Effects of Train Speed and Infrastructure Improvement on Hazardous Materials Transportation Risk

By

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Outline of Presentation

- **Introduction**
  - Overview
- **Review of Hazardous Materials Transportation Risk Analysis**
  - Factor Affecting Risk
  - Risk Model
- **Effects of Train Speed on Route Risk**
  - Development of Speed-dependent Conditional Probability of Release (CPR)
  - Route Risk Estimation Using Speed-dependent CPR
- **Effects of Infrastructure Improvement**
  - Upgrade Track to Improve Speed and Reduce Risk: A Dilemma?
  - Infrastructure Upgrade Options for Risk Reduction
  - Route Infrastructure Investment Selection Model
  - Sensitivity Analysis
- **Preliminary Benefit-cost Analysis**
- **Summary and Discussion**

Overview

- There is increased attention from industry and government on effective approaches to improve railroad hazardous materials transportation safety.

- While resource are often a constraint, the critical purpose of risk analyses is to help identify the most efficient means of reducing risk.

- Two major issues concerning risk reduction options:
  - ***Need to properly account for elements that could affect risk estimate***
  - ***Need to identify the most effective strategy under a limited budget***

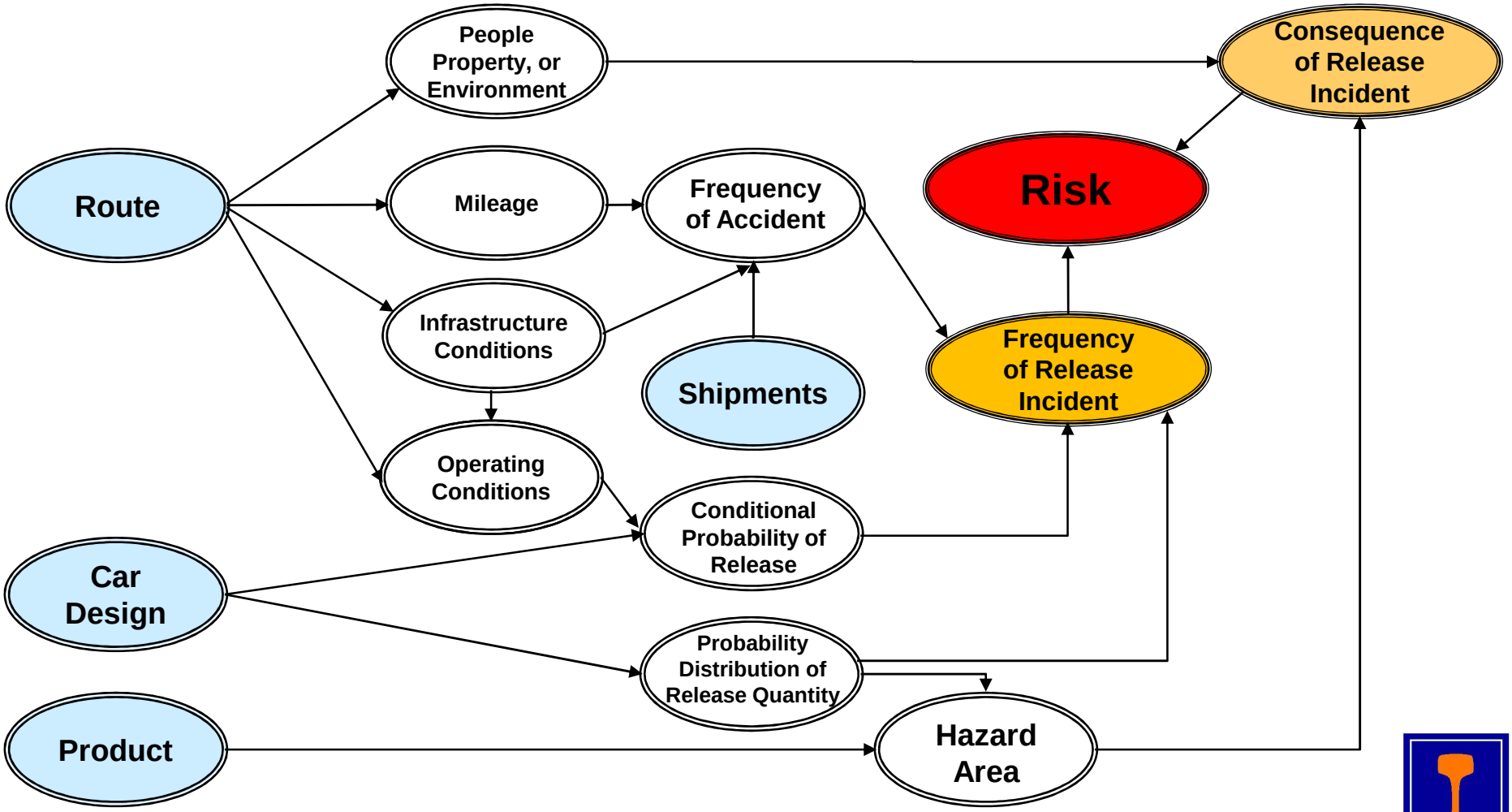
- In this study, we developed a technique to account for the effect of train speed that allows a better estimate of local risk.

- We also developed a mathematical model to illustrate application of the above. We presented a case study based on infrastructure improvement problem to facilitate consideration of this option.

Previous Research on Railroad Hazardous Materials Transportation Risk Reduction Options

- **Rerouting of hazardous materials traffic**
  - Glickman (1983)
  - Glickman et al. (2007)
  - Saat and Barkan (2006)
  - Kawprasert and Barkan (2008)
- **Improving tank car safety designs**
  - Barkan et al. (1991)
  - Saat and Barkan (2005)
  - Barkan et al. (2007)
  - Barkan (2008)
- **Using technology to monitor infrastructure and rolling stock health and conditions**
  - Ouyang et al. (2009)
- **Managing both infrastructure upgrade and train speed**
  - (none to date)

Relationships of Factors Affecting Railroad Hazardous Materials Transportation Risk



Adapted from Kawprasert, A., and C.P.L. Barkan. Communication and Interpretation of Results of Railroad Hazardous Materials Transportation Route Risk Analyses. In **Transportation Research Record: Journal of the Transportation Research Board, No. 2097,** TRB, National Research Council, Washington, D.C., 2009, pp. 125–135.

