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CAPACITY ANALYSIS FOR A FLOW CORRIDOR WITH DYNAMIC WAKE SEPARATION

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ABSTRACT

This paper gives a simulation framework to investigate the capacity benefits of employing a dynamic wake separation policy in a single lane flow corridor. The flow corridor concept is a proposed route structure in en-route airspace to increase capacity in response to growing demand. Aircraft flying in a flow corridor must be safely separated to avoid collisions as well as wake vortex encounters. Wake vortices are circular patterns of rotating air left behind a wing as it generates lift and can impose a hazard to other aircraft. This research considers a dynamic wake separation concept that uses information about weight and airspeed of aircraft and meteorological conditions to determine the minimum required wake separation between aircraft in a flow corridor. This is in contrast to a static policy that uses a fixed separation minimum based on conservative assumptions. The simulation results demonstrate capacity benefits compared to static separation standards.

1 INTRODUCTION

According to the Federal Aviation Administration (FAA) baseline forecast, the number of enplanements will grow from 840.4 million passengers in 2017 to 1.28 billion passengers in 2038 (Federal Aviation Administration 2018). Aircraft handled at en-route centers are forecast to increase from 44.7 million in 2018 to 59.4 million in 2038. Controller workload is a key limiting factor to increasing capacity for air traffic operations. To ensure safe and efficient flow of traffic through airspace sectors, a Monitor Alert Parameter (MAP) value is calculated for each sector, which is the maximum number of aircraft that can be safely managed. If traffic volume for a sector is predicted to be more than its MAP value in any 1-minute period, a monitor alert function of the Traffic Flow Management System notifies the traffic manager to reroute aircraft or to redistribute the traffic in space or time (Roychoudhury et al. 2018).

Considering the projected growth in demand, the flow corridor concept was proposed as a Next Generation Air Transportation System route structure in en-route airspace, with the main goals of reducing the airspace complexity and increasing airspace capacity (JPDO 2012). According to the definition, a corridor is “a long tube of airspace that encloses groups of flights flying along the same path in one direction. It is airspace procedurally separated from surrounding traffic and special use airspace, and it is reserved for aircraft in that group.” Flow corridors accommodate aircraft that are capable of self-separation, equipped with ADS-B and onboard conflict detection and alerting (JPDO 2011). This en-route structure has the potential to increase airspace capacity by reducing the controller workload required to manage aircraft outside the corridor and by reducing separation of aircraft within the corridor.

Before implementing any of these procedures, however, they should be assessed with respect to safety. Zhang, Shortle, and Sherry (2015) investigated the safety of flow corridors with respect to collision risk using Monte Carlo simulation and dynamic event tree analysis. Ye, Hu, and Shortle (2014) and Ye et al.

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(2019) investigated related safety and capacity trade-offs in an en-route corridor. In addition to collision risk, another risk for aircraft in a corridor is wake vortex encounter risk. Wake vortices are circular patterns of rotating air left behind a wing as it generates lift. An aircraft that flies through the wake of another aircraft can experience an un-commanded roll, which may cause injury to passenger and flight crew (particularly, those who are not wearing a seatbelt) and, in the worst case, can lead to a total loss of control. In the en-route environment, the primary concern is human injury, since an aircraft at high altitude can typically recover from an un-commanded roll. To ensure safety, minimum separation requirements are established so that the trailing aircraft does not encounter the wake from a leading aircraft. Hoogstraten et al. (2015) developed a simulation framework using historical surveillance data and a wake vortex model to generate the probable trajectories of aircraft and their wakes. Their simulation predicted that a severe wake-vortex encounter would occur approximately once every 38 days in European airspace.

2 DYNAMIC WAKE SEPARATION

The objective of this paper is to identify the capacity benefits of a dynamic wake separation policy relative to a static separation policy for a single-lane en-route corridor.

Current wake separation requirements are static, meaning that the required in-trail separation between two aircraft is a pre-specified fixed distance, possibly depending on aircraft type. In the en-route environment (above flight level 240), the required in-trail separation is 5 nautical miles (nm) for all aircraft. In the terminal area, the required separation distance depends on the wake categories of the leading and trailing aircraft. These categories are based on maximum take-off weight. For example, a Boeing 737-800 is classified in the “large” category, which includes aircraft with a maximum takeoff weight at or above 41,000 lbs and below 300,000 lbs (Federal Aviation Administration 2021).

