Optimal Location of Railroad Wayside Defect Detection Installations

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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)

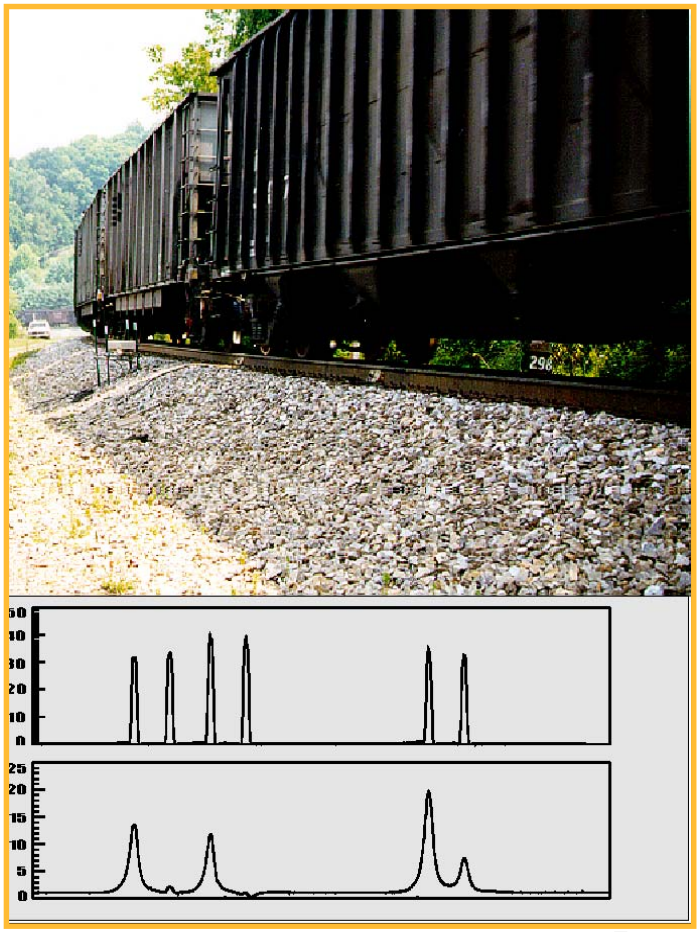
1.5 x 5 in. Shell, 106 k

Electronic Equipment

Truck Performance Detectors (TPD)

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)

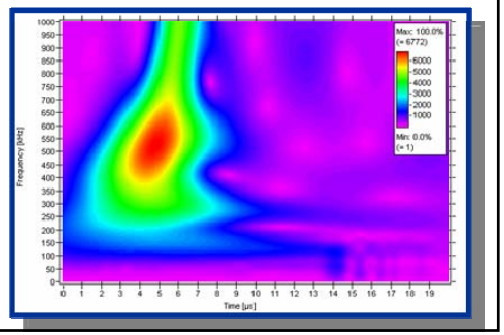
- Evaluates total damage potential of a wheel
- Hybrid system of accelerometers and strain gauges
- Linked to user-defined alarms and automatic reports

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



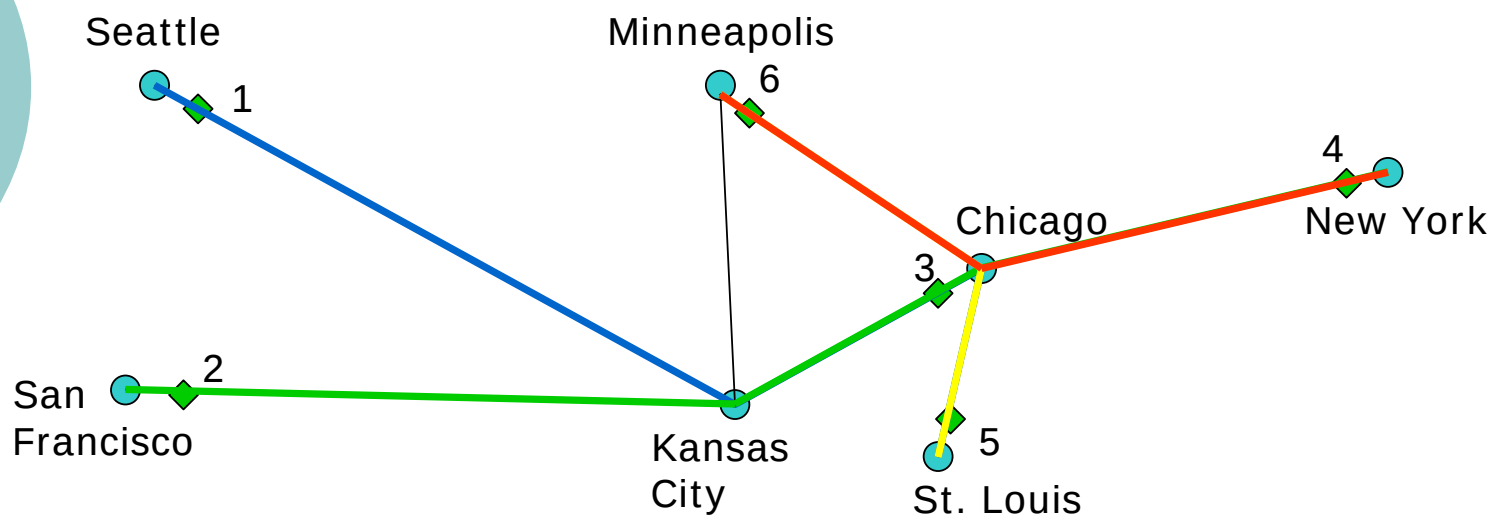
FactIS™

TADS™

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

Railcar & network info.

