This paper proposes a method for calculating hourly density and wind-based dynamic wake turbulence separation distances at airports to predict mixed operations throughput and revenue changes. Newark Liberty International Airport (EWR) anticipates Phase III dynamic wake measurement devices by 2020. EWR airport data is used to develop a predictive model to current throughput comparison. First, the effect of wake vortex decay on aircraft control and surrounding airflow is introduced. Then, a control table for the sample fleet mix is created using present (Phase I) recategorization requirements and average atmospheric data at EWR. Dynamic separation distances are predicted using two atmospheric variables - air density and surface wind directions - and compared to current throughput. An experimentally derived equation for required decay distance (RDD) is used to determine dynamic wake separation distances. Dynamic capacity impacts on airport revenue are then rivaled with current revenue data and model limitations are acknowledged. A cost-benefit analysis determines the convenience of implementing Phase III equipment relative to the change in throughput reflected by the prediction model. Areas of potential air traffic conflicts posed by the diversification of approach paths due to ground-based augmentation systems (GBAS) are highlighted. The presence of wake turbulence in areas other than the runway used for approach or departure necessitates a larger spread of wake detection systems. The following predictive model for RECAT Phase III implementation at US airports provides a convenient means for determining capacity changes in airport operations in addition to the burden of investment in Phase III infrastructure and maintenance. In this case study on Newark Liberty Airport, we concluded that dynamic turbulence spacing derived from wind and air density data increased mixed capacity throughput at EWR by 29.4%.

WTMD/A ANTICIPATION AT EWR

Wake Turbulence Mitigation for Departures and Arrivals (WTMD/A) is anticipated to be available at EWR by 2020 for Runways 4L and 4R [1]. WTMD will eliminate the need for wake vortex separation behind a Boeing 757 or Heavy aircraft departing on the adjacent runway when specific wind conditions exist that reduce the vortex hazard. Wake Turbulence Mitigation for Arrivals (WTMA) is also anticipated at EWR by 2020. WTMA features a wind detection algorithm to permit reduced separation between closely-spaced parallel arrivals to Runways 4L and 4R under specific wind conditions. This paper uses EWR as an example case for dynamic separations expected from programs like WTMD/A and FAA RECAT.

CHARACTERISTICS OF WAKE VORTEX FLOW

Before introducing calculations used in the dynamic model, it is important to describe the movement of wake vortices behind an aircraft in order to isolate surface wind conditions that minimize required spacing between the leading and trailing aircraft. Wake turbulence separation standards between aircraft on approach are determined by the initial circulation of the leading aircraft’s wake vortices, atmospheric characteristics, and the stability of the trailing aircraft. This is the primary reason why the classifications for aircraft has been divided by weight, as larger aircraft are more capable of counteracting induced roll caused by wake turbulence and produce larger wake vortices due to their larger lift creation. It was not until the collection of larger aircraft data sources that this equation could be expanded to consider dynamic qualities like air density, wind speed and direction in order to create real-time headway separations which optimize the capacity of the existing runways at an airport.

Wake vortices are created by the gradated air pressure differential along an aircraft’s wing. These vortices are centered at the tips of the wings and expand in radius as they develop behind the aircraft. The air flow profile within these vortices is strongest at the edge of the vortex core, which may exceed 300 ft/s [2]. For the purposes relevant to this report, all wake vortices considered...
are during the approach and departure paths. Airflow disruptions created by ground obstacles are not included in the calculations. Wake vortices develop as the wings of the aircraft create lift and flow both clockwise and counterclockwise in the opposite direction of the aircraft as two cylindrical vortices. Undisturbed, a set of wake vortices expand to an area of roughly two wing spans in combined width and one wing span in height of the aircraft which created the vortices. These vortices will begin to drop in altitude at a rate of 2-2.5 m/s [3] until their rate of descent levels off at roughly 150-275 m below the flightpath [4].

The flow of air behind an aircraft that results in vortices and the respective rotational directions of these vortices is illustrated in Figure 1. The vortex exerted by aerodynamic forces along the left wing rotates clockwise and the vortex exerted by forces along the right wing counterclockwise.

The primary danger introduced by wake vortices is the production of induced roll in the trailing aircraft’s flight path, resulting in uncontrollable rotation of the trailing aircraft. Trailing aircraft encounter induced roll - potentially uncontrollable rolling moment caused by airflow separation - when the rotational force of the vortex stalls the wing. This is often the case when the trailing aircraft has a smaller wingspan than the aircraft that creates the vortex. Additionally, rapid aircraft displacement can occur when a trailing aircraft does not fly directly into the center of a wake vortex, but instead crosses into it laterally. Encounters of this type can result in the aircraft deviating from the flightpath both horizontally and vertically. Figure 2 shows aircraft spatial displacement due to wake vortex flow influences as the aircraft enters the vortices laterally. Figure 3 shows aircraft spatial displacement due to wake vortex flow fields as the aircraft enters the vortices vertically.

