Impact analysis of a flexible air transportation system: Clip-Air

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Transport and mobility laboratory
EPFL

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Outline

1. Flexibility
2. Schedule Planning Model
3. Comparative Analysis
4. Conclusions
5. Future Work
Outline

1. Flexibility
2. Schedule Planning Model
3. Comparative Analysis
4. Conclusions
5. Future Work
Flexibility

- Flexibility in transportation systems
  - Robustness
  - Demand responsiveness

- Rail transportation $\Rightarrow$ modularity in fleet
- Maritime transportation $\Rightarrow$ standard unit loads, multi-modality
- Air transportation $\Rightarrow$ revenue management
Flexibility of Clip-Air
Modularity

Decoupling of wing and capsules
Illustration - Modularity

Flexibility Schedule Planning Model Comparative Analysis Conclusions Future Work
Illustration - Modularity
Multi-modality
Flexibility
Schedule Planning Model
Comparative Analysis
Conclusions
Future Work

Mixed passenger and cargo
Energy
Outline

1. Flexibility
2. Schedule Planning Model
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Model framework

- **Decisions**
  - Fleet assignment
    - Assignment of wings to the flights
    - Assignment of capsules to the wings
  - Schedule - selected optional flights
  - Seat allocation to economy and business class
  - The spilled number of passengers

- **Supply-demand interactions**
  - Spill and recapture
  - Itinerary choice model
Model framework

- Decisions
  - Fleet assignment *Modularity*
    - Assignment of wings to the flights
    - Assignment of capsules to the wings
  - Schedule - selected optional flights
  - Seat allocation to economy and business class
  - The spilled number of passengers

- Supply-demand interactions
  - Spill and recapture
  - Itinerary choice model
    *Demand management*
Integrated schedule planning model

\[
\text{Min } \sum_{f \in F} (C_w^f x_w^f + \sum_{k \in K} C_{k,f} x_{k,f}) + \sum_{h \in H} \sum_{s \in S_h} \sum_{i \in (I_s \setminus l_s')} (\sum_{j \in I_s} t_{i,j} - \sum_{j \in (I_s \setminus l_s')} t_{j,i} b_{j,i}) p_i
\]

s.t. \( \sum_{k \in K} x_{k,f} = 1 \) \( \forall f \in F^M \) (2)

\( \sum_{k \in K} x_{k,f} \leq x_f^w \) \( \forall f \in F \) (3)

\( y_{a,t}^w^- + \sum_{f \in \text{In}(a,t)} x_f^w = y_{a,t}^w^+ + \sum_{f \in \text{Out}(a,t)} x_f^w \) \( \forall [a, t] \in N \) (4)

\( \sum_{a \in A} \sum_{f \in CT} y_{a,\text{min}E_a}^- + \sum_{f \in CT} x_f^w \leq R_w \) (5)

\( y_{a,\text{min}E_a}^- = y_{a,\text{max}E_a}^+ \) \( \forall a \in A \) (6)

\( y_{a,t}^k^- + \sum_{f \in \text{In}(a,t)} k x_{k,f} = y_{a,t}^k^+ + \sum_{f \in \text{Out}(a,t)} k x_{k,f} \) \( \forall [a, t] \in N \) (7)

\( \sum_{a \in A} \sum_{f \in CT} y_{a,\text{min}E_a}^- + \sum_{f \in CT} k x_{k,f} \leq R_k \) (8)

\( y_{a,\text{min}E_a}^- = y_{a,\text{max}E_a}^+ \) \( \forall a \in A \) (9)
Integrated schedule planning model

\[ \text{Min} \sum_{f \in F} (c^w_f x^w_f + \sum_{k \in K} c_{k,f} x_{k,f}) + \sum_{h \in H} \sum_{s \in S^h} \sum_{i \in (l_s \setminus l_s')} (\sum_{j \in l_s} t_{i,j} - \sum_{j \in (l_s \setminus l_s')} t_{j,i} b_{j,i}) p_i \text{ op. costs + loss of pax.} \] (1)

s.t. \[ \sum_{k \in K} x_{k,f} = 1 \quad \text{mandatory flights} \quad \forall f \in F^M \] (2)

\[ \sum_{k \in K} x_{k,f} \leq x^w_f \quad \text{wing-capsule relation} \quad \forall f \in F \] (3)

\[ y^w_{a,t}^- + \sum_{f \in \text{In}(a,t)} x^w_f = y^w_{a,t}^+ + \sum_{f \in \text{Out}(a,t)} x^w_f \quad \text{flow cons. wings} \quad \forall [a,t] \in N \] (4)