Wakes can persist for several minutes. Their durations vary greatly depending upon meteorological conditions (e.g., wind, ambient turbulence intensity, atmospheric stability) and aircraft characteristics (e.g., airspeed, weight, and wingspan). Because of these many variables, static separation requirements are based on worst-case assumptions. For example, the required separation of a large aircraft behind a large aircraft in the terminal area is based on assuming the lead aircraft is the heaviest possible within the large category while the trailing aircraft is the lightest possible within the large category. Thus, static separations are inherently conservative.

In this paper, we consider a dynamic wake separation concept in which the minimum separation requirements are determined from real-time measurements of a variety of input variables. These variables may include atmospheric parameters, aircraft characteristics, and aircraft state variables. Figure 1 shows a notional representation of the concept. It is assumed that all relevant inputs can be obtained from airborne and/or ground sensors, that the inputs can be transmitted to the dynamic separation function (which may be implemented on the aircraft or on the ground), and that the resulting required minimum separation can be communicated to the trailing aircraft. The trailing aircraft is assumed to be equipped with a self-separation capability and can adjust airspeed in order to maintain a desired target separation with some precision. The required separation may be updated periodically (e.g., every 5 minutes) in response to changing environmental conditions. Feuerle, Steen, and Hecker (2013) considered a similar concept for wake-vortex hazard mitigation, with the basic idea that a criticality parameter is transmitted between aircraft to ensure a safe separation within new self-separation concepts.

In this paper, we specifically consider a dynamic wake separation concept based *on aircraft weight and airspeed*. By aircraft weight, we mean the actual weight, which varies by fuel load and number of passengers, versus the maximum take-off weight, which is a static value for a given aircraft. As a practical matter, airlines may be unwilling to broadcast actual weight, since it provides information about the number of passengers on board (Feuerle, Steen, and Hecker 2013). But for the purposes of this paper, we assume that each aircraft is able and willing to measure and broadcast its current weight and airspeed.

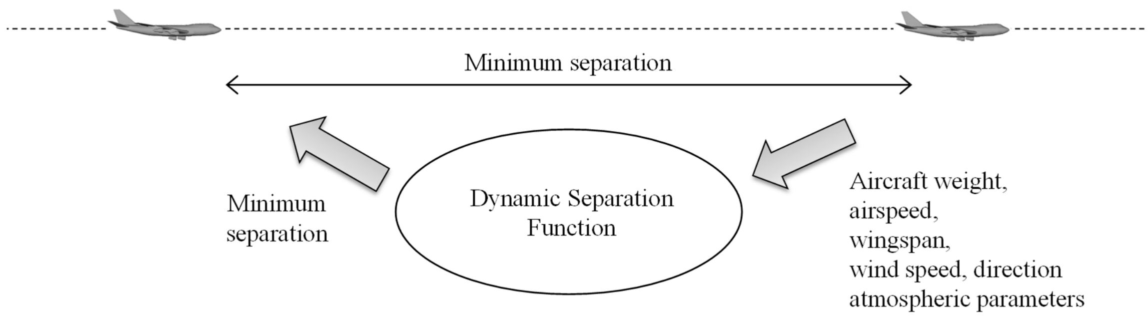

Figure 1: Concept of dynamic wake vortex separation.

Dynamic wake separation is a general concept and encompasses a variety of specific concepts that have already been implemented. For example, Wake Turbulence Mitigation for Departures (Federal Aviation Administration 2013) is a concept in which the departure interval on closely spaced parallel runways can be reduced in the presence of a crosswind (Cheng et al. 2016). The idea is that if the lead departing aircraft is on the downwind runway, then the crosswind prevents the wake from migrating to the upwind runway, so the following departing aircraft does not need to wait as long. This can be viewed as a dynamic separation concept using crosswind as an input variable.

3 SIMULATION MODEL

This section describes a simulation model of a flow corridor with dynamic wake separation. Key elements include a dynamic systems model of the aircraft, logic for discrete changes in using different control laws, and details of the minimum wake separation function. This paper considers a single lane corridor, 400 nm in length at flight level 350 (35,000 ft). Passing is not allowed in the corridor. It is assumed that all aircraft fly at the centerline of the corridor. That is, lateral and vertical movements are ignored, but variability in the along-track dimension is considered. Aircraft in the corridor are responsible for self-separation; an aircraft can adjust its airspeed to maintain the target separation from its leading aircraft. This target separation distance is determined using a real-time wake prediction model in a static or dynamic way.

3.1 Dynamic Systems Model

Aircraft are modeled as points that traverse the corridor along a one-dimensional path following trajectories generated by stochastic differential equations. The state of each aircraft includes its along-track position and along-track airspeed.