Risk Model

- Risk = f(P_f, C_f)

  P_f is the probability of system failure

  C_f is the severity of the losses from the system failure[1]

- In the context of railroad hazardous materials transportation,

  Risk = Frequency of Release Incident x Consequence

  $$S = P \times C$$

  P is the product of a series of outcome probabilities and accident rate

  C is the impact of the release

- $S = Z \times V \times L \times W \times D \times A$

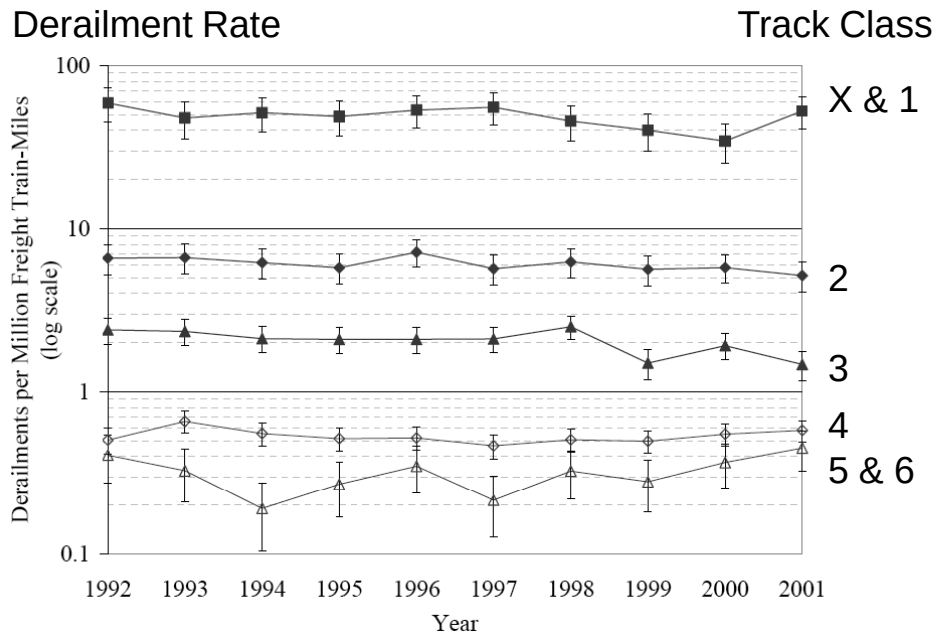
where:	Z	= accident rate per car-mile
	V	= shipments (carloads)
	L	= mileage
	W	= conditional probability of release given accident
	D	= population density
	A	= affected area per the U.S. DOT ERG recommendation[2]

[1] National Transportation Safety Board (NTSB). **Special Study: Risk Concepts in Dangerous Goods Transportation Regulations.** Report No: NSTB-STS-71-1, NSTB, Washington, D.C., January, 1971.

[2] Pipeline and Hazardous Materials Safety Administration (PHMSA), U.S. Department of Transportation. **2008 Emergency Response Guidebook (ERG).** http://hazmat.dot.gov/pubs/erg/erg2008_eng.pdf. Accessed July, 2008.

Railroad Accident Rates

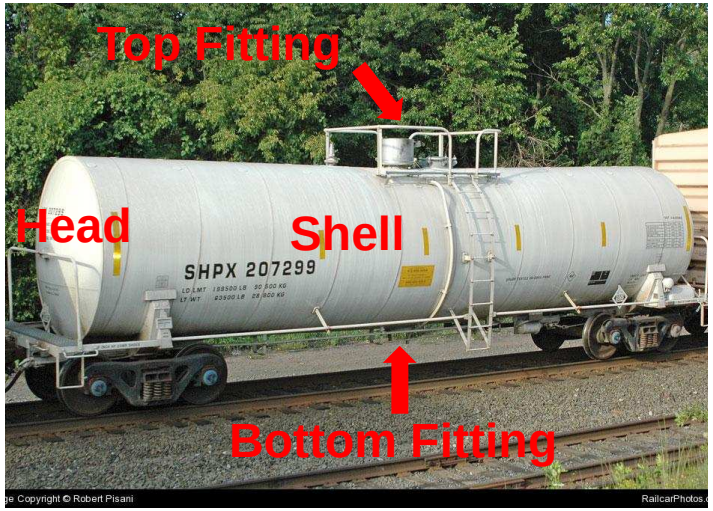
- Railroad accident rates vary with type of railroad and track quality[1].
- Lower FRA track classes (lower operating speed) have higher accident rates. Lower class track may also implied less stringent maintenance requirements and infrastructure conditions.
- Track speed from railroad timetables was used to infer the FRA track class.
- Track class-specific accident rates developed by Anderson and Barkan (2004) were used.

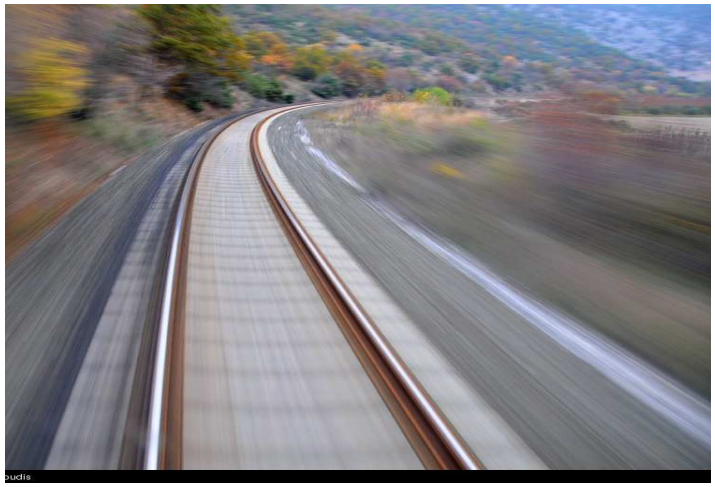


[1] Anderson, R. T., and C. P. L. Barkan. Railroad Accident Rates for Use in Transportation Risk Analysis. In **Transportation Research Record: Journal of the Transportation Research Board, No. 1863,** TRB, National Research Council, Washington, D.C., 2004, pp. 88–98.

Conditional Probability of Release (CPR)

- Tank car design has a major effect on CPR given that a car is derailed in an accident.
- Principal sources of release[1] are:
  - head
  - shell
  - top fitting
  - bottom fitting
- CPR is also affected by train speed. The higher speed, the higher likelihood of release if an accident occurs[2].

