Study on Traffic Synchronization

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EIWAC, Tokyo, November, 2010.
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1. Traffic Synchronization
2. Delay propagation
3. Delay absorption
4. Conclusions
Airspace Congestion

Figure: Inefficient arrival flow to Tokyo Int'l Airport

- Delay
- Fuel consumption
- Controller workload
Airspace Congestion

1. Traffic Synchronization

**Traffic Synchronization**

**Definition:** “Tactical establishment and maintenance of a safe, orderly and efficient flow of air traffic.” [ICAO]

**Benefits:**
- Less delay
- Less fuel consumption
- Less controller workload

[ICAO 2005, SESAR, NextGen]
Concept of Operations

“Controlled time of arrival” (CTA)

Target precision: +/- 10 sec

Current precision: +/- 30 sec

Window size: [cta-x, cta+x] sec

Window position:
- between sectors
- on waypoints
- on merge-points
(...)

Flight Trials:
CTA/ATC system integration studies (CASSIS)

Simulation studies:
Contract-based Air Transportation System project (CATS)

[CASSIS 09, CATS 08]
Concept of Operations

“Controlled time of arrival” (CTA)

Open questions

- Feasibility ?
- Number of constraints ?
- Impact of uncertainty

Flight Trials:
CTA/ATC system integration studies (CASSIS)

Simulation studies:
Contract-based
Air Transportation System project (CATS)

Window size: [CTA-x, cta+x] sec
Window position:
- between sectors
- on waypoints
- on merge-points
(...)

1. Traffic Synchronization

[CASSIS 09, CATS 08]
Delay Propagation under uncertainties

\[ \eta_{i-1} - \eta_i = \max(\eta_i - a_i + m_i, 0) \]

Queueing Delays

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>eta</th>
<th>stay delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12:01</td>
<td>12:01</td>
</tr>
<tr>
<td>B</td>
<td>12:02</td>
<td>12:03</td>
</tr>
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<td>12:05</td>
<td>12:07</td>
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</table>

[Erzberger 95, Bayen 06, Balakrishnan 09]
## Delay Propagation

under uncertainties

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Profile plot

- High altitude delay absorption (fuel efficient)
  \[(1 - \alpha)d_i\]
- Low altitude delay absorption (fuel inefficient)
  \[\alpha d_i\]
- Top of descent (TOD)
- Optimal descent

\[d_i: \text{queueing delay of aircraft i}\]
\[\alpha: \text{absorption coefficient} \quad 0 \leq \alpha \leq 1\]
\[c_h, c_l: \text{delay absorption costs} \quad c_h \leq c_l, \ [\text{min}^{-1}]\]

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### Aircraft Schedule

<table>
<thead>
<tr>
<th>Aircraft</th>
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Queueing Delays

[Erzberger 95, Bayen 06, Balakrishnan 09]
Delay Propagation under uncertainties

$d_i$ : queueing delay of aircraft $i$

$\alpha$ : absorption coefficient

$0 \leq \alpha \leq 1$

$c_h, c_l$ : delay absorption costs

$c_h < c_l, \ [\text{min}^{-1}]$

Profile plot

Top of descent (TOD)

Optimal descent

Remaining delay on low altitude

High altitude delay absorption (fuel efficient)

$(1 - \alpha)d_i$

Low altitude delay absorption (fuel inefficient)

$\alpha d_i$

Delayed arrival at TOD

Gate

Time plot

Actual time of arrival at TOD

Scheduled time of arrival at TOD

$\alpha$

$\alpha d_i$

Delay absorption cost

$(1 - \alpha)d_i$

$c_i = [(1 - \alpha)c_h + \alpha c_l]d_i$

Delay absorption

Cost:

$c_h$

Cost:

$c_l$

<table>
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<tr>
<th>Aircraft</th>
<th>$\text{eta}_{\text{sta}}$</th>
<th>$\text{eta}_{\text{sta}}$ delay</th>
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Queueing Delays

[Erzberger 95, Bayen 06, Balakrishnan 09]
Delay Propagation
under uncertainties

Profile plot

Time plot

$\eta_{\text{D}} = \eta_{\text{C}}$

$\text{Aircraft} \quad \eta_{\text{A}} \quad \eta_{\text{B}} \quad \eta_{\text{C}}$