An aircraft that has no immediate leader – that is, an aircraft that is not trying to maintain separation with any aircraft in front of itself – attempts to fly at a target airspeed. This is modeled using a mean-reverting process. Random perturbations (e.g., due to wind) cause the aircraft to deviate from the target speed. The aircraft adjusts to return to the target airspeed. This results in a process where the airspeed fluctuates with some variability centered around the target. The process is modeled by the following stochastic differential equation:

$$dv_l = -\rho(v_l - \mu)dt + \sigma dW_t, \tag{1}$$

where v_l is the aircraft's airspeed, μ is the target airspeed, ρ is the mean reversion rate, σ is a volatility parameter, and W_t is the Wiener process (standard Brownian motion). W_t is the stochastic portion of the equation. The constant σ controls the size of the perturbations, and ρ represents the rate at which the airplane corrects deviations from the target speed. The target airspeed μ is fixed, but is generated randomly for each aircraft from a normal distribution with mean equal to the nominal cruise speed of the aircraft.

An aircraft that is trying to maintain separation with a leading aircraft is modeled using a proportional-derivative (PD) controller. Specifically, the trailing aircraft tries to maintain a target separation distance D with the leading aircraft and tries to fly at the same speed as the leader. This is given by the following stochastic differential equation:

$$dv_f = k_p(x_l - D - x_f)dt + k_d(v_l - v_f)dt + \sigma dW_t \tag{2}$$

where x_f and v_f (x_l and v_l) are the along-track position and airspeed of the following (leading) aircraft, D is the target along-track separation distance, and σ and W_t are defined as before. The parameters k_d and k_p are constants representing control gains. Given a prescribed variability in aircraft separation and velocity, the constants k_d, k_p, and σ can be chosen so that the simulated flight tracks have the given characteristics. This is discussed in a subsequent section. In addition, the output acceleration from the PD controller in (2) is bounded within a certain range to match the physical constraints of the aircraft and the maximum comfortable acceleration for passengers. Lower and upper bounds for airspeed are also defined to avoid a stall and going over the maximum design speed. The vertical motion of the aircraft is not considered in this capacity model. However, it is a critical part of the safety analysis in Zare-Noghabi and Shortle (2017), where a rare-event simulation model was developed to assess the probability of a potential en-route wake encounter based on the in-trail separation distance.

3.2 Arrival Process and Separation Laws

Aircraft are assumed to arrive at the corridor entrance according to a Poisson process. An arriving aircraft immediately enters the corridor if the previously arriving aircraft has passed the minimum required separation distance in the corridor (Figure 2, left case). If the leading aircraft has not passed the minimum required separation distance, then the arriving aircraft waits (Figure 2, right case) and enters once the leading aircraft has travelled the minimum required distance.

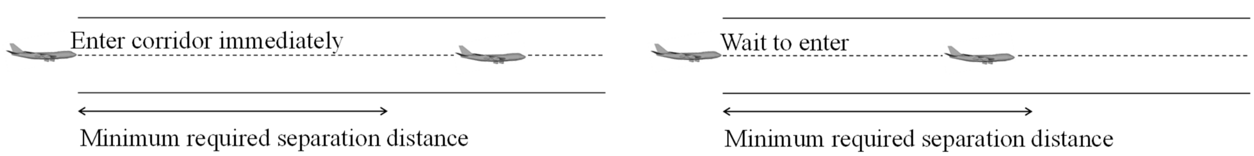

Figure 2: State of corridor when an aircraft arrives.

The following rules determine which control law governs the motion of an aircraft:

- If an aircraft has no leader, it tries to maintain its own predetermined target airspeed, following equation (1).
- If an aircraft has a leader, but there is a large gap (specifically, if the gap is greater than the minimum separation distance plus a buffer distance), the trailing aircraft tries to maintain its own target airspeed, following equation (1).
- If an aircraft has a leader, but its target airspeed is less than the observed airspeed of the leading aircraft, it tries to maintain its own target speed, following equation (1).
- If an aircraft has a leader and its target airspeed is greater than the observed airspeed of the leading aircraft and the separation distance is less than the minimum separation distance plus a buffer, the trailing aircraft tries to maintain separation with the leading aircraft following equation (2).

3.3 Wake Separation Function

To investigate the potential capacity benefits of dynamic separation, we define rules for setting both the static and dynamic separation requirements. As a guiding principle, the separation requirements should be established using similar methods so that any differences in capacity benefits can be attributable to changing from static requirements to dynamic requirements, and not due to other factors.

