A Comparative Analysis of Departure Metering at Paris (CDG) and Charlotte (CLT) Airports

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Surface congestion leads to increased taxi times, emissions and fuel burn

Departure metering can reduce these impacts
Surface congestion leads to increased taxi times, emissions and fuel burn.

Departure metering can reduce these impacts.

Significant monetary benefits ➔ part of surface management programs.

Departure metering solutions based on different approaches:

- Trajectory-based optimization
- Queue-based approaches
Overview

- Characterizing airport operations: CDG and CLT
- Departure metering approaches
  - Trajectory-based optimization
  - Queue-based approaches
    - NASA’s Airspace Technology Demonstration-2 (ATD-2) logic
    - Optimal control approach
    - Robust control approach
- Comparison of benefits with different departure metering approaches
- Summary
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Overview of surface operations at CDG

- Handles ~1,300 flights/day ⇒ 11th busiest airport in the world (2016)
- Four parallel runways; two runway configurations
  - West-flow (26L,27R|26R,27L)
  - East-flow (09L,08R|09R,08L)
- Fleet mix: 25% heavy
- Congestion primarily near departure runways
Overview of surface operations at CLT

- Handles ~1,400 flights/day ⇒ 7th busiest airport in the world (2016)
- Three parallel and one intersecting runway; two runway configurations:
  - North-flow (36C,36L,36R | 36C,36R)
  - South-flow (18L,18C,18R,23 | 18C,18L)
- Fleet mix: 2% heavy
- Congestion at multiple areas: ramp, runway crossing points, departure runways
Demand-capacity profiles: CDG vs. CLT

- Similar departure capacity: Fleet mix, IMC/VMC, mixed operations
- **CDG**: Departures spread-out ➞ Demand rarely exceeds capacity ➞ small queues ➞ low taxi-out delays (4.2 min avg.)
- **CLT**: Departures highly banked ➞ Demand exceeds capacity ➞ large queues ➞ high taxi-out delays (9 min avg.)
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Trajectory-based optimization: Node-link model

- Airport surface represented as a node-link network
- Model developed from multiple data sources: flight tracks + schedules
- Each flight specified by a 4D trajectory (3D on the surface)
- Modified pushback time determined using an optimization approach
Trajectory-based optimization: Formulation

- Decision variables: Pushback time \((p_f)\), wait time at runway crossing points and runway threshold \((w_f)\), taxi-speeds \((v_f)\)

- Formulation

\[
\min_{p_f, w_f, v_f} \left( \alpha \Phi_p + \beta \Phi_d + \gamma \Phi_a \right)
\]

Subject to:

- Minimum runway separation time based on aircraft weight class
- First-come-first-served order at runway crossing and departure runway queue
- Constraint on the max queue size at runway crossing and departure runway
- No ground conflicts: safe taxi separation

Minimize weighted sum of pushback delay, taxi-out time, taxi-in time

- Maximum push-back delay
- Maximum wait times at runway crossing and departure runway queues
- Range of taxi speeds

\[
\begin{align*}
0 & \leq w_f \leq N \cdot \Delta t, \quad \forall f \in \mathcal{F}, \\
I_f & \leq p_f \leq I_f + N_p \cdot \Delta t, \quad \forall f \in \mathcal{D}, \\
v_f^{\min} & \leq v_f \leq v_f^{\max}, \quad \forall f \in \mathcal{F}, \\
C_{fg}^R & = \begin{cases} 1, & \text{if } (t_f^u - t_f^l < s_{fg} \text{ or } t_f^u - t_g^l < s_{gf}) \text{ and } r_f = r_g, \\
0, & \text{otherwise}; \end{cases} \\
C_{fg}^H & = \begin{cases} 1, & \text{if } ((t_f^u - w_g < t_f^u - w_f \text{ and } t_f^u > t_g^u) \\
& \text{or } (t_f^l - w_f < t_f^u - w_g \text{ and } t_f^l > t_g^u)) \text{ and } h_f = h_g, \\
0, & \text{otherwise}; \end{cases} \\
O_{h,t} & = \max\{\text{Card}\{f|h_f = h \text{ and } t_f^l - w_f \leq t \leq t_f^u\} - C, 0\} \quad O_{h,t} = 0, \forall h \in \mathcal{H}, \forall t \in \mathcal{T}. \\
C_t & = C_n + C_l + C_b = 0
\end{align*}
\]

Adapted simulated annealing algorithm used to find the solution
Objective function weights chosen to avoid loss in airport throughput

Taxi-out time reduction higher at CLT (3.5 min) than at CDG (1.1 min)