**PRESENT RECATEGORYIZATION MODELS**

The FAA wake turbulence recategorization (RECAT) phases were established as part of FAA’s NextGen initiative to increase wake turbulence safety while maximizing airport throughput. RECAT Phase I, established in 2012, replaces the preceding tri-weight category separation requirements (light, medium, and heavy) with an extended six-category matrix. Most airports are only beginning to transition to Phase I recategorization rules. RECAT Phase II expands on the Phase I matrix with 10,000 aircraft model-defined pairs. Phase III implementation provides dynamic, weather-dependent wake turbulence separation distances based on real-time analysis of leading aircraft vortices.

**RECAT PHASE I**

The Phase I model for spacing was developed using LiDAR (Light Detection and Ranging), Pulse Doppler, and radar at the San Francisco (SFO), Memphis (MEM), John F. Kennedy (JFK), and London Heathrow (LHR) airports over a period of three years to derive the following conservative linear model for wake turbulence separations using a 95% confidence interval. The spacing is determined by the dissipation period of the initial vortex circulation loop (a measurement of vortex intensity), calculated using the following equation [5]:

\[
\Gamma = \frac{mg}{\rho \nu s B} \tag{1}
\]

where \( m \) is aircraft mass in kg, \( \nu \) is airspeed in m/s, \( \rho \) is air density in kg/m\(^3\), \( s \) is the wing load distribution coefficient (\( \pi /4 \)), and \( B \) is wingspan in m. The equation can be modified to include the trailing aircraft’s roll moment coefficient, useful only for larger planes with greater roll resistance:

\[
\Gamma(d) = \frac{mg}{\rho \nu s B} \left( 1 - \frac{mg}{12 \rho \pi s^2 B^3} d \right) \tag{2}
\]

where \( \Gamma(d) \) is the vortex circulation dissipation period and \( d \) is the distance of the trailing aircraft from the vortex. This model for vortex dissipation (in m\(^2\)/s) is used in the following graph to demonstrate the decay time for larger aircraft. \( \Gamma(d) \) can be rearranged to reflect the required decay distance (RDD) based on FAA minimum acceptable wake vortex circulation values (\( \Gamma_{min} \)):

\[
d_r = \frac{12 \rho \pi s^2 B^3}{mg} \left( \frac{mg}{\rho \nu s B} - \Gamma_{min} \right) \tag{3}
\]
The required decay distance can be quadratically correlated with aircraft weight as shown in Figure 4. This trend shows that a minor change in aircraft weight corresponds to a minor change in RDD, accommodating the wide RDD ranges used for each aircraft wake category A-D.

Table 1 divides wake separation minima for the following aircraft categories: A for Super Heavy, B for Upper Heavy, C for Lower Heavy, D for Upper Large, E for Lower Large, and F for Small category aircraft. [6].

**RECAT PHASE II**

The Phase II recategorization model expands on the static RDD equation used in Phase I with additional aircraft categories. Phase II follows the path of current European recategorization programs in scaling the wake turbulence separation matrix by aircraft model rather than weight. It uses a larger dataset from 230,000 pulsed LiDAR departure and approach measurements at 32 US airports to categorize 123 aircraft models between categories A-G, comprising 99% of fleet mix at US airports [7]. Like Phase I, RECAT Phase II uses wake vortex circulation and roll moment to determine aircraft separation. The roll moment coefficient can be calculated using the following equation:

\[
RMC = \frac{T}{\nu \beta}
\]

where \( T \) is the vortex circulation dissipation period of the leading aircraft calculated using Eq. 2, \( \nu \) is the trailing aircraft speed, and \( \beta \) is the trailing aircraft wingspan. Roll moment coefficient is used for larger aircraft which roll more slowly, while vortex circulation dissipation period is used for smaller aircraft which have a low roll resistance.

**RECAT PHASE III**

The Phase III recategorization model envisions dynamic separation distances based on each aircraft’s unique characteristics combined with environmental conditions using Doppler, LiDAR, and other systems. Dynamic measurements account for the effect of atmospheric conditions on vortex decay including: atmospheric turbulence, viscous interactions, surface winds, buoyancy, atmospheric instability due to non-standard pressure or temperature lapse rates, ground obstacles, and terrain geometry. Our prediction model uses hourly air density and surface wind information to measure a theoretical RECAT Phase III capacity at Newark Liberty International Airport (EWR).

