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SAFETY AND PERFORMANCE IMPLICATIONS OF WAKE VORTEX BUFFERS

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ABSTRACT

This paper presents a simulation-based study of the performance implications of spacing buffers in the United States' Air Traffic Control System. A spacing buffer is used during instrument flight operations, when radar control is active. The buffer represents additional spacing between successive flights beyond what is required so that separation violations rarely, if ever, occur. In contrast, during non-radar visual operations, spacing at or near the minimum occurs when pilots request and are granted visual clearances. Using published data derived from multilateration surveillance systems, this study describes a simulation experiment created to understand the performance implications of actual separations for controlled flights when instrument flight rules are active. The results show, unsurprisingly, that there is a statistically meaningful increase in delays as the spacing buffer increases. These results also demonstrate how, during weather-triggered radar operations, the air traffic system at busy airports can become congested and delays escalate.

1 INTRODUCTION

Frequent travelers using the Air Traffic Control System might ask the question: why are aircraft often delayed when weather conditions deteriorate, even though the winds are calm? Such delays are understandable when the deteriorating weather is accompanied with substantial wind gusts, such as experienced during convective weather or in heavy turbulence, because winds affect the performance of aircraft. However, during rainy or foggy days, when the wind is calm, why do delays accumulate at busy airports? The climb, cruise, and descent performance of modern aircraft are unaffected by rain or fog, and hence it is reasonable to expect that an airport could operate just as efficiently when visibility is poor than when it is good. If aircraft performance is a nonissue, then what is the problem?

Aviation cognoscenti know the answer to this question without requiring any detailed study: during conditions of poor visibility (rain, fog, or both), the Air Traffic Control System (hereafter, ATCS) reverts to radar control, in which separation between successive aircraft operations are enforced by human controllers viewing traffic on computer-processed radar displays. Controllers are penalized if the spacing between flights becomes less than the minimum separation standard. Because of such penalties, a *spacing buffer* is added to the minimum separations. This buffer serves as a defense against variance. Variance in aircraft spacing is due to many factors, among them are the possibility of a pilot's slow response to a controller's directive, the latency in surveillance signal processing, the workload of a controller becoming too high, and other similar factors. In contrast, during periods of good visibility, for reasons explained later in this paper, a spacing buffer is unnecessary.

The result of adding a buffer during periods of low visibility compared to the absence of a buffer during periods of good visibility is that successive operations at a busy airport are slowed down, causing a queueing-induced delay both on the ground (for departures) and in the air (for arrivals). A related factor is airline scheduling at busy airports. Schedules are set months in advance, at a point when the weather on the day of operation is unknown. Therefore, to maximize revenue at a busy airport, airlines schedule flights for a "clear weather" day, which is defined as calm winds with unlimited visibility. On the day of operation,

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if the visibility is limited, then the additional buffer creates increased inter-flight spacing, which, combined with a congested flight schedule, triggers backups that can cause delays.

The purpose of this paper is to use actual data to quantify this effect, that is, how does the spacing buffer affect operations at a single airport? Rather than compute the effect of these delays on the whole system, this paper concentrates on the effect at a single airport—delays merely caused by rain or fog that often frustrate travelers.

By combatting variance, the spacing buffer is a mechanism for ensuring the *safety of aircraft operations.* As will be discussed later, the separation standards exist because of safety concerns, and the presence of high variance leads to buffering that further enhances safety. So another way to present this research question is: to what extent does the enforcement of safety during periods of poor visibility affect flight operations?

2 BACKGROUND

Because this paper is written for a general audience, a number of issues must be discussed before the simulation results can be presented and interpreted. Aviation aficionados may skip this section as it contains well-known background material. This material includes the minimum aircraft spacing, the magnitude of the spacing buffer, and the absence of such a buffer in periods of good weather.

The distance between two aircraft is called *separation* if the aircraft are on two different routes, and *spacing* if the aircraft are traveling the same route. Regardless of the term used, the concept is the same. Because we will be dealing with aircraft arriving and departing at a single airport, we shall use the term *spacing* throughout this paper.

There are two concepts related to spacing: the minimum spacing and the optional spacing buffer that is added to the spacing. The key point is that the *actual* spacing between successive operations is the sum of these two quantities. Under radar control, the optional buffer is (usually) nonzero, while during visual operations, the buffer is very close to, if not actually, zero, and occasionally even negative. A negative buffer implies that the resulting spacing is less than the minimum spacing standard.