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

Technology choices

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

Technology performances

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

Inspection benefits

- Vector $\mathbf{k} = [k_1, k_2, \cdots, k_M] \in Z_+^M$ 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 $b_{j\mathbf{k}}$ if inspected in scenario $\mathbf{k}$

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

Decision Variables

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

$$y_{j\mathbf{k}} = \begin{cases} 1, & \text{if flow } j \text{ is inspected in scenario } \mathbf{k} \\ 0, & \text{otherwise} \end{cases}, \forall j, \mathbf{k}$$

Network Optimization Model

Maximize total expected benefit under a given budget

$$\max_{\mathbf{x},\mathbf{y}} \quad \sum_j \sum_{\mathbf{k}} b_{j\mathbf{k}} y_{j\mathbf{k}}$$ inspection benefits

$$\text{s.t.} \quad \sum_i \sum_m c_{im} x_{im} \le B$$ budget constraint

$$\sum_m x_{im} \le 1, \quad \forall i$$ one facility at one location

$$\sum_{\mathbf{k}} k_m y_{j\mathbf{k}} \le \sum_i a_{ij} x_{im}, \quad \forall j, m$$ flow j inspected in scenario $\mathbf{k}$ if it passes adequate facilities

$$\sum_{\mathbf{k}} y_{j\mathbf{k}} = 1, \quad \forall j$$ flow inspected in one scenario

$$x_{im}, y_{j\mathbf{k}} \in \{0,1\}, \quad \forall i, j, \mathbf{k}$$ integrality constraints

<u>Remarks</u>:

- Generalization of the maximum covering model (with $M = 1$, c_{im} = 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)

$$\max_{\mathbf{x},\mathbf{y}} \quad z(\mathbf{u}) = \sum_j \sum_{\mathbf{k}} b_{j\mathbf{k}} y_{j\mathbf{k}}$$

$$\text{s.t.} \quad \sum_i \sum_m c_{im} x_{im} \le B$$

$$\sum_m x_{im} \le 1, \quad \forall i$$

$$\sum_{\mathbf{k}} y_{j\mathbf{k}} = 1, \quad \forall j$$

$$x_{im}, y_{j\mathbf{k}} \in \{0,1\}, \quad \forall i, j, \mathbf{k}$$

$$\text{relax} \quad \sum_{\mathbf{k}} k_m y_{j\mathbf{k}} \le \sum_i a_{ij} x_{im}, \quad \forall j, m$$

LR Sub-problem

- For any given **u**, optimize with regard to x and y respectively

$$\max_{x} \; z(\mathbf{u}) = \sum_i \sum_m \left(\sum_j a_{ij} u_{jm} \right) x_{im} - \sum_m u_{jm} k_m$$

$$\text{s.t.} \quad \sum_i \sum_m c_{im} x_{im} \le B$$

$$\sum_m x_{im} \le 1, \quad \forall i$$

$$x_{im} \in \{0,1\}, \quad \forall i, m$$

$$\max_{y} \; \sum_j \sum_{\mathbf{k}} \left(b_{j\mathbf{k}} - \sum_m \left(\sum_j a_{ij} u_{jm} \right) k_m \right) x_{im} y_{j\mathbf{k}}$$

$$\text{s.t.} \quad \sum_{\mathbf{k}} y_{j\mathbf{k}} = 1, \quad \forall j$$

$$y_{j\mathbf{k}} \in \{0,1\}, \quad \forall j, \mathbf{k}$$

$$x_{im}, y_{j\mathbf{k}} \in \{0,1\}, \quad \forall i, j, \mathbf{k}$$

Resembles 0-1 knapsack problem, where item (i, m) has value $\left(\sum_j a_{ij} u_{jm} \right)$, cost c_{im} and total budget B

Assign $y_{j\mathbf{k}^*} = 1$ only if

$$\mathbf{k}^* = \arg\max_{\mathbf{k}} \left(b_{j\mathbf{k}} - \sum_m u_{jm} k_m \right)$$

