Airway Network Management Using Braess’s Paradox

Qing Cai, Chunyao Ma, and Sameer Alam, Banavar Sridhar, Vu N. Duong

Air Traffic Management Research Institute, School of Mechanical and Aerospace Engineering, Nanyang Technological University
University Space Research Association (USRA), at NASA Ames Research Center

USA/Europe ATM R&D Seminar
19/06/2019
Overview

➢ Background
   Air traffic congestion, airway networks

➢ Motivation
   Alleviate air traffic congestion through minor changes

➢ Methodology
   Locate links which cause inefficiency

➢ Case Study
   Singapore Airway Network (SAN)

➢ Conclusions
   Conclusions and future work
Increasing Air traffic demand

Air traffic congestion

Global Passengers (billion, segment basis)

- Policy stimulus and market liberalization
- Constant Policies scenario
- A pick-up in protectionism

2016 2020 2025 2030 2036


24 October 2017
What to do to mitigate air traffic congestion?

Structures of airway networks have influence over air traffic congestion.

The development of airway networks:

- **Major traffic flows** were identified
- **New airways** were established and added to the airway network
- A highly **rigid and complex** airspace design
- **Flights follow fixed airways** without freedom to choose their preferred routes
How to reduce congestion by modifying the structure of airway networks?

- **Complete redesign:**
  
  A challenging task that has to take into account many competing factors:
  
  ▪ **Airspace users,**
  ▪ **Traffic structure,**
  ▪ **ATM capacity,**
  ▪ **Sectorisation scheme,**
  ▪ **Connectivity** to terminal area.

Given a variety of stake-holders (Military, ANSPs, Airports, Airlines, etc.), a complete redesign of airway networks is **impractical.**
How to reduce congestion by modifying the structure of airway networks?

- Partially redesign:
  - Adding new links
    - Increase complexity of Airway Networks.
  - Instead, can we remove some existing links?
Inspiration & Motivation

1) 5 Links: \( L_1: A \rightarrow C, L_2: B \rightarrow D, L_3: A \rightarrow B, L_4: C \rightarrow D, L_5: B \rightarrow C \)

2) 3 Paths: \( P_1: A \rightarrow C \rightarrow D, L_2: A \rightarrow B \rightarrow D, L_3: A \rightarrow B \rightarrow C \rightarrow D \)

3) Total traffic flow: \( \Phi \)

4) Under equilibrium: \( T_1 = T_2 = T_3 \)

5) Total travel time: \( T_{Eq}^+ = \frac{31\Phi^2 + 1010\Phi}{13} \)

6) After removing link \( B \rightarrow C \): \( T_{Eq} = \frac{11\Phi^2 + 100\Phi}{2} \)

When: \( \Phi = 6 \)

\[ \frac{T_{Eq}^+}{\Phi} = 92 \quad \text{and} \quad \frac{T_{Eq}}{\Phi} = 83 \]

While: \( 0 < \Phi < \frac{80}{9} \)

\( T_{Eq}^+ > T_{Eq} \)

Link \( B \rightarrow C \) increases travel time
Motivation:

❖ Similarities between ground and air transportation:

- Network structure
- Follow existing routes
- Traffic congestion
- Selfish planning

Does Braess’s Paradox exist on airway networks?
**Problem Description**

❖ **Quantification of performance:**
  - Flight duration on the airway network.

❖ **Layered structure:**
  - Flights have to follow certain airways in the AN at given flight levels.

❖ **Research problem:**
  - For a given airway network,
  - At a given flight level,
  - Without decreasing the given traffic demand,
  - Identify airways/links whose removal will reduce the total flight duration of flights.
Methodology

How?

❖ To identify links causing BP:
  ▪ The influence of such links on flight duration.

❖ To determine the flight duration on a network:
  ▪ The flight duration on all links in the network under a given traffic demand.

❖ To calculate the flight duration on a link:
  ▪ The relation between the flow and the flight duration on the link.