The minimum spacing is necessary because aircraft produce wake turbulence as the wings generate lift. It is also necessary because jet engines produce a stream of turbulent air immediately behind them, often called *jet wash.* While jet wash is unstable and deteriorates into the atmosphere quickly, wake turbulence is more stable and can stay intact for many minutes. The wake is significant enough that an aircraft immediately behind can be caught up in the wake, lose all control, and spin to the ground.

Far from being theoretical, this effect is real. In February 2019 a passenger-carrying Embraer experienced a loss of autopilot function combined with a violent roll to the right due to the wake vortex of a Boeing 777 aircraft seven miles ahead of it (ASRS 1619356, 2019). Also in 2019, a regional jet approaching George Bush Intercontinental Airport in Houston (IAH), started rolling approximately 30 degrees in both directions due to a wake vortex encounter with a Boeing 737, four miles ahead of it (ASRS 1619349, 2019). Nor are wake encounters limited to small aircraft. On June 10, 2018, an Airbus A380 flying at 30,000 feet over the Pacific nosedived for about ten seconds before control could be restored, due to wake turbulence from another A380 *twenty nautical miles* ahead of it on the same route (Bloomberg News Service, 2018). There are many similar incidents that pilots routinely report.

Despite these (and other) incidents, *accidents* (i.e., hull losses) due to wake turbulence are nonexistent among commercial air carriers (although they do exist in the General Aviation community). The minimum spacing standards are credited with preventing commercial aircraft wake turbulence accidents . These minimum standards have evolved over the years, but the current standards are embodied in US Department of Transportation / Federal Aviation Administration Order JO 7110.65, effective September 2018 (FAA, 2018). There are a variety of separation standards within that order. The standards vary depending upon the weight, wingspan, wake vortex tolerability of the aircraft pair, their altitude, the mode of flight (climb, cruise, descend), whether arriving or departing, and other such variables. A consolidated summary of wake vortex standards can be found at FAA Order JO 7110.126. Typically aircraft traveling longitudinally along the same route are separated by three to eight nautical miles, depending upon the various variables involved (weight, wingspan, etc.).

For a given pair of aircraft in a particular situation, only one wake vortex value (of the many specified in 7110.65) is applicable. Controllers are responsible for providing separation between aircraft that *meets or exceeds* the particular value. If the spacing between the pair is reduced below the minimum, then penalties apply. As a result, a buffer is added to the minimum spacing to avoid the penalty.

Sometimes the responsibility for separation rests with the pilot. This delegation of responsibility occurs during clear weather (visibility greater than 10 nautical miles). Upon approach to an airport, a pilot may request a "visual clearance." If granted, then radar separation is terminated and the pilot becomes responsible for separation. The pilot, knowing the atmospheric conditions and the aircraft immediately ahead of it, may space the aircraft closer than the minimum separation. If an error occurs, the pilot is responsible.

During periods of good weather, therefore, pilots can provide their own buffers. Because airlines are under pressure to maintain a schedule, pilots will often be aggressive with the separation minima in order to land sooner than if controlled by radar. These pilot-controlled buffers are often close to zero, and sometimes negative, which is acceptable and safe as long as the pilot is able to avoid the leading aircraft's wake turbulence. Because the wake usually responds to gravity, and therefore sinks, if the trailing aircraft is slightly above the leading aircraft, then wake interactions are less likely.

But the present study is concerned with low visibility operations that require radar control. Given that a spacing buffer is present, one of the questions we must answer to carry out this study is: what is the magnitude of this buffer?

3 MAGNITUDE OF THE SPACING BUFFER

The spacing buffer varies considerably from airport to airport, flight pair to flight pair, and from one controller to another. Its value is difficult to determine. What is known is that the buffer varies across time of day, traffic volume, workload, airport configuration, and a host of other factors. By asking various experts, the author determined that the *average* spacing buffer applied during approach operations to a busy airport is somewhere between 0.6 and 0.7 nautical miles (nm) (Various Experts, 2019).

To obtain further insight into the average value and variance of the spacing buffer, we used an analysis of the timing of successive arrivals published by Shortle (Shortle, Zhang, & Wang, January, 2010). Using multilateration surveillance data for arrivals at Detroit Metropolitan Wayne County Airport (DTW), the paper presents the statistical distribution of the *time spacing* between subsequent arrivals at that airport. The paper is concerned with the tail behavior of the distribution, in particular the left tail (extremely small values), as it represents interarrival spacings that are potentially smaller than the minimums and thus may lead to safety issues. The collected data represent arrivals from 10 nm to "wheels down" from January to February 2003 for runway 21L at DTW. The paper reports approximately 2,500 arrivals during instrument meteorological conditions (or IMC, the focus of this paper: IMC landings are radar-controlled and thus contain spacing buffers) as well as approximately 5,500 arrivals during visual meteorological conditions (or VMC, conditions in which the pilots may self-separate if approved.