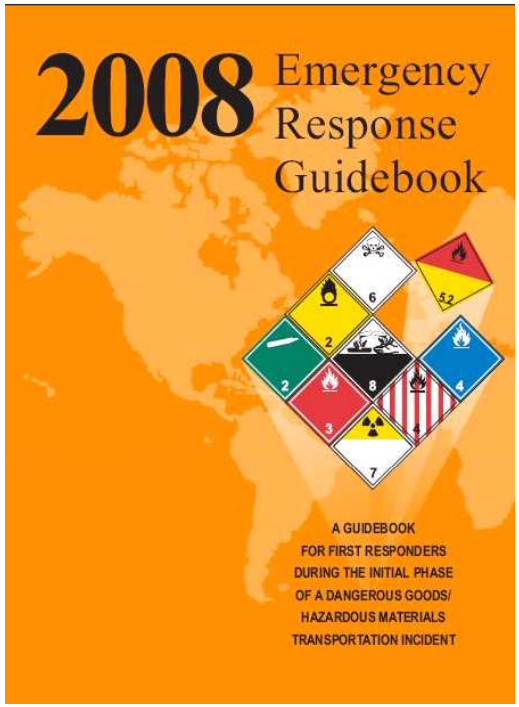


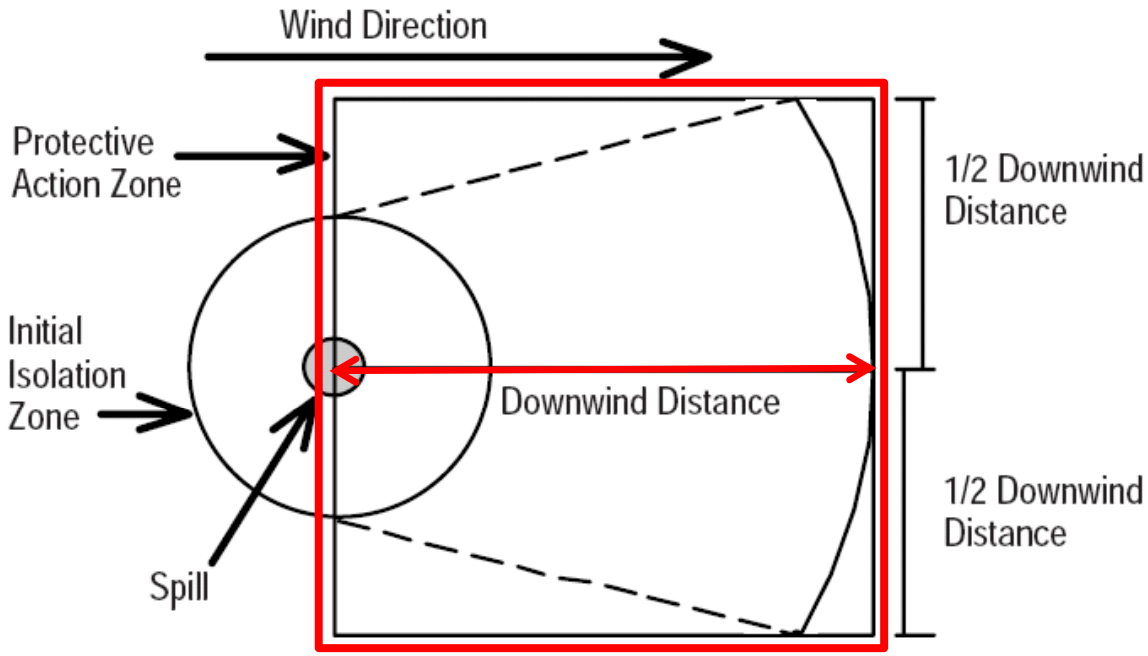


[1] Treichel, T. T., J. P. Hughes, C. P. L. Barkan, R. D. Sims, E. A. Phillips, and M. R. Saat. **Safety Performance of Tank Cars in Accidents: Probability of Lading Loss.** Report RA-05-02. RSI-AAR Railroad Tank Car Safety Research and Test Project, Association of American Railroads, Washington, D.C., 2006.

[2] Barkan, C.P.L., C.T. Dick, and R.T. Anderson. Railroad Derailment Factors Affecting Hazardous Materials Transportation Risk. In **Transportation Research Record: Journal of the Transportation Research Board, No. 1825,** TRB, National Research Council, Washington, D.C., 2003, pp. 64–74.

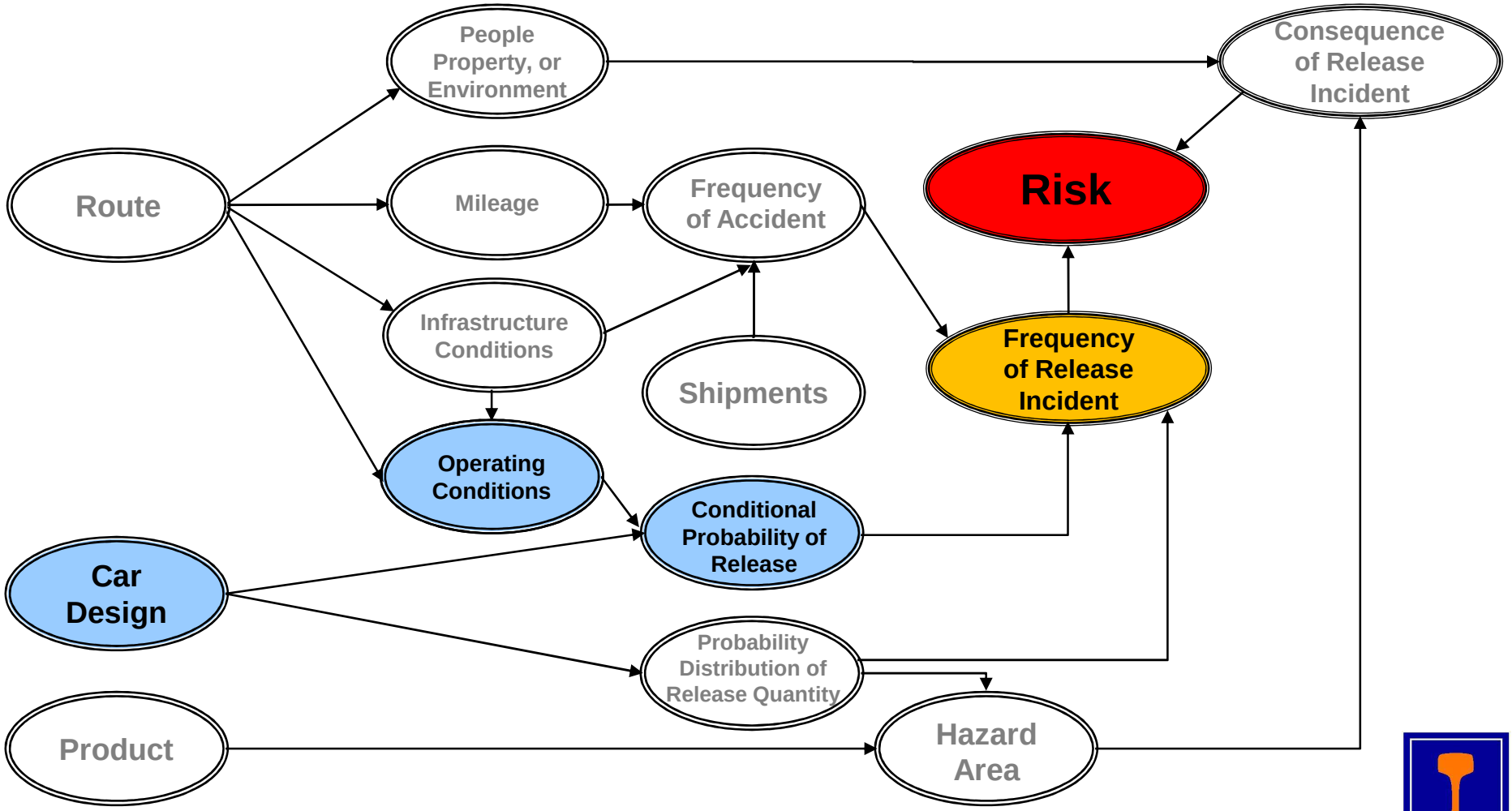
DOT 2008 Emergency Response Guidebook (ERG) Exposure Model





- The ERG recommends the downwind distance corresponding to the release scenario and chemical.
- This distance is used to determine affected area, the area where people need to be evacuated or sheltered in place in a hazmat release incident.

