INTEGRATED MODELING OF HIGH PERFORMANCE PASSENGER AND FREIGHT TRAIN OPERATION PLANNING ON SHARED USE RAIL CORRIDORS: A FOCUS ON THE US CONTEXT

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Today’s Webcast

- Background
- Literature review
- Hypergraphs
- The train schedule model
  - Modeling approach
  - Passenger train scheduling
  - Freight train scheduling
- Solution approach
- Numerical analysis
- Summary and conclusion
Background: Growth in U.S. Rail Service

• Passenger rail resurgence in the U.S.
• High performance rail systems (HSR and HrSR services)
• Midwest: Existing single track lines are being upgraded to accommodate trains running at a maximum speed of 110 mph

Background: Amtrak Ridership Soars

[Graph showing Amtrak ridership over fiscal years with a significant increase from 2011 to 2015]
Background: HSR in Illinois

- Illinois HSR: Chicago-St. Louis (current phase)
  - Single track (with sidings)
  - Shared passenger and freight use
  - High speed passenger trains operating at 110 mph

Source: IDOT (2014)

Background: Focus of Research

- Non-trivial delays to passenger and freight trains
- Interactions between passenger and freight operations
- This research develops a strategic level schedule planning model for mixed train operations on single-track, shared-use passenger and freight corridors
Literature review: Three approaches

• Three approaches in train scheduling: analytical, simulation, and optimization

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• Discrete time modeling is dominant

• Most of the studies use an “ideal timetable”

Literature review: “Ideal schedule”

• Question: What is an “ideal schedule”? 

• Very limited efforts in obtaining ideal train schedules

• Traveler schedule convenience: An important factor in designing passenger trains schedules

• A measure of inconvenience of schedule to passengers: Schedule delay
Definition: Schedule delay

The difference between one's desired departure time and the actual departure time.

![Bar chart showing the number of passengers at different times of the day.]

Literature review: Schedule Delay

- **Schedule delay** is absent in passenger rail schedule planning.
- Binary integer programming is the prevailing choice for modeling.
- Commonly used segment (block) occupancy models are less capable to capture transitions.
- The emerging **hypergraph** based scheduling approach explicitly addresses **train transitional status**.
Hypergraphs: The Model

**Deficiency of the traditional segment occupancy scheduling model**

- Commonly used capacity constraints are met
- Traditional segment (block) occupancy scheduling models **cannot** deal with conflicts during train transitions between segments
- Transition at the end of the \((t + 1)\)th period on the boundary of segments 3 and 4 is violated

![Diagram](image1.png)

Each single segment is occupied by one train

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**Hypergraphs: Harrod**

Using Hypergraphs in train schedule modeling (Harrod, 2011)

- Each train movement is represented by a hyperarc
- A chain of consecutive hyperarcs form a train path

![Diagram](image2.png)

- Segment occupancy nodes \((1,t)\) and \((2,t+1)\) and a transition node \((1,t)\)
Hypergraphs: Subtrain

Definition: subtrain

- Each sub-journey is conducted by a subtrain
- $\tau_{nw} (n = 1, \ldots, N; w \in W)$: the $n^{th}$ subtrain travelling from the origin segment of station pair $w$ to the destination segment of station pair $w$

Hypergraphs: Linkage

Linkage between subtrains

Linkage between two subtrains is established using a binary variable
Hypergraphs: Variables

Decision variables

Primary decision variable:
\[ x_{t,j,u,v}^r = \begin{cases} 
1 & \text{if subtrain } r \text{ occupies segment } i \text{ in time interval } [u, v) \text{ and moves to segment } j \in \{B \mid j \neq e_r \} \text{ at } v \\
0 & \text{Otherwise}
\end{cases} \]

Secondary decision variable:
\[ y_{t,t',i}^r = \begin{cases} 
1 & \text{if subtrain } r \text{ arrives at an artificial sink node } e_r^T \text{ at } t \text{ and its continuation } i^r \text{ resumes the journey from the origin node } o_i^r \text{ at time } t' \\
0 & \text{Otherwise}
\end{cases} \]

Modeling approach

• We approach the train scheduling problem from a central planner’s perspective
• By Public Law 110-432 (110 Congress, 2008), Amtrak trains have priority over all freight trains
• A two-level sequential modeling approach
  – Upper level: passenger train scheduling
  – Lower level: freight train scheduling
Passenger train scheduling

- Passenger-side costs
  - Train operating expenses
  - Passenger in-vehicle travel time cost
  - Passenger schedule delay cost
- We intend to design a schedule that permits two opposing passenger trains to pass without any full stop (flying meet).

