

Statistical Model to Estimate the Benefit of Wake Turbulence Re-categorization

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Abstract—Wake turbulence behind flying aircraft can be hazardous to nearby aircraft. Separation standards, also known as wake vortex minima, have been put in place to mitigate risks from wake encounters and ensure safety. These standards apply to aircraft pairs grouped into wake categories. With better wake science and improved automation assisting air traffic controllers, more refined wake categorizations and separation standards, called wake turbulence Re-Categorization (RECAT), have been introduced around the world, aiming to improve flight efficiency and airport capacity. Since runway capacity is one of the major factors limiting the growth of aviation, the benefits of RECAT have been of great interest to airlines, Air Navigation Service Providers (ANSP), and Directors General of Civil Aviation (DGCA).

Through the Joint Analysis Team (JAT) under the NextGen Advisory Committee, the FAA has worked with industry to evaluate RECAT capacity and delay improvements at five airports. These analyses used rapidly updated ASDE-X data to measure specific changes for individual aircraft pairs. One key JAT finding is that RECAT benefits vary greatly by airport due to differing aircraft mixes and traffic levels. Built on the empirical findings at the aircraft pair level, this paper introduces a set of statistical models that estimate delay savings associated with a proposed or actual implementation of RECAT at any airport. These regression models are robust enough to estimate delay savings for any version of RECAT at any airport using current or future demand and fleet mix patterns, although input adjustments may be required for alternative RECAT versions. Moreover, these models are easy to use and do not rely on runway-specific information that is hard to obtain and requires costly resources to establish accuracy. The proposed set of regression models requires only readily available data, such as arrival and departure times, and airport fleet mix and capacity. To assess the validity of the model's estimates, comparisons are made to other published analyses.

Keywords—Wake Turbulence; Separations; Quantifying Benefit; Regression Model; RECAT.

I. BACKGROUND AND INTRODUCTION

Wake turbulence behind a leading aircraft during take-off or final approach can be hazardous, resulting in destabilization of the following aircraft, possibly causing it to crash. Wake turbulence can also affect aircraft on parallel or crossing runways. While dangers of wake vortex have been known since the beginning of commercialized flights, the first standard wake vortex minima were established in 1970. The corresponding wake vortex categories were defined by using maximum takeoff weight (MTOW) as the key driver of risks from wake encounters. Interestingly, aircraft wingspan was already recognized as more relevant even in 1970, but its application to wake categorization and separation minima was considered to be more complicated than MTOW[1].

In the United States, during Instrument Meteorological Conditions (IMC) the air traffic controller assumes responsibility for separating aircraft on approach. If visual approaches are allowed, the responsibility can be transferred to the pilot.

Between 1970 and 2000, the FAA researched wake impacts and their mitigation. However, this research resulted in no reductions in wake vortex minima. To ensure safety, the minima were even increased by 1 mile for smaller aircraft during final approach.

In 2000, with a goal of adjusting wake vortex categories and minima to better accommodate newer aircraft models, the FAA started analyzing data collected over the course of three decades. Sensor advancements also enabled more accurate measurements of wind and relative positions of aircraft for various points of interest during take-off and final approach, providing for new data-driven statistical safety analyses at the aircraft type level that had not been possible in the past [1]. Furthermore, collaboration with other stakeholders, such as aircraft manufacturers, international partners and airlines, confirmed the viability of separation standard reductions while maintaining safety requirements [2].

This Re-Categorization (RECAT) effort started in 2012, as the RECAT 1.5 program. Aircraft were classified according to wingspan, takeoff weight and ability to withstand wake encounters. RECAT 1.5 expanded four categories of wake turbulence separation to six and removed greater than necessary separation distances within the heavy weight class. RECAT 1.5 is currently operational at 23 airports. RECAT Phase II, based on pairwise separation, was developed for the most common aircraft, compromising 99% of operations at 32 U.S. airports. It has been implemented at eight airports and has resulted in increased airport capacities [3]. Consolidated Wake Turbulence (CWT), the newest phase of RECAT in US, uses the most advantageous set of separation standards derived from the current set of standards. This has resulted in using all time-based wake turbulence separation standards. Under CWT, radar-based wake turbulence separations will be based on a categorical system that further refines aircraft groupings to provide throughput gains at many currently constrained airports and yet be usable at all airports throughout the NAS [4]. Other FAA wake initiatives under evaluation, such as Wake Turbulence Mitigation for Arrivals (WTMA-P) and Wake Turbulence Mitigation for Departures (WTMD) are weather-dependent and use local and forecasted wind in determining pairwise separations [1]. More advanced research in Wake area, such as Wake4D and Wake Vortex Prediction and Monitoring System, the Wirbelschleppen- Vorhersage- und Beobachtungssystem WSVBS are highlighted in NASA [5].