We first explain a method for establishing a minimum dynamic separation and use that as a basis for establishing an analogous static separation requirement. The basic idea is to use a wake evolution model to compute the decay of circulation strength as a function of time. The time it takes for the wake of the generating aircraft to get weaker than a pre-specified threshold becomes the minimum separation time for the trailing aircraft.

There are many wake evolution models that predict circulation strength (e.g., Green 1986, Robins and Delisi 2002, Holzäpfel 2003, Proctor, Hamilton, and Switzer 2006, Proctor and Hamilton 2009). We use the AVOSS Prediction Algorithm (APA) developed at NASA (Robins and Delisi 2002). One reason for this choice is that it is possible to directly implement the model equations from public sources. The APA model generates as output the circulation strength of the wake as well as its vertical and lateral coordinates as a function of time. Only the output of circulation strength is used for the purposes of this paper.

For input, the model requires a number of parameters including aircraft weight, wingspan, and airspeed, and various atmospheric parameters such as wind, eddy dissipation rate (EDR, which is a measure of turbulence), and Brunt-Vaisala frequency (BVF, a measure of stratification). For wingspan, we use the published wingspan of a given aircraft type. Airspeed is given by the current reported airspeed in the simulation model. The weight of each aircraft is assumed fixed over the duration of the simulation, but is chosen randomly for each aircraft from a uniform distribution between 75% and 95% of the maximum take-off weight (Figure 3). Reduction in weight due to fuel burn while traveling in the corridor is not considered. The worst-case values are assumed for the meteorological parameters – namely, zero wind, very weak turbulence (EDR = 10^{-7}), and no stratification (BVF = 0 sec^{-1}). These are worst-case parameters, because the wakes persist longer in these conditions and are not blown off the flight path.

In the dynamic separation concept, it is assumed that the trailing aircraft has access to the actual weight and airspeed of the leading aircraft. In addition, the trailing aircraft has access to the meteorological parameters (eddy dissipation rate and Brunt-Vaisala frequency) based on readings from ground and/or airborne sensors. The minimum required separation distance is computed by running the APA model with the associated inputs and computing the time required for the wake circulation to decay below a specific threshold. This is converted to a distance threshold based on the velocity of the leading aircraft. To avoid a situation where the minimum separation is continuously changing, the minimum separation is updated every T minutes (e.g., 5 minutes).

Static separation requirements are determined from a similar concept, but using worst-case input parameters. As in the dynamic case, the atmospheric parameters are set at their worst-case values, i.e., very weak turbulence (EDR = 10^{-7}) and neutral stratification (BVF = 0 sec^{-1}). For aircraft weight, a larger weight corresponds to a stronger wake (i.e., higher initial circulation strength) and a larger required separation distance. To assume a conservative value, the weight of the lead aircraft is set to 90% of its maximum take-off weight (MTOW) to determine the static separation requirement (Figure 3).

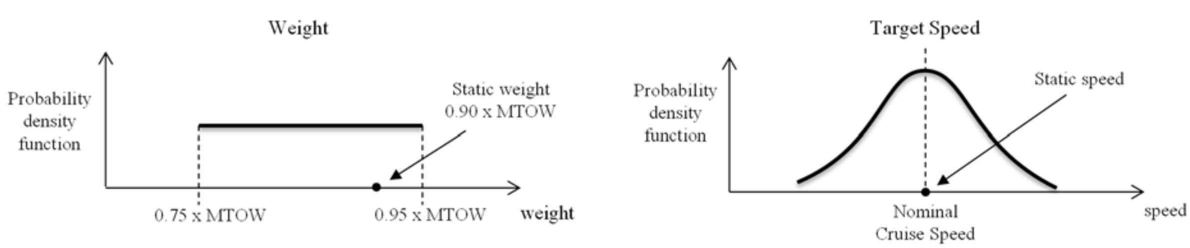

Figure 3: Probability density function for weight and target speed of aircraft in dynamic separation.

The relationship with airspeed is more complicated. Increasing airspeed results in reduced circulation strength (airspeed appears in the denominator of the equation for initial circulation strength). Intuitively, this is because a greater coefficient of lift is required with a lower airspeed, resulting in a larger wake. While increasing the airspeed reduces the circulation strength and decreases the required separation *time*, this does not necessarily translate to a decrease in separation *distance*, because the aircraft are traveling faster. Further, the worst-case airspeed, that gives the largest separation distance, changes with weight. Figure 4 shows the time and distance travelled by the generating aircraft until the vortex circulation strength decays to less than 180 m^2/s. Because there is a not a fixed "worst-case" value of the airspeed, we use the nominal cruise speed of the leading aircraft as input to APA in setting the static separation requirement (Figure 3).

