Flight Delays, Capacity Investment and Welfare under Air Transport Supply-demand Equilibrium

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Total economic impact of flight delay:
Total economic impact of flight delay: $32 billion in 2007
Total economic impact of flight delay: $32 billion in 2007


Means to mitigate flight delay

- Managing demand
Means to mitigate flight delay

- Managing demand
  - Congestion pricing
Means to mitigate flight delay

- Managing demand
  - Congestion pricing
  - Slot control
Means to mitigate flight delay

- Managing demand
  - Congestion pricing
  - Slot control


Means to mitigate flight delay

- Managing demand
  - Congestion pricing
  - Slot control


- Increasing supply
Outline

- Background
- Research Framework
- Equilibrium Model
- Conclusion
Benefits

- Airline Cost (↓)
- Passenger travel time (↓)

Flight Delay

Infrastructure Capacity (↑)

Investment

Directions:
- Background
- Framework
- Model 1
- Model 2
- Conclusion
Issues with the approach

*Ceteris paribus* assumption

Predicting future

**Benefits**
- Airline Cost (↓)
- Passenger travel time (↓)

**Investment**
- Infrastructure Capacity (↑)

Background
- Framework
- Model 1
- Model 2
- Conclusion

Flight Delay

(↓)
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Objective of the Research

Develop an innovative methodology to systematically capture supply-demand response to investment
Outline

- Background
- **Research Framework**
- Equilibrium Models
  - Airline competition model
  - User equilibrium model
- Conclusion
No congestion

Higher density

Higher flight frequency  Lower unit cost

Improved service quality  Lower fare

Reduced generalized cost

More demand
With congestion

Higher density

- Higher flight frequency
- Improved service quality

Lower unit cost

- Lower fare

Reduced generalized cost

More demand
Background

Framework

Model 1

Model 2

Conclusion

Unconstrained user supply

Demand

Generalized cost ($/passenger-mile)

Demand (passenger-miles)
Generalized cost ($/passenger-mile) vs. Demand (passenger-miles).

- Demand
- Constrained user supply
- Unconstrained user supply
Conventional view

- Investment → Infrastructure Capacity
  - Flight Delay

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Proposed framework

- Passenger Demand
- Flight Traffic
- Flight Delay
- Airline Cost
- Airfare

Investment → Infrastructure Capacity

Background  Framework  Model 1  Model 2  Conclusion
Proposed framework

- Passenger Demand
- Flight Traffic
- Airfare
- Flight Delay
- Airline Cost
- Maximizing Profit
- Investment
- Infrastructure Capacity
- Output

Background
Framework
Model 1
Model 2
Conclusion
Proposed framework

- Passenger Demand
- Flight Traffic
- Airfare
- Flight Delay
- Airline Cost
- Maximizing Profit
- Investment
- Infrastructure Capacity

Background
Framework
Model 1
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Conclusion

Output
## Outline

- Background
- Research Framework
- **Equilibrium Models**
- Conclusion
Outline

- Background
- Research Framework
- Equilibrium Models
  - Airline competition model
  - User equilibrium model
- Conclusion

Consider a duopoly market
Consider a duopoly market

Utility of a representative individual

\[
U(q_0, q_1, q_2) = q_0 + \frac{\alpha_{00}}{\alpha_{01} - \alpha_{02}} (q_1 + q_2) - \frac{1}{2} \frac{1}{\alpha_{01} - \alpha_{02}} \left( \alpha_{01}q_1^2 + 2\alpha_{02}q_1q_2 + \alpha_{02}q_2^2 \right)
\]
Consider a duopoly market

Utility of a representative individual

\[ U(q_0, q_1, q_2) = q_0 + \frac{\alpha_{00}}{\alpha_{01} - \alpha_{02}} (q_1 + q_2) - \frac{1}{2} \frac{1}{\alpha_{01}^2 - \alpha_{02}^2} (\alpha_{01}q_1^2 + 2\alpha_{02}q_1q_2 + \alpha_{01}q_2^2) \]