Similar efforts have been going on in Europe. Many re-categorizations have been recently implemented or proposed: RECAT-1, RECAT-2, Dynamic Pair Wise Separations (D-PWS) / RECAT-3, RECAT-NEW and most recently RECAT-EU [6]. RECAT-EU, published September 2018, is available for operational deployment. RECAT-EU is a combination of pair-wise spacing based on local traffic mix and six categories of aircraft [7]. Time Based Separations (TBS), a new tool focused on time-based rather than distance-based separations, is another concept developed by Eurocontrol that capitalizes on reduced risk from wake-encounter in strong headwind conditions [8]. TBS has been implemented at Heathrow and deployment is underway in Vienna and Paris [9]. Single European Sky ATM Research (SESAR) is developing new, optimized wake separation minima, RECAT-EU-Pairwise, which uses finer-grained aircraft categories. SESAR is also developing weather dependent separations (WDS) which will dynamically mitigate crosswinds to increase throughput proportionate to the number of wake-constrained aircraft pairs. WDS and RECAT-EU-Pairwise will require a separation delivery tool such as TBS [9].

Both the FAA's and Eurocontrol's RECAT efforts have been presented to various stakeholders including RTCA [10,11], International Air Transport Association (IATA) [12], International Civil Aviation Organization (ICAO) [9,13], International Transport Forum [14] and Civil Air Navigation Services Organisation (CANSO) [15].

Intuitively, reducing separations during final approach and take-off results in increased airport capacity and throughput. In the presence of arrival and departure queues, increased airport capacity leads to reduced delays and, therefore, more efficient airport operations. Capacity increase is identified as a key

benefit in most studies addressing the benefits of RECAT. Skybrary [16], went a step further and quantified it, claiming that "peak period runway throughput can increase by 5% or more depending on airport traffic mix." However, the delay reduction benefit is not linearly correlated with capacity increase, and benefits, positive or negative, can greatly vary with the underlying arrival and departure patterns. In this paper, we estimate and monetize delay savings, both positive and negative, as a function of airport fleet mix, demand and capacity.

II. PURPOSE

Quantifying delay and monetizing benefits to service providers and aircraft operators is important to every investment decision. Prior to the implementation of an operational improvement, benefit estimates help justify the investment as well as prioritize investments to maximize return on investment capital. After the implementation, benefits often motivate proliferation of the same capabilities to other sites. Determining RECAT categorization that is the most beneficial for a given airport is a tangible example of a real-world need for such benefit analyses, as are scenario analysis considering changes in demand, fleet mix, and arrival or departure patterns.

Our model is easy to implement and adapt to the airports under study, providing a quick and customized benefit estimate for otherwise resource-intensive analyses.

This model is most applicable to quantifying benefits from RECAT 1.5 and CWS in the US. With empirical data applicable to other RECAT versions, this methodology can be easily adjusted to accommodate the corresponding variations in grouping and separations.

III. INPUTS AND APPROACH

We collected and analyzed six months of detailed aircraft surveillance and airport performance data for four airports using RECAT 1.5, including Chicago (ORD), Indianapolis (IND), Midway (MDW) and Charlotte (CLT) airports. Since we worked with historical data at the individual flight level, each aircraft corresponds with an actual arrival or departure at one of these airports. Individual aircraft records included operation type (arrival or departure); aircraft type; and runway, date and arrival or departure time to the second.

First, a spreadsheet-based queueing model, described in Section IV, was used to estimate the post-implementation benefits at four airports. For each runway threshold, we compared aircraft take-off and landing times after RECAT 1.5 deployment to those they would have had under traditional wake categories and separation standards, and determined the following:

1. The number of arrivals and departures directly affected by RECAT changes.
2. The total time saved or lost by the directly affected flights. Flights are defined as unique operations for a day under study.

- The number of aircraft closely trailing the directly affected aircraft that had to be delayed to maintain safe separations from their leads.
- The total time saved or lost by the trailing aircraft.

To develop the regression model to estimate current and future benefits at other airports, the following data were added to each unique flight record, each determined by using quarter-hour records from the FAA's Aviation System Performance Metrics (ASPM) database:

- Meteorological conditions at the airport, instrument (IMC) or visual (VMC);
- Airport pressure rate, approximated by the ratio between actual arrival demand and the Effective Airport Arrival Rate (AAR) for arrivals, and by the ratio between the actual departure demand and the Airport Departure Rate (ADR) for departures.

IV. DETAILED METHODOLOGY

We first describe the spreadsheet-based queueing model used to estimate benefits of RECAT 1.5 at the four sites, and its outputs used by the regression model. Next, we describe the regression model developed to estimate benefits of RECAT at other airports. Finally, we explain how to apply the model to estimate the operational and monetized benefits at a specific proposed RECAT site.

A. Spreadsheet-based Queueing Model

Our first step in building a queueing model was to confirm if the expected changes in separations between relevant aircraft pairs were visible in empirical data records. By working with five to six months of ASDE-X surface surveillance data at each airport, we created distributions for all lead-trail aircraft pairs presented in Figure 1. Minimum Required Separations (MRS) is 2.5 or 3 miles depending on local restrictions. The large table at the bottom of the Figure 1 highlights aircraft type pairs with changed separations with RECAT 1.5, most of which are decreases. Note that the main separation reductions occur with aircraft trailing the category C and B757s.

We then determine how many aircraft-pairs are effected by the change in separations, and illustrate our findings for ORD in Figure 2. About 4.4 percent of arrival pairs and 4.7 percent of departure pairs have decreased separations, and about 0.6 percent of departure pairs have increased separation under the new RECAT rules at ORD.

