Optimizing Strategic Railway Capacity Planning

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The North American railroad industry is facing capacity problems

- Capacity and network efficiency have become more important as traffic volumes increase
- In North America, the demand for freight rail services is projected to increase by 88% in 2035 compared to 2007
- Capacity constraints are affecting network efficiency
- Problems range across many aspects of the railroad operation including:
  - Infrastructure
  - Equipment
  - Train dispatching, traffic mix
  - Human resources

Source: Reebie TRANSEARCH and FHWA Freight Analysis Framework Project
The demand for freight rail services is projected to increase by 88% in 2035 compared to 2007.

Network Capacity must be increased

A, B, C: Below Capacity
D: Near Capacity
E: At Capacity
F: Above Capacity

E & F = 45%

2035 w/o upgrade
A “Decision Support Framework” to determine how to allocate capital in the best possible way

- Railroads rely on experienced personnel and simulation software to identify bottlenecks and propose methods to reduce the congestion.
- Experienced railroaders often identify good solutions but *this does not guarantee that all possible alternatives have been evaluated*.
- Simulation usually deals with a section of the network, which *may result in moving bottleneck around* instead of solving it.
- We propose a decision support framework to generate & evaluate possible alternatives and tackle the capacity planning problems in network level.
This decision support framework contains three individual strategic planning tools

- **Alternatives Generator (AG):**
  - Enumerate possible expansion options with their cost and additional capacity

- **Investment Selection Model (ISM):**
  - Determine which subdivisions need to be upgraded with what kind of improvements (alternatives)

- **Impact Analysis Module (IAM):**
  - Evaluate the tradeoff between capital investment and delay cost
CN Parametric Capacity Model was selected to be the basis of AG

- Capacity is computed based on a set of key parameters
- Link Properties:
  - Plant parameters:
    - Length of Subdivision
    - Meet & Pass Locations
    - Signal Spacing
  - Traffic parameters:
    - Traffic Peaking
    - Priority Probability
    - Speed Ratio
    - Average Speed
  - Operating parameters
    - Track Maintenance
    - Stop on Line Time

\[
\text{Train Delay} = A_0 e^{BV} \quad (\text{Krueger, 2000})
\]

- Delay – Volume Plot

\[
A_0 = \text{Parametric Plant, Traffic, Operating Coefficient}
B = \text{Constant}
V = \text{Traffic Volume}
\]
The output of the CN parametric model is a delay-volume relationship.
Adding enumeration and cost evaluation modules into CN model to create the alternatives generator

- **Enumeration Module**: automatically enumerating alternatives based on possible engineering options – adding (1) passing sidings, (2) intermediate signals, (3) 2\(^{nd}\) main track

- **Cost Evaluation Module**: incorporating cost data into the parametric model to compute the construction cost of each alternative

- For example, a 100-mile sub with 9 sidings and no intermediate signal

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Sidings</th>
<th>Signals/Spacing</th>
<th>Capacity (trains/day)</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+0</td>
<td>+0</td>
<td>+0</td>
<td>$0</td>
</tr>
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<td>2</td>
<td>+0</td>
<td>+1</td>
<td>+3</td>
<td>$1,000,000</td>
</tr>
<tr>
<td>3</td>
<td>+0</td>
<td>+2</td>
<td>+4</td>
<td>$2,000,000</td>
</tr>
<tr>
<td>4</td>
<td>+1</td>
<td>+0</td>
<td>+3</td>
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<tr>
<td>5</td>
<td>+1</td>
<td>+1</td>
<td>+6</td>
<td>$6,570,000</td>
</tr>
<tr>
<td>6</td>
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<td>+2</td>
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<td>$10,940,000</td>
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<td>8</td>
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<td>+1</td>
<td>+9</td>
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<td>9</td>
<td>+2</td>
<td>+2</td>
<td>+10</td>
<td>$13,340,000</td>
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<tr>
<td>10</td>
<td>Adding 2nd Main Track</td>
<td>+50</td>
<td>+50</td>
<td>$204,750,000</td>
</tr>
</tbody>
</table>
This decision support framework contains three individual strategic planning tools:

- **Alternatives Generator:**
  - Enumerate possible expansion options with their cost and additional capacity

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- **Impact Analysis Module:**
  - Evaluate the tradeoff between capital investment and delay cost
Trains with different ODs are similar to multiple commodities, and they share the line capacity.

