BALANCING THROUGHPUT AND SAFETY: AN AUTONOMOUS APPROACH AND LANDING SYSTEM (AALS)

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PROBLEM

• Final approach segment and runway
  • Flights must be sequenced and spaced before the Final Approach Fix (FAF)
    • 6nm from Runway Threshold, 2000’ AGL
  • Flights are at their lowest speed for the approach and landing phase
• Highly stochastic environment impacts time at Runway Threshold
• Air Traffic Controllers manually insert “Buffer Time” between the wake vortex separation distance of the lead and the follow aircraft
  
  Minimum Safe Separation Distance
  \[ \text{MSSD} = \text{Wake Vortex Separation Distance} + \text{Spacing Buffer} \]

  3 nm

• Too short Buffer Time \( \rightarrow \) reduced safety margins
• Too long Buffer Time \( \rightarrow \) reduced runway throughput
**INTER-ARRIVAL TIME AT RUNWAY THRESHOLD**

- **Inter-Arrival Sep Distance** = Target Sep Distance – Actual Sep Distance
  - < 0 = violation of MSSD
- The magnitude of the **left-tail** of the distribution determines safety margins of the approach process.
- The magnitude of the **right tail** of the distribution represents gaps in the flow and reduced runway throughput.

**Unacceptable:** % less than MSSD (this is the law)

**Acceptable** (due to variance in control)

**Underutilization**
AS-IS APPROACH AND LANDING OPERATIONS

Downwind

No Simultaneous Runway Occupancy

Final Approach

Min Inter-arrival Distance for Wake Vortex Separation

Communications

(1) Separation Detection and Resolution
(2) Maximize Throughput

Surveillance

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CONCEPT OF OPERATIONS

• Improve safety margins
  • avoid violations of MSSD = reduce left tail
    • Autonomous Approach and Landing System (AALS)

• Improve throughput of runways
  • eliminate gaps by increasing the accuracy of spacing arriving flights at the Final Approach Fix (FAF) = reduce right tail
    • Required Time of Arrivals (RTA)/Self-separation

Acceptable
(due to variance in control)

Underutilization

Unacceptable:
% less than MSSD
(this is the law)

Minimum Safe Separation Distance (MSSD)

Target Separation Distance (TSD)

Inter-arrival Sep Distance Error (nm)
The system is constantly adjusting the Target Separation Distance (TSD) to maximize throughput while maintaining the safety margins.
GOALS FOR FLOW SPACING CONTROL LAW

• Reduce right tail:
  • **Required Time of Arrivals (RTA)** places flights at the FAF according to a pre-defined time schedule;
  • **Self-separation** “pulls” sequential flights with a specified time/distance separation;

• Reduce left tail:
  • **Autonomous Approach & Landing System (AALS)** monitors the inter-arrival times at the runway threshold and sets the buffer-time in excess of the wake vortex separation time to meet a Target Level of Safety (TLS).
• **Minimum Safe Separation Distance (MSSD)** is a required minimum distance for wake vortex between a lead and follow aircraft.

• **Spacing Buffer** is an additional time inserted by Air Traffic Controller/AALS between the wake vortex separation distance of the lead aircraft and the follow aircraft prior to the final approach segment.

• **Target Separation Distance (TSD):**
  \[ TSD = MSSD + \text{Spacing Buffer}. \]

• **Target Level of Safety (TLS)** represents the probability of a wake vortex encounter.

• **Runway Throughput** is a measure of the number of flights landed per unit time.
The control law continuously adjusts the spacing buffer based on the stochastic performance of the system to maximize throughput and maintain the TLS.
The result of the AALS is an inter-arrival time distribution that continuously balances the trade-off between throughput and safety to actively maintain the TLS.
AALS SIMULATION TOOL

Autonomous Approach and Landing System (AALS)

- Initial Velocity ($\mu$ and $\sigma$)
- Initial Spacing Buffer ($\mu$ and $\sigma$)
- Approach Path
- FAF Altitude
- MSSD
- Target Probability
- Sample Size
- # of Flights
- Inter-Arrival Time Distribution
- Actual Probability
- Error
- Target Separation Time
- Spacing Buffer Time
- Maximum Capacity Throughput
SIMULATION PARAMETERS

• **Initial Velocity Distribution** ($\mu$ and $\sigma$)
  - Models stochasticity in final segment approach

• **Initial Spacing Buffer Distribution** ($\mu$ and $\sigma$)
  - Models gaps in arrival flow at FAF

• **Actual Probability** is the current probability of “hitting” an acceptable region:
  
  $\text{Actual Probability} = \frac{\# \text{ of flights that violated MSSD}}{\text{Flight Counter}}$

• **Target Probability** is the desired TLS, set to 5%.

• **Upper/Lower Thresholds** approach Target Probability as number of flights increased:

  $\text{Upper / Lower Threshold} = \text{Target Probability} \pm (\alpha \frac{1}{\sqrt{\# \text{ of flights}}})$

• **Maximum Capacity Throughput (MCT)** is a rate of number of flights that have landed on a runway per given period of time.
**MSST** stands for Minimum Safe Separation Time, which is an equivalent of MSSD of 3nm and equals 90 seconds.