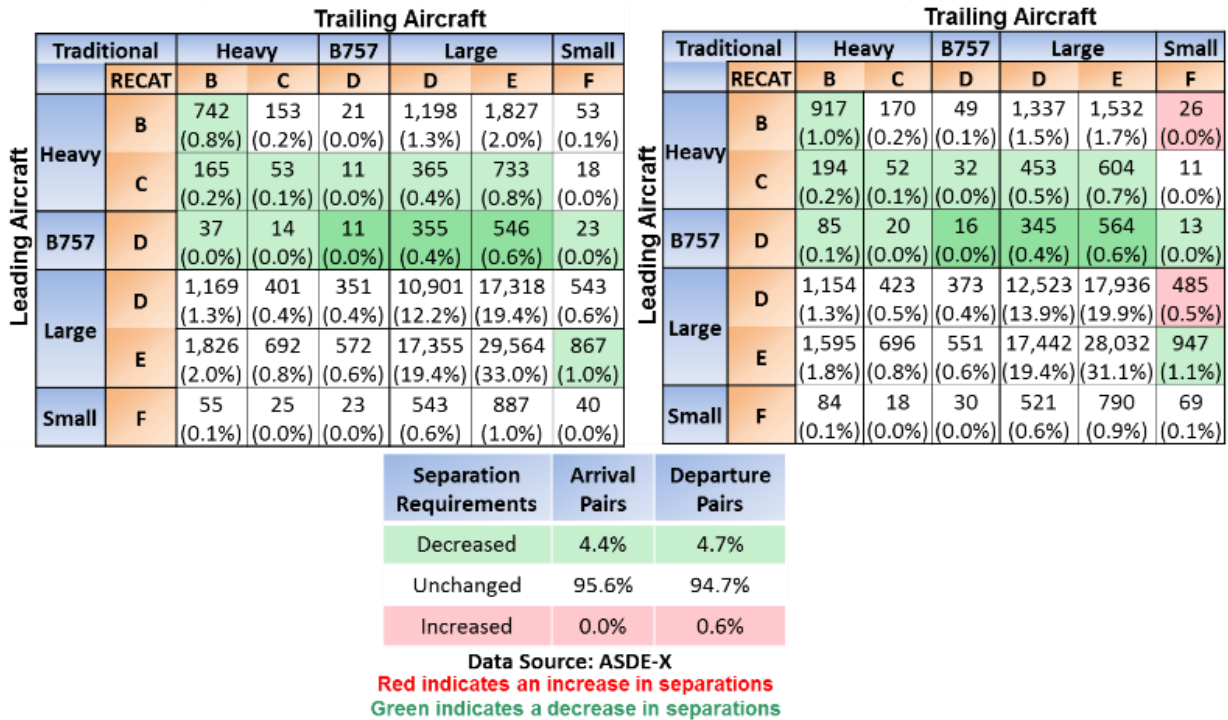
Figure 3. highlights a comparison of pre- and post-RECAT 1.5 spacing times for a few lead-trail example pairs at ORD. At the mode of the distributions, a clear reduction of 30 to 40 sec is visible. We did not recalibrate actual operational changes in spacing, but instead accepted 37 sec as equivalent and typical to a one mile reduction across the airports. This 37 sec reduction represents an empirically observed average and is applicable to both IMC and VMC conditions. The queueing model estimates the post-implementation benefits by comparing the take-off and



Figure 1. – Change in Separation Requirements (nm)

**7,569 Affected Arrival Aircraft
(7.8% of all arrivals)**

**9,040 Affected Departure Aircraft
(9.2% of all departures)**



**Figure 2. RECAT Affected Aircraft Pairs at ORD: Jul 1-Sep 25, 2015:
Reporting Hours (6am-9:59pm local time)**

landing times after RECAT 1.5 deployment to those the same aircraft would have had under traditional wake categories and separation standards.

We estimated take-off and landing times after RECAT 1.5 deployment using high-fidelity ASDE-X data. To accurately measure inter-arrival and inter-departure spacing, these times had to be estimated for the same relevant point along the runway. Arrivals were easier to process because they are quite consistent in flying over threshold as they approach to land; therefore, landing times were approximated as the moments when each arrival crossed over the threshold of the arrival runway. Departures, on the other hand, can enter the runway and start their roll at different points. Departures can also make sharp turns immediately after lift-off; for long runways, this may actually result in departures leaving the runway “sideways” as opposed to crossing over the threshold. Therefore, to account for such infrequent but important occurrences in our data, take-off times were approximated as the moment along the runway when each departure reached the speed of 30 ft/sec.

The post-RECAT 1.5 aircraft data sequence included landing and departure times and aircraft models by runway at each of the four airports. We then determined the RECAT and traditional category for each of the aircraft, actual spacing between each lead/trail pair, and applicable separation requirement under both RECAT 1.5 and traditional wake separation standards. Finally, we assumed that the traditional sequence of aircraft would be exactly the same, but adjusted departure and landing times as required to absorb the additional 37 sec in spacing between the benefiting aircraft pairs (green-

colored lead/trail combinations in Figure 2), as well as allowed for tighter sequence between Small/F following Heavy/B or Large/D departure pairs (the spacing in these cases was 37 sec shorter, and applied to the pink-colored lead/trail combinations in Figure 2).