0 otherwise

Case Studies

Test runs and an empirical study

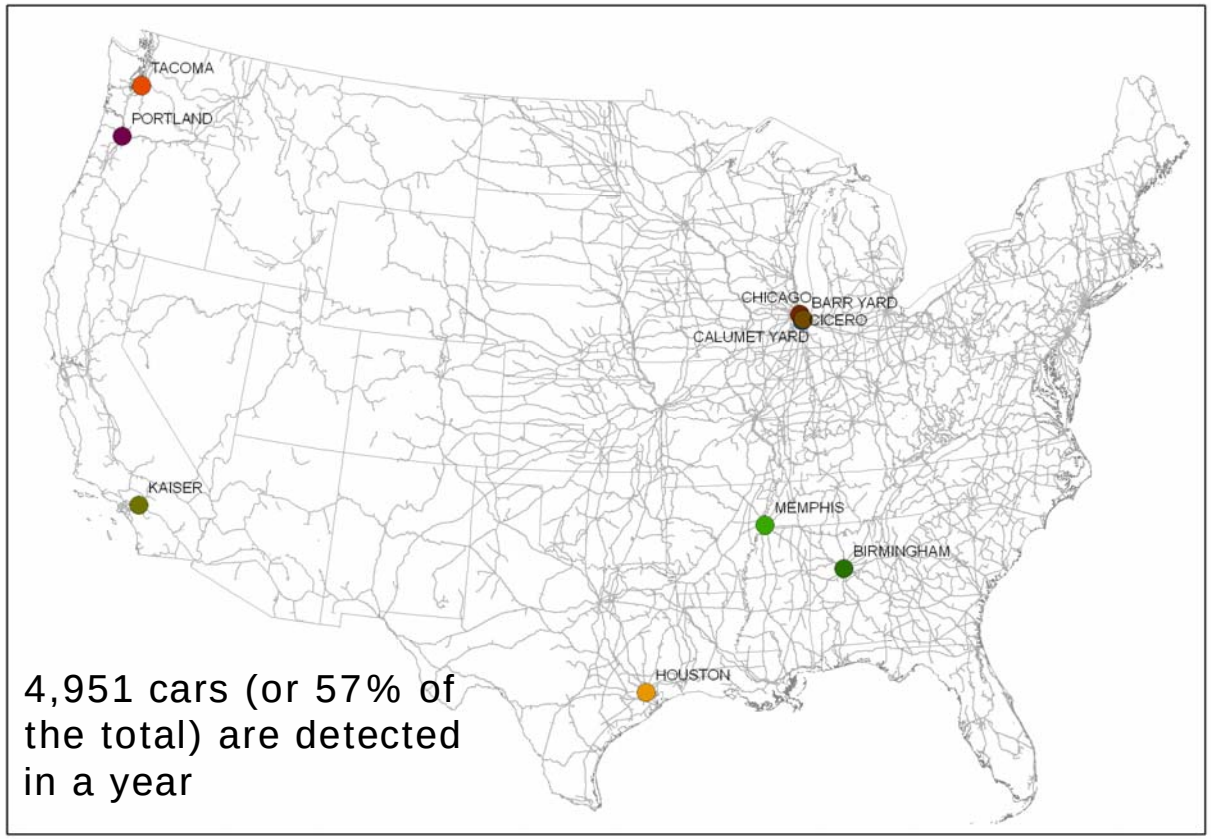
Test Run I

- 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 ($million) for all i, m, and the budget is B =10 ($million)



4,951 cars (or 57% of the total) are detected in a year

Comparing with the "Intuitive Solution"

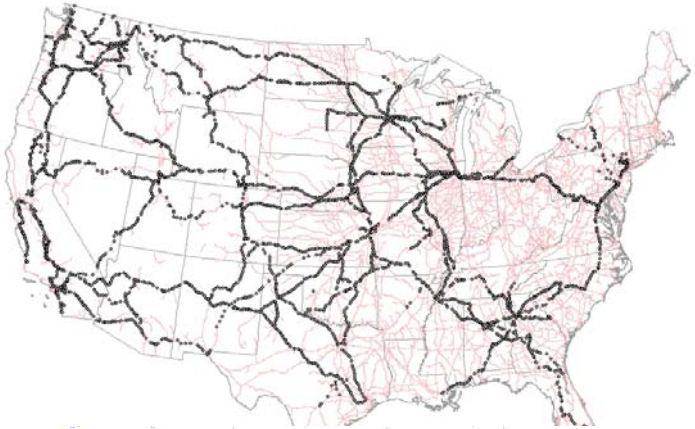
- The 10 busiest locations v.s. 10 optimal locations

Top 10 Busiest Locations	Top 10 Optimal Locations
Cicero, IL	Houston, TX
Barr Yard, IL	Tacoma, WA
Calumet Yard, IL	Portland, OR
Los Angeles, CA	Kaiser, CA
Tacoma, WA	Birmingham, AL
Memphis, TN	Chicago, IL
S Los Angeles, CA	Cicero, IL
Dallas, TX	Memphis, TN
Kearny, NJ	Calumet Yard, IL
Elizabeth Port, NJ	Barr Yard, IL

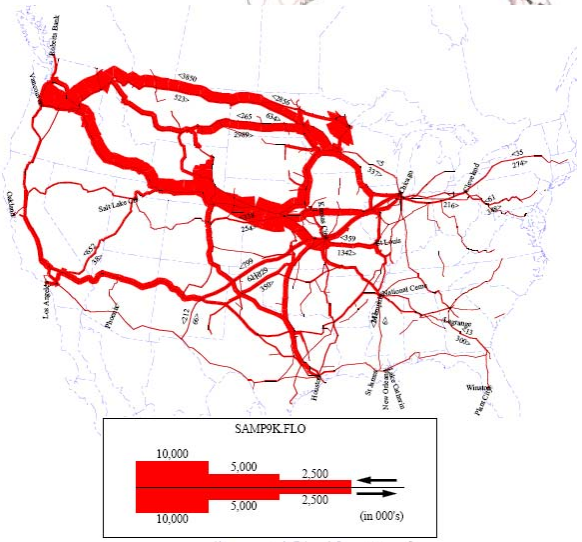
Distinct cars inspected	4,160	4,951	19% increase

