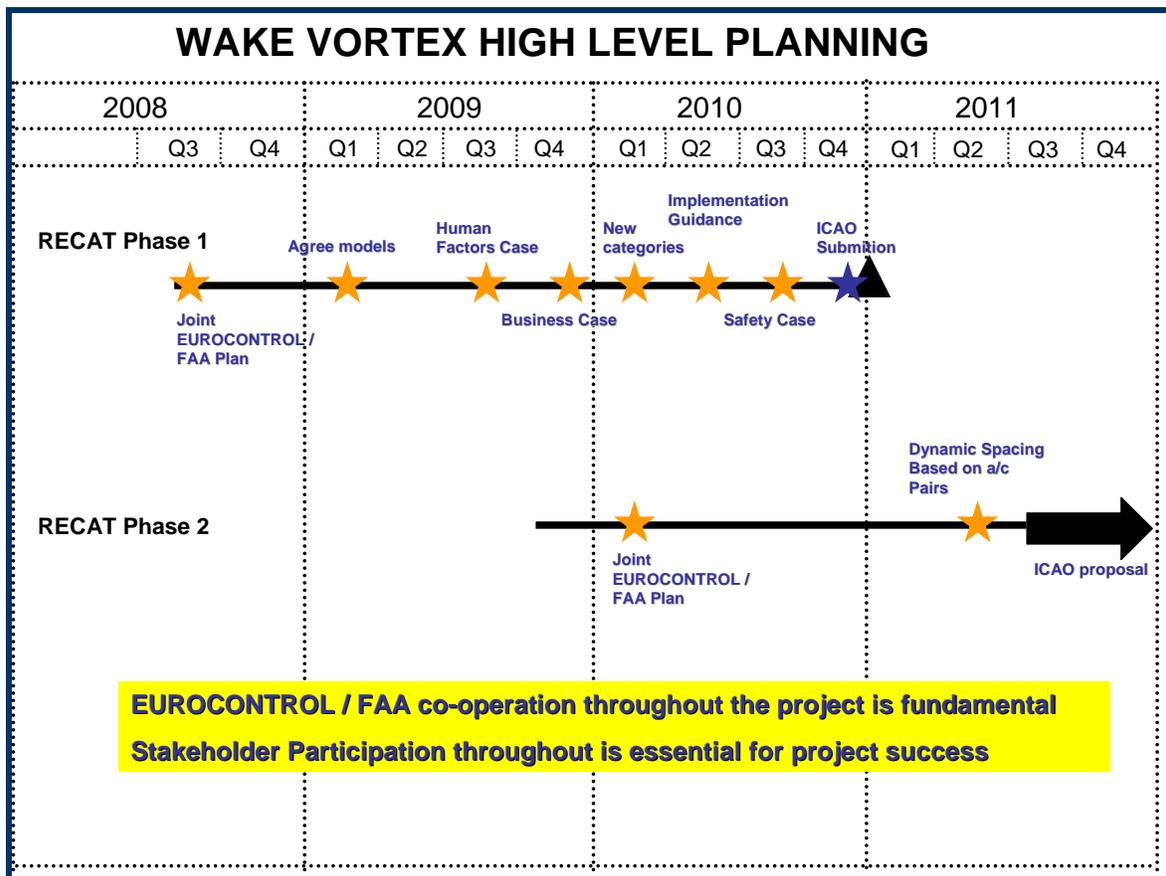


Figure 12. Tentative schedule for completion of the re-categorization study.

ACKNOWLEDGMENT

We thank Stephen Barnes, Elsa Freville, James Hallock, Shahar Ladecky, Clark Lundsford, Jean-Pierre Nicolaon, and Vincent Treve for their participation and insight in technical discussions. We also thank Wayne Bryant and Paul Wilson for guidance and direction.

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