In most cases, the actual spacing between subsequent arrivals or subsequent departures was large enough to fully absorb changed separations; in these cases, times were adjusted for only one aircraft – the trailing aircraft. However, at peak times, aircraft following the trailing one are often too close as well, so their times had to be adjusted too. Such a domino effect resulted in the rare, but nevertheless real need to adjust times for a long list of closely-spaced aircraft, further resulting in accumulation of “delay” well in excess of the simple 37 sec.

For each of the airports in our dataset, we evaluated and recorded the following values:

- Number of arrivals and departures with decreased spacing under RECAT rules, later referred to as the positive arrival or departure benefit cases
- Number of arrivals and departures with increased spacing under RECAT rules, later referred to as the negative arrival or departure benefit cases, and
- The total minutes saved or lost by the four groups of aircraft.

Interestingly, while we did observe the presence of negatively affected aircraft at the four sites, no significant increase in average spacing between arrival pairs was detected. Even at MDW, where the proportion of Small/F aircraft in the

fleet mix was the highest, total time loss was less than 50 min over the five months of the study period.

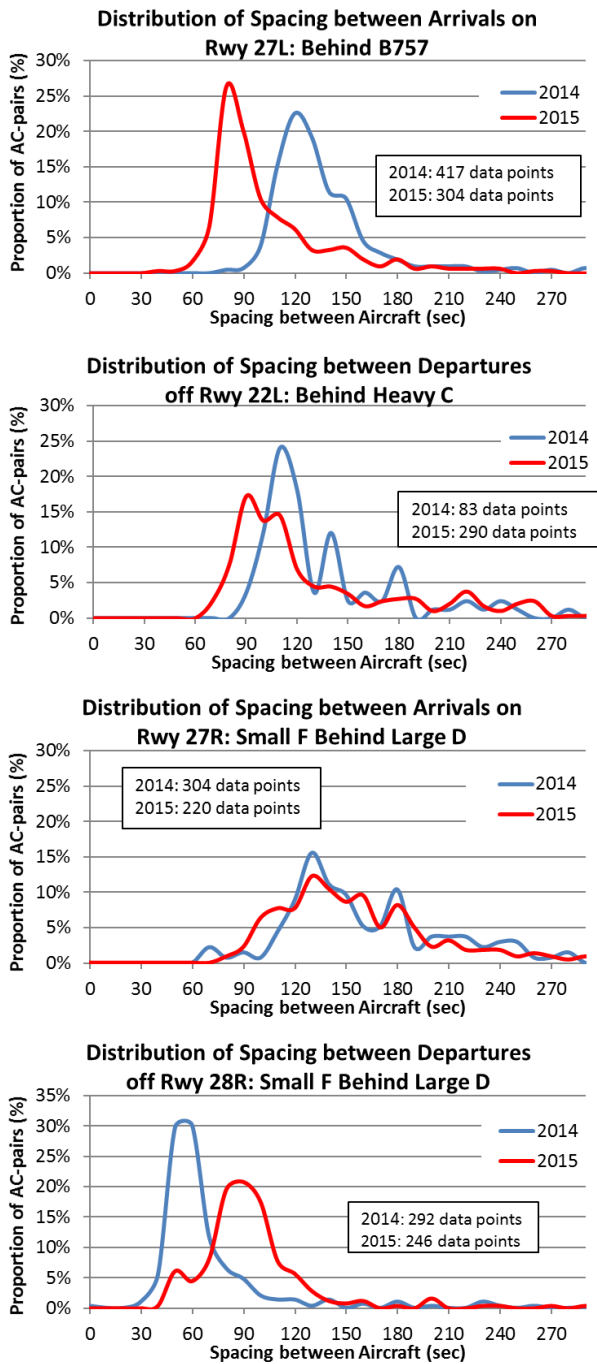


Figure 3. Examples of Changes in Aircraft Spacing at ORD

Table 1 presents the summary of our outputs from the queueing model. The loss in performance observed at MDW is clearly smaller than the gains in performance at the other three sites, with the total overall benefits exceeding 1,600 hr during the study period, and resulting annual benefits exciding \$3.5M. Saving are monetized using methodology described in Section F.

Table 1: Comparison of Benefits Estimated by Queueing Model Across the Four Airports

Impacts	IND		CLT		ORD		MDW	
	Arns	Depts	Arns	Depts	Arns	Depts	Arns	Depts
Separation Requirements								
Decreased	22.5%	23.3%	2.6%	3.3%	4.4%	4.7%	1.1%	1.1%
Unchanged	73.1%	72.9%	97.4%	95.6%	95.6%	94.7%	98.9%	91.3%
Increased	4.4%	3.8%	0.0%	1.1%	0.0%	0.6%	0.0%	7.6%
Benefits Impact								
Time Savings (hrs)	127	1035	71	29	233	183	-0.8	-16
Cost Savings (\$000s)	321	2033	180	57	590	360	-2	-32
Total Savings	\$2.4 million		\$237K		\$950K		-\$34K	

B. Regression models

To generalize the savings observed at the four study sites, we developed regressions to estimate the average times saved or lost for all aircraft pairs whose separations had been reduced or increased. Since changing take-off or departure times of a leading aircraft may affect the waiting time of other aircraft waiting to land or depart behind it, we estimated runway queue length first. The best performing regressions use airport “pressure”, the ratio between airport demand and capacity, as the predictor variable for both average time saved and the queue length.. Demand was evaluated as a 10 minute count of arrivals and departures around every single landing and take-off (five minutes before and after each operation), while capacity as the 95th percentile of AAR and ADR for the same runway configuration in IMC and VMC, as applicable. Note that AAR and ADR are set by traffic managers and are subjective to an extent; as such, they can be exceeded at times, when demand and/or the proportion of aircraft with the lowest separation requirements are high.