Consumption of numeraire goods
Consider a duopoly market

Utility of a representative individual

\[
U(q_0, q_1, q_2) = q_0 + \frac{\alpha_{00}}{\alpha_{01} - \alpha_{02}} (q_1 + q_2) - \frac{1}{2} \frac{1}{\alpha_{01}^2 - \alpha_{02}^2} (\alpha_{01}q_1^2 + 2\alpha_{02}q_1q_2 + \alpha_{01}q_2^2)
\]

Consumption of airline 1’s service
Consider a duopoly market

Utility of a representative individual

$$U(q_0, q_1, q_2) = q_0 + \frac{\alpha_{00}}{\alpha_{01} - \alpha_{02}} (q_1 + q_2) - \frac{1}{2} \frac{1}{\alpha_{01}^2 - \alpha_{02}^2} (\alpha_{01} q_1^2 + 2 \alpha_{02} q_1 q_2 + \alpha_{02} q_2^2)$$

Consumption of airline 2’s service
Consider a duopoly market

Utility of a representative individual

\[ U(q_0, q_1, q_2) = q_0 + \frac{\alpha_{00}}{\alpha_{01} - \alpha_{02}} (q_1 + q_2) - \frac{1}{2} \frac{1}{(\alpha_{01} - \alpha_{02})^2} (\alpha_{01}q_1^2 + 2\alpha_{02}q_1q_2 + \alpha_{01}q_2^2) \]

\[ \alpha_{00}, \alpha_{01}, \alpha_{02}: \text{parameters} \quad (\alpha_{01} \geq \alpha_{02}) \]
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\[
\max U(q_0, q_1, q_2)
\]

\[
s.t. \quad q_0 + \bar{P}_1 q_1 + \bar{P}_2 q_2 \leq I
\]
### Generalized cost for choosing airline 1

Maximize $U(q_0, q_1, q_2)$ subject to:

$$q_0 + \overline{P}_1 q_1 + \overline{P}_2 q_2 \leq I$$

Generalized cost for choosing airline 1
\[
\begin{align*}
\max U(q_0, q_1, q_2) \\
\text{s.t. } & q_0 + \bar{P}_1q_1 + \bar{P}_2q_2 \leq I
\end{align*}
\]

Generalized cost for choosing airline 2
\[
\max U(q_0, q_1, q_2)
\]
\[
s.t. \quad q_0 + \overline{P}_1 q_1 + \overline{P}_2 q_2 \leq I
\]
\[
\overline{P}_i = P_i + \frac{\gamma}{f_i} + kL \quad i = 1, 2
\]
Demand

\[
\max U(q_0, q_1, q_2)
\]

s.t. \( q_0 + P_1 q_1 + P_2 q_2 \leq I \)

\[
\bar{P}_i = P_i + \frac{\gamma}{f_i} + kL \quad i = 1,2
\]
**Maximization Problem**

\[
\max U(q_0, q_1, q_2)
\]

**Subject to**

\[
q_0 + \bar{P}_1 q_1 + \bar{P}_2 q_2 \leq I
\]

\[
\bar{P}_i = P_i + \frac{\gamma}{f_i} + kL \quad i = 1, 2
\]
\[ \max U(q_0, q_1, q_2) \]

s.t.  
\[ q_0 + P_1 q_1 + P_2 q_2 \leq I \]

\[ \bar{P}_i = P_i + \frac{\gamma}{f_i} + kL \quad i = 1, 2 \]
\[ \max U(q_0, q_1, q_2) \]

s.t. \[ q_0 + \bar{P}_1 q_1 + \bar{P}_2 q_2 \leq I \]

\[ \bar{P}_i = P_i + \frac{\gamma}{f_i} + kL \quad i = 1,2 \]

- Airfare
- Schedule delay
- Delay

Composite of income and travel time constraints
Individual demand

\[ q_i = \alpha_{00} - \alpha_{01}P_i + \alpha_{02}P_{-i} - \frac{\alpha_{01}}{f_i} + \frac{\alpha_{02}}{f_{-i}} - (\alpha_{01} - \alpha_{02})kL, \quad i = 1, 2 \]