Test Run II

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



- 5768 <u>hypothetical</u> railcar trips for one of the Class I railroads (from the Princeton Transportation Network Model)

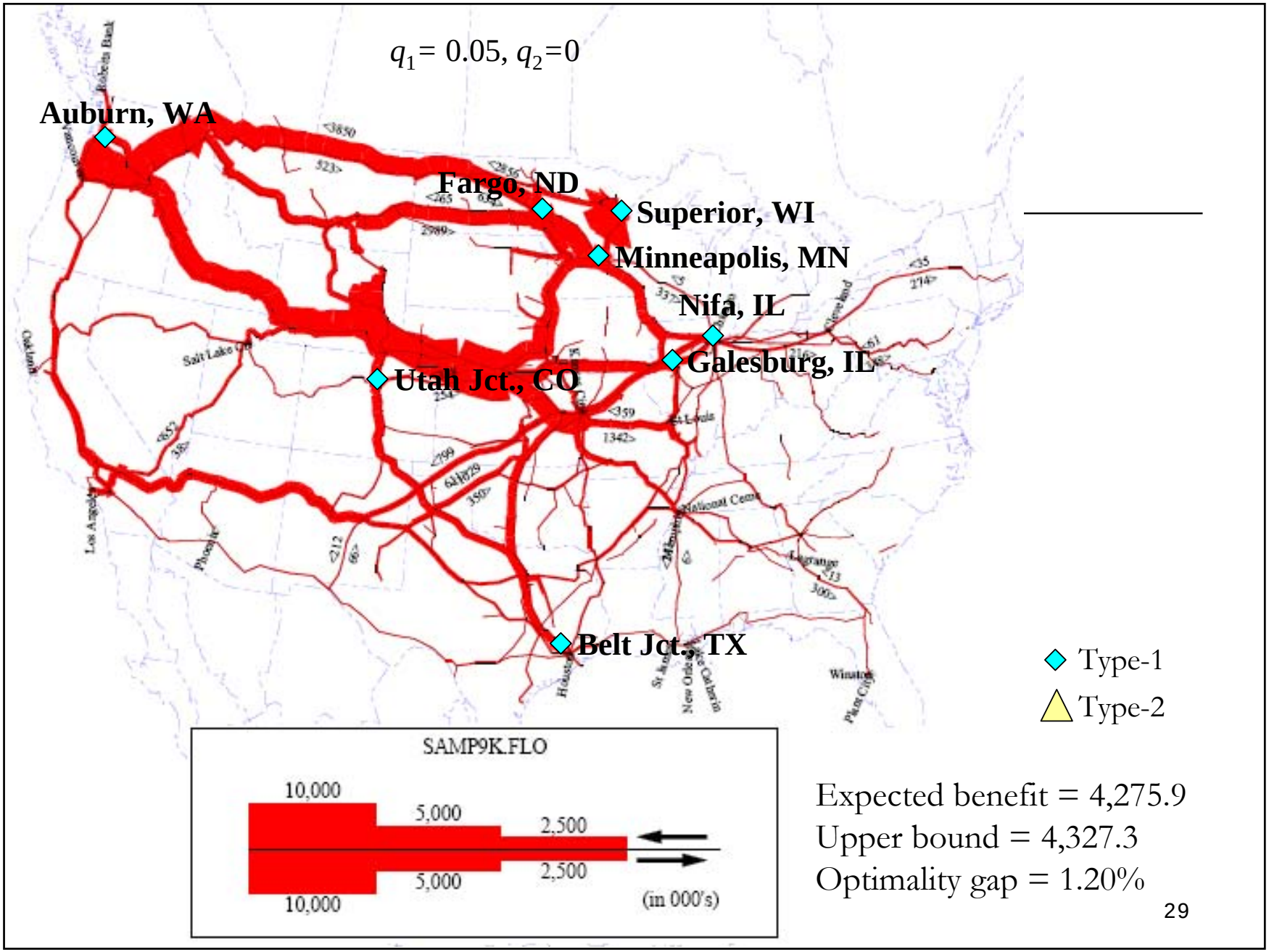


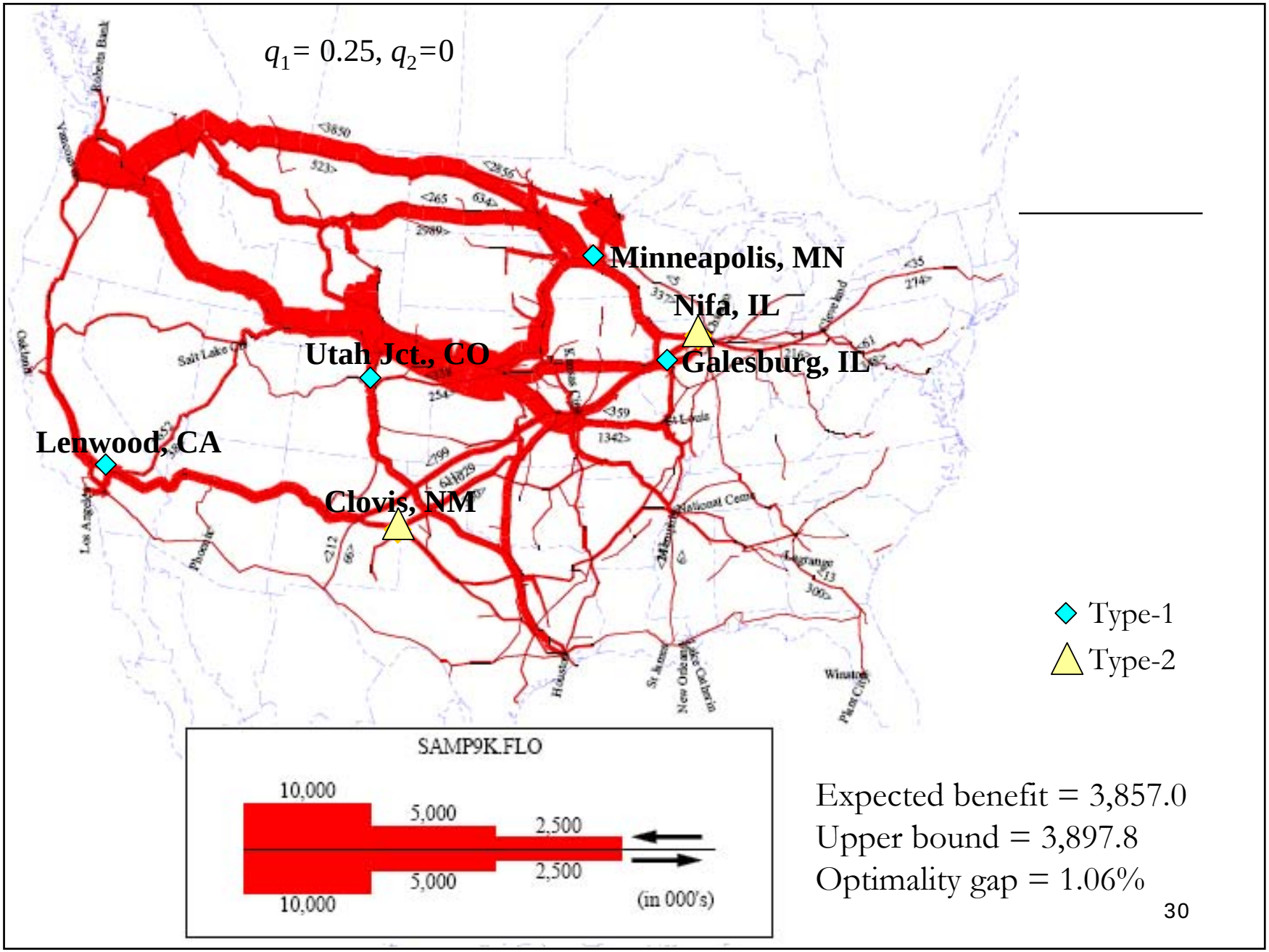