❖ To get the relation:
  ▪ Match the ADS-B data onto and airway network.
Methodology

Step 1: Trajectory registration using Airlines ADS-B data

Step 2: Cost function modelling using Singapore airway network

Step 3: BP modelling using Flow-duration network

Determine and close LOPs

Demand
Methodology

Trajectory Registration

- Map the aircraft trajectory data points, in ADS-B data, to airway network.
- Extract air traffic demand information from the ADS-B data

Data Input

- Airways
- Airway Network
- Trajectory
- ADS-B Data

Trajectory Registration

- Flow – Cost relation
- Demand

Airlines ADS-B data

Singapore airway network
Cost Function Formulation

- Determine relationship between the flow (number of trajectories) and flight duration (total flight time) for each link of airway networks.

Models:
- a. linear function,
- b. polynomial function,
- c. cubic function,
Methodology

Trajectory Registration & Cost Function Modelling

\[ L = \begin{pmatrix} l_{ij} \end{pmatrix} \]

\[ L(\text{linear}) = a_1 + a_2 x \]

\[ a = (-71.8883, 116.8632) \]
Methodology

BP Detection

- identify links in the airway network that cause BP, by non-linear programming.
BP modelling

- **UE (User Equilibrium):**
  - Users do not cooperate and each user minimizes his/her own cost

- **SE (System Equilibrium):**
  - Users cooperate with each other to minimize the total travel time

- **BE (Braess Equilibrium):**
  - SE with one more constraint;

\[
\begin{align*}
\text{UE:} & \quad \min_{x = \{x_{ij}\}} \quad F_{UE}(X) = \sum_{i=1}^{n} \sum_{j=1}^{n} \int_{0}^{x_{ij}} a_{ij} l_{ij}(t) dt \\
\text{SE:} & \quad \min_{x = \{x_{ij}\}} \quad F_{SE}(X) = \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} x_{ij} l_{ij}(x_{ij}) \\
\text{BE:} & \quad \min_{x = \{x_{ij}\}} \quad F_{BE}(X) = \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} x_{ij} l_{ij}(x_{ij}) \\
\text{s.t.} & \quad u^*_t \geq u_t
\end{align*}
\]
How to detect the links?

Flow assignment is both cost and user friendly.

\[
\frac{|x_{ij}^{SE} - x_{ij}^{BE}|}{x_{ij}^{UE}} \geq \delta x_{ij}^{BE} \\
\delta = 10
\]

Flow on link \(e_{ij}\) could have detrimental influences.

\[F_{SE}(X_{UE}) < F_{SE}(X_{UE}')\]
Case Study: Singapore Airway Network (SAN)

Cost Function

\[ L = c_0 + c_1 x \]

\[ C = (374.3214, 31.8367) \]

\[ L = c_0 + c_2 x \]

\[ C = (299.8409, 1185.8569) \]

MSE

RMSE

R²

R² = 0.98338, RMSE = 1366.9848

Residual error

R² = 0.089385, RMSE = 219.5169

Flow

Flow

Link ID

Link ID

Flow

Flow
Case Study: Singapore Airway Network (SAN)

Air traffic demand of 180 days in SAN at flight level 330.

Comparisons of total costs with respect to UE, SE and BE over the studied period of 180 days.
Case Study: Singapore Airway Network (SAN)

Day: 175
Demand: 118
BP Link: 114, 163
Link Flow: 1.655887e-01, 1.655887e-01
UE Costs (Min): 8661.152
Improve (Min): 332.509
ratio: 3.84%
Case Study: Singapore Airway Network (SAN)

Table 1: Statistical results for BP detection for SAN at flight level 330. $TC_1$ and $TC_2$ are respectively the total costs obtained by minimizing $F_{U,E}(X)$ before and after removing the BP links from SAN. $SC = TC_1 - TC_2$ is the saved cost.