\( \alpha_{01} \geq \alpha_{02} \)
Individual demand

\[ q_i = \alpha_{00} - \alpha_{01}P_i + \alpha_{02}P_{-i} - \frac{\alpha_{01} \gamma}{f_i} + \frac{\alpha_{02} \gamma}{f_{-i}} - (\alpha_{01} - \alpha_{02})kL, \quad i = 1, 2 \]

\[ (\alpha_{01} \geq \alpha_{02}) \]

Market demand

\[ Q_i = \alpha_0 - \alpha_1P_i + \alpha_2P_{-i} - \frac{\alpha_1 \gamma}{f_i} + \frac{\alpha_2 \gamma}{f_{-i}} - \mu L, \quad i = 1, 2 \]

\[ (\alpha_1 \geq \alpha_2) \]
Flight operating cost for trip $i$

$$C_i = c_0 + \tau s_i + \eta s_i L$$
Flight operating cost for trip $i$

$$C_i = c_0 + \tau s_i + \eta s_i L$$

**Fixed cost**
Flight operating cost for trip $i$

$$C_i = c_0 + \tau s_i + \eta s_i L$$

- Fixed cost
- Variable cost as a function of aircraft size $s$
Flight operating cost for trip $i$

$$C_i = c_0 + \tau s_i + \eta s_i L$$

- **Fixed cost**
- Variable cost as a function of aircraft size $s$
- Delay cost as a function of aircraft size $s$ and delay $L$
Flight operating cost for trip $i$

$$C_i = c_0 + \tau s_i + \eta s_i L$$

- Fixed cost
- Variable cost as a function of aircraft size $s$
- Delay cost as a function of aircraft size $s$ and delay $L$
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- Assumption: each flight is full
Assumption: each flight is full

\[ Q_i = f_i \cdot s_i \]

- Passenger demand
- Flight frequency
- Aircraft size
\[ \max \pi_i = P_i \cdot Q_i - f_i \cdot C_i \quad \text{for } i = 1, 2 \]
\[
\text{max } \pi_i = P_i \cdot Q_i - f_i \cdot C_i \quad \text{for } i = 1, 2
\]

- Airfare
- Passenger demand
- Flight frequency
- Operating cost per flight
Assume

- airlines compete on fare and frequency simultaneously in a Nash fashion

\[
\frac{\partial \pi_i}{\partial P_i} = 0 \quad \frac{\partial \pi_i}{\partial f_i} = 0 \quad i = 1, 2
\]
Assume

- airlines compete on fare and frequency simultaneously in a Nash fashion

\[ \frac{\partial \pi_i}{\partial P_i} = 0 \quad \frac{\partial \pi_i}{\partial f_i} = 0 \quad i = 1, 2 \]

- Symmetric airlines

\[ P_1 = P_2 = P \quad f_1 = f_2 = f \]
Price response

\[
P = \frac{\alpha_0 + \alpha_1 \tau}{2\alpha_1 - \alpha_2} - \frac{(\alpha_1 - \alpha_2)\gamma}{2\alpha_1 - \alpha_2} - \frac{\mu L}{2\alpha_1 - \alpha_2} + \frac{\alpha_1 \eta L}{2\alpha_1 - \alpha_2}
\]
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### Price response

\[
P = \frac{\alpha_0 + \alpha_1 \tau}{2\alpha_1 - \alpha_2} - \frac{(\alpha_1 - \alpha_2)\gamma}{2\alpha_1 - \alpha_2} - \frac{\mu L}{2\alpha_1 - \alpha_2} + \frac{\alpha_1 \eta L}{2\alpha_1 - \alpha_2}
\]
Price response

\[ P = \frac{\alpha_0 + \alpha_1 \tau}{2\alpha_1 - \alpha_2} \left( \frac{f}{2\alpha_1 - \alpha_2} \right) \frac{(\alpha_1 - \alpha_2) \gamma}{2\alpha_1 - \alpha_2} - \frac{\mu L}{2\alpha_1 - \alpha_2} + \frac{\alpha_1 \eta L}{2\alpha_1 - \alpha_2} \]