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>$\eta_{\text{A}}$</th>
<th>$\eta_{\text{B}}$</th>
<th>$\eta_{\text{C}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12:01</td>
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Queueing Delays

[Erzberger 95, Bayen 06, Balakrishnan 09]
Delay Propagation
under uncertainties

2. Delay Propagation

Profile plot

High altitude delay absorption (fuel efficient)
(1 − α)di

Low altitude delay absorption (fuel inefficient)
αdi

Top of descent (TOD)
Optimal descent
Remaining delay on low altitude

di: queueing delay of aircraft i
α: absorption coefficient
0 ≤ α ≤ 1
ch, cj: delay absorption costs
ch < cj, [min⁻¹]

Scheduled time of arrival
at TOD

Actual time of arrival
at TOD

High altitude delay absorption

Low altitude delay absorption

Cost:

Delay absorption cost

(1 − α)di
αdi

ci = (1 − α)ch + α cj di

Delay absorption cost

Gate

Time plot

sta

ata

(stated)

 ata

(scheduled)

sta

ata

(stated)

ata

Aircraft | eta | sta eta | delay |
--- | --- | --- | --- |
A | 12:01 | 12:01 | 0 |
B | 12:02 | 12:03 | 1 |
D | 12:04 | 12:05 | 1 |
C | 12:05 | 12:07 | 2 |

Queueing Delays

[Erzberger 95, Bayen 06, Balakrishnan 09]
2. Delay Propagation

Delay Propagation
under uncertainties

Profile plot

Time plot

Queueing Delays

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{\(d_i\): queueing delay of aircraft \(i\)}
{\(\alpha\): absorption coefficient}
{\(0 \leq \alpha \leq 1\)}

\(c_h, c_i\): delay absorption costs
\(c_h < c_i\), [min\(^{-1}\)]

\(\alpha d_i\) Delay absorption cost

\((1-\alpha)d_i\) Delay absorption cost

High altitude delay absorption (fuel efficient)
\((1-\alpha)d_i\)

Low altitude delay absorption (fuel inefficient)
\(\alpha d_i\)

Profile plot

Time plot

Queueing Delays

[Erzberger 95, Bayen 06, Balakrishnan 09]
Delay Propagation
under uncertainties

Traffic Synchronization Problem

Given:
Flow of pre-scheduled aircraft $sta_1 < sta_2 < ... < sta_n$ with queueing delays $d_i$ and trajectory prediction errors $\epsilon_i$.

Find:
Optimal delay absorption strategy.

Queueing Delays

Table:

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>$\text{eta}_{\text{ata}}$ (actual)</th>
<th>$\text{sta}_{\text{delay}}$ (re-scheduled)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12:01</td>
<td>12:01, 0</td>
</tr>
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<td>12:03, 1</td>
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<td>12:07, 2</td>
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<tr>
<td>D</td>
<td></td>
<td></td>
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</tbody>
</table>

Leader

<table>
<thead>
<tr>
<th>Follower</th>
<th>Leader</th>
<th>Heavy</th>
<th>Mid/Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>90</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Mid/Small</td>
<td>60</td>
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</table>

Delay propagation

[Erzberger 95, Bayen 06, Balakrishnan 09]
Main Results

**Speed control delay**

\[ \Delta_j \geq w_i - \frac{x_{j0} - lx_{i0}}{l v_i} + \frac{s_e}{k_i v_i} \]

with \( \Delta_j \): speed control delay for aircraft \( j \)

\( w_i \): metering delay for aircraft \( i = j-1 \)

**Average propagated delay (normalized)**

\[ E(D_i) = \sum_{k=0}^{\infty} (k+1) \int_{u=0}^{\infty} \int_{v=0}^{u/\alpha} (u - \alpha v) P(k | u, v) f(u) g(v) dv du \]

with

\( f, g \): probability density function of \( \epsilon, d \)

\( P \): distribution of length of propagation

[Gwiggner et al. 09, 10]
Main Results

In words:

Speed control itself causes no delay propagation.