\[ \sum_{a \in A} y^w_{a,\text{minE}^-} + \sum_{f \in \text{CT}} x^w_f \leq R_w \quad \text{available wings} \] (5)

\[ y^w_{a,\text{minE}^-} = y^w_{a,\text{maxE}^+} \quad \text{cyclic wings} \quad \forall a \in A \] (6)

\[ y^k_{a,t}^- + \sum_{f \in \text{In}(a,t)} k x_{k,f} = y^k_{a,t}^+ + \sum_{f \in \text{Out}(a,t)} k x_{k,f} \quad \text{flow cons. capsules} \quad \forall [a,t] \in N \] (7)

\[ \sum_{a \in A} y^k_{a,\text{minE}^-} + \sum_{f \in \text{CT}} k x_{k,f} \leq R_k \quad \text{available capsules} \] (8)

\[ y^k_{a,\text{minE}^-} = y^k_{a,\text{maxE}^+} \quad \text{cyclic capsules} \quad \forall a \in A \] (9)
**Integrated schedule planning model**

\[
\sum_{s \in S^h} \sum_{i \in (I_s \setminus I'_s)} \delta_f^i D_i - \sum_{j \in I_s} \delta_f^j t_{i,j} + \sum_{j \in (I_s \setminus I'_s)} \delta_f^j t_{j,i} b_{j,i} \leq \pi_{f,h} \\
\sum_{h \in H} \pi_{f,h} \leq \sum_{k \in K} Q_k \ x_{k,f} \\
\sum_{j \in I_s} t_{i,j} \leq D_i \\
x_f^w \in \{0,1\} \\
x_{k,f} \in \{0,1\} \\
y_w^a, t \geq 0 \\
y_k^a, t \geq 0 \\
\pi_{f,h} \geq 0 \\
t_{i,j} \geq 0
\]

(10) \quad \forall f \in F, h \in H

(11) \quad \forall f \in F

(12) \quad \forall h \in H, s \in S^h, i \in (I_s \setminus I'_s)

(13) \quad \forall f \in F

(14) \quad \forall k \in K, f \in F

(15) \quad \forall [a, t] \in N

(16) \quad \forall [a, t] \in N

(17) \quad \forall f \in F, h \in H

(18) \quad \forall h \in H, s \in S^h, i \in (I_s \setminus I'_s), j \in I_s
Integrated schedule planning model

\[
\sum_{s \in S^h} \sum_{i \in (I_s \setminus l_s')} \delta^i_f D_i - \sum_{j \in I_s} \delta^i_f t_{i,j} + \sum_{j \in (I_s \setminus l_s')} \delta^i_f t_{j,i} b_{j,i} \leq \pi_{f,h} \quad \text{demand-supply} \quad \forall f \in F, h \in H
\]  

\[
\sum_{s \in S^h} \sum_{i \in (I_s \setminus l_s')} \delta^i_f D_i - \sum_{j \in I_s} \delta^i_f t_{i,j} + \sum_{j \in (I_s \setminus l_s')} \delta^i_f t_{j,i} b_{j,i} \leq \pi_{f,h} \quad \text{demand-supply} \quad \forall f \in F, h \in H
\]  

\[
\sum_{h \in H} \pi_{f,h} \leq \sum_{k \in K} Q k x_{k,f} \quad \text{k capsules up to 3} \quad \forall f \in F
\]  

\[
\sum_{j \in I_s} t_{i,j} \leq D_i \quad \text{spilled passengers} \quad \forall h \in H, s \in S^h, i \in (I_s \setminus l_s')
\]  

\[
x^f \in \{0,1\} \quad \forall f \in F
\]  

\[
x_{k,f} \in \{0,1\} \quad \forall k \in K, f \in F
\]  

\[
y^w_{a,t} \geq 0 \quad \forall [a,t] \in N
\]  

\[
y^k_{a,t} \geq 0 \quad \forall [a,t] \in N
\]  

\[
\pi_{f,h} \geq 0 \quad \forall f \in F, h \in H
\]  

\[
t_{i,j} \geq 0 \quad \forall h \in H, s \in S^h, i \in (I_s \setminus l_s'), j \in I_s
\]
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## Configuration - Comparison with Airbus A320