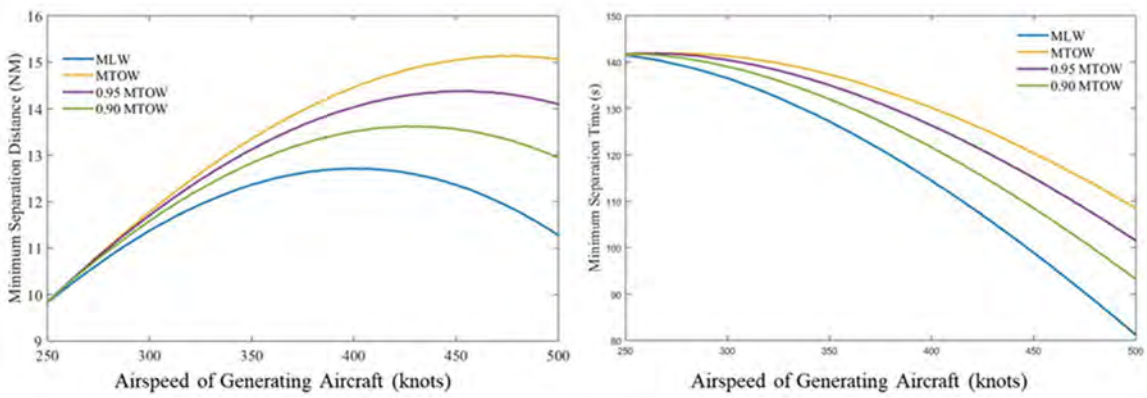

Figure 4: Separation distance and separation time for different weights and airspeeds of generating aircraft.

3.4 Aircraft Fleet Mix In Corridor

For the aircraft fleet mix in the corridor, we use the top five models in the U.S. commercial aircraft inventory. In 2017, the inventory included 7,309 aircraft. The most popular aircraft were the Boeing 737-800 with 794 units (10.9% of total), the Boeing 737-700 with 585 units (8.0%), the Airbus A320 with 505 units (6.9%), the Boeing 757-200 with 456 units (6.2%) and the Bombardier CRJ200 with 393 units (5.4%) (source: Forecast International). The following table summarizes the properties of these aircraft.

Table 1: Properties of aircraft in the fleet mix.

Aircraft Type	MTOW (kg)	Wingspan (m)	Cruise Speed (knots)	Maximum Speed (knots)	Stall Speed (knots)
B737-800	79,016	34.32	455	470	149
B737-700	70,080	34.32	450	470	143
A320-200	78,017	35.8	450	470	145
B757-200	115,660	38.1	460	495	164
CRJ200	24,041	21.21	425	465	116.6

3.5 Setting the Control Parameters

We seek to set the control gains, k_d and k_p, and variability parameter σ in (2) so that the distributions of separation and airspeed approximately match those observed today. Zare-Noghabi (2019) carried out a data collection effort to identify en-route in-trail aircraft pairs from five weeks of track data in the U.S. and Europe. Pairs of aircraft flying within 20 nm of each other for more than 10 minutes were identified as candidate in-trail pairs. There were some additional selection criteria (see Zare-Noghabi 2019 for details).

This yielded about 3,000 in-trail pairs in the U.S. and 2,000 in Europe. Table 2 provides summary statistics from this data collection effort.

Table 2: In-trail separation statistics from track data study (Zare-Noghabi 2019).

Observable Parameter	Observed Value	Associated Model Parameter
Average separation distance	15.1 nm	D
Standard deviation of separation distance	1.1 nm	$\sigma_f / \sqrt{2k_d k_p}$
Target speed for leading aircraft	436 knots	μ
Standard deviation of speed for leading aircraft	16 knots	$\sigma_l / \sqrt{2\rho}$
Standard deviation of speed for following aircraft	16 knots	$\sigma_f / \sqrt{2k_d}$

The right column provides the mapping of parameters in the simulation model to the corresponding statistics identified from the track data. There are a few caveats. First, there are more parameters than equations, so determining k_d, k_p, ρ, σ_f, and σ_l is under-constrained. Nevertheless, the parameters can be determined uniquely up to a linear scaling of the solution in time. By assuming a specific time constant for the system, the parameters are uniquely determined.