Maximize Expected Inspection Benefits

- Budget B = 8 ($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

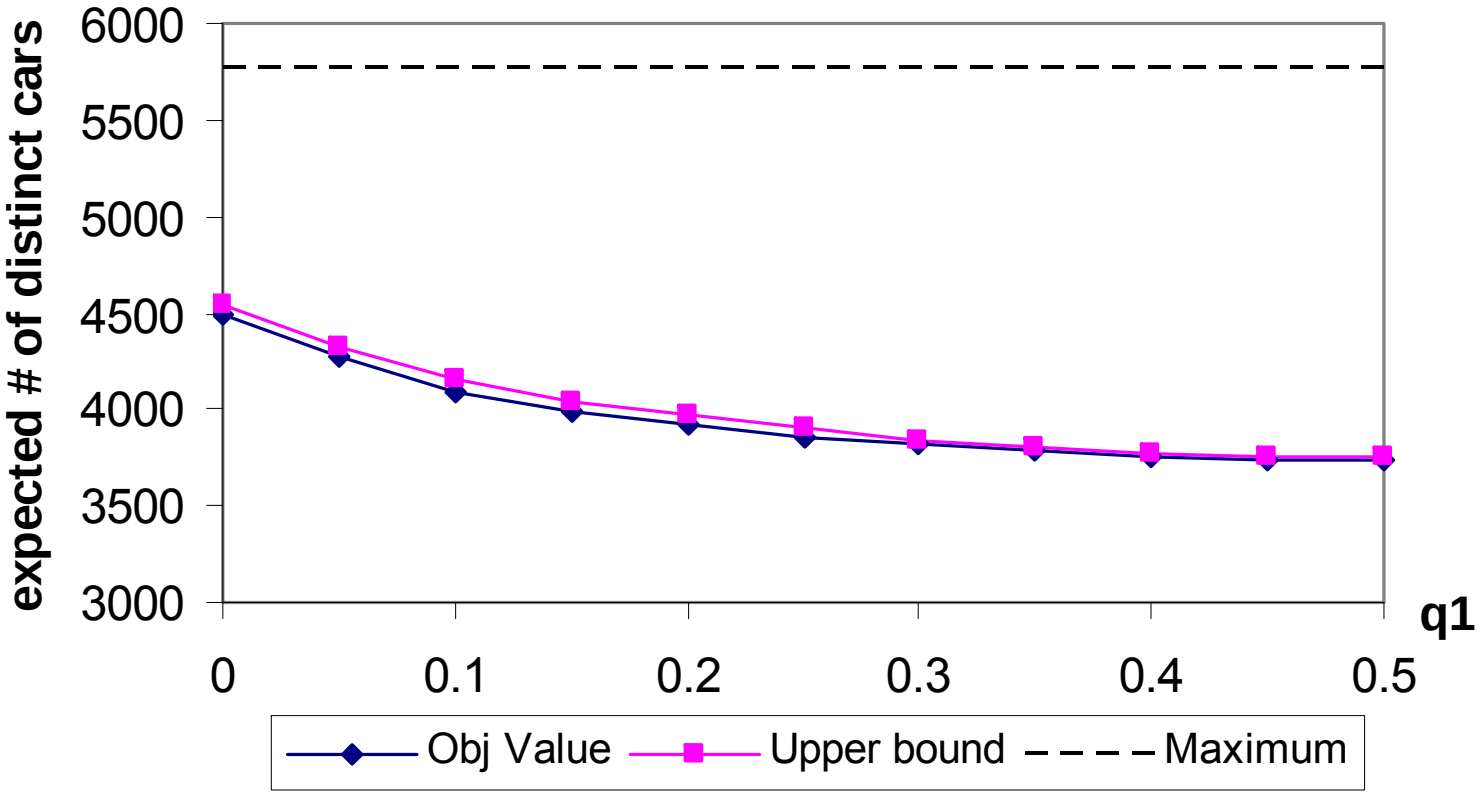
	Type-1 (m =1)	Type-2 (m =1)
Installation cost c_{im}	1	2
Error-detection probability q_m	0.05, 0.25	0