**PREDICTIVE MODEL CALCULATIONS**

**PROCEDURE**

Developing a predictive model begins with the control case table for Phase I RECAT mixed capacity. The table uses existing FAA separation ratios to define separations for each combination of aircraft in the sample mix. Then, hourly wind and density data from 2015 New Jersey ASOS measurements [11] are incorporated into separation calculations using capacity formulas based on wind velocity components and Phase I experimentation. Finally, an estimate of revenue impact generated by predicted Phase III capacity changes in
MODEL CONTROL SEPARATIONS FOR SAMPLE FLEET MIX

The dynamic model uses a fleet mix of four aircraft for categories A-D. Total circulation (m²/s) is calculated using the Hallock-Burnham wake vortex model [8] for each aircraft and substituted into Eq. (2) along with the average air density at EWR in 2015 to derive control case RDD values for each aircraft (Table 2).

The full RDD value of the leading aircraft is used for the maximum separation scenario, which occurs when the lowest-weight aircraft (aircraft D) trails the leading aircraft. For all other scenarios (leading-A/B/C/D and trailing-A/B/C), each RDD value is scaled using RECAT Phase I wake separation allowances for the following control case separations (Table 3).

With the same category fleet mix used as the dynamic model, the control case yields a mixed capacity of 63 aircraft per hour and average arrival separation 112 seconds. This throughput represents a minor increase from 2015 average hourly capacities at EWR (47 aircraft per hour). The control capacities will be used to determine the change in throughputs and airport revenue brought about by dynamic model capacities.

DYNAMIC WAKE VORTEX RDD VARIABLES

Air Density

The following equation is used to obtain hourly air density levels at EWR in 2015 [9]:

\[
\rho = 1.2929 \times \frac{273.15}{T} \times \frac{B-0.3783 \rho_v}{1.013 \times 10^5}
\]

where \( T \) is temperature in Kelvin, \( B \) is barometric pressure in Pa, \( \rho \) is partial vapor pressure in Pa, and \( \rho_v \) is density in kg/m³. Phase I and Phase II recategorization use a density-dependent equation for RDD, but separation is determined using an aggregate measurement over several years as opposed to a Phase III dynamic model which calculates RDD based on real-time air density values. The predictive model at EWR uses hourly New Jersey ASOS data to simulate near-
real-time density changes encountered by wake turbulence sensors. The RDD equation (Eq. 3) makes evident that the largest dynamic spacing distances will be employed between March and November when air density is lowest (Figure 6).

Surface Winds

Surface crosswinds with reference to runway orientation 040° are used to measure parallel mixed operations capacities for runways 04L and 04R at EWR. The length of time ($\tau_{\text{clear}}$) before the crosswind displaces the leading aircraft’s vortices clear of the trailing aircraft’s wingspan can be calculated using Eq. (6):

$$\tau_{\text{clear}} = (\alpha - \beta) \frac{1}{V_x} + \beta$$

where $\alpha$ is the wingspan of the larger category aircraft in m, $\beta$ the wingspan of the smaller category aircraft in m, and $V_x$ the crosswind component in m/s perpendicular to a 040° approach path. $V_x$ can be calculated by taking the absolute value of wind direction subtracted from 040° and multiplying the velocity by $\sin(\phi)$. $\tau_{\text{clear}}$ assumes that leading aircraft wake vortices must be completely clear of the trailing aircraft and that the vertical component of the surface wind does not extend or diminish intensity of the vortices. If $\tau_{\text{clear}}$ is greater than separation time using density-based dynamic RDD Eq. (3), then RDD is used for minimum separation distances. The equations are illustrated using trailing and leading aircraft and a sample left-bound crosswind (Figure 7).

**Figure 6.** Air density changes during the year 2015 at Newark Liberty International Airport based on New Jersey hourly ASOS data. Wake turbulence spacing increases with air density.

**Figure 7.** The set of equations used to determine the length of time before a wake vortex clears the wingspan of the trailing aircraft. On the left, a small trailing aircraft follows a heavy leading aircraft. On the right, a heavy tailing aircraft follows a small trailing aircraft. The equation for $\tau_{\text{clear}}$ remains the same for both cases.

