Optimal Location of Railroad Wayside Defect Detection Installations

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- Some pictures of wayside detectors are adapted from various sources on the Internet
Outline

- Introduction
- Mathematical model
  - Formulation
  - Solution technique
- Case studies
- Conclusions
Introduction

Background, motivation and objective
Background

- New wayside detector technologies are used to monitor the health of railcars/tracks and provide advance notice of possible failures
  - detect damage to equipment and infrastructure
  - provide “predictive” notice of impending failures
  - reduce the risk of derailments
  - potentially reduce inspection costs (e.g., labor)

- Examples of new technologies
  - Wheel impact load detector (WILD), Truck Performance Detectors (TPD), Fully Automated Car Train Inspection System (FACTIS), Machine vision systems
Wheel Impact Load Detectors (WILD)

1.5 x 5 in. Shell, 106 k

Electronic Equipment
Identify Poorly Performing Trucks
• Based on strain-gauge sensors on rails in reverse curves
• Increase safety, reduce fuel costs, reduce damage to track & equipment
Teknis Wheel Condition Monitor (WCM)

- Evaluates total damage potential of a wheel
- Hybrid system of accelerometers and strain gauges
- Linked to user-defined alarms and automatic reports
Optical Geometry Inspection

- Monitoring for correct alignment
- Measures the angle of attack and tracking position of individual wheelsets of a passing train in real time.
Newer Technologies

- Image-Based (e.g. FactISTM)
  - Wheel Profile
  - Missing, Worn or Damaged Components
- Acoustic (e.g. TADS™)
  - Acoustic Bearing Detection
  - Leaking Air Sensors
- Ultrasonic
  - Cracked Wheel
  - Cracked Axle
FactIS™
TADSTM
Motivation

- Sophistication and capability of new systems means higher costs
  - purchase/installation cost
  - maintenance cost
- Benefits from multiple installations are inter-dependent
- Need to optimally locate (new) wayside installation sites
  - save capital investments, and
  - maximize the efficiency of installations
Where to Install?

- Seattle – St. Louis railcar flow could be inspected at 1, 3, or 5
- San Francisco – New York flow could be inspected at 2, 3, or 4
- Minneapolis – St. Louis flow could be inspected at 5 or 6
- New York – Minneapolis?
- …
The Network Problem

- Railroad networks are made up of a complex system of intersecting lines and routes
  - Each year, approximately 1.5 million freight cars in the North American fleet make over 30 million trips widely across the network
  - There are thousands of candidate locations for installations

- Where to locate wayside inspection facilities?
  - Busiest locations?
Objective

- To develop a network design framework that
  - Captures benefits and costs associated with installations
  - Formulates network optimization models
  - Proposes suitable optimization approaches

considering factors such as
- General railcar network (regional or national level)
- Multiple types of installations (e.g., FACTIS, TPD)
- Reliability in inspection technologies
- Multiple types of railcars, importance, and inspection priority
- Budget constraints
A Mathematical Model

Formulation and solution techniques
Formulation

Parameters

- Let $a_{ij} = 1$ if railcar flow $j \in J$ passes candidate location $i \in I$; 0 otherwise;

- Installation of technology type $m \in M$ at candidate location $i \in I$ requires capital investment $0 < c_{im} \leq \infty$;

- Type-$m$ technology correctly inspects a passing railcar with an independent probability of $(1 - q_m)$;

- Vector $k = [k_1, k_2, \ldots, k_M] \in Z_+^M$ specifies that a railcar flow is inspected by type-$m$ facility $k_m$ times, for all $m \in M$; let $k_m \in \{0, 1\}$;

Railcar flow $j \in J$ receives certain benefit $b_{jk}$ if inspected in scenario $k$:

$$b_{jk} := h_j f_j \left(1 - \prod_m q_m^{k_m}\right), \forall j, k$$
Decision Variables

- Two sets of decision variables, $x = \{x_{im}, \forall i,m\}$ and $y = \{y_{jk}, \forall j,k\}$, where

  - Installation decisions
    
    $x_{im} = \begin{cases} 1, & \text{if facility type } m \text{ is installed at location } i \\ 0, & \text{otherwise} \end{cases}, \forall i,m$

