An Analysis of En Route Wake Turbulence Behavior based on In-Flight Measurements

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Abstract

The recent incident involving the encounter of an Airbus A380 wake vortex by a Challenger 604 has drawn attention to the potential hazard of wake vortices en route. To broaden the understanding of the risks associated with en route vortex systems, the FAA in collaboration with the National Research Council of Canada (NRC) has collected high altitude wake turbulence data. An analysis of wake vortex fields based on such in-flight measurements has shown that wake turbulence may exist at distances well beyond minimum separation. The strength of these vortices, as well as transport and decay rates, was found to be highly dependent on atmospheric conditions. A study of historical weather data provided herein suggests that the likelihood for atmospheric conditions that trigger a wake encounter increases as longitudinal separations are reduced. Implementing wake mitigation strategies may allow increasing NAS capacity without compromising safety. Along track separation increases, altitude changes or lateral offsets are discussed as potential mitigations that may be useful in avoiding wake turbulence.

Introduction

Reducing en route longitudinal separation is a natural step in increasing the capacity of the National Airspace System (NAS). However, wake turbulence upsets are a limiting factor when considering the implications of new separation standards. Wake upsets continue to be reported at in-trail distances well beyond the minimum separation. Maintaining or improving current levels of safety while increasing capacity requires an assessment of the behavior and transport of wake vortex fields. Conversely, a lack of measured data at high altitudes has limited the understanding of aircraft vortex behavior during the en-route phase of flight. To address this data gap, the Federal Aviation Administration (FAA), in collaboration with the National Research Council of Canada (NRC) has collected high altitude aircraft vortex data. The data was collected by directly measuring wake vortex wind fields when in-trail of commercial transport category aircraft. This research presents a study of the atmospheric conditions that increase the potential for an encounter based on transport and behavior of vortex fields. In scenarios where wake turbulence avoidance is necessary, mitigation options are discussed such as altitude changes, vectors off route or procedural maneuvers in oceanic airspace. A need exists for a more complete understanding of wake turbulence behavior in the upper atmosphere and also for mitigation procedures that offer the optimum efficiency and enable wake safe head-on passing and in-trail altitude changes.

In-Flight Vortex Wind Field Measurements

The high altitude wake measurements were conducted by the NRC using a retrofitted CT-133 aircraft equipped with research grade sensors. Each of the data collection flights were conducted behind large, heavy or super heavy weight class transport aircraft in revenue service. The flights were coordinated with ATC to ensure minimum separation at the start of the data collection. As the run progressed, the separation between the CT-133 and the generating aircraft increased as an artifact of the speed differential between the two aircraft. To visually identify the location of the vortex pairs and ensure that measurements were obtained by intercepting the vortices, the condensate trail was used as a marker. Analysis of these vortex systems has enabled an estimation of their overall circulation strength, decay rate and descent.

A sample set of vortex intercepts is presented in **Figure 1** with corresponding in-flight cockpit imagery from the measuring aircraft. A Google Earth depiction of the generator and measuring aircraft paths along with the vortex system trajectory was produced using WakeWISE, a 4-D probabilistic modeling tool developed by the National Center of Excellence for Aviation Operations Research (NEXTOR). WakeWISE utilizes the position data for both aircraft along with the measured atmospheric parameters and generates a probabilistic estimate of the wake vortex transport. Because the model also accounts aircraft characteristics, it is able to estimate the strength of the vortex pair. In this example, vortex wind fields were measured nearly 20 nautical miles in-trail of the generating aircraft.