<table>
<thead>
<tr>
<th>i</th>
<th>j</th>
<th>Alternatives</th>
<th>Capacity (trains/day)</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>+ 3</td>
<td>$1,000,000</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>2</td>
<td>+ 4</td>
<td>$2,000,000</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>+ 6</td>
<td>$6,570,000</td>
</tr>
</tbody>
</table>

Task:

• Which link(s) to upgrade?
• With what kind of capacity improvement alternative?
General Investment Selection Model (ISM)

\[
\min \left( \alpha \sum_{i} \sum_{j} \sum_{q} h_{ij}^q y_{ij}^q + \gamma \sum_{i} \sum_{j} \sum_{k} c_{ij} x_{ij}^k \right) \quad \text{capital invest + flow cost}
\]

s.t.

\[
\sum_{i} \sum_{j} \sum_{q} h_{ij}^q y_{ij}^q \leq B \quad \text{budget constraint}
\]

\[
\sum_{k} x_{ij}^k \leq U_{ij} + \sum_{q} u_{ij}^q y_{ij}^q \quad \forall \; i, j \; (i \neq j) \quad \text{capacity constraint}
\]

\[
\sum_{q} y_{ij}^q \leq 1 \quad \forall \; i, j \; (i \neq j) \quad \text{alternative constraint}
\]

\[
\sum_{j} x_{ij}^k - \sum_{j} x_{ji}^k = \begin{cases} 
  d_k & \text{if } i \in S_k \\
  -d_k & \text{if } i \in T_k \\
  0 & \text{otherwise}
\end{cases} \quad \forall \; k \quad \text{flow conservation}
\]

and

\[
x_{ij}^k \in \text{positive integer}, \; y_{ij}^q \in \{0,1\}
\]
This decision support framework contains three individual strategic planning tools

- **Alternatives Generator:**
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Diagram:

1. Link (sub) properties
2. Alternatives generator
3. Capacity expansion alternatives (cost & additional capacity)
4. Investment Selection Model
5. Impact Analysis
6. Feasible solution?
7. Done
8. Yes
9. No
There is a trade-off between “Capital Investment” and “Train Delay Cost”

- ISM determines the best set of capacity improvement alternatives with the premise that "Level of Service remains the same"
- However, it is possible to gain modest capacity by increasing delay (lowering Level of Service)

- Impact analysis module determines if the capital investment is cost-effective by comparing the capital investment & delay cost
- The output will be a set of options that eventually the capacity planner will make the final decision
There is a trade-off between “Capital Investment” and “Train Delay Cost”

**Net Cost from Upgrading Infrastructure** vs **Delay Cost = Unit Delay Cost x Hours x Trains**

**Benefit = Delay Cost / Net Cost**

*(return on investment)*
Empirical Case Study

39 nodes, 42 links, ~ 1,000 of OD pairs
Capacity improvement for 50% demand increase

No. of Variables: 89,712
No. of Equations: 41,015
Solution Time: 3.5 sec
Impact analysis module compares capital investment with train delay cost

- ISM determines required upgrade with the premise “LOS is unchanged”
- It is possible to gain a little bit capacity by increasing delay (reduce LOS)
- Train Delay Cost = $ 261 per train-hour
### Net Cost vs. Train Delay Cost

<table>
<thead>
<tr>
<th>Link i j</th>
<th>Capacity Current Max</th>
<th>Cost ($,k) Train Delay</th>
<th>Net Cost</th>
<th>Difference ($,k) Delay - Net Cost</th>
<th>Benefit</th>
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<tbody>
<tr>
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<tr>
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<tr>
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<tr>
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A decision support framework is developed to assist railway capacity planning projects

- AG can enumerate possible expansion options with their cost and additional capacity
- ISM successfully and efficiently solved the problem regarding where to upgrade and what kind of engineering options should be conducted
- IAM can further explore the trade-off between capital investment and train delay cost
- This process will help RRs maximize their benefit from expansion projects and thus be better able to provide reliable service to their customers, and return on shareholder investment
- Future work:
  - Enable demand rejection scenario for insufficient budget
  - Develop a multi-period decision making model with stochastic future demand