  - Inspection decisions
    
    $y_{jk} = \begin{cases} 1, & \text{if flow } j \text{ is inspected in scenario } k \\ 0, & \text{otherwise} \end{cases}, \forall j,k$
Network Optimization Model

Maximize total expected benefit under a given budget

\[
\text{Max } \sum_j \sum_k b_{jk} y_{jk} \quad \text{inspection benefits}
\]

\[
\text{s.t. } \sum_i \sum_m c_{im} x_{im} \leq B \quad \text{budget constraint}
\]

\[
\sum_m x_{im} \leq 1, \quad \forall i \quad \text{one facility at one location}
\]

\[
\sum_k k_m y_{jk} \leq \sum_i a_{ij} x_{im}, \quad \forall j, m \quad \text{flow } j \text{ inspected in scenario } k \text{ if it passes adequate facilities}
\]

\[
\sum_k y_{jk} = 1, \quad \forall j \quad \text{flow inspected in one scenario}
\]

\[
x_{im}, y_{jk} \in \{0,1\}, \quad \forall i, j, k \quad \text{integrality constraints}
\]

Remarks:

- Generalization of the maximum covering model (with \( M = 1, c_{im} = \text{constant}, q_m = 0 \) for all \( m \))
- Many possible variants or extensions (different inspection benefit measures, etc.)
Optimization Techniques

- Practical problem size very large: $|I| \sim 10^5$, $|J| \sim 10^6$
- Commercial solver (CPLEX)
- **Lagrangian relaxation (LR)**
- Meta-heuristics (e.g., simulated annealing, genetic algorithm)

\[
\begin{align*}
\max_{x, y} \quad & z(u) = \sum_j \sum_k b_{jk} y_{jk} \\
\text{s.t.} \quad & \sum_i \sum_m c_{im} x_{im} \leq B \\
& \sum_m x_{im} \leq 1, \quad \forall i \\
& \sum_k y_{jk} = 1, \quad \forall j \\
& x_{im}, y_{jk} \in \{0,1\}, \quad \forall i, j, k
\end{align*}
\]
LR Sub-problem

- For any given \( u \), optimize with regard to \( x \) and \( y \) respectively

\[
\max_{x,y} \sum_{i,m} (\sum_{j} a_{im} b_{jm} x_{im} - \sum_{m} u_{jm} k_{m} y_{jm}) \sum_{k} \sum_{j} b_{jk} (\sum_{j} u_{jm} k_{m}) x_{jm} y_{jm}
\]

s.t.
\[
\sum_{i,m} c_{im} x_{im} \leq B
\]
\[
\sum_{i,m} x_{im} \leq 1, \quad \forall i
\]
\[
\sum_{i,m} x_{im} \leq 1, \quad \forall i
\]
\[
\sum_{k} y_{jk} \in \{0,1\}, \quad \forall j, k
\]

Resembles 0-1 knapsack problem, where item \((i,m)\) has value \( \sum a_{jm} \), cost \( c_{im} \) and total budget \( B \)

Assign \( y_{jk} = 1 \) only if

\[
k^* = \arg \max_k \left( b_{jk} - \sum_{m} u_{jm} k_{m} \right)
\]

0 otherwise
Case Studies

Test runs and an empirical study
Test Run I

- 8,920 hypothetical railcar trips, \( J \), for one of the Class I railroads, sampled from the Princeton Transportation Network Model (PTNM) Software
- 1,820 candidate locations include origins, junction, and termination locations of the railcar flows on the railroad network.