**Dynamic Separation Model**

Dynamic separation distances for different A-D leading and trailing combinations are calculated using data from each hourly EWR ASOS recording. Eq. (3) is used to calculate distance separation with hourly density as input, and Eq. (6) to calculate time separation using hourly wind velocities. A landing roll buffer of 60 seconds is added to each separation distance. Density-based
dynamic separation distances are then converted to time-based separations using the following conservative headway formulas and corresponding interarrival diagram [10]:

\[ C_m = \frac{1}{E(T_{ij})} \left( 1 + \sum_{n} \eta_d p_{rd} \right) \]  

Opening Case \((V_j < V_i)\)

\[ \Gamma_{ij} = \frac{\delta_{ij} + \kappa}{V_j} \]  

Closing Case \((V_j > V_i)\)

where \(V_i\) is the speed of the trailing aircraft, \(V_j\) is the speed of the leading aircraft, \(T_{ij}\) is the separation time for each aircraft. In the opening case, the velocity of the trailing aircraft is lower than that of the leading aircraft. In the closing case, the opposite is true; thus, the time interval between the two aircraft is only affected by wake turbulence separation and does not include approach path distance. The lower minimum separation time for each ASOS recording is then multiplied by a probability matrix for the 16 A-D combinations using 2014 fleet mix data:

\[ \eta_d = 1 \text{ and } p_{rd} = 1 \] (100% probability that the number of departures \(\eta_d\) will be released between each arrival) to obtain the mixed capacity for runways 04 Left and 04 Right at Newark Liberty International Airport.

RESULTS

The dynamic density and wind-based model yields an arrival capacity of 45 aircraft per hour and a mixed capacity of 90 aircraft per hour. Compared to control separations without hourly density or wind-based adjustments at EWR, model mixed capacity projections represent a 29.4% increase in average mixed operations on runways 04L and 04R. The 120 operations/hr maximum cap occurs when high crosswind velocity shifts leading aircraft wake vortices clear of the trailing aircraft’s path within a few seconds, leaving only the 60 second buffer for spacing. A 50 operations/hr minimum cap occurs when light wind conditions prevail, prioritizing density-based spacing. Instances where spacing reaches the maximum cap of 120 or minimum cap of 50 are identified as outliers and eliminated in the final operations/hr graph (Figure 8).

Using FAA ASPM data [11] for 2015 throughput at EWR, the projected 29.4% increase in operations per hour would result in a total of 529,389 operations and incidental (both aeronautical and non-aeronautical) airport revenue $1.4 billion (Figure 9). The percent revenue increase from predictive density and wind-based spacing compared to static Phase I/II revenue added to yearly infrastructure expenses demonstrates that the implementation of dynamic spacing equipment at Phase III-compatible airports is a worthwhile investment.

LIMITATIONS

RDD VARIABLES

Wind data used in this model does not account for gusts or wind shear. Minimized wake turbulence separation distances due to dynamic readings operates under the assumption that weather conditions will remain at nearly the same state for the duration of the trailing aircraft’s approach or departure procedures. Rapid changes in wind velocity can affect the distribution of wake vortices unpredictably and impact aircraft safety before action can be taken by the trailing aircraft to extend its separation. Air density is measured at the surface and assumes a standard lapse rate for temperature (1.98 °C / 1,000 ft) and air pressure (1.08” Hg / 1000 ft). Wind and air density, while major factors of wake vortex movement and dissipation, are only two atmospheric variables that can affect wake turbulence. Weather conditions, atmospheric turbulence and unstable pressure or temperature lapse rates can affect dissipation as well.

CONTROL AIRCRAFT

The RDD fluctuates rapidly with a small change in weight when using Eq. (3). As a result, category A and B control aircraft RDD inputs use experimental data rather than the RDD equation [12]. The fleet mix also represents a limited group of aircraft (one aircraft for categories A-D) compared to Phase II average and Phase III dynamic fleet mix measurements.
MODEL SEPARATION DISTANCES

For distances defined in both the control and dynamic separations tables, the model assumes a constant landing roll duration of 60 seconds. Separations based on crosswinds rely on static initial vortex circulation strength values (regardless of atmospheric-induced dissipation intensifying with time) and a linear displacement of vortices matching crosswind velocity. Finally, crosswind velocity is taken from ASOS data, which reflects surface winds only and may not accurately reflect wind conditions at different altitudes on approach beginning at the location where ATC authorizes RECAT spacing for trailing aircraft. For example, an aircraft on a curved area navigation (RNAV) approach path may encounter different density and wind direction values at its final waypoint than those detected by dynamic wake turbulence measurement devices at the airport surface. This can result in an inconsistent flow of wake vortex turbulence from the leading aircraft through the atmosphere to the trailing aircraft and affect control of the trailing aircraft unpredictably.

