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

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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

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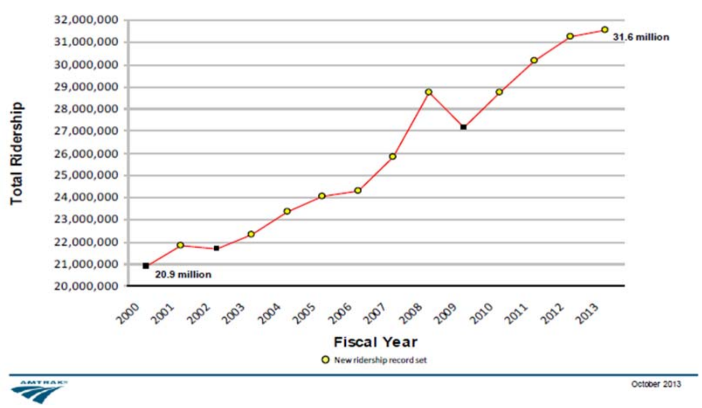
Background: Amtrak Ridership Soars



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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)

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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

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Literature review: Three approaches

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

Authors	Objective	Modeling priority	Discrete time	Model structure
Brännlund et al., 1998	Min schedule deviation	Y	Y	ILP
Oliveira and Smith, 2000	Min schedule deviation	N	Y	---
Caprara et al., 2002	Min schedule deviation	N	Y	ILP
Caprara et al., 2006	Min schedule deviation	Y	Y	ILP
Canca et al., 2011	Min passengers' waiting time	N	Y	INLP
Harrod, 2011	Max total utility of trains	Y	Y	ILP
Liu and Kozan, 2011	Min schedule makespan	Y	N	MILP

- 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

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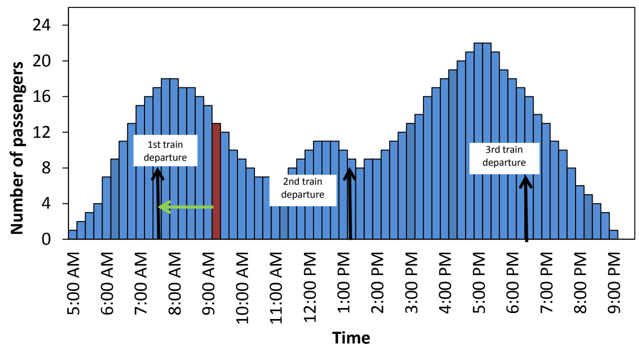
Definition: Schedule delay

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



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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

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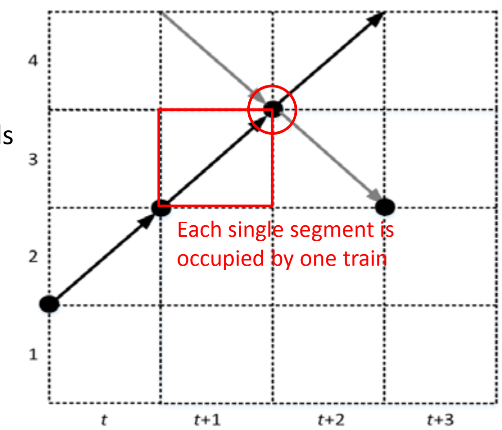
Hypergraphs: The Model

Deficiency of the traditional segment occupancy scheduling model

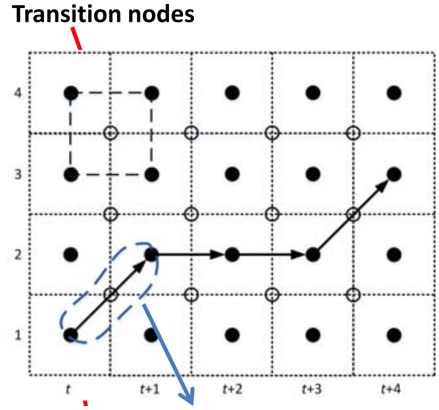
- Commonly used capacity constraints are met
- Traditional segment (block) occupancy scheduling models <u>cannot</u> deal with conflicts during train transitions between segments
- Transition at the end of the $(t+1)^{th}$ period on the boundary of segments 3 and 4 is violated



Hypergraphs: Harrod

Using Hypergraphs in train schedule modeling (Harrod, 2011)