Effect of Train Speed on Risk



Introduction to Speed-dependent CPR

- Previous analyses have simplified risk estimation by considering a single value for CPR, which is independent of train speed.
- Depending on the situations, using it will have the effect of over-estimating or under-estimating release probabilities and consequently the local risks[1].
- To properly account for this effect, the speed-dependent CPR should be considered in both risk analysis and risk optimization models.
- Recent research and development of speed-dependent CPRs include: Nayak et al. (1983)[2], CCPS (1995)[3], Treichel et al. (2006)[4].

[1] Kawprasert, A., and C.P.L. Barkan. **Effects of Train Speed on Hazardous Material Transportation Route Risks.** Accepted for Presentation at the 89th Annual Meeting of the Transportation Research Board, Washington, D.C., 2010.

[2] Nayak, P.R., D.B. Rosenfield, and J.H. Hagopian. **Event Probabilities and Impact Zones for Hazardous Materials Accidents on Railroads.** Report DOT/FRA/ORD-83/20. Federal Railroad Administration, U.S. Department of Transportation, Washington, D.C., November 1983.

[3] Center for Chemical Process Safety (CCPS), American Institute of Chemical Engineers. **Guidelines for Chemical Transportation Risk Analysis.** New York, NY, 1995.

[4] Treichel, T. T., J. P. Hughes, C. P. L. Barkan, R. D. Sims, E. A. Phillips, and M. R. Saat. **Safety Performance of Tank Cars in Accidents: Probability of Lading Loss.** Report RA-05-02. RSI-AAR Railroad Tank Car Safety Research and Test Project, Association of American Railroads, Washington, D.C., 2006.

Previous Studies on Speed-dependent CPR

- Nayak et al. (1983) developed the relationship between speed and CPR using one-parameter function: $CPR_v = 0.045v^{0.5}$.
  - Applicable to mainline & yard, derailment & collision
- CCPS (1995) suggested the following relationships:
  - For mainline accidents

    $CPR_v = (0.29)(0.096v^{0.7})$ for non-pressure cars

    $= (0.08)(0.096v^{0.7})$ for pressure cars
  - For yard accidents (all speeds)

    $CPR = 0.13$ for non-pressure cars

    $= 0.02$ for pressure cars
- These relationships do not consider the specific safety design features of the tank cars.

Previous Studies on Speed-dependent CPR (cont'd)

- Treichel et al. (2006)[1] used a logistic regression to describe the relationships between CPR and various tank car design parameters affecting it, e.g.

$$\mathrm{CPR}_{\mathrm{head,mainline}} = \frac{\exp(-0.4492 - 1.1672(HST) - 1.9863(HMT) - 0.9240(INS) - 0.4176(SHELF) - 0.4905(YARD))}{1 + \exp(-0.4492 - 1.1672(HST) - 1.9863(HMT) - 0.9240(INS) - 0.4176(SHELF) - 0.4905(YARD))}$$

- These relationships account for the specific safety design features of the tank cars, but train speed was not included.

- The linear relationships between speed and CPR were developed by the same authors, e.g.

$$\mathrm{CPR}_v = 0.0054v + 0.1937 \qquad \text{for all cars}$$

- However, the specific tank car safety design parameters were not incorporated in these relationships.

[1] Treichel, T. T., J. P. Hughes, C. P. L. Barkan, R. D. Sims, E. A. Phillips, and M. R. Saat. **Safety Performance of Tank Cars in Accidents: Probability of Lading Loss.** Report RA-05-02. RSI-AAR Railroad Tank Car Safety Research and Test Project, Association of American Railroads, Washington, D.C., 2006.

Recent Development on Speed-dependent CPR

- Kawprasert and Barkan (2010)[1] developed a method to adjust the CPR for speed using the data from Treichel et al. (2006)[2].

$$\mathrm{CPR_v} = 1 - \prod_i \left(1 - R_i J_{v,i}\right)$$

where R_i: average speed CPR corresponding to release source *i* from Treichel et al.

J_i: speed-adjustment factor for release source *i*

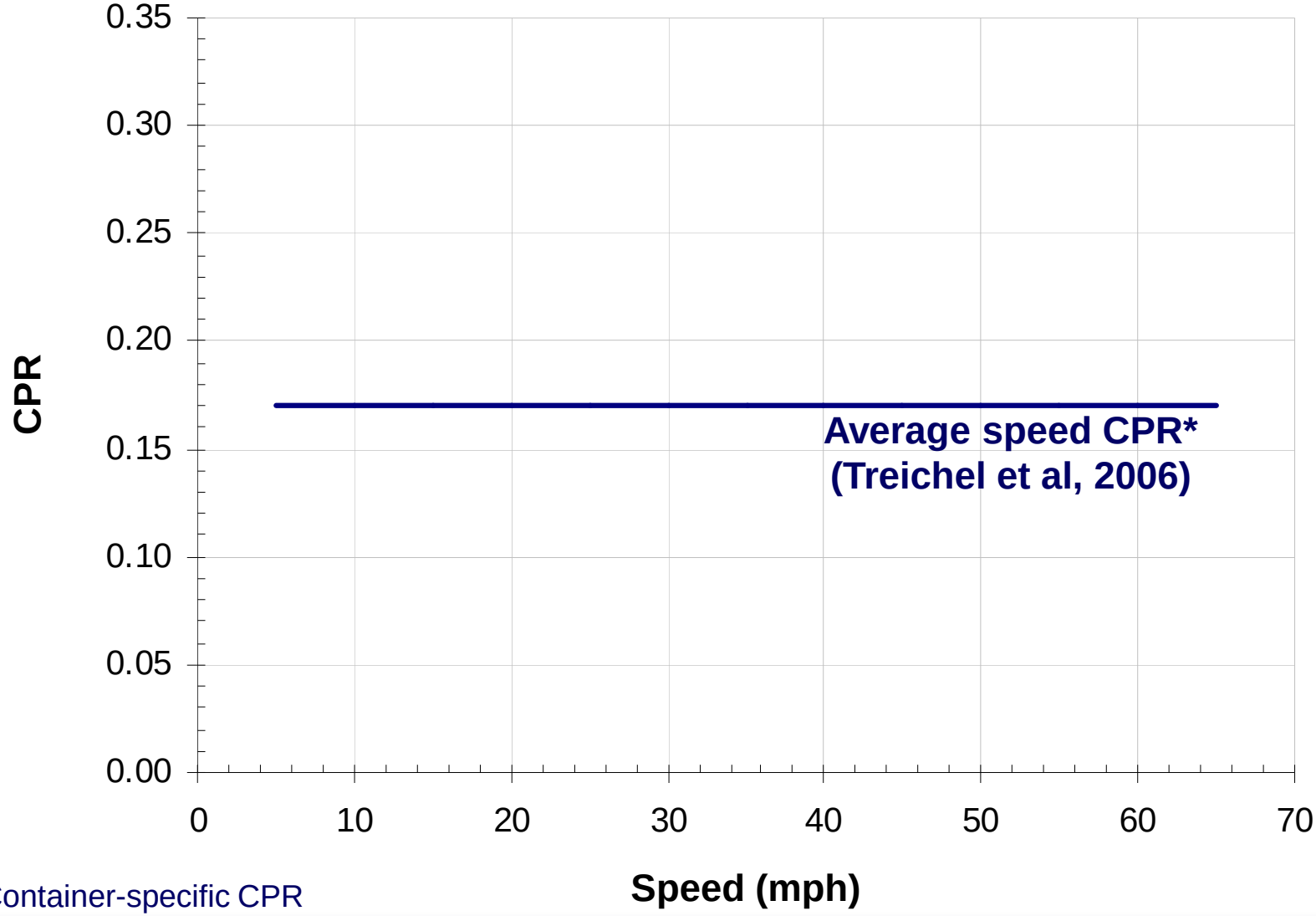
- The formula assumes that the likelihoods of release from the four major sources are independent[2].