Figure 5 from that paper provides the probability density function (PDF) of the resulting interarrival time spacing. That figure includes separate PDFs for IMC and VMC, which is ideal for our purposes. Focusing on the IMC curve in that figure, it appears that the minimum time-based separation is 50 seconds, the most likely is 100 seconds, while the extreme value appears to be 170 seconds. The figure contains probability beyond the 170-second time spacing. We set the maximum at 170 seconds because, in our opinion, time separation values beyond 170 seconds represent successive arrivals that are spaced far apart in time prior to entering the terminal area. These flight pairs occur during times when arrival demand is weak. Aircraft pairs are therefore naturally separated by distance and time well above any wake vortex consideration, such that spacing buffers are unnecessary. The 170-second cutoff was obtained by taking the steepest part of the PDF curve to the right of the most likely value and extrapolating it to the horizontal axis.

Therefore, we conclude that the minimum time-based separation is 50 seconds, the most likely is 100 seconds, while the maximum is 170 seconds.

Although the ATCS is transforming towards a time-based spacing system, the regulations in place specify separations by distance. Thus the next step is to transform these time-based numbers into distance. This transformation is difficult, as converting time-based separations to distance requires knowledge of the approach speed of aircraft. DTW has a mix of different aircraft arriving to it. Using the FAA's Aviation System Performance Metrics (ASPM) database, and querying it for flights at DTW in January and Feburary 2003, the number of different aircraft types using the airport is obtained (Federal Aviation Administration, January-February 2003). In 2003, for wake vortex separation purposes, aircraft were categorized as Heavy, B757 (Boeing 757), Large, Medium, and Small. The A380 aircraft was nonexistent back then. From the ASPM database, we find that during January and February of 2003 there were approximately 38,000 total arrivals. Of those arrivals, approximately 2.9% were the "Heavy" wake vortex category, 7.1% were "B757," 86% were "Large," 2.6% were "Medium," and 1.4% were in the "Small" wake vortex category, the remaining being unknown. Obviously the largest wake category is Large, and most of the pairings will be large following large. In the terminal area, this spacing would be 3 nm.

A Boeing 737 (B737) is an example of an aircraft that would have been in the "Large" wake vortex category in 2003. In order to translate the time-based separations into distance, the approach speed of the aircraft must be known. The approach and landing speed of an aircraft, such as a B737, is itself dependent on many factors. The landing speed, in particular, is dependent upon the weight of the aircraft, the presence of headwinds or tailwinds, the flap configuration, whether auto-thrust is enabled for landing (or not), the presence of any system failures that may require a higher landing speed, and the airfield elevation (Ritest, January 26, 2018). Of these factors, only the airfield elevation is constant across all flights landing at DTW during the study period. A B737, for example, has landing speeds anywhere from 107 knots (kts) for a lightly loaded, full-flap configuration to approximately 170 kts for a fully-loaded, light flap configuration. The expected landing speed seems to be in the range of 125 to 145 kts (Brady, 1999).

Using various acceptable values of the landing speed, and using the three time-based spacing values that we identified from the published data (50 second minimum, 100 second most likely, and 170 second maximum), we computed a table of the spacing buffer as a function of landing speed and time-based spacing, shown in Table 1 below.

Table 1. Spacing Buffers for Various Combinations of Arrival Spacing and Landing Speed.

Spacing (secs)	Landing Speed (kts)	Distance (nm)	Spacing Buffer (nm)
50	125	1.7	−1.3
100	125	3.5	0.5
170	125	5.9	2.90
50	135	1.9	−1.1
100	135	3.8	0.8
170	135	6.4	3.4
50	160	2.2	−0.8
100	160	4.4	1.4
170	160	7.6	4.6

Table 1 is computed assuming a minimum wake separation distance of 3 nm. Therefore if successive arrivals are spaced 50 seconds apart, and the landing speed is 125 kts (first data row in the table), then the interarrival spacing for that pair will be 1.7 nm. Because 1.7 nm is less than the minimum distance of 3 nm, the spacing buffer is negative: −1.3 nm in this instance. Negative buffers are of concern because they may represent safety violations, which we shall investigate in this study.