Transition nodes

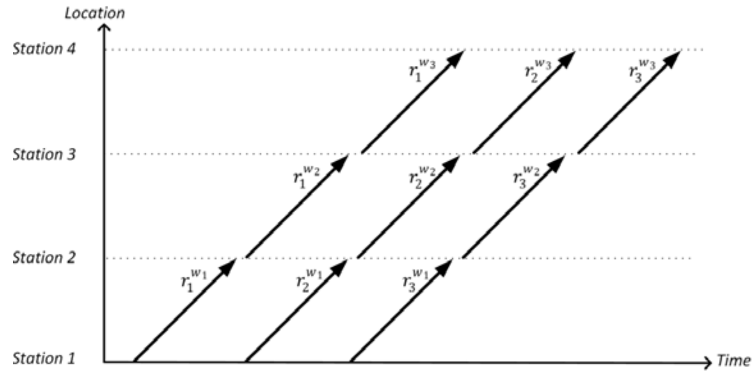


- Each train movement is represented by a hyperarc
- A chain of consecutive hyperarcs form a train path

Segmei Segment **occupancy nodes** (1,t) and (2,t+1) and a **transition node** (1,t)

Hypergraphs: Subtrain

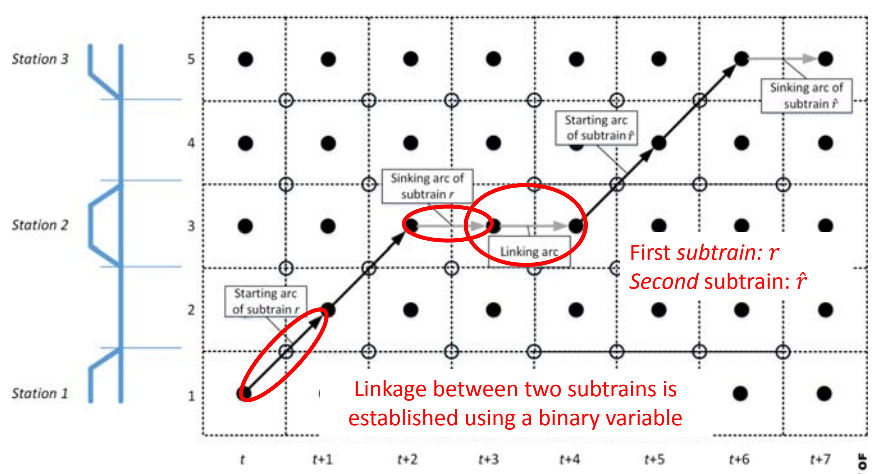
Definition: subtrain



- Each sub-journey is conducted by a subtrain
- r_w^n $(n = 1, \dots, N; w \in W)$: 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



Hypergraphs: Variables

Decision variables

Primary decision variable:

$$x^{r}_{i,j,u,v}\begin{cases}1 & \text{if subtrain } r \text{ occupies segment } i \text{ in time interval } [u,v) \text{ and moves to segment } j \in \{B \mid j \neq e_r\} \text{ at } v\\ 0 & \text{Otherwise}\end{cases}$$

Secondary decision variable:

$$y^{r,\hat{r}}_{t,\hat{t}}\begin{cases}1 & \text{if subtrain } r \text{ arrives at an artificial sink node } e^{r} \text{ at } t \text{ and its continuation } \hat{r} \text{ resumes the journey from the origin node } o^{\widehat{w}} \text{ at time } \hat{t}\\ 0 & \text{Otherwise}\end{cases}$$

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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

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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

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A function of passenger demand profile

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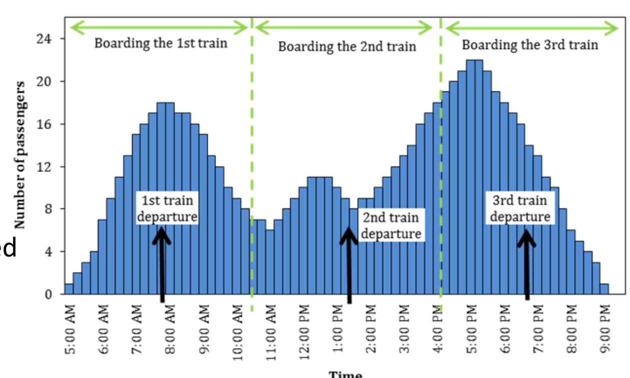
Passenger demand profile