We developed distinct regressions for the change in average spacing time and for average queue length. Since the queueing model revealed no significant increase in average spacing between arrival pairs, the two distinct regressions were developed separately for:

- 1) Arrivals with time savings (positive arrival case);
- 2) Departures with time savings (positive departure case); and
- 3) Departures with time loss (negative departure case).

The six distinct regressions, illustrated in Figures 4 through 9, use pressure as the independent variable. Figures 4, 6 and 8 display estimated average time saving or loss. Figure 5, 7 and 9 display estimated queue length.

Due to a paucity of observations with pressure greater than 1.2, the predictions for changes in average spacing times and average queue length were held constant at the values obtained for pressure equal to 1.2.

We experimented with five sets of regression models, each based on the original observations at the four airports. They include separate models for each airport, as well as a few different models of combined observations at two or more airports. While airport capacity depends on MC and appropriate

values were used to accurately evaluate airport pressure, the 37 sec proxy for the average time saving or loss between the affected aircraft under RECAT was based on data in both IMC and VMC. Therefore, the regression models we developed can be used to estimate time savings/loss and queue length under any MC.

We choose one model to present and discuss in detail. The set of regression models presented in the remainder of this paper is based on combined data from IND, ORD and CLT.

C. Application of Regression Models at Other Sites

Between 2012 and 2017, RECAT 1.5 was implemented at 18 other sites. To estimate the post-implementation benefit, we used all available data since the date of RECAT implementation. In some cases, such as MEM, several years had passed since the implementation, while in others, such as ANC, only 6 months. We first calculated the proportion of flights that have the potential to be affected by RECAT. Table 2 shows a notional fleet mix and RECAT matrices for arrivals and departures. Fa_{ij} and Fd_{ij} represent the proportion of aircraft type j following aircraft type i in arrival and departure sequence, respectively. These proportions are calculated using ASPM data. In Table 2, green and pink cells represent separation reductions and increases, respectively, between the aircraft pairs. Let the binary variables, α_{ij} , β_{ij} and γ_{ij} take value 1 for all green arrival, green departure and pink departure cells respectively and 0 otherwise, in Table 2. PF_a is the percentage of arrivals positively affected by RECAT implementation:

$$PF_a = \sum_i^n \sum_j^n \alpha_{ij} \times Fa_{ij} \quad (1)$$

Similarly, PF_{dp} and PF_{dn} are the percentage of departures positively and negatively affected by RECAT:

$$PF_{dp} = \sum_i^n \sum_j^n \beta_{ij} \times Fd_{ij} \quad (2)$$

$$PF_{dn} = \sum_i^n \sum_j^n \gamma_{ij} \times Fd_{ij} \quad (3)$$

Table 2: Notional Fleet mix and RECAT matrices

		Trailing Departure					
		RECAT	A ₁	A ₂	...	A _{n-1}	A _n
Leading Departure	A ₁		Fd ₁₁	Fd ₁₂		Fd _{1(n-1)}	Fd _{1n}
	A ₂		Fd ₂₁	Fd ₂₁		Fd _{2(n-1)}	Fd _{2n}
	...						
	A _{n-1}		Fd _{(n-1)1}	Fd _{(n-1)2}		Fd _{(n-1)(n-1)}	Fd _{(n-1)n}
	A _n		Fd _{n-1}	Fd _{n2}		Fd _{n(n-1)}	Fd _{nn}
		Trailing Arrival					
		RECAT	A ₁	A ₂	...	A _{n-1}	A _n
Leading Arrival	A ₁		Fa ₁₁	Fa ₁₂		Fa _{1(n-1)}	Fa _{1n}
	A ₂		Fa ₂₁	Fa ₂₁		Fa _{2(n-1)}	Fa _{2n}
	...						
	A _{n-1}		Fa _{(n-1)1}	Fa _{(n-1)2}		Fa _{(n-1)(n-1)}	Fa _{(n-1)n}
	A _n		Fa _{n-1}	Fa _{n2}		Fa _{n(n-1)}	Fa _{nn}

Next, we considered airport pressure, calculated as the ratio between airport demand and capacity, as applicable to the actual MC at the time of take-off or landing.

Demand is calculated for every single flight as the number of other aircraft during the 10-minute period around its take-off or landing (5 min prior to and 5 min after each operation). Airport capacity is determined as the 95th percentile of AAR or ADR in the corresponding weather condition.

The regression equations then estimated average time saved or lost, and the average queue length behind each aircraft. The detailed calculations are as follows.