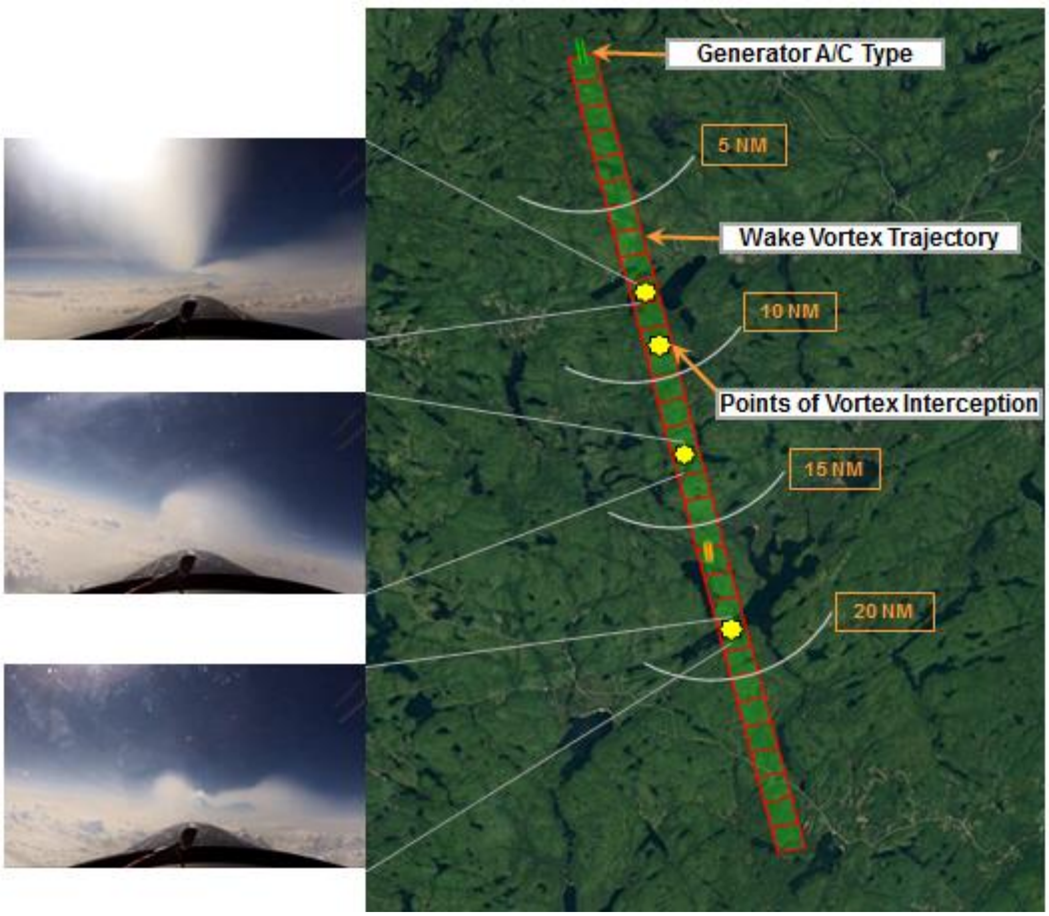

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Figure 1: In-Trail Wake Vortex Trajectory

Wake Vortex Characteristics and Behavior

Wake vortices are a result of the pressure difference between the top and bottom surfaces of the aircraft wing. The higher pressure air from beneath the wing flows around the wingtips, and due to the forward movement of the aircraft, forms two counter-rotating vortices that are transported with the air mass. By decomposing the measured winds on the cross-sectional plane of the vortex system, it is possible to define the vortex and analyze its behavior and strength. Using the in-flight data collected by the NRC, vortex crossings were defined by rapid changes to winds in both the vertical Z-axis and the lateral Y-axis, as diagrammed in **Figure 2**.

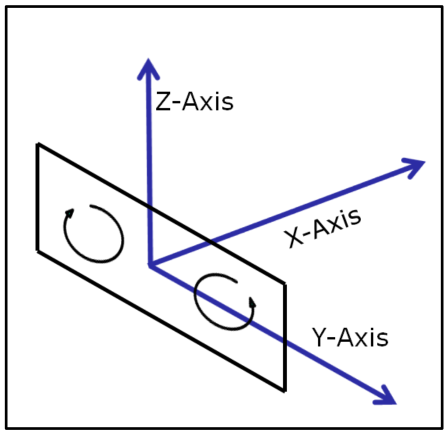

Figure 2: Axis Orientation

In **Figure 3**, the distinct shapes of vertical winds that define a vortex system are illustrated. The left vertical wind plot is an example of winds measured during a horizontal traverse of the left and right wing tip vortices, while the right vertical wind plot is typical of a single vortex core.