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



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Passenger train scheduling

Objective function

$$
\begin{aligned}
Min \sum_{\substack{w\in W \\ (o^w,j,u,v)\in\Psi^{p,r_1^w}}} & \left(c_d^L \underline{S_{u,L}^{r_1^w}} + c_d^R\, \underline{S_{u,R}^{r_1^w}}\right) x_{o^w,j,u,v}^{r_1^w} \\
+ \sum_{\substack{w\in W \\ n=2,3,\dots,N-1 \\ (o^w,j,u,v)\in\Psi^{p,r_n^w}}} & \left(c_d^L \underline{S_{u,L}^{r_n^w}} + c_d^R\, \underline{S_{u,R}^{r_n^w}}\right) x_{o^w,j,u,v}^{r_n^w} \\
+ \sum_{\substack{w\in W \\ (o^w,j,u,v)\in\Psi^{p,r_N^w}}} & \left(c_d^L \underline{S_{u,L}^{r_N^w}} + c_d^R\, \underline{S_{u,R}^{r_N^w}}\right) x_{o^w,j,u,v}^{r_N^w} \\
+ \sum_{\substack{(r,\hat{r})\in Z^p \\ (t,\hat{t})\in L_{r,\hat{r}}^p}} & d^r(\hat{t} - t - (l_{min}^r + 1))\, y_{t,\hat{t}}^{r,\hat{r}}
\end{aligned}
$$

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

$$
\sum_{\substack{w\in W \\ n=2,3,\dots,N \\ (u,u')|u'\geq u \\ (o^w,j,u',v')\in\Psi^{p,r_{n-1}^w} \\ (o^w,j,u,v)\in\Psi^{p,r_n^w}}} M \times x_{o^w,j,u',v'}^{r_{n-1}^w} \times x_{o^w,j,u,v}^{r_n^w}
$$

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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

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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

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Freight train scheduling

Objective function

Departure delay cost

En-route delay cost

$$Min \sum_{\substack{r \in R^f \\ (o^w, j, u, v) \in \Psi^{f,r}}} \left(c_e^r (u - EADT^r) - c_p^r \right) x^r_{o^w, j, u, v} + \sum_{\substack{r \in R^f \\ (i, j, u, v) \in \Psi^{f,r} | i = j}} c_s^r x^r_{i,j,u,v}$$

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:

$$\sum_{(o^w,j,u',v')\in\Psi^{p,r^w_{n-1}}} u' * x^{r^w_{n-1}}_{o^w,j,u',v'} \leq \sum_{(o^w,j,u,v)\in\Psi^{p,r^w_n}} u * x^{r^w_n}_{o^w,j,u,v}$$

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

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Solution approach: Binary variable

Linearizing the quadratic objective function

- Replace each quadratic term with a new binary variable

$$z^{r^w_{n-1},r^w_n}_{u',u} = x^{r^w_{n-1}}_{o^w,j,u',v'} \cdot x^{r^w_n}_{o^w,j,u,v}$$

$$\forall w \in W, \{\forall n = 2,3,\dots,N\}, \{\forall (u',u) | u' < u, (o^w,j,u',v') \in \Psi^{p,r^w_{n-1}}, (o^w,j,u,v) \in \Psi^{p,r^w_n}\}$$

- For each new variable, three inequality constraints need to be added

$$z^{r^w_{n-1},r^w_n}_{u',u} \leq x^{r^w_{n-1}}_{o^w,j,u',v'}$$

$$z^{r^w_{n-1},r^w_n}_{u',u} \leq x^{r^w_n}_{o^w,j,u,v}$$

$$x^{r^w_{n-1}}_{o^w,j,u',v'} + x^{r^w_n}_{o^w,j,u,v} \leq 1 + z^{r^w_{n-1},r^w_n}_{u',u}$$

z is less than either of the associated *x* variable values; *z* equals one only when both *x*'s are equal to one

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Solution approach: New constraint

Further simplifying the problem

- Replace the last inequality constraint in the previous slide by

$$\sum_{\substack{(u',u)|u'<u \\ (o^w,j,u',v')\in\Psi^{p,r^w_{n-1}} \\ (o^w,j,u,v)\in\Psi^{p,r^w_n}}} z_{u',u}^{r^w_{n-1},r^w_n} = 1$$

$$\forall w \in W, \{\forall n = 2,3,\ldots,N\}$$

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

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Numerical analysis

- A small problem
- Impact of speed heterogeneity
- A larger problem

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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

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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))