<table>
<thead>
<tr>
<th>Day</th>
<th>Demand</th>
<th>BP Demand</th>
<th>Link Flow</th>
<th>$TC_1$ (Min.)</th>
<th>$TC_2$ (Min.)</th>
<th>$SC$ (Min.)</th>
<th>$SC/TC_1$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>49</td>
<td>67</td>
<td>2.887e-02</td>
<td>2021.312</td>
<td>2014.060</td>
<td>7.251</td>
<td>0.359</td>
</tr>
<tr>
<td>8</td>
<td>63</td>
<td>134</td>
<td>1.804e-01</td>
<td>3593.380</td>
<td>3501.663</td>
<td>1.717</td>
<td>0.049</td>
</tr>
<tr>
<td>12</td>
<td>60</td>
<td>121</td>
<td>8.996e-02</td>
<td>2765.423</td>
<td>2764.178</td>
<td>1.245</td>
<td>0.045</td>
</tr>
<tr>
<td>17</td>
<td>58</td>
<td>27</td>
<td>2.160e-02</td>
<td>3536.038</td>
<td>3516.810</td>
<td>19.228</td>
<td>0.544</td>
</tr>
<tr>
<td>28</td>
<td>82</td>
<td>144</td>
<td>1.003e-01</td>
<td>5170.283</td>
<td>5161.725</td>
<td>8.558</td>
<td>0.166</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>158</td>
<td>1.891e-01</td>
<td>1131.530</td>
<td>1123.548</td>
<td>7.982</td>
<td>0.705</td>
</tr>
<tr>
<td>38</td>
<td>84</td>
<td>78</td>
<td>1.270e-01</td>
<td>7108.310</td>
<td>7107.388</td>
<td>9.922</td>
<td>0.013</td>
</tr>
<tr>
<td>44</td>
<td>92</td>
<td>70</td>
<td>8.820e-02</td>
<td>9612.960</td>
<td>9590.713</td>
<td>22.247</td>
<td>0.542</td>
</tr>
<tr>
<td>45</td>
<td>94</td>
<td>156</td>
<td>1.856e-02</td>
<td>8848.947</td>
<td>8846.660</td>
<td>2.286</td>
<td>0.026</td>
</tr>
<tr>
<td>48</td>
<td>92</td>
<td>45</td>
<td>3.807e-02</td>
<td>7120.268</td>
<td>7101.940</td>
<td>18.328</td>
<td>0.257</td>
</tr>
<tr>
<td>54</td>
<td>88</td>
<td>28</td>
<td>2.964e-02</td>
<td>6265.240</td>
<td>6269.498</td>
<td>25.743</td>
<td>0.411</td>
</tr>
<tr>
<td>64</td>
<td>115</td>
<td>45</td>
<td>1.099e-01</td>
<td>13823.800</td>
<td>13814.417</td>
<td>9.384</td>
<td>0.068</td>
</tr>
<tr>
<td>66</td>
<td>102</td>
<td>78</td>
<td>2.061e-02</td>
<td>9909.997</td>
<td>9909.807</td>
<td>0.166</td>
<td>0.002</td>
</tr>
<tr>
<td>67</td>
<td>99</td>
<td>58</td>
<td>8.086e-02</td>
<td>11840.828</td>
<td>11836.217</td>
<td>4.412</td>
<td>0.037</td>
</tr>
<tr>
<td>71</td>
<td>87</td>
<td>134</td>
<td>5.167e-02</td>
<td>7670.403</td>
<td>7668.630</td>
<td>1.773</td>
<td>0.023</td>
</tr>
<tr>
<td>72</td>
<td>107</td>
<td>74</td>
<td>5.831e-02</td>
<td>11172.495</td>
<td>11169.220</td>
<td>3.475</td>
<td>0.031</td>
</tr>
<tr>
<td>78</td>
<td>111</td>
<td>21</td>
<td>8.476e-02</td>
<td>14063.982</td>
<td>14091.357</td>
<td>2.695</td>
<td>0.019</td>
</tr>
<tr>
<td>91</td>
<td>119</td>
<td>114</td>
<td>2.279e-02</td>
<td>10629.088</td>
<td>10397.757</td>
<td>231.312</td>
<td>2.18</td>
</tr>
</tbody>
</table>

Link Flow: 0.0228
Original Cost: 10629.088
New Cost: 10397.777
Cost Saved: 231.312
Improvement: 2.18%
Braess’s Paradox does exist on airway networks.

To remove some links on an airway network could reduce congestion.

Total travel time 1 > Total travel time 2
Future Work

- Detect BP in more complex airway networks, such as TMAs
- Incorporate airspace constraints into detection.
- Detect BP in several flight levels.
Thank You!