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Outline

• Background
• The model
  – Modeling framework
  – Pre-negotiation
  – Bargaining game with complete information
  – Bargaining game with incomplete information
• Numerical analysis
• Concluding remarks
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Background

- Passenger rail resurgence in the US
- High performance rail systems (HSR and HrSR services)
- Eight billion dollars for construction as a part of the American Recovery and Reinvestment Act
- Midwest: existing single track lines are being upgraded to accommodate trains running at a maximum speed of 110 mph
Background

• 15% increase in Class I Railroads’ revenue ton-miles between 2001 and 2011

• About 6800% increase in originated carloads of crude oil on Class I Railroads
Background

- Challenges of Higher Speed Rail lines
  - Single tracks with siding (meets and overpasses)
  - Shared passenger and freight use (negative impacts on capacity utilization, heterogeneity)
  - High speed passenger trains operating at 110 mph (on-time performance is essential)

It is important to develop a capacity allocation mechanism taking into consideration different characteristics of the US railway market.
Background

• Issues to be considered in allocating rail capacity in the US:
  – Complementary feature of rail tracks
  – Capacity is endogenous
  – Amtrak’s priority (Public Law 110-432)
  – Temporal variations in passenger demand
  – Train schedule inconvenience to passengers
  – Freight railroads keep their operating and financial information confidential
Background

• Capacity allocation mechanisms:
  – Administered mechanisms

  Appropriate for rail networks fully owned and controlled by governments
  Do not provide incentive for train operators to seek a more efficient use of capacity

  – Value based mechanisms

  Value based
  Yield management
  Value of service

  – Market-based mechanisms

  Neglect congestion impacts and scarcity of capacity, both prominent in the U.S. rail sector
  Possession of private information is not incorporated into the above the capacity allocation mechanisms

The first sequential bargaining approach to capacity allocation in US rail system

Efficient and effective schemes for capacity allocation in the U.S. rail industry must account for its specific characteristics
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The model

Modelling Framework

Pre-negotiation stage

- Input data
  - Input parameters
  - Set of feasible passenger train schedules

Module 1
Passenger delay components calculation

Module 2
Freight train schedule generation

Module 3
Utility and cost calculation

Module 4
- Upper-level: schedule bargaining model
- Lower-level: price bargaining model

Negotiation stage
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The model

Module 1: Computing passenger delay components

- A set of feasible passenger train schedules is given ($FPTS$)
- Constant fare
- An initial schedule (baseline schedule) and associated travel demand are given
- Delay components:
  - Schedule delay
  - En-route delay
The model

Module 1: Computing passenger delay components

- **Schedule delay:** The difference between one's desired departure time and the actual departure time.
The model

Module 1: Computing passenger delay components

- Each O-D pair has a passenger demand profile (Preferred Departure Time)
- Passengers are served by a predetermined number of trains
Module 1: Computing passenger delay components

- Passenger demand is elastic w.r.t. schedule delay
- Find the number of passengers departing the origin of station pair \( w \) at each time period \( s \):

\[
q_{s_i}^{w,m} = q_{s_b}^{w,m} \left( 1 - \frac{e_{d/w}}{1 - \frac{S_{s_i}^{w,m}}{S_b^{w,m}}} \right)
\]

Total number of passengers leaving the origin of station pair \( w \) towards the destination of station pair \( w \) and desire to leave between \( t=m-1 \) and \( t=m \), when schedule \( s_b \) is in place.

Elasticity of demand w.r.t. schedule delay
Module 1: Computing passenger delay components

- We account for passenger en-route delay in two situations:
  - When a train stops at a siding
  - While a train is conducting layover at an intermediate station
The model

Module 2: Solving the freight train scheduling problem

• Freight train scheduling is not precise and stringent in the US
• Freight trains are inserted among passenger trains (scheduling priority is granted to passenger trains)
• Minimize total freight side cost: sum of lost demand cost, train en-route delay cost, and train departure delay cost

Module 3: Establishing utility and cost values

\[ u_{s_i}^P = TOR_{s_i} - TOC_{s_i} - (TSC_{s_i} - TSC_{s_b}) - (TEC_{s_i} - TEC_{s_b}) \]