EXTERNAL IMPACTS

GBAS AREAS OF CONCERN

Encounters with wake turbulence before established separation distances can be fatal. A dynamic model highlights further concerns brought about by the future implementation of Ground-Based Augmentation Systems (GBAS) at EWR and other U.S. airports which allow curved, stacked, and continuous-descent approaches out of current ILS localizer and glideslope ranges. High density air coupled with high wind conditions can create problems for any instance when a plane flies near the path of the other. In a parallel, independent approach scenario for runways 4L and 4R, a West-bound crosswind can direct the wake vortices from the 4R-inbound aircraft approach path to the 4L path. High density conditions minimize vortex encounters until short-final and low approach speeds. A predictive model should be used in order to prevent wake turbulence accidents caused by atmospheric effects.

Figure 8. Simulated dynamic mixed capacity at EWR for runways 4L and 4R. Model mixed capacity projections yield a significant increase in aircraft throughput and airport revenue.

Figure 9. Phase I and Phase III Post-RECAT implementation revenue comparison. All airport revenue sources are directly proportional to aircraft throughput.
on vortex direction and dissipation rate.

PHASE III TECHNOLOGY

LiDAR
A Light Detection and Ranging system, also known as LiDAR, is a crucial technology for future research and development in the FAA RECAT program. LiDAR emits infrared light pulses into the atmosphere and measures the time it takes for light to travel back into the sensor after reflecting off of the dust particles in the air. By calculating the time traveled and comparing the frequency of the transmitted and received light, LiDAR is able to provide wind velocity data and other information relevant to the strength and behavior of wake turbulence [13]. It can also detect hazards such as wind shear from far away and provide information necessary for air traffic controllers to warn pilots of potential conflicts outside of approach and departure paths. This technology, however, is not perfect. It works best under clear and dry air, so the system would need to be complemented by traditional weather radar, such as Doppler Radar [14].

DOPPLER RADAR
Unlike the transmission and relay of infrared light with LiDAR systems, Doppler radar uses microwave signals to analyze the effect of object’s motion on the frequency of the returned signal. Doppler is generally unreliable for minor variations in wind speed, but can accurately detect spectrum spreads caused by large shifts in speed [15]. Doppler radar can be used in tandem with ASOS station instruments to more accurately detect wind changes near the surface.

DETECTION HOTSPOTS
Another task that Phase III implementation faces associated with particle detection equipment is infrastructure placement on the airfield in such a way that all near-field wake turbulence hazard areas are included in vortex detection. Radar blind spots prevent vortex detection outside of the approach and departure flight paths parallel and in-line with the runway. As a result, one system design seeks to emit a laser beam from two radars placed in different areas on the airfield to capture turbulence from crosswind and downwind flight paths (Figure 10) [16]. A signal processing device ensures that the radar observations do not overlap each other, and the larger wake turbulence decay times are reported in the form of dynamic separation distances to the controller.

ATMOSPHERIC VARIABLES
The predictive model will always have capacity for more atmospheric variables and higher sampling rate. Currently, the ASOS samples hourly and only two dynamic variables are measured: crosswind components perpendicular to the flight path of the trailing aircraft and air density data based on stable temperature and pressure lapse rates. In future models, the effect of the vertical component on the spread and intensity of wake leading wake vortices will be taken into account. Vertical component measurements are imperative for approaches or departures behind leading aircraft which have made a crosswind turn. Increased weather technology, especially at different altitudes along flight paths within vicinity of the airport, will factor the effect of unstable lapse rates, gusts, and wind shear into predictive vortex RDDs.

FUTURE RESEARCH

CONCLUSIONS
The current state of wake turbulence recategorization can be further improved using dynamic vortex measurement technology. While research is still ongoing and initial testing of particle detection equipment is not expected until 2020, it is necessary for airports to determine how the technology will impact current capacity, safety, and revenue. This paper provides the backbone framework for
predictive modeling of FAA Phase III Recategorization based on crosswind and air density measurements. The results for 2015 EWR modeling returned a substantial increase in capacity and revenue compared to static capacity data. Dynamic spacing distances were greatest between the months of March and November, when air density is low. A quadratic relationship between aircraft weight and RDD allows users of the predictive model to confidently estimate separation distances for aircraft types which have not been monitored by vortex detection equipment. Safety as a consideration for Phase III technology increases with the integration of GBAS technology at airports globally. Future enhancements to the predictive model will include wind measurements at all altitudes of the approach where turbulence conflicts remain possible, unstable atmospheric data, and a larger turbulence conflicts remain possible, all altitudes of the approach where wind measurements at will include wind measurements at 

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REFERENCES

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