Second, the formulas in the right column are derived under the assumption of a single pair of aircraft with the leading aircraft flying a constant velocity. The flow corridor simulation has many complicating factors. For example, there are typically multiple aircraft in the corridor, each one following the next, so the leading aircraft of a pair is not flying a constant speed. There are also two different control laws, (1) and (2), depending on the situation, whereas most of the equations in the table are derived based on (2). Also, the target separation is not fixed but varying. These all tend to add variability to the system. That is, the simulated system tends to have more variability than the observed data, when using parameters obtained by matching the two columns of the table. To provide a closer match to the observed data, the volatility parameter σ_f was reduced. It was found that setting $\sigma_f = 0$ gave a reasonable match. Further details can be found in Zare-Noghabi (2019). This translates to having PD controllers with zero noise, so sources of variance in separation distance and velocity are intrinsic features of the flow corridor like changes in target airspeed or target separation distance.

4 RESULTS

The first experiment evaluates the effect of the arrival rate to the corridor. Figure 5 compares results for two different fleet mixes and two different separation policies. The *y*-axis is the average throughput of the corridor. Throughput increases as the arrival rate to the corridor increases. The throughput eventually reaches a stable maximum and this is the approximate capacity of the corridor. In the uniform fleet mix, all aircraft are B737-800. In the mixed fleet, the five aircraft types in Table 1 are used, each randomly chosen with equal probability. In the dynamic policy, the minimum separation distance is updated every 5 minutes. All simulations are conducted with the assumption of neutral stratification and very weak turbulence intensity. Each point in the figure is the average throughput of ten simulation runs, where each run is five hours of simulated time. The variability of these outputs over multiple runs can be seen in Figures 6 and 7.

As expected, the dynamic separation concept yields a higher throughput than static separation for both fleet mixes. This is because the static separation requirements are based on conservative values for the input variables in the wake model. The corridor has higher capacity with a uniform fleet than with a mixed fleet. This is because there is less variability in the target speeds of the aircraft when the aircraft types are all the same. In particular, the uniform fleet has no CRJ200 aircraft, which has a smaller nominal cruise speed and tends to slow down aircraft behind it in the corridor.

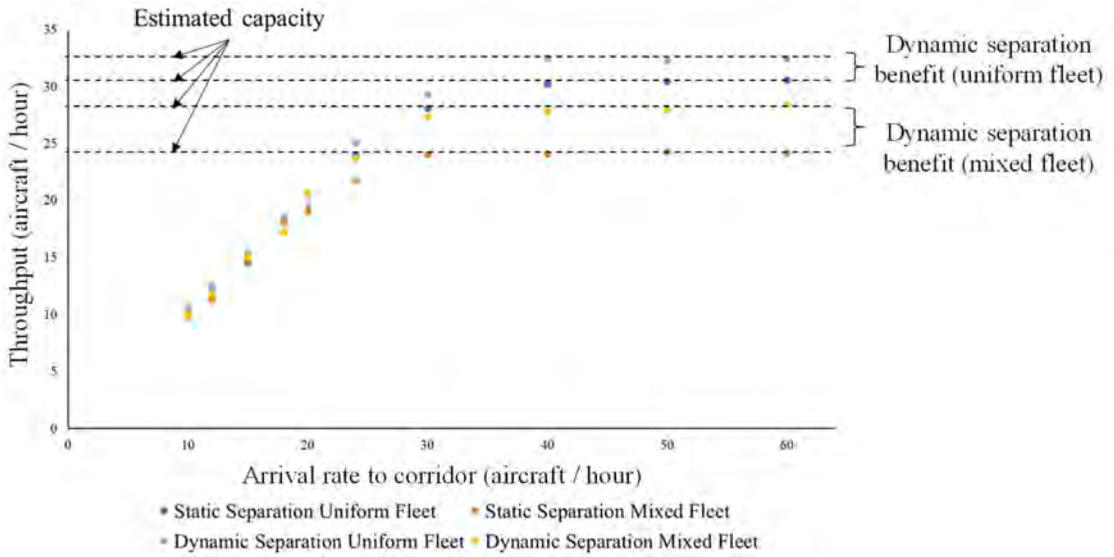

Figure 5: Throughput versus arrival rate for different policies and fleet mixes.