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
Type-1
Type-2
SAMP9K.FLO
10,000
5,000
2,500
2,500
5,000
10,000
(in 000's)
Expected benefit = 4,275.9
Upper bound = 4,327.3
Optimality gap = 1.20%


q_1= 0.25, q_2=0
Minneapolis, MN
Nifa, IL
Galesburg, IL
Utah Jct., CO
Lenwood, CA
Clovis, NM
Type-1
Type-2
SAMP9K.FLO
10,000
5,000
2,500
2,500
5,000
10,000
(in 000's)
Expected benefit = 3,857.0
Upper bound = 3,897.8
Optimality gap = 1.06%
30

Budget $B = 8M$

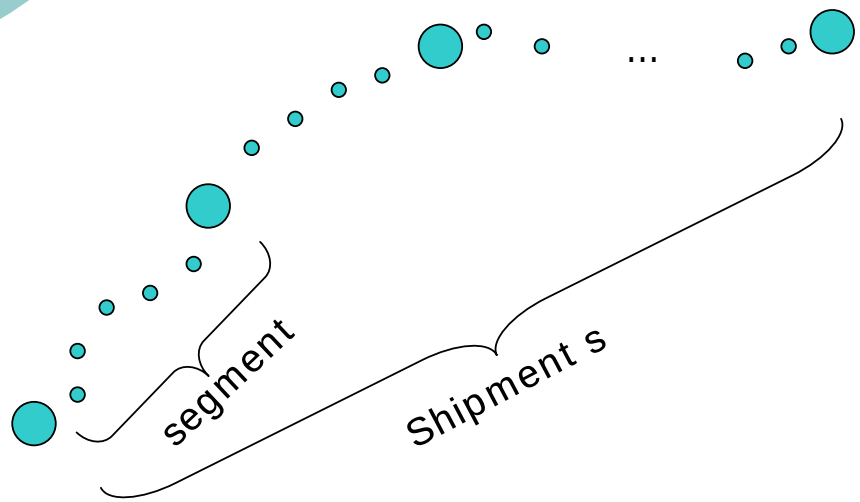

expected # of distinct cars
6000
5500
5000
4500
4000
3500
3000
0
0.1
0.2
0.3
0.4
0.5
q1
Obj Value
Upper bound
Maximum

