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

Nastaran Coleman, Ph.D., Dave Knorr, Almira Ramadani
Federal Aviation Administration, U.S.A. (FAA)

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Outline

• Background and Purpose
• Input and Approach
• Methodology
• Results
• Conclusion
• Wake turbulence can be hazardous.
• To ensure safety, separation standards, a.k.a. wake vortex minima, are in place to mitigate risks from wake encounters.
• Better wake science, improved automation led to introduction of more refined separation standards, called wake turbulence Re-Categorization (RECAT), worldwide.
  - Improve airport capacity, flight efficiency.
• Runway capacity is major factor limiting aviation growth.
  - RECAT’s benefits are of great interest to airlines and Air Navigation Service Providers (ANSPs).
  - RECAT benefits, measured by increased capacity and delay reduction, vary greatly by airport due to differing aircraft mixes, traffic levels.
RECAT history in USA

• In 1970, 4 categories based on MTOW introduced.
• RECAT phase I started in 2012.
  ✦ Aircraft classified according to wingspan, takeoff weight and ability to withstand wake encounters. Expanded weight categories from 4 to 6.
  ✦ Implemented at 23 airports.
• RECAT phase II started 2016.
  ✦ Based on pairwise separation.
  ✦ Developed for the most common aircraft types.
  ✦ Implemented at 8 airports.
• Consolidated Wake Turbulence (CWT) started 2018.
  ✦ Derived from current set of standards.
  ✦ Further refines aircraft groupings to provide throughput gains at constrained airports and yet be usable at all airports throughout the NAS.
Purpose

• Use results of empirical studies of reduction in spacing between aircraft due to RECAT implementation to build generic models for estimating benefits of RECAT at other sites.

• Introduce set of statistical models to estimate time savings associated with proposed or actual implementation of RECAT at any airport.
  + Input from empirical studies include
    - Six months of detailed aircraft surveillance and airport performance data for the four airports where RECAT phase I was implemented.
    - Individual aircraft records containing aircraft type, runway, estimated arrival or departure time to the second using high-fidelity surface and terminal surveillance data.

• Regression models robust enough to estimate delay savings for any version of RECAT at any airport using current or future demand and fleet mix patterns.
  + Easy to use. Do not rely on runway-specific information
    Hard to obtain, requires costly resources
  + Inputs include arrival, departure times, airport fleet mix and capacity.
  + Validated the models’ estimates.
    - Comparisons to other published analyses
INPUTS FROM EMPIRICAL STUDIES

Spreadsheet Based Queueing Model
Surveillance Data
- Aircraft Type
- Operation Type
- Date and Time
- Runway

Operational Data
by Quarter Hour
- ARR Throughput and Called Rate
- DEP Throughput and Called Rate
- Meteorological Conditions
- Runway Configurations

Emperical Studies

<table>
<thead>
<tr>
<th>Potential Benefit</th>
<th>Arrs</th>
<th>Deps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft Spacing (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Throughput (ops/hr)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Control for
- Runway Pressure
  - Throughput ≥ Called Rate
- Typical or Specific Runway Configurations
Throughput Improvement Potential at ORD
Jul 1-Sep 25, 2015, Reporting Hours (0600-2159 local time)

Red indicates an increase in separations
Green indicates a decrease in separations

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

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

<table>
<thead>
<tr>
<th>Separation Requirements</th>
<th>Arrival Pairs</th>
<th>Departure Pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decreased</td>
<td>4.4%</td>
<td>4.7%</td>
</tr>
<tr>
<td>Unchanged</td>
<td>95.6%</td>
<td>94.7%</td>
</tr>
<tr>
<td>Increased</td>
<td>0.0%</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Change Potential</th>
<th>Arrivals</th>
<th>Departures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reporting Hours</td>
<td>Aircraft Spacing (%)</td>
<td>-1.9%</td>
</tr>
<tr>
<td></td>
<td>Throughput (ops/hr)</td>
<td>+1.27</td>
</tr>
<tr>
<td>Peak Periods</td>
<td>Aircraft Spacing (%)</td>
<td>-1.9%</td>
</tr>
<tr>
<td></td>
<td>Throughput (ops/hr)</td>
<td>+1.70</td>
</tr>
</tbody>
</table>

Data Source: ASDE-X
Examples of Changes in Aircraft Spacing at ORD
Arrivals on Same Runway

Distribution of Spacing between Arrivals on Rwy 27R:
Behind B757

Distribution of Spacing between Arrivals on Rwy 27L:
Behind B757

Data Source: ASDE-X
REGRESSION MODELS
Summary of Empirical Inputs

• 6 months of detailed data for 4 airports including
  ✦ Date and time of arrival or departure
  ✦ All arrivals and departures affected by RECAT
  ✦ Seconds saved or lost, if any
  ✦ Number of following aircraft affected by RECAT
  ✦ Seconds saved or lost for all following aircraft
  ✦ Instrument Meteorological Conditions (IMC) or Visual Meteorological Conditions (VMC)
  ✦ Airport acceptance rates (arrivals and departures)
Definitions for Regression Models

• Airport utilization rate (pressure)
  ✷ Ratio between actual arrival demand and the Airport Acceptance Rate (AAR)
    • Departure pressure defined similarly using ADR.