- Adjustment was not made for CPR from top and bottom fittings because speed does not have essential effect on the likelihood of release from these two sources[2].

[1] Kawprasert, A., and C.P.L. Barkan. **Effects of Train Speed on Hazardous Material Transportation Route Risks.** Accepted for Presentation at the 89th Annual Meeting of the Transportation Research Board, Washington, D.C., 2010.

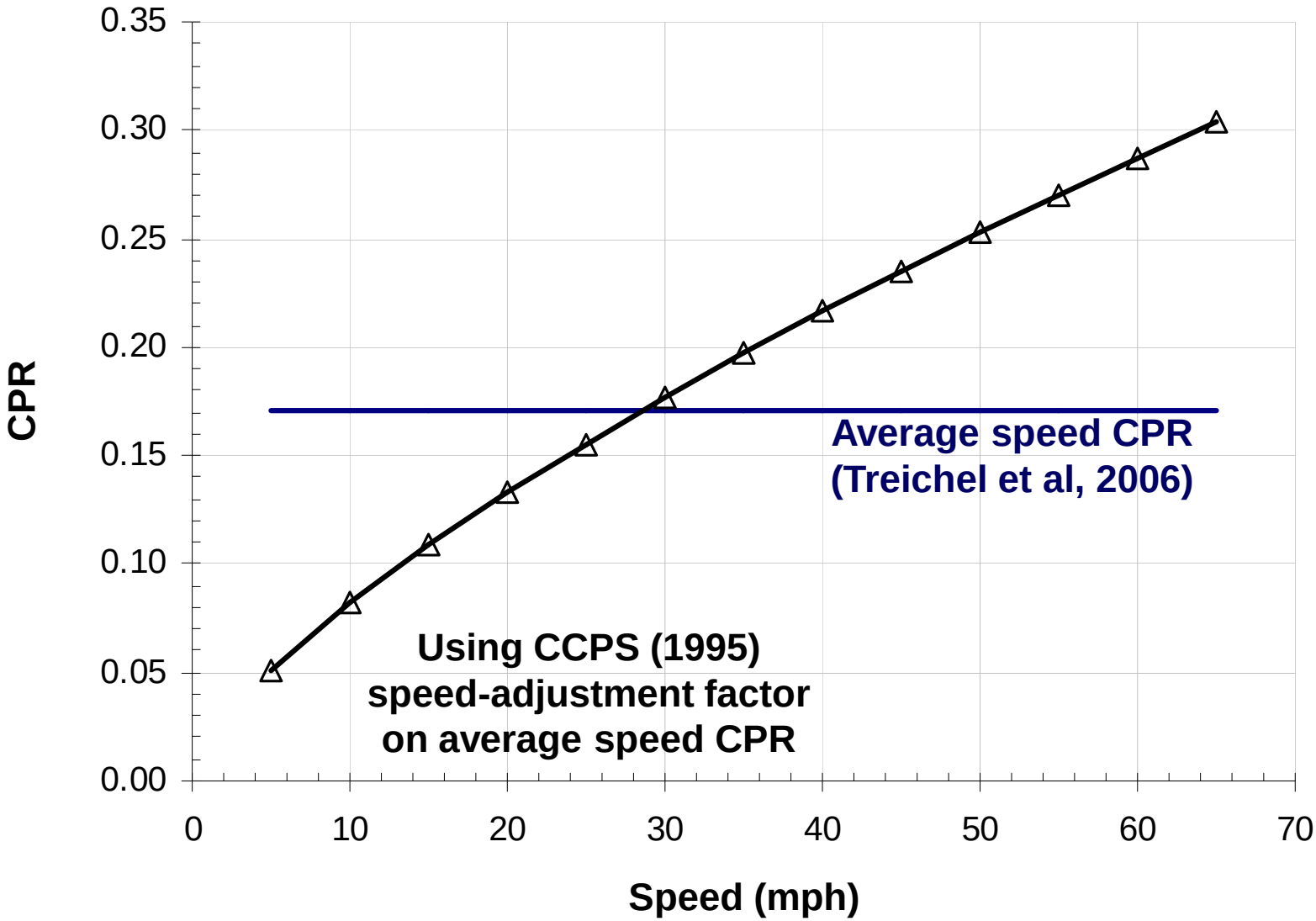
[2] Treichel, T. T., J. P. Hughes, C. P. L. Barkan, R. D. Sims, E. A. Phillips, and M. R. Saat. **Safety Performance of Tank Cars in Accidents: Probability of Lading Loss.** Report RA-05-02. RSI-AAR Railroad Tank Car Safety Research and Test Project, Association of American Railroads, Washington, D.C., 2006.