After some experimentation, it was decided to use the spacing buffers computed from the 125 kt landing speed. The minimum buffer is set at −1.26 nm, the most likely buffer is 0.47 nm, and the maximum buffer is 2.90 nm. When an analyst has a good estimate of the minimum, most likely, and maximum values of a random variable, a triangular distribution is appropriate. A triangular distribution with these parameters has an average value of 0.70 nm, which conveniently is in the range (albeit at the high end) of the expert opinion, which suggested a value between 0.6 and 0.7 nm. The standard deviation of this distribution is 0.64 nm, representing a coefficient of variation of 0.91, a well-behaved distribution.

4 SIMULATION EXPERIMENT

In this section we describe the simulation experiment that has been conducted to gain insight into the overall question of spacing buffers in inclement weather. We shall present the experimental design using a formal process.

4.1 Study Question

The study question is, what is the impact on the performance of airports when a nonzero spacing buffer is present?

4.2 Metrics

The term "airport performance" is difficult to estimate because it can describe any number of observable quantities that define how efficiently an airport operates. In this context, we are concerned about successive arrivals to and successive departures from an airport, where the flights are assigned to the same arrival (or departure) route and therefore may be affected by the presence of the spacing buffer. Our main quantity of interest shall be flight delays, defined as the amount of extra time it takes a flight to travel to and from the airport. The "excess time" is excess time relative to an unimpeded flight. Unimpeded and impeded time is measured at a point 150 nm from the airport. The times for arrivals are therefore measured from a point 150 nm distant from the airport to "wheels on." The times for departures are measured from "wheels off" to a point 150 nm away from the airport. Each flight is computed twice, once "unimpeded" and once will all constraints included. Both the unimpeded and impeded instance of each flight travel the same route to and from the airport.

4.3 Experimental Design

Although the interarrival distribution in time, and then in distance, was derived from published data using DTW airport, the experiment conducted herein was centered at Dallas Ft. Worth International Airport (DFW). There are two reasons DFW is used. First, route files for performance-based navigation (PBN) Standard Arrival Routes (STARS) and Standard Instrument Departures (SIDS) were available for DFW with little additional work. Secondly, DFW has a heavier traffic volume than DTW (used in the reference study), meaning that any spacing buffer is likely to exacerbate airport performance at DFW. We are assuming that the distribution of spacing buffer that we have derived at DTW is applicable to DFW as well. To the extent that this assumption proves unwarranted, then the spacing buffers will have to be adjusted and the results recomputed.

For this experiment we shall use the Metrosim simulation, a tool developed at IAI and widely used for analysis of single or multiple airports that share airspace within a metropolitan area. Details of the Metrosim tool can be found in other papers (Wieland, Tyagi, Kumar, & Krueger, 16-20 June 2014), (Wieland, Sharma, Tyagi, Santos, & Zhang, 2016). Airport capacity, such as the capacity at DTW, is implicit in Metrosim. Instead of enforcing a specific capacity, the tool enforces spacing between subsequent arrivals and departures, and ensures that the spacing is maintained within the terminal area as the arrivals and departures follow established routes. The spacing therefore dictates the capacity. This model represents the method by which air traffic is handled at an airport, and is ideal for this study. The input table that represents wake separations for various pairs of aircraft wake separation types can be changed to study the effect of the various spacing buffers determined in Section 3.

For the study, the Metrosim tool requires at least two other input sources: a list of waypoints that define each route to and from an airport (DFW in this case), and a list of flights that are arriving and departing from DTW. The flights used in the aforementioned statistical analysis were from 2003. At IAI, we have access to flight data from November 2017 onwards, through the FAA's System Wide Information Management (SWIM) system. From that system, we extracted DFW flights for a 29-hour period commencing 5 AM local time (at DFW) on November 2, 2017 and ending at 10 AM local time on November 3, 2017. We extracted 1,073 departures and 1,086 arrivals during this time period from the SWIM data. The total operations count in our flight dataset—2,159 for the two days—compares to 2,263 operations recorded by ASPM for the same twenty-nine hour period. The difference, 104 flights (4.8%) can be attributable to greater flight access by the ASPM system: the SWIM system filters out certain flights, does not include flights using VFR, as well as certain general aviation and military flights. ASPM contains all these flights. The extracted data were flight plans and routes. The distribution of operations by hour for the flights that we extracted is shown in Figure 1 below. The routes used for this study are shown in Figure 2 below.