- Total operating revenue for schedule \( s_i \)
- Total operating cost for schedule \( s_i \)
- Total schedule delay cost for schedule \( s_i \)
- Total schedule delay cost for the baseline schedule
- Passenger en-route delay cost for schedule \( s_i \)
- Passenger en-route delay cost for the baseline schedule
The model

Module 3: Establishing utility and cost values

Lost demand cost for schedule $s_i$

Lost demand cost for pure freight traffic

Departure delay cost for schedule $s_i$

Departure delay cost for pure freight traffic

Line-haul costs for schedule $s_i$

Line-haul costs for pure freight traffic

Total maintenance costs for schedule $s_i$

Total maintenance costs for pure freight traffic

$$C^F_{S_i} = (LDC_{S_i} - LDC_{PFT}) + (DDC_{S_i} - DDC_{PFT}) + (LHC_{S_i} - LHC_{PFT}) + (TMC_{S_i} - TMC_{PFT})$$
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Negotiation stage

• A two-level, bargaining-based mode:
  Upper-level: Schedule bargaining
  Lower-level: Price bargaining

• A backward approach: first determine the price of each schedule. Then, solve for the equilibrium schedule

• We solve the game for two settings with complete and incomplete information
The model

Complete information price bargaining game

Step 1
- PRA
- \( p_{s_i}^1 \)

Step 2
- FRR
- Reject
- Accept

Step 3
- FRR
- \( (u_{s_i}^P - p_{s_i}^1, p_{s_i}^1 - C_{s_i}^F) \)

Step 4
- PRA
- Reject
- Accept

Step 5
- PRA
- \( (\delta_P(u_{s_2}^P - p_{s_i}^2), \delta_F(p_{s_i}^2 - C_{s_2}^F)) \)

- Net transfer from PRA to FRR is employed to solve the game:
  \[ p_{s_i}^1 = 1 - \delta_F \cdot C_{s_i}^F \]

- The net payment from PRA to FRR shows positive correlations with PRA’s utility and FRR’s cost.

1st subgame

2nd subgame
The model

Complete information schedule bargaining game

- The schedule maximizing the difference between \( PRA's \) valuation and \( FRR's \) cost \( u_s = P - T_s \) is the efficient schedule.
- The efficient schedule is invariant to players' discount factors.
- Who initiates the bargaining does not change the equilibrium schedule.
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Incomplete information price bargaining game

Class I freight railroads consider their operating and financial information highly critical to profitability and thus confidential.

PRA (uninformed player) is aware of his utility associated with each schedule (\( s_i \in FFR_T \)), but is uncertain about FRR's cost related to the same schedule.

FRR could be of two types: low-cost FRR (LFRR) and high-cost FRR (HFRR).

PRA's prior belief: probability of HFRR is \( \theta \).

Step 1

Step 2

Step 3

Step 4

Step 5

Step 6

Step 7
The model

Incomplete information price bargaining game

- We conjecture two equilibria for the game (only one equilibrium will occur depending on $\theta$ value)
- Equilibrium 1: PRA is highly confident that FRR is HFRR; therefore, he offers the price high enough such that HFRR accepts it
- Equilibrium 2: PRA highly believes that FRR is low-cost; therefore, he lowers the price such that only LFRR accepts the offer
The model

Incomplete information schedule bargaining game

- Given\(^{\text{Stage 1}}\) the price of each schedule, PRA and FRR bargain to determine an equilibrium schedule.
- We construct\(^{\text{Stage 2}}\) a pooling equilibrium in which LFRR and HFRR offer the same schedule to PRA, and PRA also offers the same schedule to both types of FRR.