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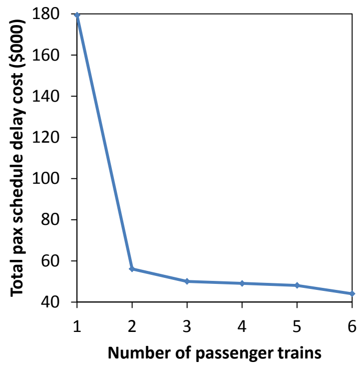
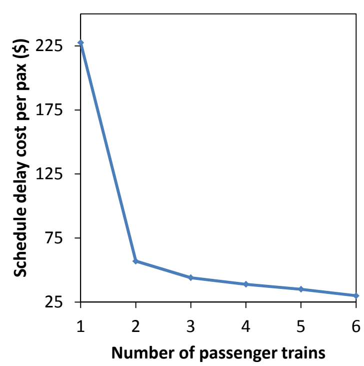
A small problem: Results

Passenger schedule delay cost





Marginal schedule delay cost reduction diminishes with passenger train frequency

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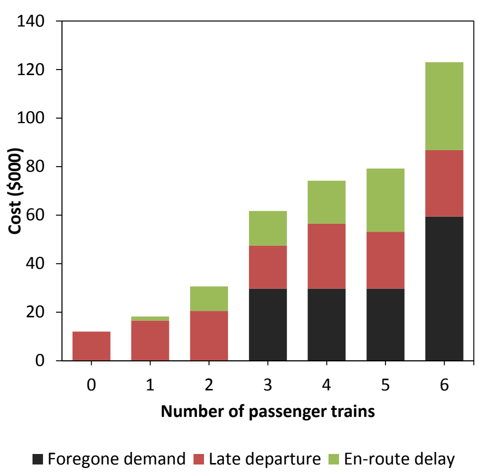
A small problem: Results

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

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Impact of speed heterogeneity

Setup:

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

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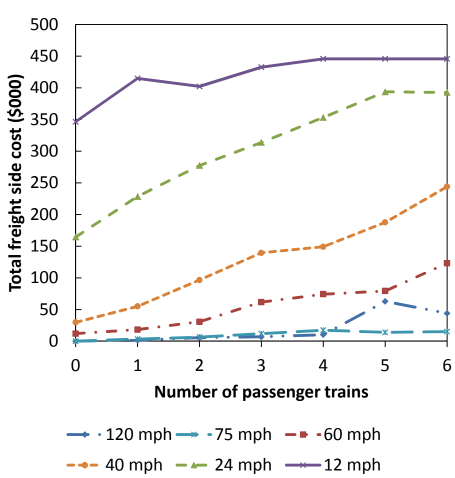
Impact of speed heterogeneity

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

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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

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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

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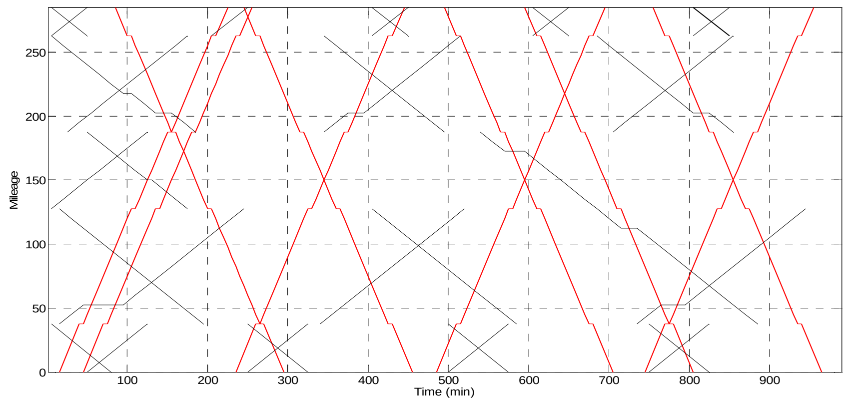
A larger problem: Hypergraph

2015 demand



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

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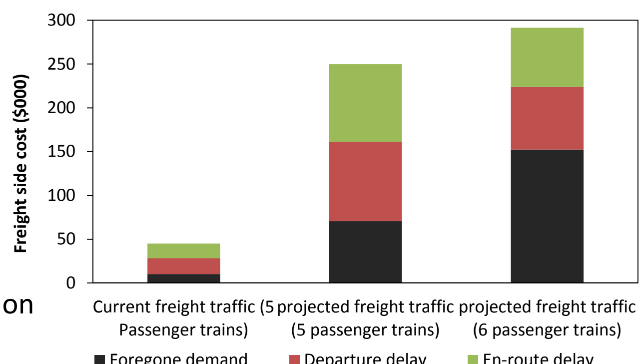
A larger problem

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



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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

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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

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Ongoing research

- Extending hypergraph based modelling
- Incorporating developed scheduling models into capacity allocation schemes

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Thank you!

Questions?

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