Let x_j be the pressure calculated for each arrival flight j and n_a be the total number of arrivals in the period of study. The total arrival time saved in hours HS_a is

$$HS_a = \frac{PF_a \times \sum_{j=1}^{n_a} Q_a(x_j) \times T_a(x_j)}{3600} \quad (4)$$

where $Q_a(x_j)$ and $T_a(x_j)$ are the number in the arrival queue and time saved in seconds, respectively, based on the regressions

$$Q_a(x) = \begin{cases} -1.9759x^2 + 7.7294x - 1.0136 & x \leq 1.2 \\ 6.24 & x > 1.2 \end{cases} \quad (5)$$

$$T_a(x) = \begin{cases} .4897x^3 - 23.459x^2 + 46.692x + 1.9211 & x \leq 1.2 \\ 25.7 & x > 1.2 \end{cases} \quad (6)$$

Let x_k be the pressure calculated for each departure flight k and n_d be the total number of departures in the period of study. The total departure time saved in hours HS_{dp} is

$$HS_{dp} = \frac{PF_{dp} \times \sum_{k=1}^{n_d} Q_{dp}(x_k) \times T_{dp}(x_k)}{3600} \quad (7)$$

where $Q_{dp}(x_k)$ and $T_{dp}(x_k)$ are the numbers in the departure queue and time saved in seconds, respectively, based on the regressions for positive departure savings:

$$T_{dp}(x) = \begin{cases} -22.693x^2 + 47.852x + 1.872 & x \leq 1.2 \\ 26.26 & x > 1.2 \end{cases} \quad (8)$$

$$Q_{dp}(x) = \begin{cases} -12.125x^3 + 5.5896x^2 + 20.022x - 3.4524 & x \leq 1.2 \\ 7.67 & x > 1.2 \end{cases} \quad (9)$$

Let x_k be the pressure calculated for each departure flight k and n_d be the total number of departures in the period of study. The total departure time lost in hours HL_{dn} is

$$HL_{dn} = \frac{PF_{dn} \times \sum_{k=1}^{n_d} Q_{dn}(x_k) \times T_{dn}(x_k)}{3600} \quad (10)$$