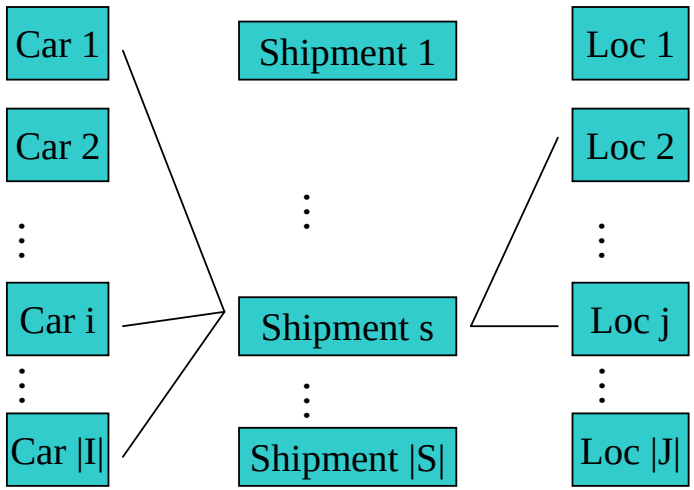
Empirical Case Study

- 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

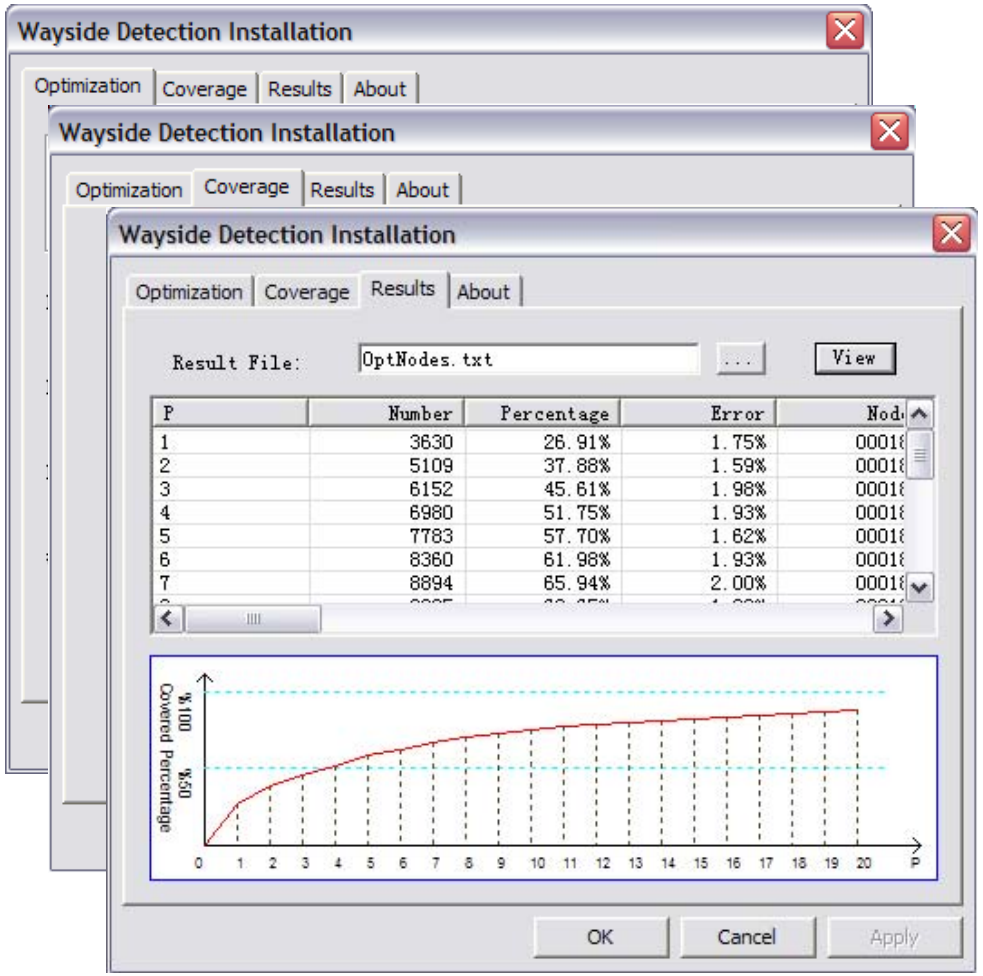
- For each shipment, determine the exact path (shortest path algorithm)
- For each location, determine the subset of cars passing it