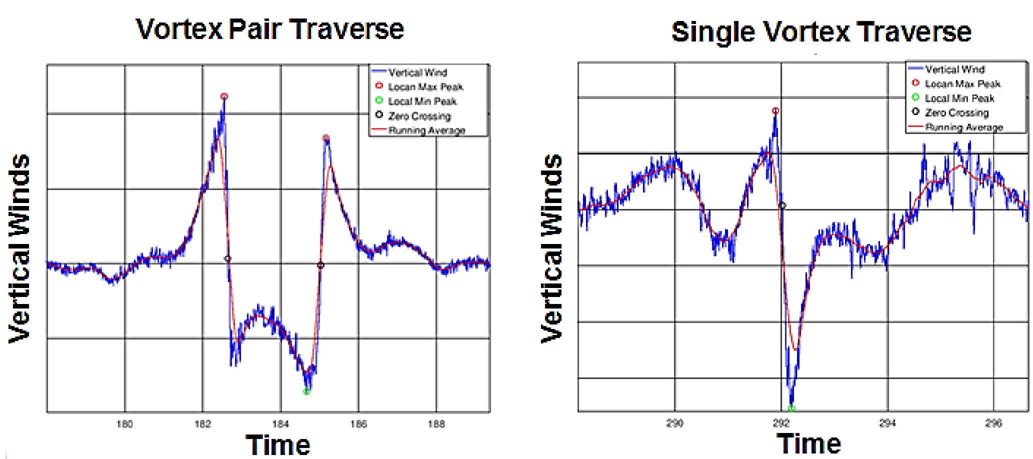

Figure 3: Vertical Wind Component Plots

The vortex pair is transported with the surrounding air mass and simultaneously begins to descend below the altitude of the generating aircraft's trajectory. Typically, wake vortices decay over a period of 2-3 minutes to near “background” turbulence levels. However, the analysis of high altitude wake vortex data provided by NRC has demonstrated that, in some instances, significantly strong vortex cores exist at distances in trail well beyond current separation minimums. Descent and decay rates can also vary, depending on atmospheric conditions, making precise predictability difficult.

Wake Vortex Transport

Under most wind conditions the vortex windfield is drifted with the air mass away from the operating route before a trailing aircraft reaches a point of interception. For the basis of this analysis, the wake is required to drift a distance larger than the pair-wise cross-track navigational positional uncertainty to completely clear the operating route. This distance is notionally assigned for the purposes of this paper as 0.3NM. Wind speed variability, which is also a factor, is not included in this estimate.

Because the wake is drifted with the air mass, the wind component perpendicular to the operating route is the key factor in determining the rate of cross-track transport. An analysis was conducted to calculate the crosswind velocity that transports wake turbulence away from a primary navigation route. The specific conditions for this analysis take the following variables into consideration: pair-wise separation distance, operating speeds, and a notional 0.3NM cross-track drift distance.

In **Figure 4**, the minimum threshold crosswind velocity to transport the wake turbulence away from the operating route was calculated for a set of ground speeds, varying from 300 to 450 KTS, and distances in trail between 3 and 20 NM.

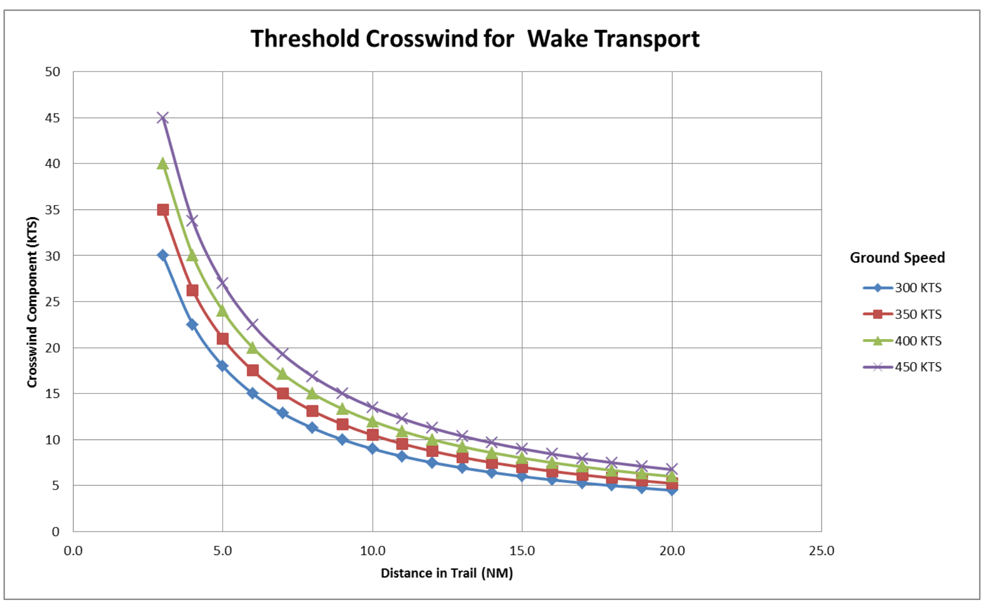

Figure 4: Threshold Crosswind Analysis

While the likelihood of these wind conditions to exist in combination with decay and descend rates that result in an encounter is minimal, it can be observed that in general, as separation distances are reduced, a higher crosswind is required to transport the wake away from the operating route.