• Demand for every single flight
  ✷ Number of other aircraft during the 10 minute window around take-off or landing (5 minutes prior to and 5 minutes after each operation).

• Airport capacity determined as 95th percentile of AAR or ADR in the corresponding weather condition.
Regression Methodology

• Calculate rolling counts of arrivals and departures.
  ✧ Use 10 minutes rolling counts of arrivals and departures for every single flight.
  ✧ This method more accurately represents true demand around arrival or departure time of aircraft.

• Assign capacity:
  • Use 95th percentiles AAR and ADR.

• Calculate pressure for every single flight.
  ✧ Build pressure distribution.
Regression Methodology (cont.)

- Regression models for average time savings
  - Focused on all flights affected by RECAT including flights with zero time savings.
    - Determine average seconds saved for all pressure levels.
- Regression models for number of queued aircraft.
  - At peak times, following aircraft in arrival or departure queue can benefit from reduced separations between two aircraft in front of them, type of domino effect.
    - Determine average number of affected aircraft for all pressure levels.
- Graph data and develop trend lines.
  - Extend curves using straight lines for all pressures greater than 1.2.
Average Departure Time Savings

Empirical Observations
Polynomial Regression

\[ y = -22.936x^2 + 47.852x + 1.872 \]

\[ R^2 = 0.9162 \]
Average Departure Queue Length

\[ y = -12.125x^3 + 5.5896x^2 + 20.022x - 3.4524 \]

\[ R^2 = 0.8492 \]
Average Arrival Time Savings

\[ y = 0.4897x^3 - 23.459x^2 + 46.692x + 1.9211 \]

\[ R^2 = 0.9627 \]
Average Arrival Queue Length

Empirical Observations

Polynomial Regression

\[ y = -0.9759x^2 + 7.7201x - 1.0136 \]

\[ R^2 = 0.9619 \]
Average Departure Time Increase

- Empirical Observations
- Polynomial Regression

\[ y = 20.091x^2 - 44.678x + 3.049 \]

\[ R^2 = 0.9578 \]
Average Queue Length During Departure Time Increase

Empirical Observations
Polynomial Regression

\[ y = 1.9463x^2 + 0.9965x - 0.0214 \]

\[ R^2 = 0.9632 \]
Regression Methodology (cont.)

• Use trend lines to extrapolate savings to other sites.
  ✴ Using fleet mix, estimate the percentage of flights that may be positively or negatively affected by RECAT
  ✴ Use same methods to determine pressure for each flight at new site.
    • Rolling 10 minutes arrival, departure counts
    • 95th percentile AAR and ADR in IMC and VMC
Step 1

- Collect fleet type count, usually based on 12 months of operational data.
- Use fleet mix counts to calculate expected percentage of arrivals and departures that may be affected positively or negatively by RECAT.

\[
PF_a = \sum_{i} \sum_{j} \alpha_{ij} \times Fa_{ij}
\]

where the binary variables \( \alpha_{ij} \) are 1 for all green arrivals, 0 otherwise.
STEP 2

• For period under study
  + Obtain 95th percentile airport arrival and departure rates.
    • Use as capacities for calculating pressures.
• For every flight, calculate 10 minutes rolling count (demand).
  + 5 minutes prior to through 5 minutes after arrival or departure.
• For every flight, determine pressure.
  + Demand divided by capacity

<table>
<thead>
<tr>
<th>Facility</th>
<th>Weather</th>
<th>95 Percentile rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAR ADR</td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Facility</th>
<th>Weather</th>
<th>95 Percentile rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>APT x VMC</td>
<td>22</td>
<td>29</td>
</tr>
<tr>
<td>APT x IMC</td>
<td>19</td>
<td>27</td>
</tr>
</tbody>
</table>

Arrival flights example

<table>
<thead>
<tr>
<th>Flight time</th>
<th># of Arr/Dep 10 minutes interval</th>
<th>Capacity</th>
<th>MC</th>
<th>Pressure</th>
<th>Arr/Dep</th>
</tr>
</thead>
<tbody>
<tr>
<td>0817</td>
<td>10</td>
<td>22</td>
<td>V</td>
<td>.45</td>
<td>ARR</td>
</tr>
<tr>
<td>0819</td>
<td>12</td>
<td>22</td>
<td>V</td>
<td>.55</td>
<td>ARR</td>
</tr>
</tbody>
</table>
Regression Model Applications (cont.)