- Constant
- Frequency effect on WTP
Price response

\[ P = \frac{\alpha_0 + \alpha_1 \tau}{2\alpha_1 - \alpha_2} \left( \frac{(\alpha_1 - \alpha_2)\gamma}{f} \right) \left( \frac{\mu L}{2\alpha_1 - \alpha_2} \right) + \frac{\alpha_1 \eta L}{2\alpha_1 - \alpha_2} \]

- Constant
- Frequency effect on WTP
- Delay effect on WTP
### Price response

\[
P = \frac{\alpha_0 + \alpha_1 \tau}{2 \alpha_1 - \alpha_2} \left( \frac{(\alpha_1 - \alpha_2) \gamma}{f} \right) + \frac{\mu L}{2 \alpha_1 - \alpha_2} + \frac{\alpha_1 \eta L}{2 \alpha_1 - \alpha_2}
\]

- **Constant**
- **Frequency effect on WTP**
- **Delay effect on WTP**
- **Airline delay cost passed onto passengers**

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Compare equilibrium with and without congestion
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Compare equilibrium with and without congestion

- With congestion
  - Frequency (↓)
Compare equilibrium with and without congestion

- With congestion
  - Frequency (↓)
  - Passenger generalized cost (↑)
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Compare equilibrium with and without congestion

- **With congestion**
  - Frequency (↓)
  - Passenger generalized cost (↑)
  - Passenger demand (↓)
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Compare equilibrium with and without congestion

- **With congestion**
  - Frequency (↓)
  - Passenger generalized cost (↑)
  - Passenger demand (↓)
  - Fare (?)
  - Aircraft size (?)
  - Unit operating cost per passenger (?)
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Simulation analysis
Simulation analysis

Assumption about airport delay $L$

- Delay on a market is determined by the more congested airport

- $N$ independent and identical markets into that airport
Simulation analysis

Assumption about airport delay \( L \)

\[
L = \delta \left[ N \left( f_1 + f_2 \right) \right] / K^\theta, \quad \theta > 1
\]
Simulation analysis

- Assumption about airport delay $L$

$$L = \delta [N(f_1 + f_2) / K]^\theta, \quad \theta > 1$$

- All other parameters derived from empirical evidence
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<th>Aircraft size</th>
<th>Unit operating cost ($/passenger)</th>
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<tr>
<td>Infinite capacity (no delay)</td>
<td>98.9</td>
<td>63.6</td>
<td>91.4</td>
</tr>
<tr>
<td>Finite capacity (720 operations per day, with delay)</td>
<td>96.0</td>
<td>71.9</td>
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### Scenarios

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Decreased WTP dominates airlines’ tendency to pass part of the delay cost to passengers
### Scenarios

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Use larger planes to avoid high delays
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Delay cost partially offset by economies of aircraft size.
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Comparison between equilibrium and conventional approaches
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- Increase airport capacity by 50%
Increase airport capacity by 50%

Conventional

Equilibrium

Airport delay saving (min/flight)
Increase airport capacity by 50%

Conventional

Airport delay saving (min/flight)

Equilibrium

Equilibrium shift

Model 1

Model 2

Conclusion

Demand

Supply

Equilibrium

Equilibrium

Consumer surplus (million$)

- Conventional
  - 5.6
  - Equilibrium 4.7

- Equilibrium
  - 163

- Conventional
  - 70

- Equilibrium
  - 76
Outline

- Background
- Research Framework
- **Equilibrium Models**
  - Airline competition model
  - User equilibrium model
- Conclusion
Introduction of basic concepts

Route
Segment
Market

Spoke city A
Spoke city B
Hub city C

Segment AB
Segment AC
Segment CB

Non-stop Route
One-stop Route
Demand estimation
Nest structure

User equilibrium formulation

\[ \text{Demand} = G_1(\text{Fare, Flight Traffic, Airport delay}) \]

\[ s.t. \quad \text{Constraints} \]
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- **Passenger Demand**
- **Flight Traffic**
- **Airfare**
- **Flight Delay**
- **Airline Cost**
- **Maximizing Profit**