Relationships Between Speed and Conditional Probability of Release

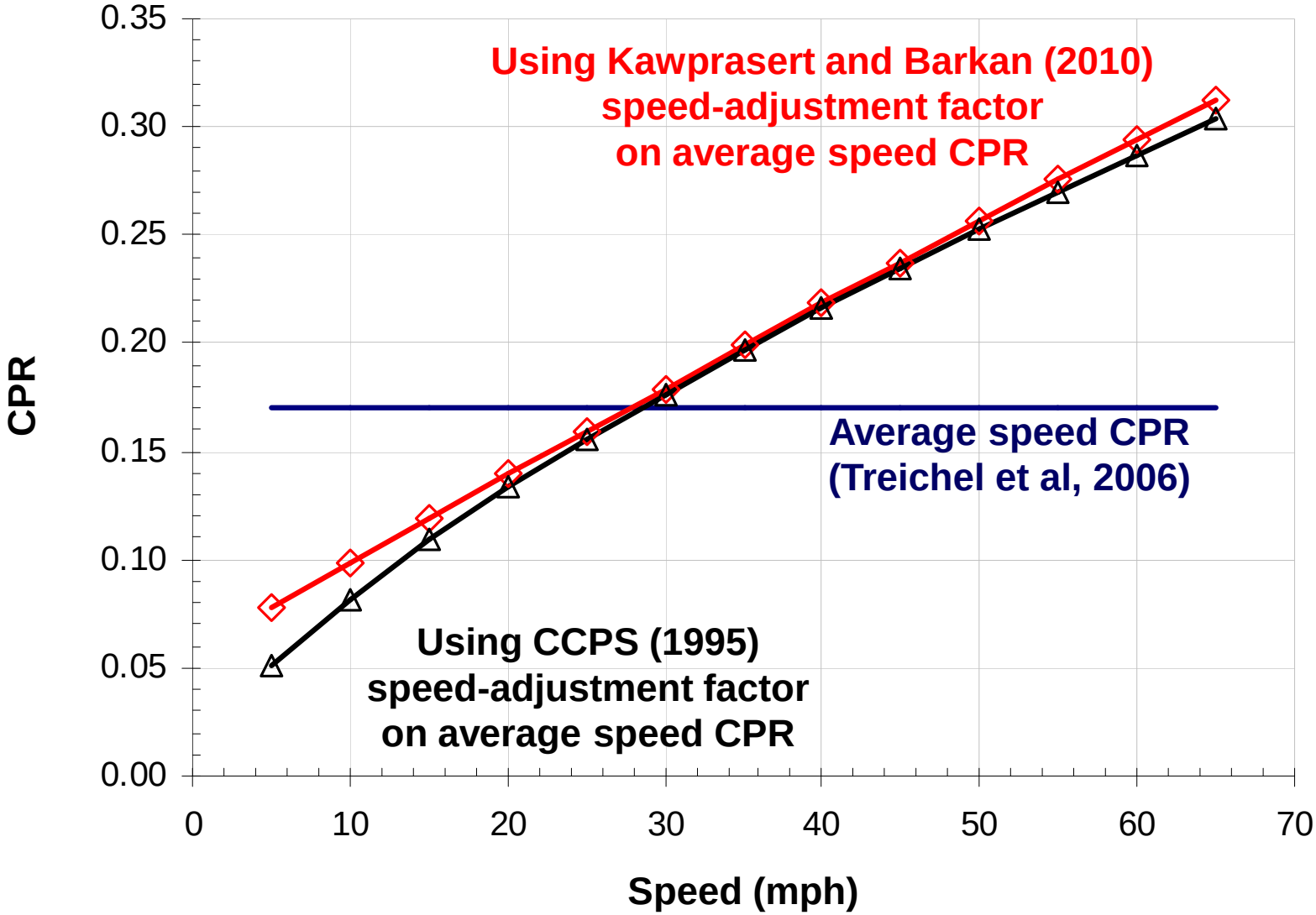


*Container-specific CPR

Relationships Between Speed and Conditional Probability of Release



Relationships Between Speed and Conditional Probability of Release



Case Study

- Carloads: 100
- Total route length: 1,400 miles (600 segments)
- Track segment data: BTS (2007)[1]
- Derailment rates: Anderson and Barkan (2004)[2]
- Speed-dependent CPR: Kawprasert and Barkan (2010)[3]
- Affected area: 0.785 sq.mi. (ERG, 2008)[4]
- Population density: ESRI (2005)[5]

[1] Bureau of Transportation Statistics (BTS), U.S. Department of Transportation. **National Transportation Atlas Database.** www.bts.gov/publications/national_transportation_atlas_database/. Accessed May 1, 2007.

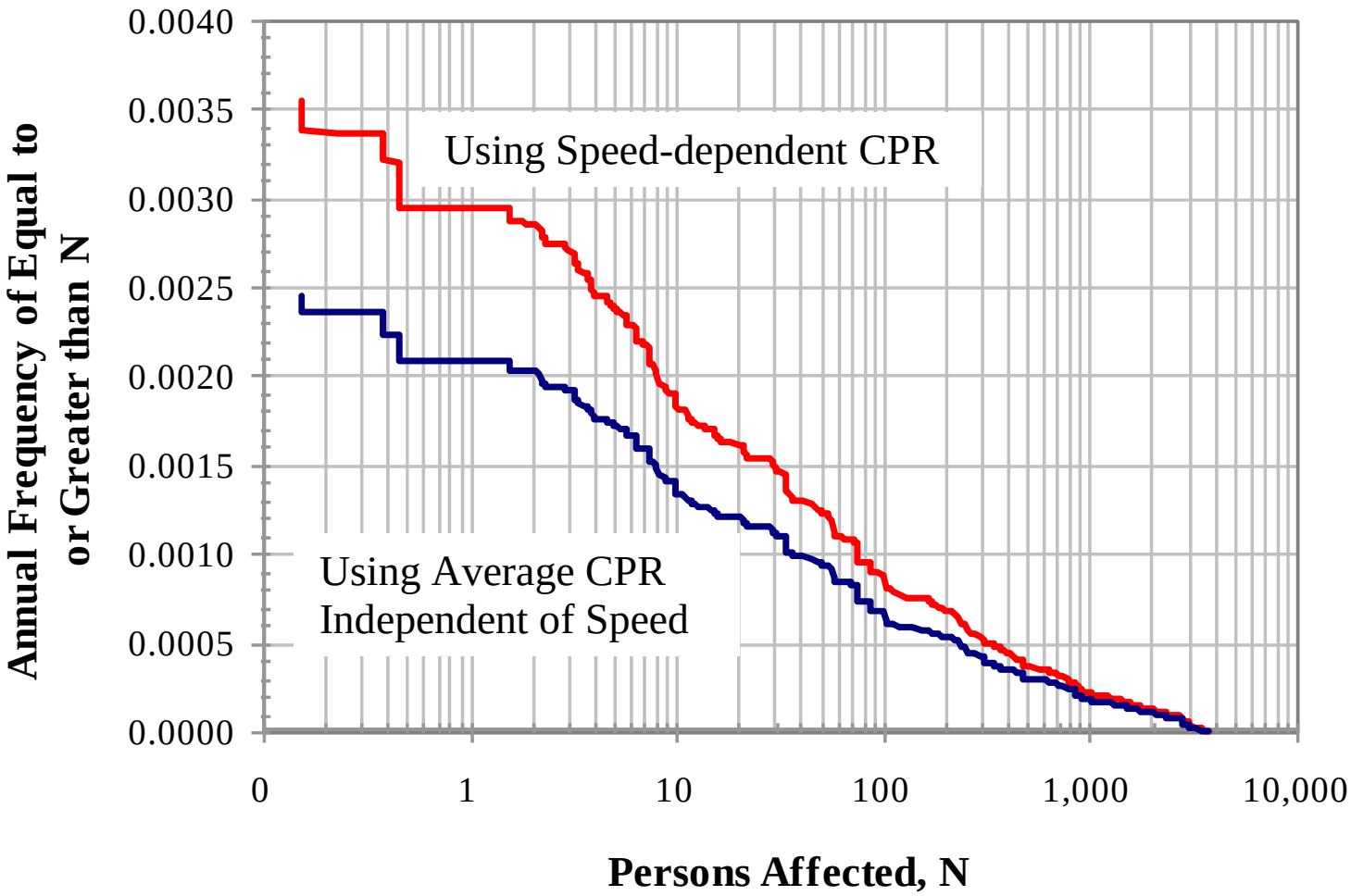
[2] Anderson, R. T., and C. P. L. Barkan. Railroad Accident Rates for Use in Transportation Risk Analysis. In **Transportation Research Record: Journal of the Transportation Research Board, No. 1863,** TRB, National Research Council, Washington, D.C., 2004, pp. 88–98.