<table>
<thead>
<tr>
<th></th>
<th>A320</th>
<th>Clip-Air</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum Capacity</strong></td>
<td>150 seats</td>
<td>3 x 150 (450 seats)</td>
</tr>
<tr>
<td><strong>Engines</strong></td>
<td>2 engines</td>
<td>3 engines</td>
</tr>
<tr>
<td><strong>Maximum Aircraft Weight</strong></td>
<td>78t</td>
<td>139t (+78%)</td>
</tr>
<tr>
<td></td>
<td>2 x 78t (156t)</td>
<td>173.5t (+11%)</td>
</tr>
<tr>
<td></td>
<td>3 x 78t (234t)</td>
<td>208t (-11%)</td>
</tr>
<tr>
<td></td>
<td>3 (planes/capsules)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 (planes/capsules)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 (plane/capsule)</td>
<td></td>
</tr>
</tbody>
</table>
Operating costs for *Clip-Air*

- Based on standard flight operating costs
- Adjustment based on weight differences:
  - Fuel costs $^1$ (25.3% of the total op. cost)
  - Airport and air navigation charges $^2$ (6%)
- Crew cost $^1$ (24.8%) is separated between wing (flight crew) and capsules (cabin crew):
  - flight crew constitutes a 60% of the total crew cost
  - gain of 30% with 2 capsules
  - gain of 40% with 3 capsules

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$^1$IATA, 2010

$^2$Castelli and Ranieri, 2007; ICAO, 2012
Conservative Assumptions

- Fleet composition
Conservative Assumptions

- Fleet composition
  - Standard fleet optimizes the fleet composition
Conservative Assumptions

- **Fleet composition**
  - Standard fleet optimizes the fleet composition
  - Clip-Air capsules are of same size
Conservative Assumptions

- Fleet composition
  - Standard fleet optimizes the fleet composition
  - Clip-Air capsules are of same size
- Operating cost of Clip-Air is higher
Conservative Assumptions

- Fleet composition
  - Standard fleet optimizes the fleet composition
  - Clip-Air capsules are of same size

- Operating cost of Clip-Air is higher

- The repositioning of empty capsules is ignored
Conservative Assumptions

- Fleet composition
  - Standard fleet optimizes the fleet composition
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- Operating cost of Clip-Air is higher

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- We ignore potential savings related to maintenance, number of engines
Conservative Assumptions

- Fleet composition
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  - Clip-Air capsules are of same size

- Operating cost of Clip-Air is higher

- The repositioning of empty capsules is ignored

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- Only passenger transportation
Conservative Assumptions

- Fleet composition
  - Standard fleet optimizes the fleet composition
  - Clip-Air capsules are of same size
- Operating cost of Clip-Air is higher
- The repositioning of empty capsules is ignored
- We ignore potential savings related to maintenance, number of engines
- Only passenger transportation
- Total fleet investment cost is ignored
Conservative Assumptions

- Fleet composition
  - Standard fleet optimizes the fleet composition
  - Clip-Air capsules are of same size

- Operating cost of Clip-Air is higher

- The repositioning of empty capsules is ignored

- We ignore potential savings related to maintenance, number of engines

- Only passenger transportation

- Total fleet investment cost is ignored

- The schedule and the demand is assumed to remain the same
Towards results

- **Input:** data from Air France (ROADEF Challenge 2009)
  - set of optional and mandatory flights
  - set of airports
  - set of itineraries: demands and fares
  - set of aircraft for the standard fleet

- **Performance measures**
  - ASK: available seat kilometers
  - TPASK: transported pax. per available seat kilometers

- **Tests:**
  - Network effect
  - Fleet composition
  - Available capacity
  - Sensitivity analysis on the costs
## Network effects - Airport pair

### Data

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Airports</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Flights</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>Density (Flights/route)</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Passengers</td>
<td>13,965</td>
<td></td>
</tr>
<tr>
<td>Itineraries</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Standard fleet types</td>
<td>A320(150), A330(293), B747-200(452)</td>
<td></td>
</tr>
</tbody>
</table>