1) Positive Departure Benefits

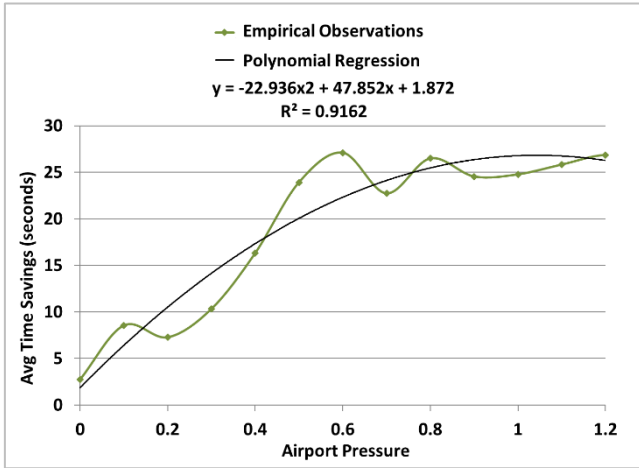


Figure 4. Pos Dep Case: Average time saving

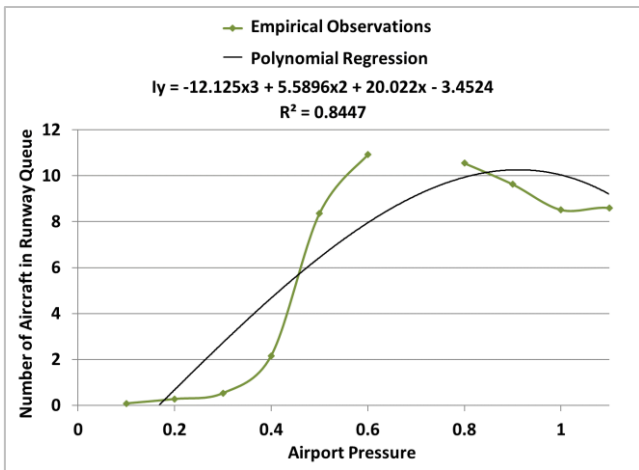


Figure 5. Pos Dep Case: Number of aircraft in the queue

2) Positive Arrival Benefits

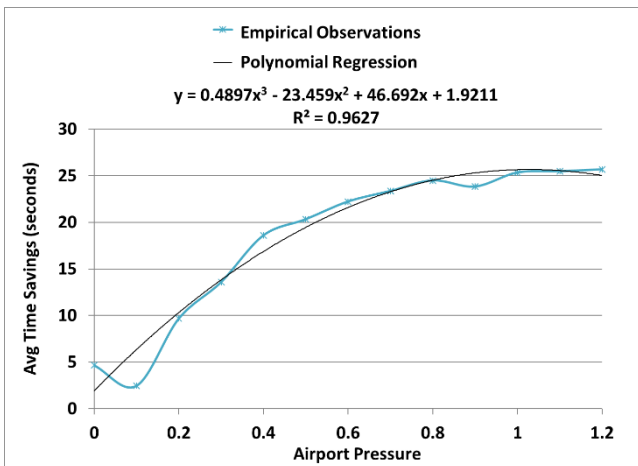


Figure 6. Pos Arr Case: Average Time Saving

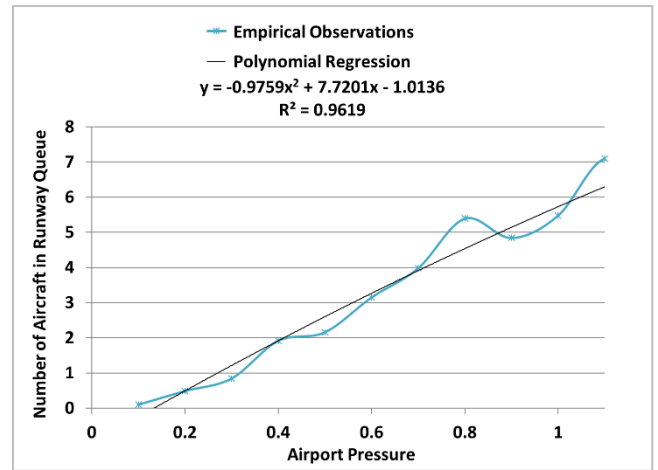


Figure 7. Pos Arr Case: Number of aircraft in the queue

3) Negative Departure Benefits

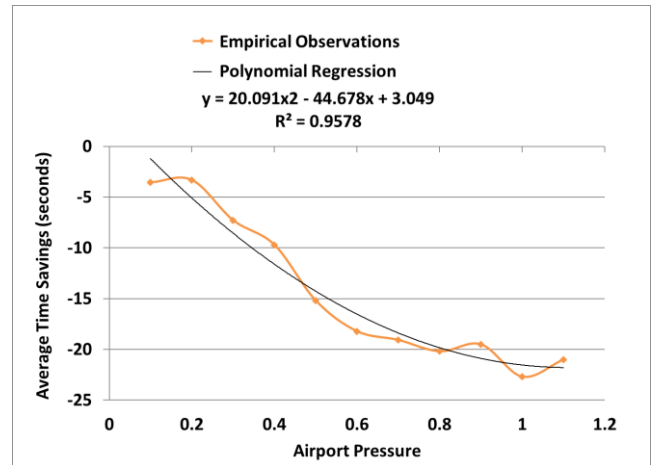


Figure 8. Neg Dep Case: Average Time Increase

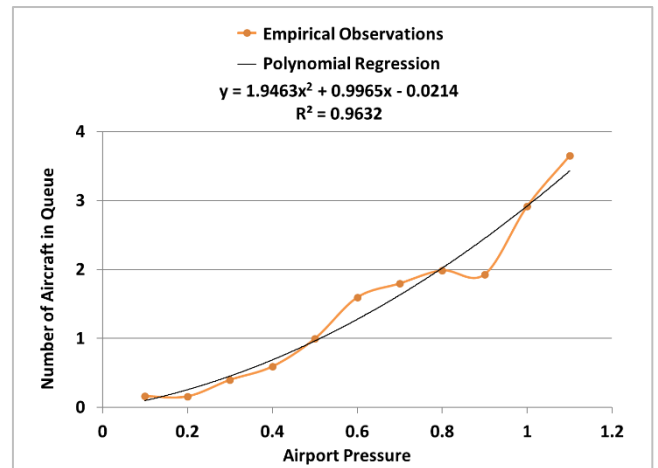


Figure 9. Neg Dep Case: Number of aircraft in the queue

$Q_{dn}(x_k)$ and $T_{dn}(x_k)$ are the number in the departure queue and time lost in seconds, respectively, based on the regressions for negative departures:

$$Q_{dn} = \begin{cases} 1.9463x^2 + .9965x - 0.0214 & x \leq 1.2 \\ 3.98 & x > 1.2 \end{cases} \quad (11)$$

$$T_{dn}(x) = \begin{cases} 20.091x^2 - 44.678x + 3.049 & x \leq 1.2 \\ -21.6 & x > 1.2 \end{cases} \quad (12)$$

D. Adjustment for a Specific New Site

Current arrival and departure times and counts for a proposed RECAT site do not reflect the effects of RECAT on capacity. Therefore, for an airport where we consider using RECAT in the future, we need to adjust its current airport capacity to reflect future gains or losses as expected to happen after the use of RECAT commences. This is approximated by $PF_a \times 95$ th percentile of AAR for arrivals and $(PF_{ap} - PF_{dn}) \times 95$ th percentile of ADR for departures. Then, savings are calculated in the same manner as reported in the previous section.

It should be noted that in the US, RECAT separation reductions are typically between 1.0 and 1.5nm for both RECAT 1.5 and RECAT 2.0. This regression model could be used for other versions of RECAT as long as the corresponding changes in separation requirements are similar. If, however, these changes prove significantly different for a different version of RECAT, the methodology would still be applicable, but the average change in aircraft spacing would have to be adjusted accordingly.

E. Forecasting Future Benefits

To calculate benefits in a future year, the demand pattern may need to be adjusted to reflect the corresponding future demand forecast. This will result in a change in airport pressure inputs. These values then become the new inputs to our regression models for benefit estimation.

However, at some congested airports, the demand pattern can also change with traffic growth. We chose to be conservative in our estimates by linearly extrapolating demand growth.