[3] Kawprasert, A., and C.P.L. Barkan. **Effects of Train Speed on Hazardous Material Transportation Route Risks.** Accepted for Presentation at the 89th Annual Meeting of the Transportation Research Board, Washington, D.C., 2010.

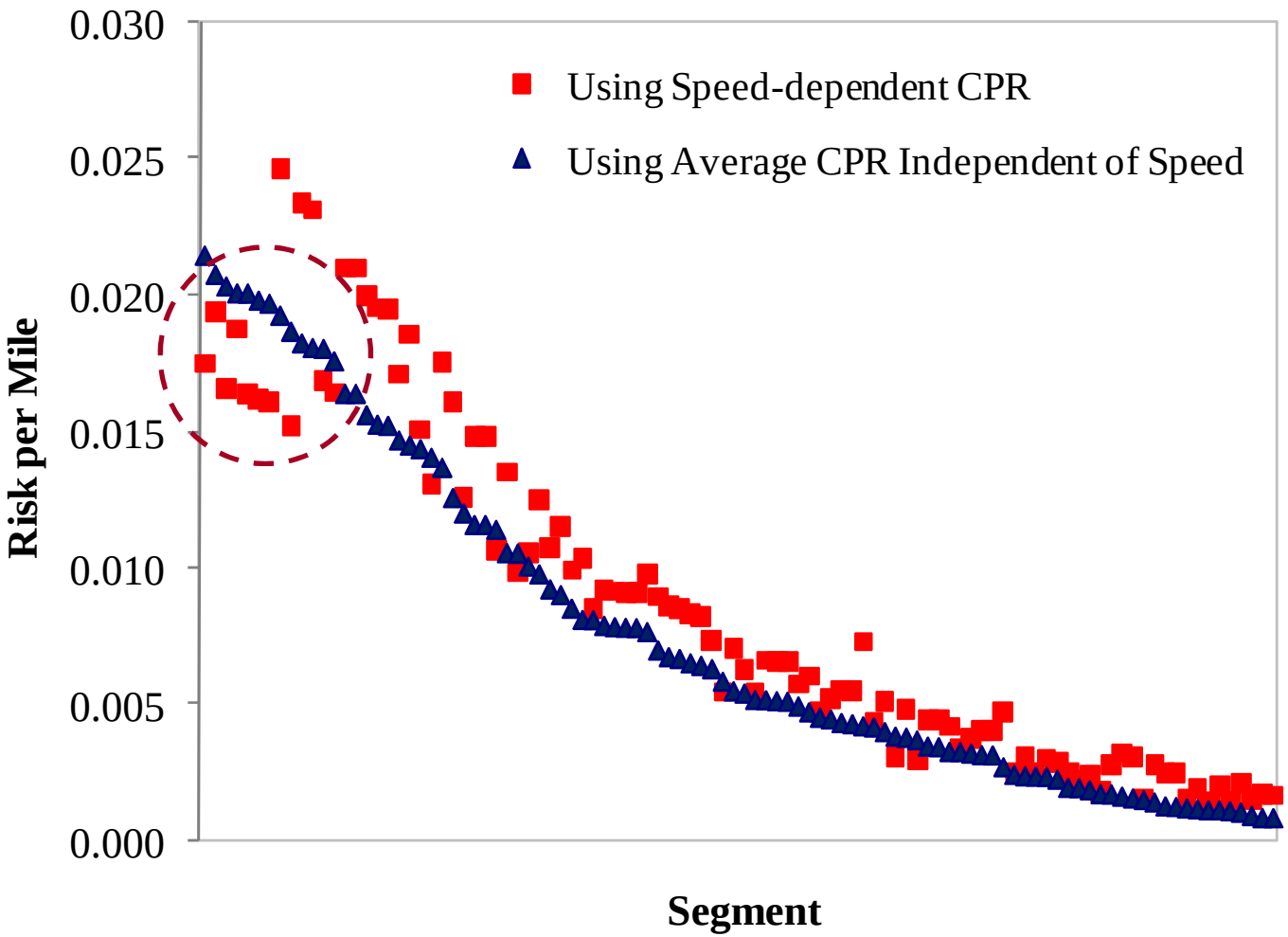
[4] Pipeline and Hazardous Materials Safety Administration (PHMSA), U.S. Department of Transportation. **2008 Emergency Response Guidebook (ERG).** http://hazmat.dot.gov/pubs/erg/erg2008_eng.pdf. Accessed July, 2008.

[5] ESRI. **Data & Maps.** Electronic Database (DVD-ROM), ESRI, 2005.