Better sequencing of runway crossings leads to

- Increased airport throughput: Manifests as negative wheels-off delay at CLT
- Reduction in taxi-in times

<table>
<thead>
<tr>
<th>Average values*</th>
<th>CLT</th>
<th>CDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi-out time reduction (min)</td>
<td>3.5</td>
<td>1.1</td>
</tr>
<tr>
<td>Taxi-in time reduction (min)</td>
<td>1.7</td>
<td>0.0</td>
</tr>
<tr>
<td>Gate-hold time (min)</td>
<td>3.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Wheels-off delay</td>
<td>-0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>% of flights held at the gate</td>
<td>61%</td>
<td>50%</td>
</tr>
</tbody>
</table>

*Averages computed over 3 days of operations
Characterizing airport operations: CDG and CLT

Departure metering approaches

- Trajectory-based optimization
- Queue-based approaches
  - NASA’s Airspace Technology Demonstration-2 (ATD-2) logic
  - Optimal control approach
  - Robust control approach

Comparison of benefits with different departure metering approaches

Summary
Queue-based approach: Models

- Queuing network representations

- Fluid-flow model for a single queue:
  \[ \dot{x} = -\mu \frac{C x}{C x + 1} + u(t - \tau) \]
  - \( x \): queue length; \( \mu \): mean service rate
  - \( C \): parameter based on service-time distribution
  - \( u \): pushback rate; \( \tau \): unimpeded time

- Model extended to network of queues using “flow-conservation”
- Taxi time = wait time in the queue + unimpeded time
- Service time distributions empirically determined
Queue-based approach: Model validation

- Error metrics indicate good match between model and observations

### Comparisons for CDG

<table>
<thead>
<tr>
<th>Airport</th>
<th>Number of departures</th>
<th>Taxi-out time (min)</th>
<th>% of flights</th>
<th>error</th>
<th>&lt; 5 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDG</td>
<td>14,100</td>
<td>13.3</td>
<td>-0.3</td>
<td>3.0</td>
<td>82.4</td>
</tr>
<tr>
<td>CLT</td>
<td>7,464</td>
<td>20.1</td>
<td>-1.4</td>
<td>4.4</td>
<td>69.0</td>
</tr>
</tbody>
</table>

Validation using test-set
Queue-based approach: NASA’s ATD-2 logic

(a) Default scenario (no metering)

(b) Departure metering (ATD-2)

- Buffer parameter accounts for uncertainties (e.g., taxi-out time prediction errors), to avoid losing runway utilization

- NASA’s ATD-2 logic: \( \text{TOBT} = \text{EOBT} + \max(0, \text{predicted wait time} - \text{buffer}) \)

[S. Verma et al. 2018; S. Sharma et al. 2018; Jung et al. 2019]
Optimal sizing of buffer for ATD-2

- Taxi-out time reduction depends on the choice of excess queue buffer
  - Larger the buffer, lower the benefits
- Excess queue buffer picked to ensure no loss in runway utilization
- Results with a planning horizon of 20 min for CLT:
Queue-based approach: Optimal control

- **Objective:** Determine optimal pushback rate \( u_d(t) \) to obtain smaller queues on airport surface without losing throughput.

- **Formulation:**

  \[
  \min_{u_d(t)} \int_0^T \left( x^T Q x + h^T R h \right) dt
  \]

  Subject to:

  \[
  \begin{align*}
  \dot{x} &= f(x(t), x(t - \tau_1), \ldots, x(t - \tau_m), u_d(t - \tau_{m+1}), \ldots, u_d(t - \tau_w), t) \\
  \dot{h} &= d(t) - u_d(t) \\
  0 &\leq x_i, h_i; \quad 0 \leq u_{di} \leq u_m; \quad i = 1, 2, 3, \ldots, w \\
  u_{di}(t) &= g_i(t), \quad t \in [-\tau_{di}, 0]; \quad i = 1, 2, 3, \ldots, w \\
  x_i(t) &= \phi_i(t), \quad t \in [-\tau_{ki}, 0], \quad h(0) = h_0; \quad i = 1, 2, 3, \ldots, w
  \end{align*}
  \]

- **Weights chosen to avoid loss of runway utilization.**

- **Optimal control problem is solved in a receding horizon framework.**

- **Transformed into a nonlinear programming problem by discretizing variables.**
Queue-based approach: Robust control