**Optimal train schedule:**
- Minimum passenger schedule delay

A function of passenger demand profile

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Passenger demand profile

- Each O-D pair has a passenger demand profile (Preferred Departure Time)
- Passengers are served by a predetermined number of trains
Passenger train scheduling

**Objective function**

\[ \begin{align*}
\text{Min} & \quad \sum_{\substack{w \in W, (u,v) \in \psi^p_w}} \left( c_d^{L,w} r_{u,v}^w + c_d^{R,w} s_{u,v}^w \right) x_{o^w,j,u,v}^w \\
& + \sum_{\substack{w \in W, n=2,3,\ldots,N-1, \psi^p_{w,n}}} \left( c_d^{L,w} r_{u,v}^w + c_d^{R,w} s_{u,v}^w \right) x_{o^w,j,u,v}^w \\
& + \sum_{\substack{w \in W, (u,v) \in \psi^p_w, (u,v) \neq (u',v')}} \left( c_d^{L,w} r_{u,v}^w + c_d^{R,w} s_{u,v}^w \right) x_{o^w,j,u,v}^w \\
& + \sum_{\substack{(r,t) \in E^p \setminus (0,t) \in E^p}} d^r (t - (l_{\text{min}} + 1)) y_{t,t}^r.
\end{align*} \]

Schedule delay for passengers who take the **first** subtrain travelling between each station pair

Schedule delay for passengers who take an **intermediate** subtrain travelling between each station pair

Schedule delay for passengers who take the **last** subtrain travelling between each station pair

Penalty for staying longer than scheduled stop time at stations

Each term has to be calculated at preprocessing stage

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**Passenger train scheduling**

**Objective function**

Maintaining the order among subtrains

- Maintaining the order among subtrains essentially ensures maintaining the order among physical trains

- Penalize any combination of the starting arcs of two consecutive subtrains which violates the order of subtrains by a large number \( M \)

- We add the following term to the objective function

\[ \sum_{\substack{w \in W, (u,v) \in \psi^p_w, (u,v) \neq (u',v')}} M \times x_{o^w,j,u',v'}^w \times x_{o^w,j,u,v}^w \]
Constraints: Eight Identified

• Unique departure from origin
• Unique sinking at the destination
• Flow conservation
• Linkage between trains
• Binary variables
• Segment capacity constraint
• Segment transition constraint
• Headway management

Freight train scheduling

• Freight trains are inserted among the fixed schedule of passenger trains
• A freight train is dispatched whenever the train receives enough load
• Freight train scheduling is less precise and stringent
• Freight side costs
  – Foregone demand cost (loss of operating revenue)
  – Departure delay cost
  – En-route delay cost

Optimal train schedule:
Minimum total freight cost
Freight train scheduling

Objective function

\[ \text{Min } \sum_{r \in \mathcal{R}} \left( c_r^e (u - EADT^r) - c_r^f x_{o,w,j,u,v} + \sum_{r \in \mathcal{R}} c_r^i x_{i,j,u,v} \right) \]

Departure delay cost

En-route delay cost

Foregone demand cost

Solution approach: QIP

- The top-level problem is a Quadratic Integer Programming (QIP) problem
- QIPs are in general NP-hard; therefore, solving a large problem within a reasonable time is difficult
- Remedies:
  - Dropping the term involving big \( M \)
  - Linearizing the quadratic objective function
  - Further simplifying the problem
Solution approach: Dropping $M$

**Dropping the term involving big $M$**
- Large differences in values of different terms in the objective function leading to large round-off errors
- Instead, we suggest the following constraint:
  $$\sum_{(o^w,j,u',v') \in \Psi^{p,r^w_n}} u' \cdot x_{o^w,j,u',v'}^{r^w_{n-1}} \leq \sum_{(o^w,j,u,v) \in \Psi^{p,r^w_n}} u \cdot x_{o^w,j,u,v}^{r^w_n}$$

Starting arc of a train is no earlier than the starting arc of its preceding train
- Avoids round-off errors and introduces new cuts which help improve computational efficiency