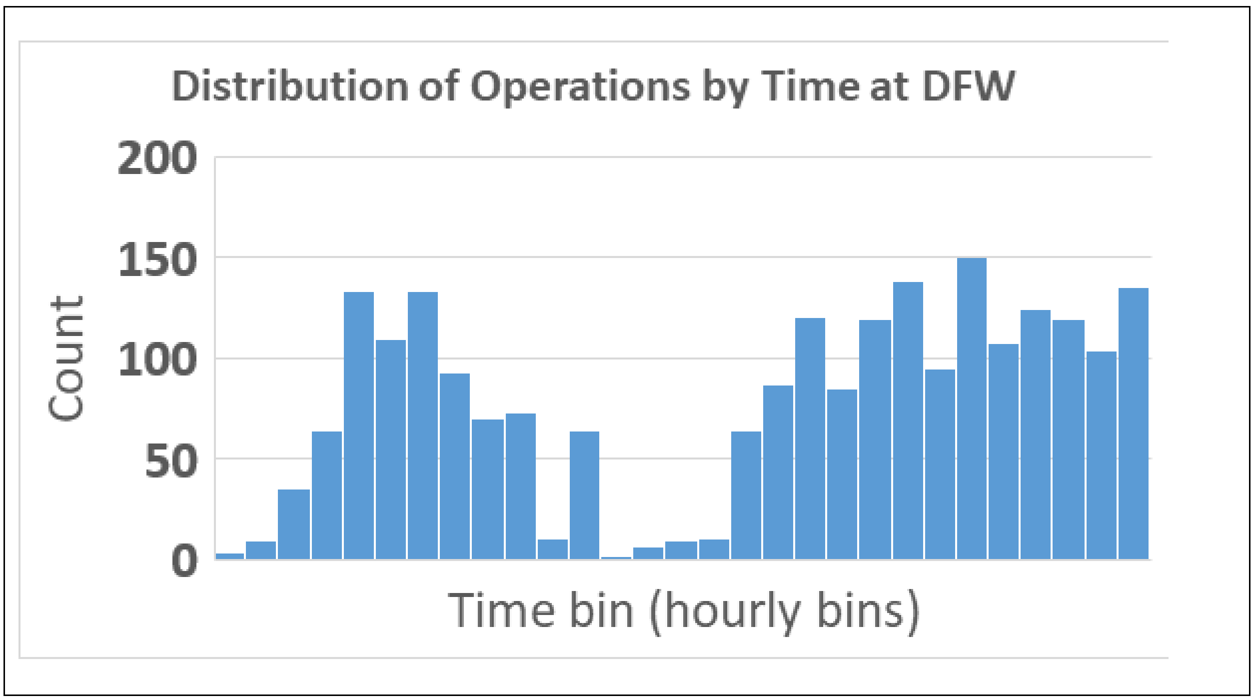

Figure 1. Distribution of operations (arrivals + departures) by hour, DFW (FAA SWIM Data).