- Obtain pushback rate, while accounting for model uncertainties

\[ \dot{x}_{ri} = -\mu_{ri}(t) \frac{C_{ri}(t)x_{ri}(t)}{C_{ri}(t)x_{ri}(t) + 1} + u_{di}(t) = \bar{\alpha}_i(x_{ri}, t) + u_{di}(t) \]

\[ |\alpha_i(x_{ri}, t) - \bar{\alpha}_i(x_{ri}, t)| \leq F_i(x_{ri}, t) \]  

Bounds on model uncertainty

- Sliding mode controller to maintain runway queue length at desired value:

\[ u_{di}(t) = \max \left( \bar{\alpha}_i(x_{ri}(t), t) - k_i \text{ sat}(x_{ri}(t) - x_{ri,d}), 0 \right) \]

- Time-delays in the dynamics handled using predictor-based feedback
- Target runway queue length chosen to avoid loss in runway utilization
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Comparison of departure metering approaches

- Benefits evaluated using stochastic simulations
- Validation of simulations:

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<th>&lt; 5 min</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>ME</td>
<td>MAE</td>
</tr>
<tr>
<td>CDG</td>
<td>14,202</td>
<td>13.3</td>
<td>-0.3</td>
<td>3.0</td>
</tr>
<tr>
<td>CLT</td>
<td>6,474</td>
<td>20.1</td>
<td>1.1</td>
<td>4.6</td>
</tr>
</tbody>
</table>

- Taxi-out time reduction
Comparison of departure metering approaches

- Taxi-out time reduction at CLT > Taxi-out time reduction at CDG
- **Benefits**: Robust ctrl > ATD-2 logic > Trajectory-based optimization > Optimal ctrl
- Stochastic simulations reveal “brittleness” of deterministic solutions
- Propensity to gate conflicts low: Hold times are relatively small
- Potential fuel savings of ~30 kg/flight at CLT

<table>
<thead>
<tr>
<th>Mean statistics</th>
<th>CDG</th>
<th></th>
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<th>CLT</th>
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<tr>
<td></td>
<td>Trajectory based</td>
<td>ATD-2 logic</td>
<td>Optimal control</td>
<td>Robust control</td>
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<td>ATD-2 logic</td>
<td>Optimal control</td>
<td>Robust control</td>
</tr>
<tr>
<td>Taxi-out reduction (min)</td>
<td>0.16</td>
<td>0.52</td>
<td>0.39</td>
<td>0.53</td>
<td>2.22</td>
<td>2.60</td>
<td>1.31</td>
<td>2.89</td>
</tr>
<tr>
<td>Hold time (min)</td>
<td>1.12</td>
<td>0.61</td>
<td>0.52</td>
<td>0.65</td>
<td>3.04</td>
<td>2.71</td>
<td>1.51</td>
<td>2.97</td>
</tr>
<tr>
<td>Wheels-off delay (min)</td>
<td>0.97</td>
<td>0.09</td>
<td>0.12</td>
<td>0.12</td>
<td>0.81</td>
<td>0.10</td>
<td>0.21</td>
<td>0.08</td>
</tr>
<tr>
<td>Fraction of flights held</td>
<td>0.50</td>
<td>0.26</td>
<td>0.17</td>
<td>0.17</td>
<td>0.61</td>
<td>0.63</td>
<td>0.34</td>
<td>0.35</td>
</tr>
<tr>
<td>Hold time of flights held</td>
<td>2.20</td>
<td>2.36</td>
<td>3.09</td>
<td>3.96</td>
<td>4.96</td>
<td>4.33</td>
<td>4.5</td>
<td>8.40</td>
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• Departure metering approaches can mitigate surface congestion
  • Trajectory-based optimization
  • Queue-based approaches: ATD-2 logic, Optimal control, Robust control

• Approaches applied to CLT and CDG
  • Validation of models and simulations
  • Impacts evaluated using stochastic simulations

• Taxi-out time reductions vary by approach
  • CDG: 0.2 to 0.5 min
  • CLT: 1.3 to 2.9 min

• Robust control approach performs better in stochastic environments
• Departure metering can yield high taxi-out time reduction without an adverse impact on airport throughput
Extensions and next steps

• Adaptation to other major airports (BOS, EWR, LGA, PHL, DFW, SIN)

• Evaluation of the impact of EOBT uncertainty on departure metering
  • Analyze EOBT error distributions by airline and airport
  • Reduction in departure metering benefits due to EOBT uncertainty (~50%)
  • Analyze incentives for airlines to improve the accuracy of EOBT data

• Robust optimization techniques to handle uncertainty using trajectory-based optimization

• Departure metering algorithms that can explicitly account for uncertainties in arrival times and EOBT