Historical Wind Frequency Analysis

An analysis was performed to assess cross-track winds on select high altitude jet routes. Historical wind reports were analyzed to assess the frequency of cross-wind velocities that would not transport the wake away from the operating route on the previously presented scenarios. The route segments used for analysis were selected between four city pairs that might be expected to absorb high volumes of air traffic and that were also located in geographically diverse areas of the Continental United States (CONUS). The selected routes were situated in the Mid-Atlantic, Northeast and Western seaboards of the CONUS. A weather reporting station located in close proximity to each route segment was identified in order to obtain a dataset of historical winds and atmospheric conditions.

A section of the aviation chart depicting the route segments utilized for the analysis and their associated weather station locations is presented in **Figure 5**.

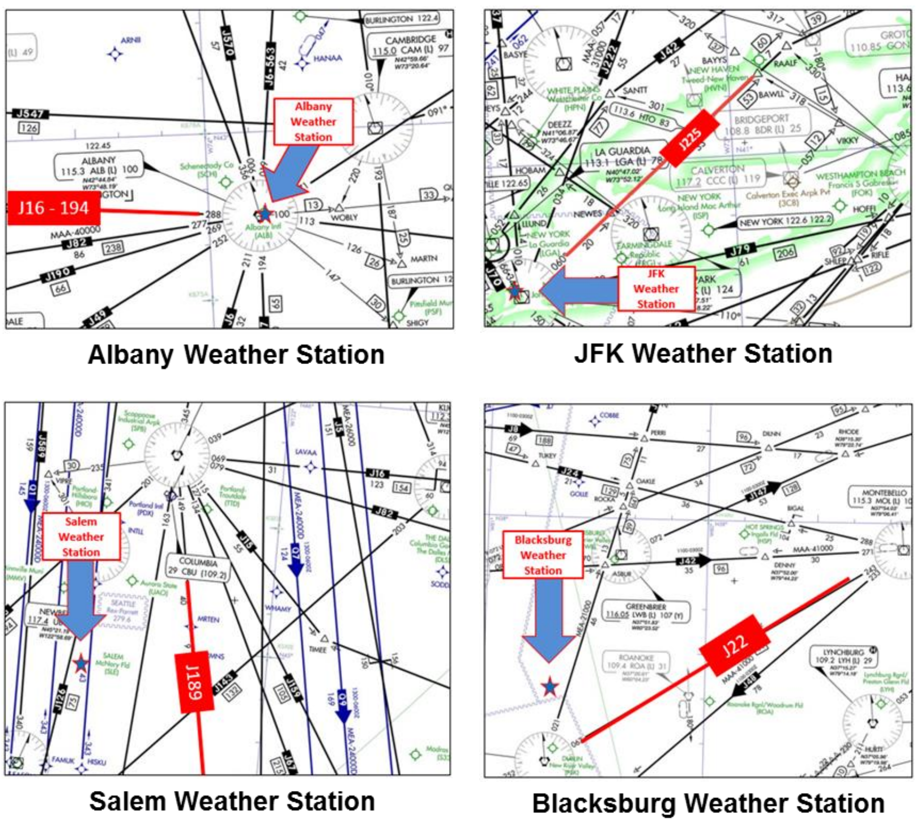

Figure 5: Route and Weather Station Selection

Radiosonde weather balloon data was obtained for pressure altitudes of 200, 300, 400 and 500mb for a reporting period of 10 years. In the example below, a crosswind component of 5KTS was used as the minimum velocity to transport wake away from the operating route. The data sets were parsed to determine the number of instances when reported winds resulted in crosswind components less than the calculated value. **Table 1** presents a summary of the recorded wind data reported as the percentage of instances when the crosswind component of the reported winds was calculated as 5 knots or less.

Pressure Reading (mb)	Altitude (ft)	Station			
		ALB	Blacksburg	JFK	Salem
500	18,300	17.0%	16.8%	9.6%	10.7%
400	23,500	14.6%	13.9%	9.7%	8.8%
300	30,000	11.5%	11.9%	7.5%	7.7%
200	38,700	12.3%	9.6%	6.1%	6.8%
Average Across All Altitudes		**13.8%**	**13.0%**	**8.2%**	**8.5%**

Table 1 Radiosonde Readings - Crosswind ≤ 5KTS

Besides crosswinds, same route wake encounters are also dependent on aircraft positional uncertainty, operating speed and atmospheric conditions, and require a comprehensive evaluation to accurately assess likelihood.