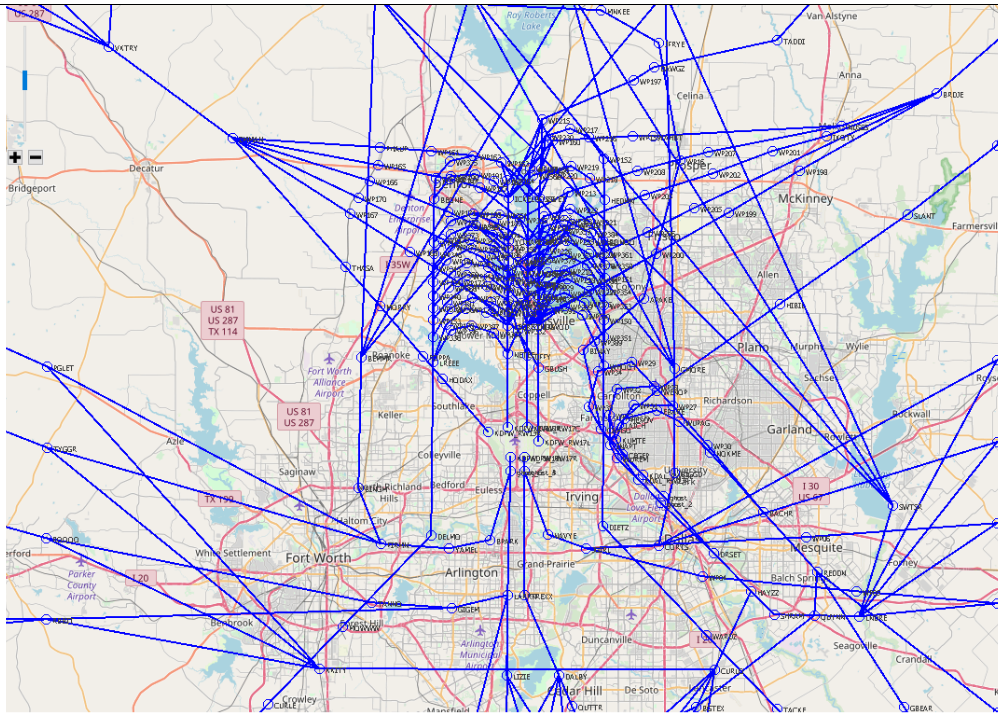

Figure 2. Routes Used at DFW for the Current Study. South Flow is Modeled.

4.4 Use of the Predictive Query Language

This simulation experiment is expressed in the *Predictive Query Language,* or PQL, a scripting language developed at IAI specifically for defining and executing simulation experiments. PQL is a general language, applicable to any simulation tool that can be executed in batch mode. Details of PQL can be found in (Wieland, Sharma, Vlachou, Hoban, & Trapaidze, January 2019). In this section we present the script used to execute the experiment outlined above.

```
PREDICT
     TrajectoryMetrics,
     DelayMetrics,
USING
      MetroSim
WHERE
      EXPERIMENT_NAME = Baseline_zero
AND   REPORTS_WORKSPACE = ReportsWorkspaceLocation
AND   MetroSim.overwriteExisting = 'true'
AND   MetroSim.simulationStartDateHour = '2017-02-11 00'
AND   MetroSim.flightPlanDataSetPath  = 'FlightDataLocation/KDFW_flights.csv'
AND   MetroSim.routeFilePath = 'RouteDataLocation/DFW_SOUTHFLOW_110217.xml'
AND   Metrosim.wakeSeparationBuffer = 0.47
AND   TrajectoryMetrics.innerRadiusNm = 150
AND   TrajectoryMetrics.outerRadiusNm = 250
AND   TrajectoryMetrics.airports = 'KDFW'
AND   DelayMetrics.innerRadiusNm = 150
AND   DelayMetrics.outerRadiusNm = 250
AND   DelayMetrics.airports = 'KDFW'
```

```
;

PREDICT BASED_ON Baseline_zero
WHERE
      EXPERIMENT_NAME = Treatment1_Minus126
AND   MetroSim.wakeSeparationBuffer = -1.26
;

PREDICT BASED_ON Baseline_zero
WHERE
      EXPERIMENT_NAME = Treatment_Plus290
AND   MetroSim.wakeSeparationBuffer = 2.90
;

COMPARE Baseline_zero AND Treatment1_Minus126 USING TrajectoryMetricsCompare;
COMPARE Baseline_zero AND Treatment1_Minus126 USING DelayMetricsCompare;

COMPARE Baseline_zero AND Treatment_Plus290 USING TrajectoryMetricsCompare;
COMPARE Baseline_zero AND Treatment_Plus290 USING DelayMetricsCompare;

COMPARE Treatment1_Minus126 AND Treatment_Plus290 USING TrajectoryMetricsCompare;
COMPARE Treatment1_Minus126 AND Treatment_Plus290 USING DelayMetricsCompare;
```

Figure 3. PQL Script that Specifies the Experiment Defined in this Paper.

Without describing the details of this scripting language, which is beyond the scope of the paper, the experiment it describes can be summarized as follows. Three runs of the Metrosim simulation tool are specified. The first run is the first PREDICT statement up to the first semicolon, and describes a baseline simulation run with a wake separation buffer of 0.47 nm, flights and routes for DFW from November 2, 2017, and parameters for the metrics computation scripts. Two metrics are to be computed: trajectory metrics (time/distance flown), and delay metrics (comparison of impeded and unimpeded flight times. The other two simulation runs are treatment cases, which inherit all the configuration information from the baseline. Treatment case #1 specifies a wake vortex buffer of -1.26 nm, while treatment case #2 specifies a buffer of +2.90 nm, which is the result of our analysis presented in section 3 of this paper. Six different comparisons are described, whereby each of the two metrics are compared to each other for the three simulation runs specified.

In summary, this script implements three simulation runs, where each run will compute two different metrics. The six sets of metrics are then compared to each other and the results presented to the analyst.