### Results

<table>
<thead>
<tr>
<th></th>
<th>Standard fleet</th>
<th>Clip-Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating cost</td>
<td>1,607,166</td>
<td>1,725,228</td>
</tr>
<tr>
<td>Spill costs</td>
<td>604,053</td>
<td>448,140</td>
</tr>
<tr>
<td>Revenue</td>
<td>2,419,306</td>
<td>2,575,219</td>
</tr>
<tr>
<td>Profit</td>
<td>812,140</td>
<td>849,991 (+4.66 %)</td>
</tr>
<tr>
<td>Transported pax.</td>
<td>10,276</td>
<td>11,035 (+7.39 %)</td>
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<tr>
<td>Flight count</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>Total flight duration</td>
<td>3135 min</td>
<td>3135 min</td>
</tr>
<tr>
<td>Used fleet</td>
<td>2 A320</td>
<td>7 wings</td>
</tr>
<tr>
<td></td>
<td>5 A330</td>
<td>12 capsules</td>
</tr>
<tr>
<td>Used aircraft</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Used seats</td>
<td>1765</td>
<td>1800</td>
</tr>
<tr>
<td>ASK</td>
<td>78,388,063</td>
<td>79,942,500</td>
</tr>
<tr>
<td>TPASK (×10⁻⁵)</td>
<td>13.11</td>
<td>13.80</td>
</tr>
</tbody>
</table>

- Aircraft sizes are almost equivalent to 1, 2, 3 capsules ⇒ same usage of capacity
- High flight density ⇒ improved profit
Network effects - Hub and spoke

<table>
<thead>
<tr>
<th>Data</th>
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<tbody>
<tr>
<td>Airports</td>
<td>5</td>
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<tr>
<td>Flights</td>
<td>26</td>
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<td>Density (Flights/route)</td>
<td>3.25</td>
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<tr>
<td>Passengers</td>
<td>9,573</td>
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<tr>
<td>Itineraries</td>
<td>37</td>
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<tr>
<td>Standard fleet types</td>
<td>A320(150), A330(293), B747-200(452)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Results</th>
<th>Standard fleet</th>
<th>Clip-Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating cost</td>
<td>817,489</td>
<td>938,007</td>
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<tr>
<td>Spill costs</td>
<td>484,950</td>
<td>393,677</td>
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<tr>
<td>Revenue</td>
<td>1,247,719</td>
<td>1,338,992</td>
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<tr>
<td>Profit</td>
<td><strong>430,230</strong></td>
<td><strong>400,985 (- 6.80 %)</strong></td>
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<tr>
<td>Transported pax.</td>
<td>5,031</td>
<td>5,721 (+ 13.71 %)</td>
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<tr>
<td>Flight count</td>
<td>24</td>
<td>22</td>
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<tr>
<td>Total flight duration</td>
<td><strong>1850 min</strong></td>
<td><strong>1700 min</strong></td>
</tr>
<tr>
<td>Used fleet</td>
<td>5 A320</td>
<td>6 wings</td>
</tr>
<tr>
<td></td>
<td>2 A330</td>
<td>12 capsules</td>
</tr>
<tr>
<td></td>
<td>1 B747</td>
<td></td>
</tr>
<tr>
<td>Used aircraft</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Used seats</td>
<td>1788</td>
<td>1800</td>
</tr>
<tr>
<td>ASK</td>
<td><strong>46,860,500</strong></td>
<td><strong>43,350,000</strong></td>
</tr>
<tr>
<td>TPASK (×10⁻5)</td>
<td><strong>10.74</strong></td>
<td><strong>13.20</strong></td>
</tr>
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</table>

- Low flight density
  - less potential
  - lower profit
## Network effects - Peer-to-peer network

### Data

<p>| | |</p>
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<tr>
<td>Airports</td>
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<tr>
<td>Flights</td>
<td>98</td>
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<td>Density (Flights/route)</td>
<td>8.17</td>
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<td>Passengers</td>
<td>28,465</td>
</tr>
<tr>
<td>Itineraries</td>
<td>150</td>
</tr>
<tr>
<td>Standard fleet types</td>
<td>A320(150), A330(293), B747-200(452)</td>
</tr>
</tbody>
</table>