![Game tree diagram]

\(s_1\)

\(s_2\)

\(s_3\)

\(s_4\)

\(s_5\)

\(s_6\)

Stage 1

Stage 2

Stage 3

Stage 4

Stage 5

Stage 6

\(U_{s_1}^p, U_{s_1}^F\)

\(U_{s_1}^p, \overline{U}_{s_1}^F\)

\(U_{s_1}^p, \overline{U}_{s_1}^F\)

\(U_{s_1}^p, \overline{U}_{s_1}^F\)

\(\delta_p U_{s_2}^p, \delta_U U_{s_2}^F\)

\(\delta_p U_{s_2}^p, \delta_U U_{s_2}^F\)
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Numerical analysis

• Set up:
  – 11 blocks: 6 track segments and 5 sidings
  – 2 O-D pairs (one in each direction)
  – Each track segment 18 miles long
  – Sidings evenly distributed along the corridor, each 2 miles long
  – Total corridor length: 120 miles
  – Planning time horizon: 5 AM to 9:30 PM (i.e., 16.5 hours), discretized into 5 minutes time periods
  – Consider daily service frequency of 1-5 trains
Numerical analysis

• Set up (cont’d)
  – Operating speed: 120 mph for passenger trains and 60 mph for freight trains
  – Elastic passenger demand (elasticity: 0.4, based on Adler et al. (2010))
  – Parameter values are obtained from the literature
    – $\delta_P = 0.9$, $\delta_F = 0.85$
  – Total en-route delay for each physical train is less than the pre-specified maximum en-route delay time (MED)
Numerical analysis

• Results
  – Increasing service frequency generally elevates the amount of net payment as it imposes additional costs to the host freight railroad

![Graph showing net transfer vs. MED (time periods) for different passenger loads (1 to 5 pax)]

![Graph showing net transfer per passenger train vs. MED (time periods) for different passenger loads (1 to 5 pax)]
Numerical analysis

• Results
  – Elevating service frequency generally lowers the value of net transfer per train: the net payment disproportionally increases with rail service frequency
Numerical analysis

• Results
  – In 2009, Amtrak’s average track usage payment is $4.44 per train-mile, which translates to $549 per train for the use of a 120-mile segment.
Numerical analysis

• Results
  – Given passenger service frequency, FRR’s payoff generally increases with maximum en-route delay time
  – The host freight railroad prefers higher maximum en-route delays
Numerical analysis

• Results
  – The vertical axis denotes increase percentage in net transfer value due to altering the player initiating the game
  – If FRR initiates the schedule bargaining, the net payment will increase by 17.7%
  – The impact of the initiator is amplified when we reduce passenger service frequency
Numerical analysis

• Results
  – The net payment in each panel falls in the wide range of $30,000-40,000
Numerical analysis

• Results
  – When one of the players is extremely patient or impatient, the problem takes on a special form
Numerical analysis (incomplete information)

• Results
  – Assume FRR is of high-cost type
  – We incrementally increase PRA’s prior belief ($\theta$) that FRR is of high-cost type
  – PRA makes a mistake in recognizing FRR’s type. Thus FRR reduces the net payment offer to avoid delays
  – Inefficiency (due to inaccurate PRA’s perception of FRR’s type) could lead to lower payments from PRA to FRR
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• Proposed the first sequential bargaining game model to identify capacity shares and associated charges on shared-use rail corridors in the US
• The effect of passenger train schedule on rail passenger demand is explicitly incorporated into valuation of passenger train schedules
• Two stages: pre-negotiation and negotiation
• A two level negotiation model: upper-level schedule bargaining game and lower-level price bargaining game
Concluding remarks

• Negotiation: complete and incomplete information settings

• The game of complete information is analytically solved. Efficient passenger train schedule is the one maximizing the utility of passenger rail agency minus freight side cost

• The equilibrium schedule is independent of discount factors, as well as who initiates the bargaining
Concluding remarks

• Bargaining with incomplete information: the freight railroad keeps its cost values confidential

• Using realistic parameter values, applicability of the models is demonstrated on a single track shared-use corridor

• Net payment significantly increases with passenger train frequency. However, the rate of increase is less than proportional
Policy insights

• The payment from Amtrak to the freight railroads seems lower than it should be (given that Amtrak receives true scheduling priority)
• The freight railroad prefers Amtrak trains to have higher en-route delays (in the planning stage)
• Who initiating the bargaining makes a difference to net payment, but not the equilibrium schedule
• Discounting factor (the impact of delayed agreement) critically determines the net payment
Thank you!

Questions and comments

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