5 RESULTS OF THE EXPERIMENT

As indicated in the previous section, two metric sets were computed for each simulation run: trajectory metrics and delay metrics. Of these two metrics, the trajectory metrics showed zero variation in the distance flown among each scenario, which is expected because the arrival and departure routes for DFW were unchanged between the different simulation runs. The times along those routes, however, did change, and those changes are captured by the delay metrics. Thus the results below will concentrate only on the delay metrics.

5.1 Delay Metric—General Model

A general mathematical model of the delay metric for this test case is as follows. The time an arrival will touch down on the runway will be equal to (or greater than) the time of the previous arrival plus the minimum spacing plus the buffer. Assuming that the arrivals are dense in time, then mathematically:

$$t(a+1) = t(a) + s_{min} + s_{buf},$$

where $t(a+n)$ denotes the time of the n^{th} arrival in the stream, while s_{min} represents the minimum wake vortex separation *expressed in time*, and s_{buf} represents the spacing buffer expressed as a time value. As noted earlier, the conversion from distance to time includes a number of factors, including the relative airspeeds between the two aircraft. At a 125 kt landing speed, with a 3 nm separation (used in this study) the distance spacing translates into 86 to 87 seconds of time spacing. In the presence of winds, this number can change.

For the n^{th} arrival, the wheels-on time is simply $t(a+n) = t(a) + n\, s_{min} + n\, s_{buf}$. An "unimpeded" flight would land at the earliest time possible, which is simply given by $t(a) + n\, s_{min}$. Thus the delay is solely given by $n\, s_{buf}$. The largest buffer used in this study is 2.9 nm, which at 125 kts converts to a time value of approximately 83.5 seconds.

The actual delay for the subsequent operation is dependent upon two variables: the applied spacing $(s_{min} + s_{buf})$ and the spacing of the two operations before any control is applied. For example, if two operations are already spaced five minutes apart—which might occur during a non-busy period at the airport—then most likely the applied spacing will be a nonissue and the delay zero.

5.2 Delay Metric—Simulated Results

To estimate the value of the delay in the presence of spacing buffers, we ran the experiment outlined in section 4 of this paper. We measured the "delay" metric, which is the time between an impeded and unimpeded flight run in the simulation tool. This metric can occasionally be less than zero, which occurs if, during the impeded run, a more efficient route is flown, or the aircraft is sped up on approach for spacing concerns due to a trailing aircraft, or if an aircraft ahead of it on the arrival stream enters a holding pattern.

A histogram of the delays recorded in two of the scenarios is shown below. In the first scenario, the spacing buffer was set to the minimum -1.26 nm (see section 3 for the justification). In the second scenario, the spacing buffer was set to the maximum 2.90 nm. Thus we would expect to see less delays in the first than we do in the second scenario, and that is evident with the two histograms below.

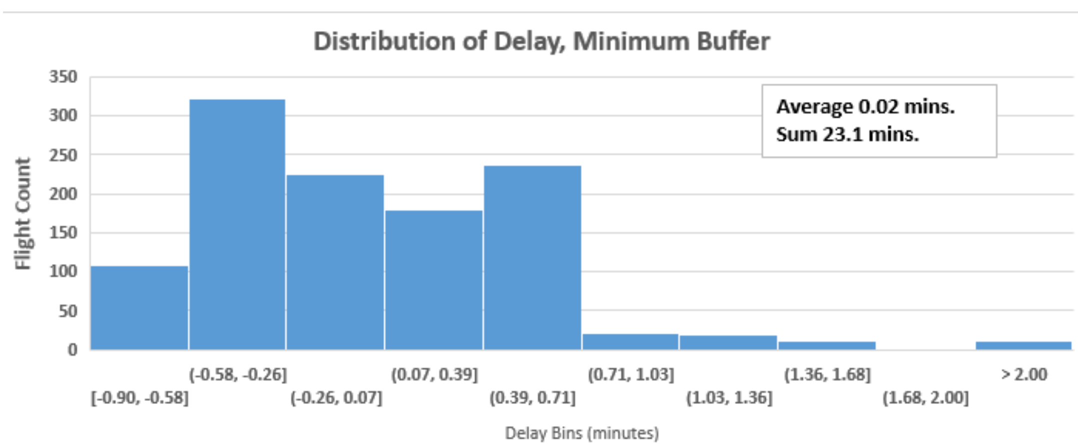

Figure 4. Distribution of Flight Delays, Buffer -1.26 nm.