### Results

<table>
<thead>
<tr>
<th></th>
<th>Standard fleet</th>
<th>Clip-Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating cost</td>
<td>3,189,763</td>
<td>3,117,109</td>
</tr>
<tr>
<td>Spill costs</td>
<td>982,556</td>
<td>978,683</td>
</tr>
<tr>
<td>Revenue</td>
<td>5,056,909</td>
<td>5,060,782</td>
</tr>
<tr>
<td>Profit</td>
<td>1,867,146</td>
<td>1,943,673 (+ 4.1 %)</td>
</tr>
<tr>
<td>Transported pax.</td>
<td>20,840</td>
<td>21,424 (+ 2.8 %)</td>
</tr>
<tr>
<td>Flight count</td>
<td>91</td>
<td>84</td>
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<tr>
<td>Total flight duration</td>
<td>6650 min</td>
<td>6160 min</td>
</tr>
<tr>
<td>Used fleet</td>
<td>7 A320</td>
<td>13 wings</td>
</tr>
<tr>
<td></td>
<td>10 A330</td>
<td>28 capsules</td>
</tr>
<tr>
<td></td>
<td>3 B747</td>
<td></td>
</tr>
<tr>
<td>Used aircraft</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>Used seats</td>
<td>5336</td>
<td>4200 (- 21.3 %)</td>
</tr>
<tr>
<td>ASK</td>
<td>502,695,667</td>
<td>366,520,000</td>
</tr>
<tr>
<td>TPASK ($\times 10^{-5}$)</td>
<td>4.15</td>
<td>5.85</td>
</tr>
</tbody>
</table>

- High flight density
- Better connected network
  - increased potential
  - higher profit
  - less allocated capacity
  - significantly less aircraft
Network effects

- Enhanced performance when...
  - High flight density
  - Well connected network
Fleet composition

The same data as peer-to-peer network
Clip-Air always carries more passengers
Standard fleet has more profit when the fleet is highly heterogeneous
## Available capacity

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Airports</td>
<td>5</td>
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<tr>
<td>Flights</td>
<td>100</td>
</tr>
<tr>
<td>Density (Flights/route)</td>
<td>6.25</td>
</tr>
<tr>
<td>Passengers</td>
<td>35,510</td>
</tr>
<tr>
<td>Itineraries</td>
<td>140</td>
</tr>
<tr>
<td>Standard fleet types</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A319(124), A320(150), A321(185), A330(293), A340(335), B737-300(128), B737-400(146), B737-900(174), B747-200(452), B777(400)</td>
</tr>
</tbody>
</table>
Available capacity

Constraint on the total number of seats for the assigned fleet
Sensitivity analysis on the cost of Clip-Air

The same data used for the test on the available capacity
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Conclusions

- Clip-Air better utilizes the capacity
Conclusions

• Clip-Air better utilizes the capacity
• More passengers...
Conclusions

• Clip-Air better utilizes the capacity
  • More passengers...
  • ... with less allocated capacity
Conclusions

- Clip-Air better utilizes the capacity
  - More passengers...
  - ... with less allocated capacity
- Clip-Air deals better with the insufficient capacity
Conclusions

- Clip-Air better utilizes the capacity
  - More passengers...
  - ... with less allocated capacity
- Clip-Air deals better with the insufficient capacity
- Results are robust to the cost values of Clip-Air
Conclusions

- Clip-Air better utilizes the capacity
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- Clip-Air deals better with the insufficient capacity
- Results are robust to the cost values of Clip-Air

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Different wing and capsule sizes

- Clip-Air has a strength with one single wing/capsule type
- Different sizes can be studied
- Small wings/capsules: easier transport
Multi-modality of Clip-Air capsules

- Clip-Air capsules can be transferred via other means of transport
- Empty capsule management
- Demand fluctuations
- Unbalanced demand
- European market - railways
Thank you very much for your attention!

Any question?
Spill and recapture Model

\[ V_i = -[2.23(-3.48) \times \text{nonstop}_i + 2.17(-3.48) \times \text{stop}_i] \times \ln(p_i/100) \]
\[ - [0.102(-2.85) \times \text{nonstop}_i + 0.0762(-2.70) \times \text{stop}_i] \times \text{time}_i \]
\[ + 0.0283(1.21) \times \text{morning} \quad \forall i \in l_s, s \in S^{\text{econ}}, \]

\[ V_i = -[1.97(-3.64) \times \text{nonstop}_i + 1.96(-3.68) \times \text{stop}_i] \times \ln(p_i/100) \]
\[ - [0.104(-2.43) \times \text{nonstop}_i + 0.0821(-2.31) \times \text{stop}_i] \times \text{time}_i \]
\[ + 0.0790(1.86) \times \text{morning} \quad \forall i \in l_s, s \in S^{\text{bus}}, \]

\[ b_{i,j} = \frac{\exp(V_j)}{\sum_{k \in l_s \setminus \{i\}} \exp(V_k)} \quad \forall h \in H, s \in S^h, i \in (l_s \setminus l'_s), j \in l_s, \]
## Spill and recapture

<table>
<thead>
<tr>
<th></th>
<th>class</th>
<th>nonstop</th>
<th>morning</th>
<th>time</th>
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