There are two factors that differentiate the dynamic policy from the static policy – weight and airspeed. That is, the dynamic policy uses the weight and airspeed of the leading aircraft to determine the separation requirement, instead of assuming conservative static values. To see which of these factors contributes most to increasing the capacity, we test three versions of the dynamic policy: (a) one in which both the weight and airspeed are known and used to dynamically update the separation requirement (as was done previously), (b) one in which the weight is known, but the airspeed is unknown and set equal to the assumed static value (i.e., the typical cruise speed for the aircraft type), and (c) one in which the airspeed is known, but the weight is unknown and set equal to the assumed static value (i.e., 90% of the maximum take-off weight for the associated aircraft type). Figure 6 shows the maximum throughput obtained for the various policies with a mixed fleet (5 aircraft types), carried out over multiple simulation replications. The maximum throughput is obtained by simulating the system with a suitably large arrival rate.

For the mixed fleet mix, the speed-based dynamic separation policy provides better improvement than the weight-based policy. This can be explained by the fact that with the introduction of small aircraft, all the aircraft behind the small aircraft fly with airspeeds much slower than their nominal cruise speed, so the weight-based policy that uses the nominal cruise speeds to determine the minimum separation gives more conservative separations.

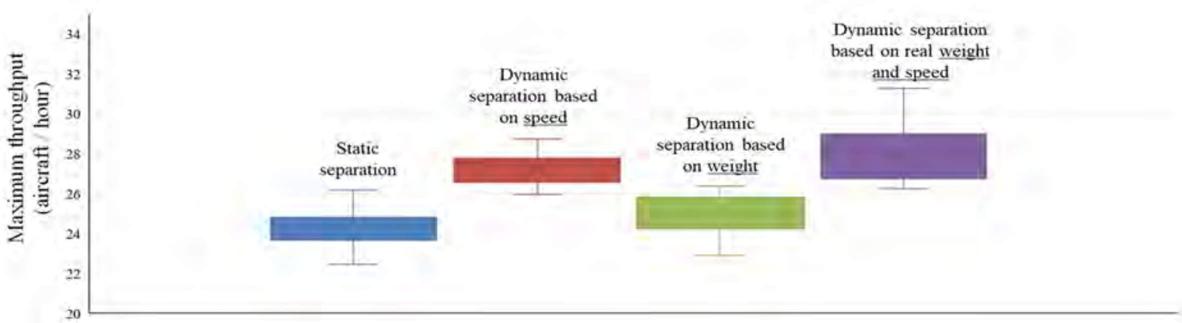

Figure 6: Capacity of the flow corridor for different separation policies (mixed fleet mix, 5 aircraft types).

Figure 7 shows results for the same experiment with a more homogenous fleet consisting of the first four aircraft in Table 1 without the smaller CRJ300. In this case, the weight-based separation policy provides greater improvement than the speed-based policy. These experiments show that, depending on the fleet mix, different factors may be important in increasing the corridor capacity.

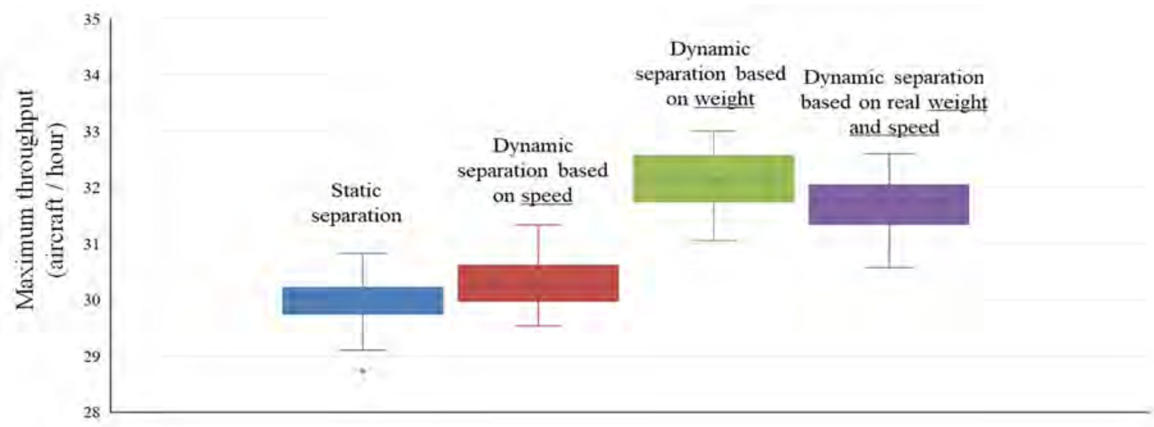

Figure 7: Capacity of the flow corridor for different separation policies (uniform fleet mix).

