Delay Reduction Service in the ATM

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Background

- Aviation in future EU: rapid growth and severe air traffic delay.
- Delay harms society: airlines and passengers.
- Single European Sky ATM Research programme (SESAR) founded by European Union and EUROCONTROL: satisfying future safety needs and reducing delays.
- Air Navigation Service Provider (regulator) can provide delay reduction service.
Delay Reduction Service: An Example

- Airline will contact regulator when facing potential delay.
- Regulator can find out several equilibria satisfying all constraints.
- By costly calculation, evaluation, and coordination, regulator can determine the equilibrium which can reduce delay most and then implement it.
Delay Reduction Contract: A Real Problem

- In the short run, delay reduction service can be provided for free because of generous funds of SESAR.
- In the long run, however, regulator will face financial constraints.
- Delay reduction contract: authority is thinking about asking airlines to pay for funding the service.
Research Question and Contribution

- Research question: study the optimal design of delay reduction contracts.
- Build a model which fits characteristics of EU air transport sector.
  - Slot controls and thus no congestion of flights at all major European airports
    ⇒ A delay function only including exceptional event delay.
  - Grandfather right and “use it or lose it” rule in EU slot allocation mechanism
    ⇒ Fixed number of flights.
- Derive optimal contracts analytically.
  - With or without using public funds.
- Study the effects of some relevant exogenous variables on optimal contracts.
  - Safety standard and passenger’s value of time.
The Model: Harm of Delay to Passengers

- Passenger utility: \( v = y - p + b + a(s) - \alpha D(s) \).

  \( s \): safety standard.

  \( \alpha \): passenger’s value of time.

  \( D(s) \): expected delay per flight, i.e., exceptional event delay.

\[
D(s) = 2 \left[ \sum_{k=0}^{+\infty} \frac{\left( \frac{\beta T}{f} \right)^k}{k!} \cdot \left( e^{-\left( \frac{\beta T}{f} \right)} - 1 \right) \cdot k^g(s) + \gamma \beta \left( \frac{T}{f} \right)^{-1} \cdot g(s) \right].
\]

  \( i \): delay due to exceptional events in own slot.

  \( ii \): delay induced by the delayed flights in previous slots.

- Outside option: \( v_0 = y + z \).
The Model: Harm of Delay to Airline

- Monopoly airline’s profit:

\[
\pi (\theta, s) = p(s)q(s) - (\tau q(s) + cf + \theta fD(s))
\]

\[
= \frac{1}{4}\eta [2 (\xi - \tau + a(s) - z) - \alpha D(s)] \alpha D(s)
\]

- demand side delay cost

\[- \theta fD(s)
\]

- supply side delay cost

\[+ \frac{1}{4}\eta (\xi - \tau + a(s) - z)^2 - cf.
\]

\(\theta\): airline’s value of time; may be unobservable to regulator; common knowledge: \(\theta \in \{\overline{\theta}, \underline{\theta}\}\).
The Model: Delay Reduction

- Delay reduction contract \((r, t)\).
  
  \(r\): degree of delay reduction service.

  \(t\): transfer.

- An airline who signs a delay reduction contract \((r, t)\) decreases its delay from \(D(s)\) to \(D(s)[1 - \sigma \ln(1 + r)]\) where \(\sigma \in [0, \sigma]\).

  \(\sigma\): a parameter which measures the effectiveness of service.
The Model: Benefit of Service

\[ \Pi(\theta, s, r) = \pi(\theta, s) + \frac{1}{4} \eta \alpha^2 D(s)^2 \sigma^2 [\ln (1 + r)]^2 + q(s) \alpha D(s) \sigma \ln (1 + r) \]

- initial profit
- demand side delay reduction benefit

\[ + \theta f \sigma D(s) \sigma \ln (1 + r) \]

- supply side delay reduction benefit

\[ CS(s, r) = \frac{cs(s)}{\text{initial consumer surplus}} \]

\[ + \frac{1}{2} \left\{ \frac{1}{4} \eta \alpha^2 D(s)^2 \sigma^2 [\ln (1 + r)]^2 + q(s) \alpha D(s) \sigma \ln (1 + r) \right\} \]

- consumer delay reduction benefit
The Model: Regulator’s Problem

- Regulator’s cost: $C_{\text{reg}}(s, r) = m(s) r$.
- Regulator maximizes social welfare:

$$\mathcal{W} = CS(s, r) + \Pi(\theta, s, r) - C_{\text{reg}}(s, r) - \lambda(C_{\text{reg}}(s, r) - t)$$

s.t. $t \leq C_{\text{reg}}(s, r)$.

- $t = C_{\text{reg}}(s, r)$: without using public funds.
  - Separating contracts: not incentive-compatible $\Rightarrow$ pooling contract.

- $t < C_{\text{reg}}(s, r)$: with using public funds.
  - Separating contracts: incentive-compatible.
  - $\bar{r}^{FB} = \bar{r}^{SB} > \bar{r}^{FB} > \bar{r}^{SB}$. 
The Effect of Safety Standard on Degree

- **Notations**
  - Safety elasticity of delay (cost): $\varepsilon_{gs}$ ($\varepsilon_{ms}$);
  - Marginal benefit (cost) of society: $MB$ ($MC$).

- $s \uparrow \Rightarrow g(s) \uparrow$
  - $\Rightarrow MB \uparrow$ (direct effect, given $q(s)$ fixed);
  - $\Rightarrow q(s) \downarrow \Rightarrow MB \downarrow$ (indirect effect, allow $q(s)$ changes).

- $s \uparrow \Rightarrow a(s) \uparrow \Rightarrow q(s) \uparrow \Rightarrow MB \uparrow$.

- $s \uparrow \Rightarrow m(s) \uparrow$, i.e., $MC \uparrow$.

- **Overall effect:**
  $$\frac{\partial r^{SB}}{\partial s} \geq 0 \iff \varepsilon_{gs} - \varepsilon_{ms} \geq -A \cdot \frac{\partial V(s, \bar{r}^{SB})}{\partial s},$$

  where $A \equiv \frac{(3+2\lambda)\eta \alpha D(s)\sigma s}{2(1+\lambda)(1+\bar{r}^{SB})m(s)} > 0$. 
The Effect of Passenger’s Value of Time on Degree

- $\alpha \uparrow$
  - $\Rightarrow MB \uparrow$ (direct effect, given $q(s)$ fixed);
  - $\Rightarrow q(s) \downarrow \Rightarrow MB \downarrow$ (indirect effect, allow $q(s)$ changes).

**Overall effect:**

$$\frac{\partial \bar{r}^{SB}}{\partial \alpha} \geq 0 \iff \alpha \leq \bar{\alpha}^{SB} \equiv \frac{\xi - \tau + a(s) - z}{2D(s)[1 - \sigma \ln(1 + \bar{r}^{SB})]}.$$