Wake Encounter Scenarios

Aircraft Operating In Trail

For aircraft operating en route and in trail of other aircraft, the greatest wake turbulence risks are anticipated to occur during altitude changes. A common wake encounter scenario is presented on Figure 6. An aircraft pair is operating on the same route and the trailing aircraft is executing a change in altitude. The leading aircraft generates a wake vortex that descends through the altitude of the trailing aircraft. When atmospheric conditions are such that do not drift the wake away from the operating route, the trailing aircraft is at higher risk of encountering the vortex field.

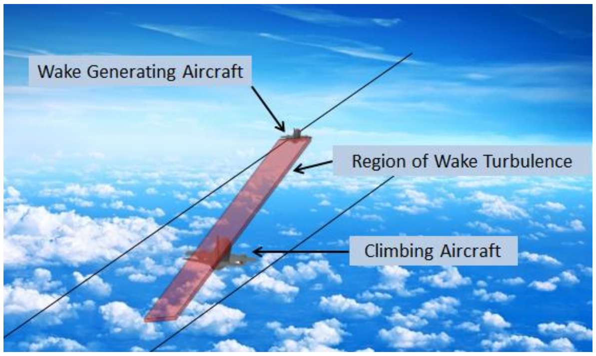

Figure 6: In-Trail Operating Scenario

Head-On Pass Scenario

A head-on pass scenario is one in which two aircraft are operating in opposite directions on the same route with a net altitude difference of 1,000 feet. Two of the many factors that contribute to the likelihood of a wake encounter during a head-on passing scenario are the aircraft pair vertical separation and the descent rate of the wake turbulence. While the cross-track wind velocity remains a mitigating factor, the time it takes for the vortex to descend to the altitude of the lower aircraft will determine the precise cross-track wind velocity needed transport the wake turbulence off route. Research has shown that, in general, wake descent rates vary between aircraft types and are also affected by atmospheric conditions.

En Route Wake Mitigation

In scenarios where cross-track wind threshold does not provide adequate wind mitigation of the wake turbulence, other options to reduce the risk of an encounter may include increasing along-track separation, altitude changes or lateral offsets. In-trail same altitude separation increases would require a speed change for one or both aircraft and may not be operationally feasible or desirable. Altitude changes or increased vertical separation can avoid areas of wake turbulence or provide additional time for wake transport or decay to occur. In some cases, altitude changes may not be possible due to traffic conflicts. A third option, lateral offsets, may be an option for applying mitigation to reduce en route wake turbulence risk.

A lateral offset is a maneuver that establishes an aircraft on a parallel route or trajectory at some fixed distance from the primary route. Offset distances may be in increments of as little as 0.1NM to in some cases 5.0NM. The offset route is defined by the flight crew using the aircraft's Flight Management Computer (FMC) and is a parallel clone of the original route. The ability of FMC's to perform an incremental distance offset is present in most "modern" FMC's, although some early first-generation FMC's be limited to offset distances in whole increments of 1.0 NM.

The assessment of the current wind conditions is an important aspect of the use of a lateral offset. Guidance in the ICAO Doc 4444 PANS for implementation of the Strategic Lateral Offset Procedure (SLOP) states that the "decision to apply a strategic lateral offset shall be the responsibility of the flight crew". The use of "standardized" maneuvers as part of the offset procedure also serves to enhance the predictability of the maneuver and better ensure that the desired separation from wake turbulence is maintained. These offsets can be classified as two basic types; those that are procedural and conducted without regard to wind conditions, and those that are wind dependent and consider cross-track winds.

Procedural Offsets

The most common procedural offset is the Standard Lateral Offset Procedure (SLOP), which is currently used in oceanic airspace. The SLOP authorizes an offset in incremental distances of

0.1NM to a maximum limit that is dependent on the route centerline spacing. For areas where the route centerline spacing is 23NM or more, the maximum limit of the offset distance is 2NM. In areas where the centerline spacing is at least 6NM but less than 23NM, the maximum offset distance is limited to 0.5NM. The SLOP is always made to the right of course direction and without regard for wind direction or velocity. Adverse crosswinds transport wake in the direction of an offset. Under these wind conditions, the use of the SLOP by crews expecting a wake mitigation benefit, may actually be placing the aircraft in a region with the highest probability of encountering wake turbulence.