- Hours saved estimated separately for
  - Arrivals, positive savings
  - Departures, positive savings
  - Departures, negative savings

- For each arrival or departure flight, using appropriate regression
  - Multiply:
    - Average spacing reduction (seconds)
    - Average queue length

<table>
<thead>
<tr>
<th>Flight time</th>
<th># of Arr/Dep 10 minutes interval</th>
<th>Capacity</th>
<th>MC</th>
<th>Pressure</th>
<th>Arr/Dep</th>
<th>Saved Sec</th>
<th>Aircraft in the queue</th>
</tr>
</thead>
<tbody>
<tr>
<td>0817</td>
<td>10</td>
<td>22</td>
<td>V</td>
<td>.45</td>
<td>ARR</td>
<td>18.23</td>
<td>2.06</td>
</tr>
<tr>
<td>0819</td>
<td>12</td>
<td>22</td>
<td>V</td>
<td>.55</td>
<td>ARR</td>
<td>18.67</td>
<td>2.64</td>
</tr>
</tbody>
</table>

- Add all values and multiply by percentage of affected arrivals or departures
## Results

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TEB</td>
<td>703</td>
<td>11%</td>
<td>11.1%</td>
<td>5%</td>
<td>0.31</td>
<td>113.91</td>
</tr>
<tr>
<td>IAH</td>
<td>762</td>
<td>5%</td>
<td>4.8%</td>
<td>1%</td>
<td>1.47</td>
<td>534.74</td>
</tr>
<tr>
<td>LGA</td>
<td>703</td>
<td>1%</td>
<td>0.8%</td>
<td>0%</td>
<td>0.31</td>
<td>113.67</td>
</tr>
<tr>
<td>DEN</td>
<td>397</td>
<td>4%</td>
<td>4.3%</td>
<td>4%</td>
<td>1.46</td>
<td>532.01</td>
</tr>
<tr>
<td>SMF</td>
<td>215</td>
<td>3%</td>
<td>2.8%</td>
<td>4%</td>
<td>0.03</td>
<td>9.99</td>
</tr>
<tr>
<td>SFO</td>
<td>215</td>
<td>10%</td>
<td>10.8%</td>
<td>2%</td>
<td>4.48</td>
<td>1,634.27</td>
</tr>
<tr>
<td>OAK</td>
<td>215</td>
<td>11%</td>
<td>10.8%</td>
<td>10%</td>
<td>0.25</td>
<td>90.73</td>
</tr>
<tr>
<td>SJC</td>
<td>215</td>
<td>4%</td>
<td>4.2%</td>
<td>9%</td>
<td>0.35</td>
<td>129.17</td>
</tr>
<tr>
<td>ATL</td>
<td>366</td>
<td>11%</td>
<td>11.2%</td>
<td>0%</td>
<td>9.39</td>
<td>3,428.46</td>
</tr>
<tr>
<td>SDF</td>
<td>1,219</td>
<td>51%</td>
<td>52.8%</td>
<td>1%</td>
<td>3.64</td>
<td>1,329.58</td>
</tr>
<tr>
<td>MEM</td>
<td>1,553</td>
<td>61%</td>
<td>61.9%</td>
<td>1%</td>
<td>6.68</td>
<td>2,439.38</td>
</tr>
<tr>
<td>CVG</td>
<td>1,037</td>
<td>15%</td>
<td>13.3%</td>
<td>1%</td>
<td>0.24</td>
<td>86.24</td>
</tr>
<tr>
<td>ANC</td>
<td>153</td>
<td>13%</td>
<td>17.1%</td>
<td>8%</td>
<td>1.21</td>
<td>440.25</td>
</tr>
<tr>
<td>ISP</td>
<td>671</td>
<td>2%</td>
<td>2.5%</td>
<td>8%</td>
<td>0.00</td>
<td>1.03</td>
</tr>
<tr>
<td>HOU</td>
<td>762</td>
<td>1%</td>
<td>0.9%</td>
<td>10%</td>
<td>0.13</td>
<td>48.93</td>
</tr>
<tr>
<td>HPN</td>
<td>672</td>
<td>16%</td>
<td>15.4%</td>
<td>8%</td>
<td>0.39</td>
<td>142.71</td>
</tr>
<tr>
<td>EWR</td>
<td>672</td>
<td>16%</td>
<td>15.5%</td>
<td>0%</td>
<td>8.01</td>
<td>2,925.04</td>
</tr>
<tr>
<td>JFK</td>
<td>672</td>
<td>17%</td>
<td>18.5%</td>
<td>0%</td>
<td>7.27</td>
<td>2,653.31</td>
</tr>
</tbody>
</table>
Monetizing Benefits