The railroad network and candidate locations for the case study
Maximize the Total Number of Inspected Railcars

- One type of wayside technology ($M=1$)
- Installation cost $c_{im}=1$ ($\text{million}$) for all $i, m$, and the budget is $B = 10$ ($\text{million}$)

4,951 cars (or 57% of the total) are detected in a year
Comparing with the “Intuitive Solution”

- The 10 busiest locations v.s. 10 optimal locations

<table>
<thead>
<tr>
<th>Top 10 Busiest Locations</th>
<th>Top 10 Optimal Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cicero, IL</td>
<td>Houston, TX</td>
</tr>
<tr>
<td>Barr Yard, IL</td>
<td>Tacoma, WA</td>
</tr>
<tr>
<td>Calumet Yard, IL</td>
<td>Portland, OR</td>
</tr>
<tr>
<td>Los Angeles, CA</td>
<td>Kaiser, CA</td>
</tr>
<tr>
<td>Tacoma, WA</td>
<td>Birmingham, AL</td>
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<tr>
<td>Memphis, TN</td>
<td>Chicago, IL</td>
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<tr>
<td>S Los Angeles, CA</td>
<td>Cicero, IL</td>
</tr>
<tr>
<td>Dallas, TX</td>
<td>Memphis, TN</td>
</tr>
<tr>
<td>Kearny, NJ</td>
<td>Calumet Yard, IL</td>
</tr>
<tr>
<td>Elizabeth Port, NJ</td>
<td>Barr Yard, IL</td>
</tr>
</tbody>
</table>

Distinct cars inspected

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<tbody>
<tr>
<td></td>
<td>4,160</td>
<td>4,951</td>
<td>19% increase</td>
</tr>
</tbody>
</table>
Test Run II

- 4500 candidate locations include origins, junction, and termination locations of the railcar flows on the railroad network.

- 5768 hypothetical railcar trips for one of the Class I railroads (from the Princeton Transportation Network Model)
Maximize Expected Inspection Benefits

- Budget $B = 8$ ($\text{million}$)
- Two types of wayside technologies ($M=2$)
  - Type-1 (benchmark technology) is relatively inexpensive, but may yield error detection
  - Type-2 (new technology) is reliable but relatively expensive

<table>
<thead>
<tr>
<th></th>
<th>Type-1 ($m=1$)</th>
<th>Type-2 ($m=1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation cost $c_{im}$</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Error-detection probability $q_m$</td>
<td>0.05, 0.25</td>
<td>0</td>
</tr>
</tbody>
</table>

The LR algorithm yields a near-optimum feasible solution within less than 30 CPU minutes on a 2.3 GHz PC.
$q_1 = 0.05, q_2 = 0$

- Auburn, WA
- Fargo, ND
- Superior, WI
- Minneapolis, MN
- Nifa, IL
- Galesburg, IL
- Utah Jct., CO
- Belt Jct., TX

Expected benefit = 4,275.9
Upper bound = 4,327.3
Optimality gap = 1.20%
$q_1 = 0.25, q_2 = 0$

Expected benefit = 3,857.0
Upper bound = 3,897.8
Optimality gap = 1.06%
Budget $B = 8M$
Empirical Case Study

- **Large-scale Real-world Problem**
  - Network (more than $10^4$ nodes and $10^4$ links)
  - Shipment (millions of shipments in up to 90 days)

- **Tasks**
  - Determine detailed shipment paths based on shortest path algorithm
  - Prepare car-passing-location relationship (up to $10^{10}$ records)
    - Sparse matrix for processing and storage
    - Custom-designed link-table data structure/search algorithm

- **Output**
  - Optimal locations for arbitrary P installations
  - List of detected and undetected cars/shipments
  - Detection percentage of existing installations
Data Processing

- For each shipment, determine the exact path (shortest path algorithm)
- For each location, determine the subset of cars passing it
**RWDLSTM™ Software**

- Software programmed in C++
- Stand-alone
- For any railroad network and railcar flows
- Any Installation budget
- No problem size constraint
- User’s guide available
Computational Results

- On a 2.3 GHz CPU, 2G memory personal computer, the model yields near-optimum solutions in about one hour
- Optimality gap threshold $\approx 3\%$ for all computed cases
- Compared with the existing installations on this railroad’s network, the solution (with the same number of installations) will improve the inspection benefit by a relative amount ranging from 20% to 60%
Conclusions
Conclusions

- This work presents a network design model to optimize the installation placement of wayside technologies.
- The formulation allows options such as locations, technology types, general costs and benefits.
- A Lagrangian relaxation approach is developed.
- The approach is able to yield near-optimum solution for large-scale problem in reasonable time
- Stand-alone software has been developed and transferred to the industry
Thank you!