Wind Dependent Offsets

A wind dependent offset is one that also utilizes either an incremental or whole integer offset distance, but is performed in the upwind direction and enables the cross-track wind to provide additional separation between the aircraft and wake turbulence. A standardized offset is a procedure that combines a standard set of maneuvers and a wind based "intelligent" offset direction over a prescribed offset distance. A standardized offset for an in-trail climb is depicted in **Figure 7**.

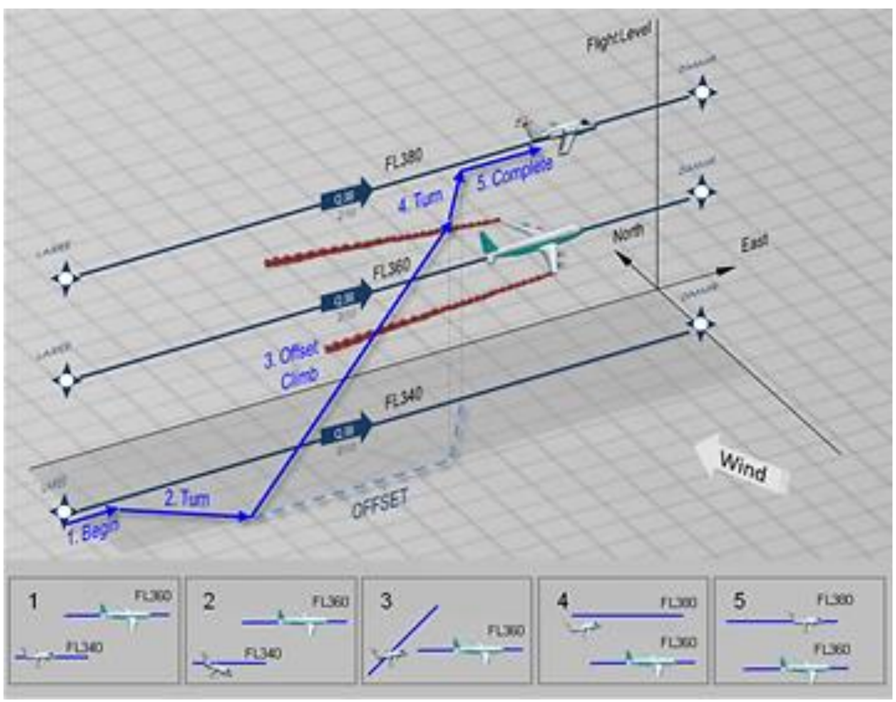

Figure 7: Wind Dependent Standardized Offset

Summary and Conclusion

Consistent reports from pilot and controllers of wake turbulence encounters at high altitudes suggest that en route wake turbulence is a recurrent safety concern and will need to be considered when reducing aircraft separation and increasing NAS capacity. While a significant amount of research and wake turbulence data has been collected at low altitudes near airports, the lack of measured data at high altitudes has limited the understanding of aircraft vortex behavior during the en-route phase of flight. The FAA in collaboration with NRC has collected high altitude wake turbulence data to broaden the understanding of the risks associated with these vortex systems.

As some of the en route wake reports suggest, the analysis of high altitude wake vortex data has demonstrated that, in some instances, significantly strong vortex cores exist at distances in trail well beyond current separation minimums. In some cases, vortex fields were measured beyond 20 nautical miles in-trail of the generating aircraft. The strength of these vortices, as well as transport and decay rates is highly dependent on atmospheric conditions, limiting the potential to predict the risk associated with a wake vortex system. This research calculated those atmospheric conditions for which there is a higher the potential for a wake encounter, and evaluated historical wind data to estimate the frequency of occurrence of such events.

Finally, implementing wake mitigation strategies may allow increasing NAS capacity without compromising safety. These strategies include along track separation increases, altitude changes or lateral offsets. While increasing along track separation or altitude changes may reduce the likelihood of an encounter, it doesn’t contribute to increasing capacity. Lateral offsets, such as the currently used SLOP take best advantage of the airspace. However this specific offset does not account for wind conditions and is authorized to only the right side of the direction of the route, which can increase the potential for a wake encounters when the crosswind transports the wake in the direction of the offset. Wind dependent offsets are concluded as a potential mitigation to reduce the likelihood of wake encounters and increase capacity, as it can utilize small incremental offsets that remain well within route containment boundaries.