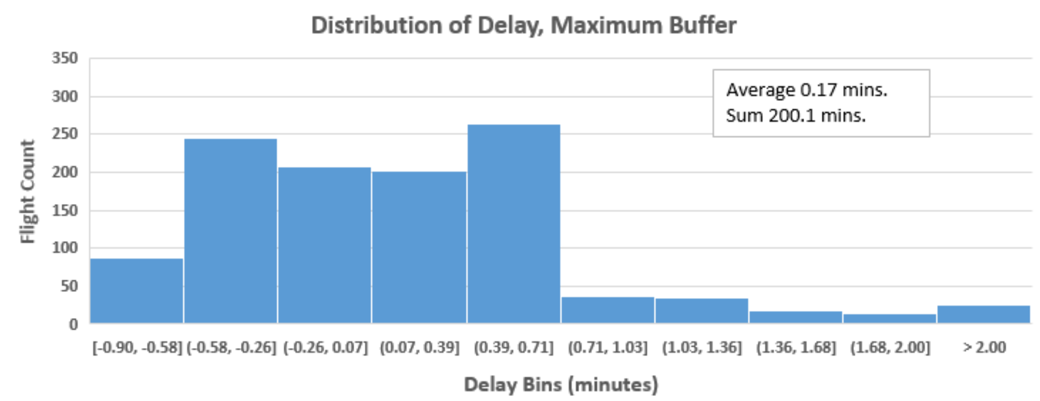

Figure 5. Distribution of Flight Delays, Buffer +2.90 nm.

Figures 4 and 5 represent delays with a minimum and maximum spacing buffer. The minimum buffer, which is negative in this case, would most likely occur in visual conditions when separation authority is delegated to the pilot. The maximum buffer would most likely occur in extremely poor visibility conditions when other factors drive up controller workload to the extent that a large buffer is necessary.

The results are interesting. The negative buffer nevertheless has a small delay (relative to an unimpeded flight), which sums to 23.1 minutes across the operating day—truly a small total delay that would impact operations only marginally. In contrast, the large buffer has a larger total delay of 200.1 minutes, or about three and one-third hours. This delay would be spread over the operating day, lengthening it by that amount—unless flights are canceled or diverted (which they most likely would be).

5.3 Delay Metric—Implications

The implications of these results is that the spacing buffer, unsurprisingly, will cause delays to flights. Because the buffer is most often applied during periods of inclement weather, when the visibility is poor, the delays computed—up to three and a third hours—would occur during rainy or foggy days. These are close to actual delays observed under such conditions. Therefore, we can tentatively assert that delays in poor visibility (rain, fog) can be attributed to the additional spacing buffer applied to the minimum required buffer in order to handle the variance of inter-flight spacing.

In this experiment, the extra delay amounted to 177 minutes during the course of the operational day (200.1 minutes – 23.1 minutes). The 177 minutes of extra delay would cause havoc to the arrival schedule at the airport, because (as noted earlier) airlines tend to schedule flights—months ahead of time—assuming visual conditions are active at the major airports. Thus the airlines' schedules will be disrupted, and procedures for handling such disruptions will be executed.

6 CONCLUSIONS

This paper began with the question as to why delays occur during foggy or rainy conditions, given that aircraft performance is unaffected by fog or rain. The answer is that, because the system is primarily human-controlled, and because there are penalties for spacing violations, spacing buffers are added to prevent such violations from occurring. These buffers are only applicable when flights are being controlled by radar, which is precisely what happens during periods of low visibility. During clear weather, good visibility days, spacing is often delegated to pilots, whereby a "negative buffer" may occur as pilots will fly as close as possible to the aircraft ahead without encountering its wake vortex. The pilots are under pressure to land the flight as soon as possible, and the airline is under pressure to maintain a schedule. The combination of both of these pressures contribute to negative spacing buffers.

While this simulation experiment is illustrative, further work can concentrate on describing the delays through a variable spacing buffer. Because the spacing buffer will vary between each flight pair and the buffers will change as the visibility changes. Therefore a more realistic experiment would take this variability into account.

One final implication of these results concerns the automation of the ATCS. Sometime in the (distant) future, both aircraft and the ground control will be fully automated. When this occurs, variance will be greatly reduced. The ground control systems can therefore compute more precisely where each aircraft will be as time evolves. This additional precision, and reduction of variance, will cause the spacing buffer to shrink to near zero, which should eliminate all delays on poor visibility days.

7 ACKNOWLEDGEMENTS

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