**TST** is Target Separation Time, which is a time equivalent of TSD.
In this case, Average Spacing Buffer = 20.16 seconds with standard deviation of 3.59 s. Maximum Capacity Throughput = 32.6 flights per hour. Actual Probability = 4.9% (<5% of Target Probability).
The experiment was run to compare the **Runway Throughput** performance and **Safety Margins** (i.e. probability of violating the MSDD).

Simulation settings:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AALS Status</strong></td>
<td>Active/Inactive</td>
</tr>
<tr>
<td><strong>Initial Velocity</strong></td>
<td>$\mu$ 120, $\sigma$ 5, 10</td>
</tr>
<tr>
<td><strong>Initial Spacing Buffer</strong></td>
<td>$\mu$ 10, 20, 40, $\sigma$ 0, 5, 10</td>
</tr>
<tr>
<td><strong>Approach Path</strong></td>
<td>6 nm</td>
</tr>
<tr>
<td><strong>Final Approach Fix</strong></td>
<td>2000 ft</td>
</tr>
<tr>
<td><strong>Target Probability</strong></td>
<td>5%</td>
</tr>
<tr>
<td><strong># of Flights</strong></td>
<td>10 000</td>
</tr>
</tbody>
</table>
## RESULTS OF EXPERIMENT – LOW STOCHASTIC APPROACH

<table>
<thead>
<tr>
<th>Low Approach Stochasticity</th>
<th>Input</th>
<th>Output</th>
<th>Throughput P (Left-tail)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V = 120 knots, σ = 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>V = 120 knots, σ = 5</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Row Configuration</strong></td>
<td><strong>μ</strong></td>
<td><strong>σ</strong></td>
<td><strong>μ</strong></td>
</tr>
<tr>
<td>Ideal Sep</td>
<td>10</td>
<td>0</td>
<td>100.1</td>
</tr>
<tr>
<td>RTA/Self-Sep</td>
<td>10</td>
<td>5</td>
<td>99.9</td>
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<tr>
<td>Manual Sep</td>
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<td>10</td>
<td>100.15</td>
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<tr>
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<td>20</td>
<td>0</td>
<td>110</td>
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<tr>
<td>RTA/Self-Sep</td>
<td>20</td>
<td>5</td>
<td>109.99</td>
</tr>
<tr>
<td>Manual Sep</td>
<td>20</td>
<td>10</td>
<td>110.14</td>
</tr>
<tr>
<td>RTA/Self-Sep with AALS</td>
<td>AALS</td>
<td>5</td>
<td>110.98</td>
</tr>
<tr>
<td>High Approach Stochasticity</td>
<td>Input</td>
<td>Output</td>
<td></td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>$V = 120$ knots, $\sigma = 10$</td>
<td>Spacing Buffer, secs</td>
<td>Inter-Arrival Time, secs</td>
<td>Excess Spacing Buffer, secs</td>
</tr>
<tr>
<td><strong>Row Configuration</strong></td>
<td>$\mu$</td>
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<td>$\mu$</td>
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<td>Ideal Sep</td>
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<tr>
<td>9</td>
<td>RTA/Self-Sep</td>
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<td>10</td>
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<tr>
<td>13</td>
<td>Manual Sep</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>14</td>
<td>RTA/Self-Sep with AALS</td>
<td>AALS</td>
<td>10</td>
</tr>
</tbody>
</table>
Row #8
Input:
V = 120 knots
σ_{IV} = 10 knots
Buffer = 10 s
σ_{SB} = 0

Output:
P = 30.5%
Buffer = 10 s
MCT = 36
IAT = 102.17 s
σ_{IAT} = 23.21 s

This scenario leads to extreme safety violations.
Row #13

Input:

\[ V = 120 \text{ knots} \]
\[ \sigma_{IV} = 10 \text{ knots} \]
\[ \text{Buffer} = 40 \text{ s} \]
\[ \sigma_{SB} = 10 \text{ s} \]

Output:

\[ P = 6.1\% \]
\[ \text{Buffer} = 39.99 \text{ s} \]
\[ \sigma_{SB} = 9.75 \text{ s} \]
\[ \text{MCT} = 28 \]
\[ \text{IAT} = 129.75 \text{ s} \]
\[ \sigma_{IAT} = 25.49 \text{ s} \]

This scenario also leads to safety violations.
Row #14
Input:
V = 120 knots
σ_{IV} = 10 knots
Buffer = AALS
σ_{SB} = 10 s

Output:
P = 4.72%
Buffer = 37.55 s
σ_{SB} = 4.31 s
MCT = 28
IAT = 127.7 s
σ_{IAT} = 23.09 s
CONCLUSIONS

- The AALS improves **safety margins** of the approach process by adjusting Target Separation Distance (TSD = MSSD + Spacing Buffer).
- The **Spacing Buffer** reduces left tail of the inter-arrival time distribution by shifting its mean to the right.
  - The AALS calculates the correct Buffer Time for $P = 0.05$.
- The AALS **continuously adjusts** as the stochastic approach factors change over time.
- The AALS coupled **with RTA/Self-separation** can actively balance safety and throughput.
  - RTA/Self-Separation improves **runway throughput** by reducing right tail (“under-utilization”) of the inter-arrival time distribution by closing any gaps in the flow.
FUTURE WORK

• A homogeneous fleet mix → a non-homogeneous fleet mix.
• Single minimum safe separation distance requirement of 3nm → multiple pair-wise separation distances.
• Integrate into runway simulation models for demo.
• Human-in-the-loop simulation & testing.