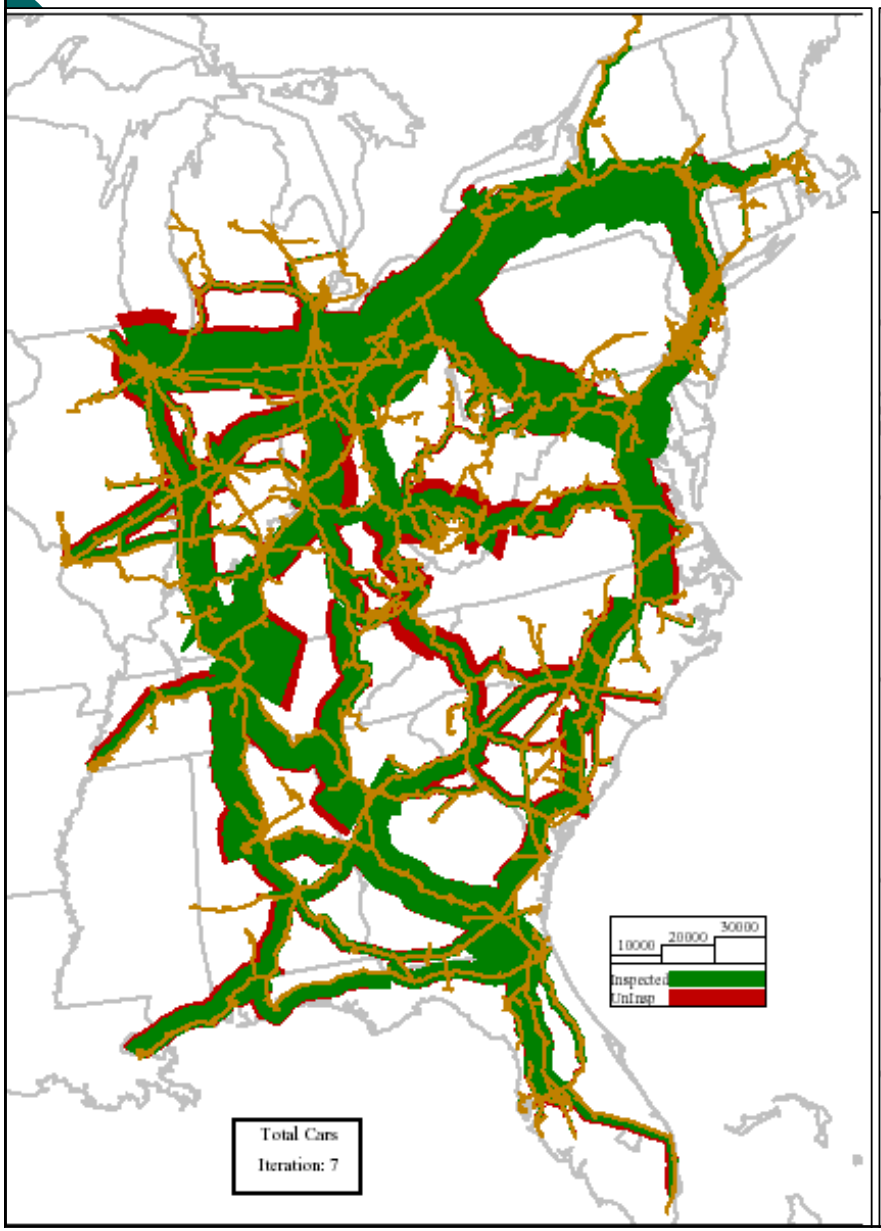


RWDLS™ Software

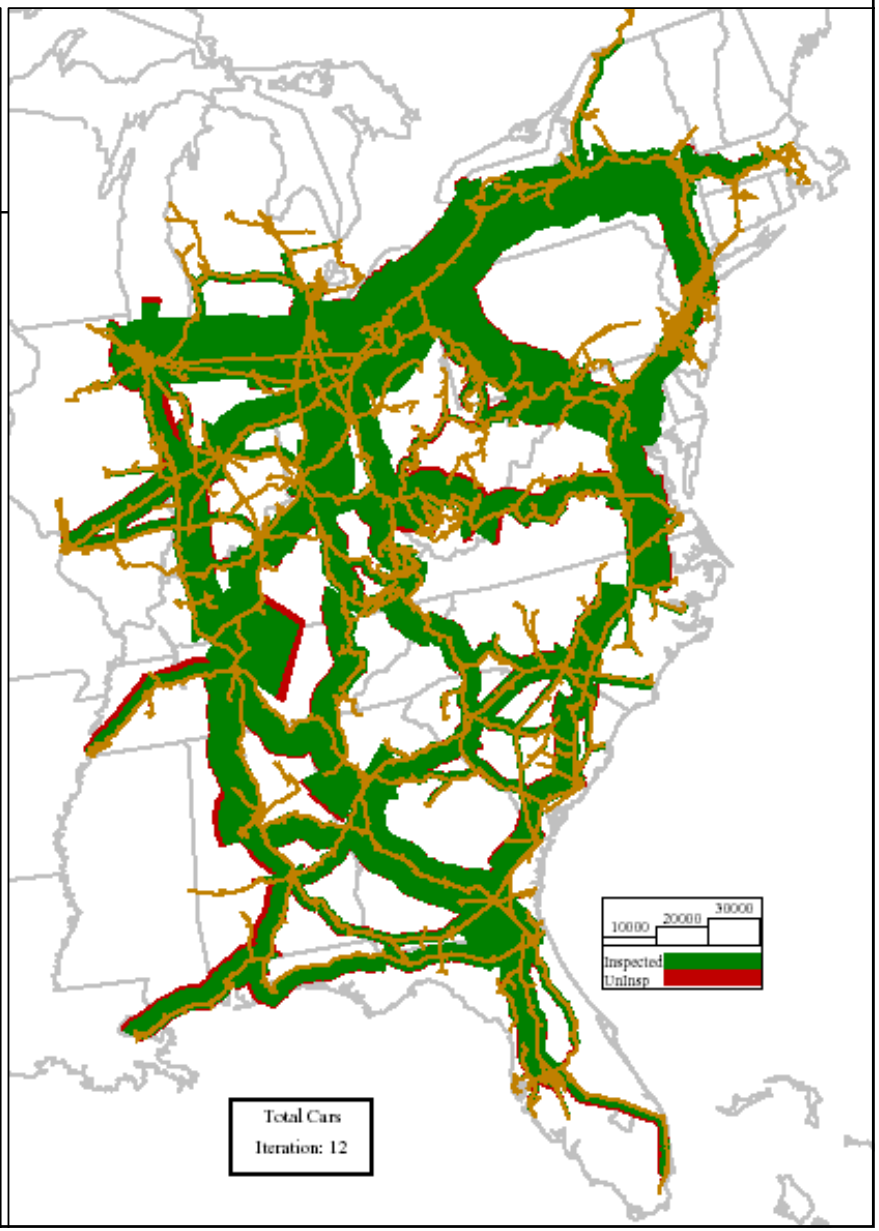
- Software programmed in C++
- Stand-alone
- For any railroad network and railcar flows
- Any Installation budget
- No problem size constraint
- User's guide available



7 installations



12 installations



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 ≈ 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!