**Investment**

**Infrastructure Capacity**

**Output**
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Flight traffic $= G_2(\text{Demand, Airport Delay})$

Fare $= G_3(\text{Demand, Airport delay})$

Airport delay $= G_4(\text{Flight traffic})$

**Zou, B., Hansen, M.** *Flight Delay Impact on Airfare and Flight Frequency: A Comprehensive Assessment.* Paper to be submitted to Transportation Research Part A.
Flight traffic = $G_2(\text{Demand, Airport delay})$

Fare = $G_3(\text{Demand, Airport delay})$

Airport delay = $G_4(\text{Flight traffic})$
User equilibrium formulation

\[ \text{Demand} = G_1(\text{Fare}, \text{Flight Traffic, Airport delay}) \]

\textit{s.t.} \hspace{1cm} \text{Flight traffic} = G_2(\text{Demand, Airport delay})

\hspace{1cm} \text{Fare} = G_3(\text{Demand, Airport delay})

\hspace{1cm} \text{Airport delay} = G_4(\text{Flight traffic})
Simultaneous equation system

Demand = G₁(Fare, Flight Traffic, Airport delay)

Flight traffic = G₂(Demand, Airport delay)

Fare = G₃(Demand, Airport delay)

Airport delay = G₄(Flight traffic)
## Simulation analysis

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Network

Demand
Supply
Equilibrium
Equilibrium shift

400 miles
Network
Spoke-spoke market demand

- 0-stop
- 1-stop
Total demand is low because the distance is too short.
Spoke-spoke market demand

1-stop routes more attractive because of reduced **circuity** (actually distance/OD distance)

Background | Framework | Model 1 | **Model 2** | Conclusion
--- | --- | --- | --- | ---
Demand | Supply | **Equilibrium** | Equilibrium shift | Conclusion
Spoke-spoke segment frequency

Flights/quarter vs. Segment Distance (miles)
<table>
<thead>
<tr>
<th>Delay (min/flight)</th>
<th>Hub</th>
<th>Spoke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
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<td>11.6</td>
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Increase hub capacity by 50%

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<td>11.6</td>
</tr>
<tr>
<td>After</td>
<td>17.5</td>
<td>11.4</td>
</tr>
</tbody>
</table>
Spoke-spoke market demand shift

- 0-stop (before)
- 1-stop (before)
- 0-stop (after)
- 1-stop (after)

Demand vs. O-D Distance (miles)

Demand:
- 0-stop (before)
- 1-stop (before)
- 0-stop (after)
- 1-stop (after)

O-D Distance (miles):
- 0
- 200
- 400
- 600
- 800

Total spoke-spoke market demand

- Before
- After

Induced demand

Model 1
Model 2
Conclusion
Spoke-spoke segment frequency change

- Before
- After

Flights/quarter vs. Segment Distance (miles)
Spoke-hub segment frequency change

- Background
- Framework
- Model 1
- Model 2
- Conclusion

<table>
<thead>
<tr>
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Demand Supply Equilibrium Equilibrium shift
Consumer surplus change per air travel decision making
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</table>

Comparison between equilibrium and conventional approaches
**Model**

**Equilibrium shift**

<table>
<thead>
<tr>
<th>Conventional</th>
<th>Equilibrium</th>
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<tbody>
<tr>
<td>14.2</td>
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</table>

**Hub delay savings**

(min/flight)
**Model**

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<td>Equilibrium</td>
<td>218.4</td>
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<tr>
<td>Passenger welfare gain (million$/qtr)</td>
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<td>User equilibrium model</td>
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Summary

- An equilibrium framework
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- Larger and broader benefits
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- Additional insights
  - Delay triggers investment
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  - Returns more than delay savings
  - Delay reduction less than expected
  - Investment paradox: some markets can be worse off
## Extensions

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Extensions

- Infrastructure investment decision making
  - Size, location, timing
Extensions

- Infrastructure investment decision making
  - Size, location, timing
  - Environmental externalities
Extensions

- Infrastructure investment decision making
  - Size, location, timing
  - Environmental externalities

- Consider intermodal competition
Thank you!

Questions?