• Aircraft Direct Operating Cost (ADOC), passenger time savings (PVT) calculated by airport and RECAT categories using fleet mix.
  ✤ Use ADOC airborne unit costs for arrivals and ground unit costs for departures.
  ✤ Unit costs are larger for positive departure benefits compared to negative departure benefits.
    ✤ Driven by fleet mix affected positively or negatively by RECAT.
  ✤ Load factor, average seat used in passenger time savings calculation calculated separately for each RECAT category.
    ✤ PVT based on aircraft via average passenger count.
Validation of Results

EXAMPLES

• American Airlines (AA) performed a post-implementation analysis to evaluate the benefits of RECAT phase II in PHL for the NextGen Advisory Committee (NAC)’s Joint Analysis Team (JAT).
  - Used AA internal data and FAA’s Operational data for 53 days.
  - Our regression model results lie within 25 percent of AA’s results.

• Fedex claims nearly $1.8m monthly benefits at MEM.
  - We estimate $1.56m (in 2017 dollars) annual benefits.
    • Within 13 percent of Fedex’s claim.
Summary

• This paper presents a set of statistical models to estimate delay savings resulting from proposed or actual use of RECAT at any airport.
• The models are robust enough to estimate delay savings for any version of RECAT at any airport using current or future demand patterns.
  + Input adjustments may be required to account for significant differences in separation reductions between RECAT phase I and RECAT version of interest.
• The models are easy to use and require readily available data,
• The models’ validity established by comparison to other published analyses.
• A future enhancement to the model could include developing regression models for IMC and VMC separately.
  + Requires several years of raw data to accurately reflect IMC.
Formulas used slide 24

\[
H S_a = \frac{P F_a \times \sum_{j=1}^{n_a} Q_a(x_j) \times T_a(x_j)}{3600}
\]

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

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

- \(T_a(x) = \begin{cases} 
.4897x^3 - 23.459x^2 + 46.692x + 1.9211 & x \leq 1.2 \\
25.7 & x > 1.2 
\end{cases}\)
Monetizing Benefit ATL example

• Unit cost table for ATL are shown below

<table>
<thead>
<tr>
<th>UNIT COST AIRBORNE</th>
<th>UNIT COST TAXI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Airports</strong></td>
<td><strong>Airports</strong></td>
</tr>
<tr>
<td>CatB</td>
<td>Heavy</td>
</tr>
<tr>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>ATL</td>
<td>111.0</td>
</tr>
<tr>
<td></td>
<td>15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AVERAGE SEAT</th>
<th>LOAD FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Airports</strong></td>
<td><strong>Airports</strong></td>
</tr>
<tr>
<td>CatB</td>
<td>Heavy</td>
</tr>
<tr>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>ATL</td>
<td>295.0</td>
</tr>
</tbody>
</table>

• Using Fleet mix ATL unit cost is calculated

<table>
<thead>
<tr>
<th>APT</th>
<th>ADOC (Hour)</th>
<th>PVT (hourly)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Arrival</td>
<td>Departure</td>
</tr>
<tr>
<td></td>
<td>Positive</td>
<td>Negative</td>
</tr>
<tr>
<td>ATL</td>
<td>$2,425</td>
<td>$1,753</td>
</tr>
</tbody>
</table>

• Total monetized Benefit for period 2016-2030
  + Using linear extrapolation and average of 6 models: 369.97 M$
  + Adjusting future demand increase at Utilization level : 390.57 MS
PHL RECAT 2.0

- Ran the models for PHL
  - Use AA applicable aircraft pair rates
  - Same time period Nov 2016-Jan 2017 (62 days)
  - Adjust average saving when applicable to 30 sec instead of 37
  - Results and comparisons are summarized below
  - One of the model’s result (ORD only) matches closely with AA result. 309 vs 327 hrs.
  - Our range is 111-734 hrs where AA result is right in the middle.
  - AA might have included negative arrivals

<table>
<thead>
<tr>
<th>Type</th>
<th>Applicables%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive arrivals</td>
<td>4.35%</td>
</tr>
<tr>
<td>Departure</td>
<td>4.88%</td>
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<tr>
<td>Negative Dep</td>
<td>0.48%</td>
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</table>

<table>
<thead>
<tr>
<th>Models</th>
<th>Results</th>
<th>Annual Hours Saved (Arr+Dep)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Models</td>
<td></td>
<td>217</td>
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<tr>
<td>AA Result</td>
<td>327.3</td>
<td></td>
</tr>
<tr>
<td>Average of 6 Models</td>
<td>406</td>
<td></td>
</tr>
<tr>
<td>Range (6 models)</td>
<td>111---733</td>
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</table>