The reason for delay propagation: trajectory prediction errors

\[ \Delta_j \geq w_i - \frac{x_{j0} - lx_{i0}}{lv_i} + \frac{s_e}{k_i v_i} \]

with \( \Delta_j \): speed control delay for aircraft \( j \)
\( w_i \): metering delay for aircraft \( i = j-1 \)

\[ E(D_i) = \sum_{k=0}^{\infty} (k+1) \int_{u=0}^{\infty} \int_{v=0}^{u/\alpha} (u - \alpha v) P(k \mid u, v) f(u) g(v) dvdu \]

with

\( f, g \): probability density function of \( \epsilon, d \)
\( P \): distribution of length of propagation

[Gwiggner et al. 09, 10]
Delay absorption strategy

\[ c(\alpha) = [c_L \alpha + c_H (1 - \alpha)]d(\alpha) \]

\[ d(\alpha) = d_0 + d_p(\alpha), \]

where
\[ c_L \gg c_H : \text{cost of delay absorption (kg/min)} \]
\[ d_0 : \text{average queueing delay} \]
\[ d_p(\alpha) : \text{propagated delay} \]

- **Delay absorption strategy**
- **Trade-off**
- **Fuel efficiency**
- **Workload sharing**

Consequences:
- Even in the future, there is a need for radar vectoring.
- Sequencing strategies under uncertainties should be studied.
Conclusions

- Traffic Synchronization
  - Tactical management of queues of aircraft
- Delay Propagation
  - Delay propagation due to trajectory prediction errors
- Delay absorption strategy
  - Trade-off between high altitude (fuel efficient) and low altitude (fuel inefficient)
  - Even when the objective is to minimize fuel (!)
Future work

- Fundamental Research
  - Conditions for existence of minimum
  - Delay propagation in transportation networks
- Operational Concept
  - Ground delay vs. en-route delays
  - Delay management strategies
Thank you.

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Traffic Synchronization

Global ATM Concept (ICAO)

Traffic Synchronization
- Departure
- Arrival
- Interaction

Demand/Capacity Balancing

Conflict Management

Traffic Management Coordinator (TMC)

Air Traffic Controller (ATCo)

ATM PLANNING PHASES

Years
- Long Term
- Mid/Short Term

Tactical phase

[ICAO 2005, ATM Masterplan]
Aircraft sequencing

Basic Operations

- Sequencing
  - First-come-first-served (FCSF)
  - Constrained position shifting (CPS)

- Metering
  - Flow control with separation constraints $m_i$

Queueing Delay

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FCFS delay: 4 min
CPS delay: 3.2 min

$\text{FCFS delay: } d_{i+1} = \max(d_i - a_i + m_i, 0)$

$\text{CPS delay: } d_i = \max(d_i - a_i, 0)$

$m_i, m_{i-1}$

Table:

<table>
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<th>$m_i$</th>
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[Erzberger 95, Bayen 06, Balakrishnan 09]
2. Delay propagation

Condition for delay propagation:

\[ \epsilon_i \geq \alpha d_i \]
\[ (\epsilon_i - a_i) \geq \alpha d_{i+1} \]

... \[ (\epsilon_i - a_i) - \sum_{j=1}^{k} a_{i+j} \geq \alpha d_{i+k+1} \quad (1) \]

Delay triggered by aircraft \( i \):

\[ D_{p,i} = \left[ k (\epsilon_i - a_i) - (k-1)a_{i+1} - ... - a_{i+k} \right] - \alpha \sum_{j=0}^{k} d_{i+j+1} \quad (2) \]

\[ = k \epsilon_i - \sum_{j=0}^{k} (k-j)a_{i+j} - \alpha \sum_{j=0}^{k} d_{i+j+1} \quad (3) \]

where \( k \) is smallest number, such that (1) is smaller than \( d_k \)

Propagation approximation (high-congestion):

\[ D_{p,i} \approx \begin{cases} (n-i)(\epsilon_i - \alpha d_i), & \epsilon_i \geq \alpha d_i \\ 0, & \text{else} \end{cases} \quad (4) \]

Expectation:

\[ E(D_{p,i}) = (n-i) \int_{u=0}^{\infty} \int_{v=0}^{u/\alpha} (u-\alpha v)f(u)g(v) dv du \quad (5) \]

with \( f, g \): probability density function of \( \epsilon, d \)