Solution approach: Binary variable

**Linearizing the quadratic objective function**
- Replace each quadratic term with a new binary variable
  $$z_{u',u}^{r^w_{n-1},r^w_n} = x_{o^w,j,u',v'}^{r^w_{n-1}} \cdot x_{o^w,j,u,v}^{r^w_n}$$
  for all $w \in W, \forall n = 2,3,\ldots,N, (u',u) | u' < u, (o^w,j,u',v') \in \Psi^{p,r^w_n}, (o^w,j,u,v) \in \Psi^{p,r^w_n}$
- For each new variable, three inequality constraints need to be added
  $$z_{u',u}^{r^w_{n-1},r^w_n} \leq x_{o^w,j,u',v'}^{r^w_{n-1}}$$
  $$z_{u',u}^{r^w_{n-1},r^w_n} \leq x_{o^w,j,u,v}^{r^w_n}$$
  $$x_{o^w,j,u',v'}^{r^w_n} + x_{o^w,j,u,v}^{r^w_n} \leq 1 + z_{u',u}^{r^w_{n-1},r^w_n}$$
  where $z$ is less than either of the associated $x$ variable values; $z$ equals one only when both $x$'s are equal to one
Solution approach: New constraint

Further simplifying the problem

• Replace the last inequality constraint in the previous slide by

\[
\sum_{(u',u) \mid u' < u} \sum_{(w,j,u',v')} \Psi_{p,r_{n-1}} z_{u',u}^{w} = 1
\]

\[
\forall w \in W, \forall n = 2,3, ..., N
\]

- Each subtrain has a unique departure. Therefore only one combination of starting arcs of two consecutive subtrains is equal to one.

- The new constraint set represents the same characteristics with much fewer constraints

Numerical analysis

• A small problem
• Impact of speed heterogeneity
• A larger problem
Numerical analysis
A small problem – Part 1

• Set up:
  – 11 segments: 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

Numerical analysis:
A small problem – Part 2

• Set up (cont’d)
  – Operating speed
    • Freight trains: 60 mph
    • Passenger trains: 120 mph
  – Consider daily service frequency of 1-6 trains
  – Elastic passenger demand (elasticity: 0.4, based
    on Adler et al. (2010))
A small problem: Results
Passenger schedule delay cost

Marginal schedule delay cost reduction diminishes with passenger train frequency

A small problem: Results
Freight side costs

- The total cost increases with passenger train frequency
- Departure delay cost is relatively stable across all the six scenarios
- En-route delay cost has an increasing trend
- Foregone demand becomes the most important cost component when more than three passenger trains are scheduled
Impact of speed heterogeneity

Setup:

• Passenger train speed: 120 mph
• Freight train speed: 12 mph-120 mph

Impact of speed heterogeneity
Total freight cost

• Greater speed heterogeneity leads to higher freight side cost
• Sensitivities of freight side cost to number of passenger trains vary by speed
A larger problem – Part 1

• Set up
  – Chicago-St Louis HSR corridor
  – 285 mile-long shared corridor
  – 17 double-track and 14 single-track segments
  – Passenger train speed: 90 mph (accounting for acceleration and deceleration)
  – Freight train speed: 30 mph
  – Two ends and four intermediate stations on the Chicago-St Louis Corridor

A larger problem – Part 2

• Set up (Cont’d)
  – O-Ds among these stations account for more than 95% of total O-D traffic
  – Three scenarios (based on IDOT HSR study report):
    • 2015 projected passenger demand (5 trains) and current freight demand
    • 2020 projected passenger demand (5 trains) and projected freight demand
    • 2020 projected passenger demand (6 trains) and projected freight demand
A larger problem: Hypergraph
2015 demand

On average, each passenger incurs $46.6 passenger schedule delay cost (rail ticket price between Chicago & St. Louis is $39)

A larger problem
Freight side costs

• When projected freight demand is in place, the freight railroad will suffer significant cost increase
• Strong presence of capacity constraints on this line given passenger and freight demand growth in the future

Current freight traffic (5 passenger trains)
Projected freight traffic (6 passenger trains)
- Foregone demand
- Departure delay
- En-route delay
Concluding remarks (I)
Contributions to planning and methodology

• Proposed a two-level modeling framework for shared-use rail corridor planning
• Comprehensive consideration of cost and time components, including passenger schedule delay and elastic demand
• Employed a hypergraph based modeling approach which is more capable of dealing with train conflicts
• Designed an efficient solution approach to solve the planning problem within short computation time

Concluding remarks (II)
Policy implications

• Schedule delay is an important component in passenger generalized travel cost
• Schedule delay cost diminishes with the number of passenger trains
• Some freight trains will be forced out of service, and foregone demand cost will substantially increase as more passenger services are scheduled
• The heterogeneity of train speed significantly affects freight side cost. It may be desirable to increase freight train speed when HSR is introduced to shared use corridors
Ongoing research

• Extending hypergraph based modelling

• Incorporating developed scheduling models into capacity allocation schemes

Thank you!

Questions?

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