Figure 8 shows the impact of ambient turbulence on corridor capacity. In general, an increase in the ambient turbulence leads to faster decay of the vortices, resulting in smaller required separation distances and increased throughput of the system. As before, a uniform fleet results in higher throughput than the mixed fleet.

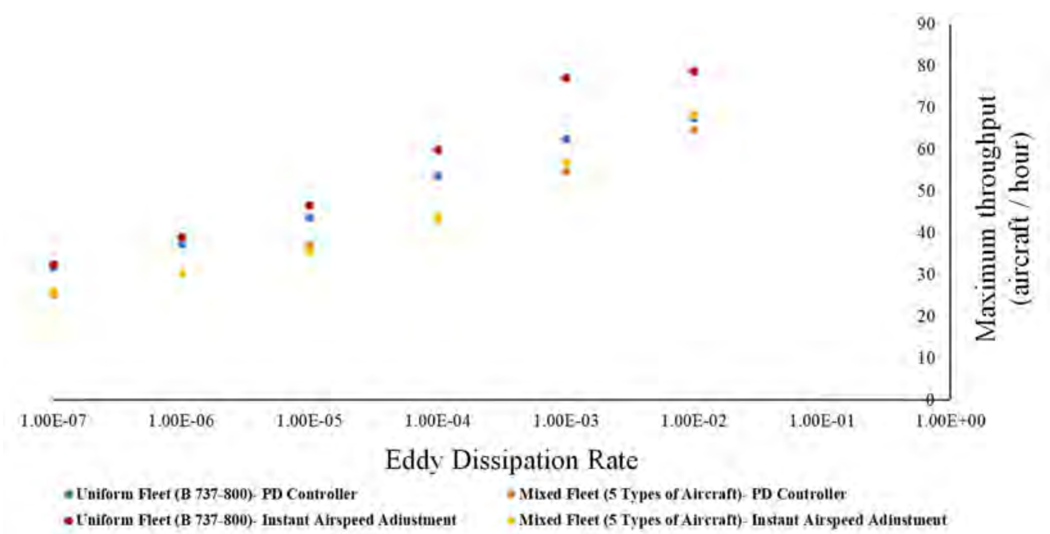

Figure 8. Throughput versus ambient turbulence for different fleet mixes.

Figure 8 also shows results based on a hypothetical control function in which an aircraft is able to *instantly* adjust its airspeed to the desired target (i.e., infinite acceleration), rather than accelerating over time according to equations (1) and (2). When required aircraft separations are relatively large, as in the case with low turbulence, there is little difference in maximum throughput between the hypothetical control function and the original control functions, (1) and (2). This is because the trailing aircraft has more room to adjust to match the speed of the leading aircraft. However, when required aircraft separations are relatively small, as in the case with high turbulence, then the original control function yields lower throughput compared to the hypothetical control function. This happens because when simulating aircraft trajectories with PD controllers, a small reduction in speed of the leading aircraft leads to a bigger reaction in the following aircraft and more reduction in its airspeed. When there is a chain of leaders and followers, this can add up. This is similar to the phantom traffic jam phenomena for vehicles in a highway. When aircraft are further apart, they recover faster from this chain reaction. This behavior is reduced when a control law is used that allows instantaneous accelerations.

5 CONCLUSIONS

This paper provided a simulation framework to explore the benefits of a dynamic wake separation concept in an en-route corridor. The concept uses the weight and airspeed of the leading aircraft, as well as atmospheric parameters, to dynamically update the minimum required separation distance based on evaluation of a wake-evolution model. This policy was compared to an analogous static policy that uses conservative inputs to the wake-evolution model. Aircraft dynamics were modeled via a PD controller and stochastic differential equations. Parameters in the dynamic systems model were quantified so that the output of the simulation approximately matched separation distributions observed from real-world data of in-trail aircraft pairs. Capacity analysis was performed for different separation policies and different meteorological conditions. Results indicated that using a dynamic separation policy can increase the capacity of the flow corridor, though the benefits may significantly depend on the fleet mix within the corridor.

Future work could follow a number of different directions. The flow corridor model could be extended to include multiple lanes (stacked vertically and horizontally) to allow for passing within the corridor. This could also be used to investigate dynamic wake separation for ascending and descending traffic. The PD controller could be modified or replaced with a more sophisticated controller to avoid creating chained slowdowns when simulating trajectories of the aircraft in the corridor. Effects of using different fast-time wake models within the dynamic separation function could be studied. Also, the effects of sudden changes in meteorological parameters could be studied in terms of both capacity and safety considerations.

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