F. Monetizing the Benefits

The FAA uses Aircraft Direct Operating Cost (ADOC) and passenger time savings by airport, and analyzes RECAT categories using airport-specific fleet mixes. We used ADOC airborne unit costs for arrivals, and unit ground costs for departures.

Hourly cost is larger for airports with positive departure benefits compare to those with negative departure benefits. This is driven by the new categorization of aircraft under RECAT as driven by the airport-specific fleet mix.

Similarly, load factors and average seats used in passenger time savings are calculated separately for each RECAT category. Passenger Value of Time (PVT) is the same for arrivals and departures of each aircraft type.

V. RESULTS

Table 3 summarizes estimates of time saved using the regression models for 18 airports where RECAT 1.5 has been implemented. “Num. Days” represents the numbers of days since the implementation of RECAT 1.5 at each site.

Table 3 : Estimated results using Regression Model for 18 sites

Apt.	Num. Days	App. Arrs Pos Case (%)	App. Deps Pos Case (%)	App Deps Neg Case (%)	Avg Daily Savings (hr)	Annual Savings (hr)
TEB	703	11%	11.1%	5%	0.31	113.91
IAH	762	5%	4.8%	1%	1.47	534.74
LGA	703	1%	0.8%	0%	0.31	113.67
DEN	397	4%	4.3%	4%	1.46	532.01
SMF	215	3%	2.8%	4%	0.03	9.99
SFO	215	10%	10.8%	2%	4.48	1,634.27
OAK	215	11%	10.8%	10%	0.25	90.73
SJC	215	4%	4.2%	9%	0.35	129.17
ATL	366	11%	11.2%	0%	9.39	3,428.46
SDF	1,219	51%	52.8%	1%	3.64	1,329.58
MEM	1,553	61%	61.9%	1%	6.68	2,439.38
CVG	1,037	15%	13.3%	1%	0.24	86.24
ANC	153	13%	17.1%	8%	1.21	440.25
ISP	671	2%	2.5%	8%	0.00	1.03
HOU	762	1%	0.9%	10%	0.13	48.93
HPN	672	16%	15.4%	8%	0.39	142.71
EWR	672	16%	15.5%	0%	8.01	2,925.04
JFK	672	17%	18.5%	0%	7.27	2,653.31

We used all six models to estimate a range of post-implementation benefits of RECAT 2.0 at PHL as shown in Table 4. It contains estimates provided by American Airlines (AA) to the NextGen Advisory Committee (NAC)’s Joint Analysis Team (JAT) [17]. AA performed a post-implementation analysis to evaluate the benefits of RECAT 2.0 in PHL using AA internal data as well as ASPM for 53 days. They observed changes in separation times in empirical data similar to our spreadsheet queueing model described in Section A. The results presented in this paper are within 25 percent of AA’s results. Furthermore, AA’s results are well within the range of benefits produced by all 6 models. Similarly, FedEx [16] claims nearly \$1.8M monthly benefits at MEM. Our model estimates \$18.75M (in 2017 dollars) annual benefits for MEM, less than the FedEx estimate, but still within 13 percent.

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Table 4: PHL RECAT 2.0 estimates

PHL Models	Annual Arrival and Departure Time Saved (hr)					
	1	2	3	4	5	6
Results	217	111	309	656	409	734
AA Result	327.3					
Model presented here	409					
Range (6 models)	111-733					

I. SUMMARY

This paper presents a set of statistical models for estimation of delay savings resulting from proposed or actual use of RECAT at a specific airport. While the models are robust enough to estimate delay savings for any version of RECAT at any airport using current or future demand patterns, adjustments of its inputs may be required to account for significant differences in separation reductions between RECAT 1.5 and another RECAT version of interest. The models are easy to use and require readily available data, such as arrival and departure times, and airport demand, capacity and fleet mix. The validity of the model's estimates is compared to other published analyses.

A future enhancement to the model could include developing separate regression models for IMC and VMC conditions. However, several years of raw data to accurately reflect IMC conditions would be required.

BIOGRAPHIES

Nastaran Coleman is a Senior Analyst with the FAA, in the NAS Systems Engineering and Integration Directorate. Dr. Coleman has extensive research experience in queueing systems, designing and developing databases, statistical and stochastic models and discrete event simulations. She has extensive experience in conducting benefit analyses and studying trends in operations and delays under different conditions.

Almira Ramadani holds a BS degree in Air Transportation Engineering from the University of Belgrade, and an MS degree in Civil and Environmental Engineering from the University of California at Berkeley. Strengthened by over twenty years of hands-on experience with ATM and NextGen projects in academia, private sector, and at the FAA, her expertise is in performance analysis of current and future NAS operations, and in validation of ATM concepts.

With over 25 years of experience at the FAA, Mr. Knorr is the Division Manager for NextGen Systems Analysis and Modeling. Mr. Knorr is also co-chair of the NextGen Advisory Committee (NAC) Joint Analysis Team (JAT) with the Airline Industry. His previous experience includes being the FAA Senior Representative in Paris and the FAA Liaison to Germany's Air Traffic Organization. Mr. Knorr has co-authored more than 15 technical papers related to aviation performance and operational efficiency. He holds a BS in Mathematics and a Masters in Engineering Administration - both from Virginia Tech.