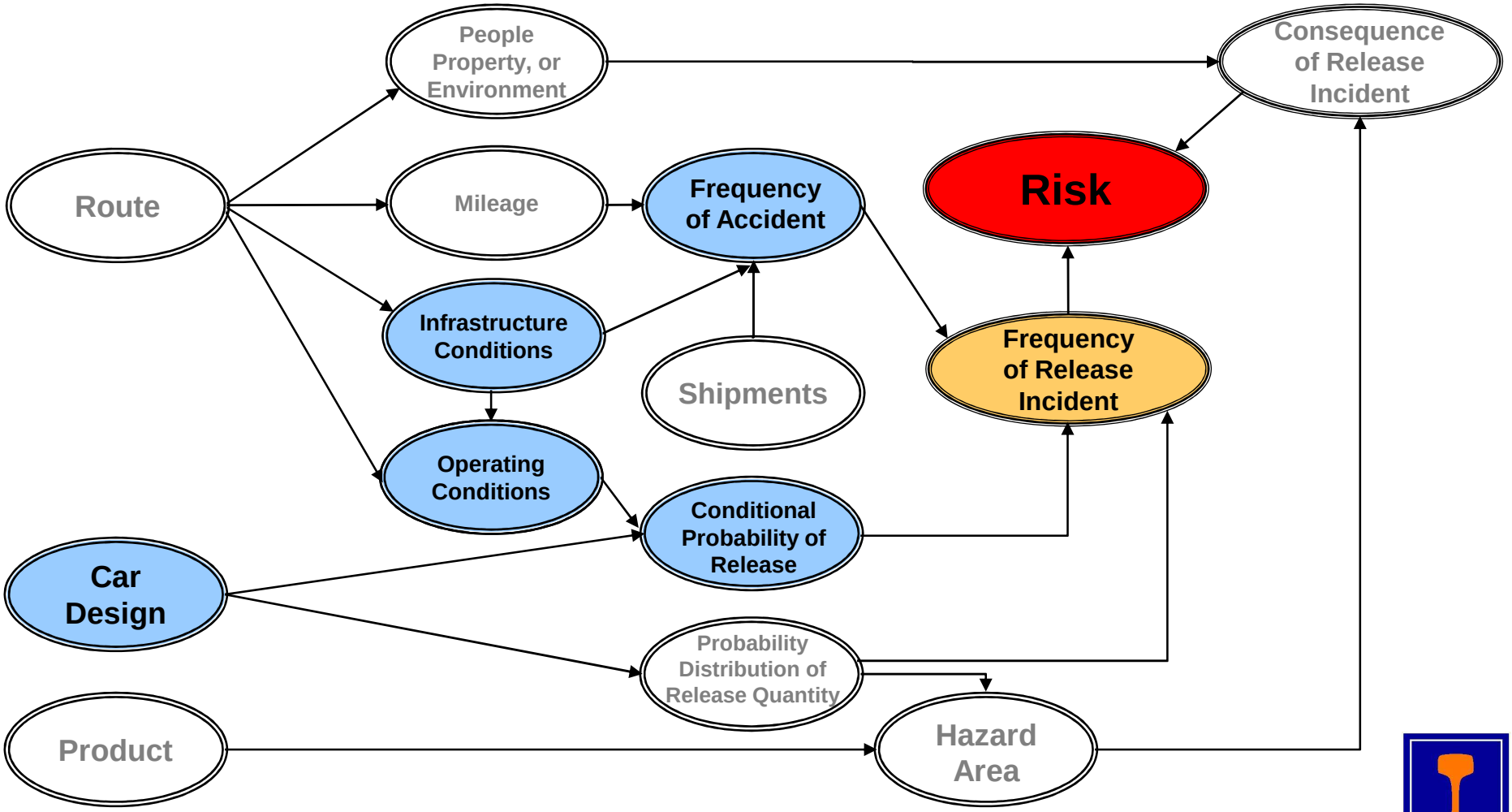
Comparison of Risk Profiles when Speed-dependent CPR is Used



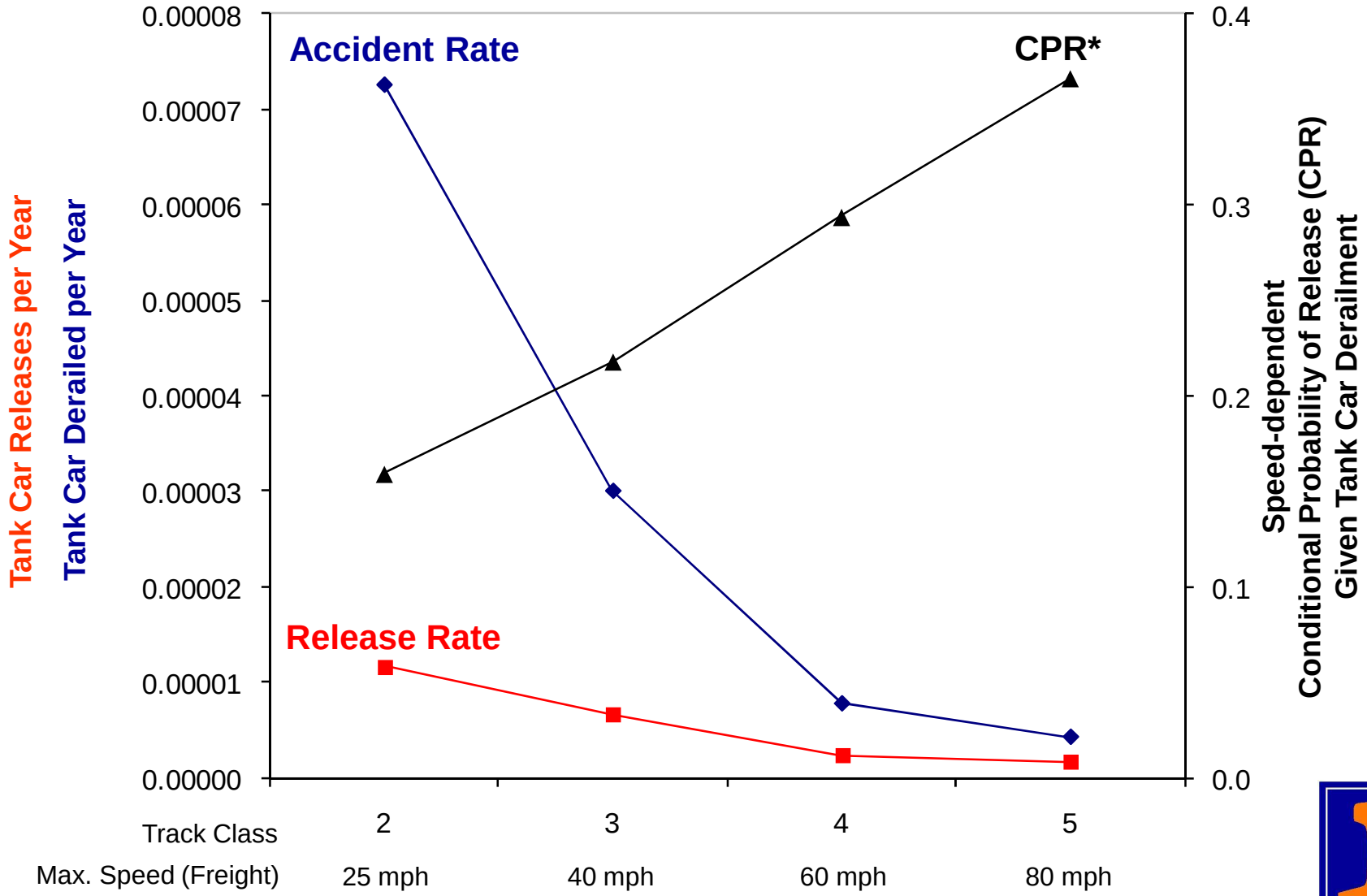
Comparison of Segment-specific Risk when Speed-dependent CPR is Used



Combined Effects of Speed and Infrastructure Improvement on Risk

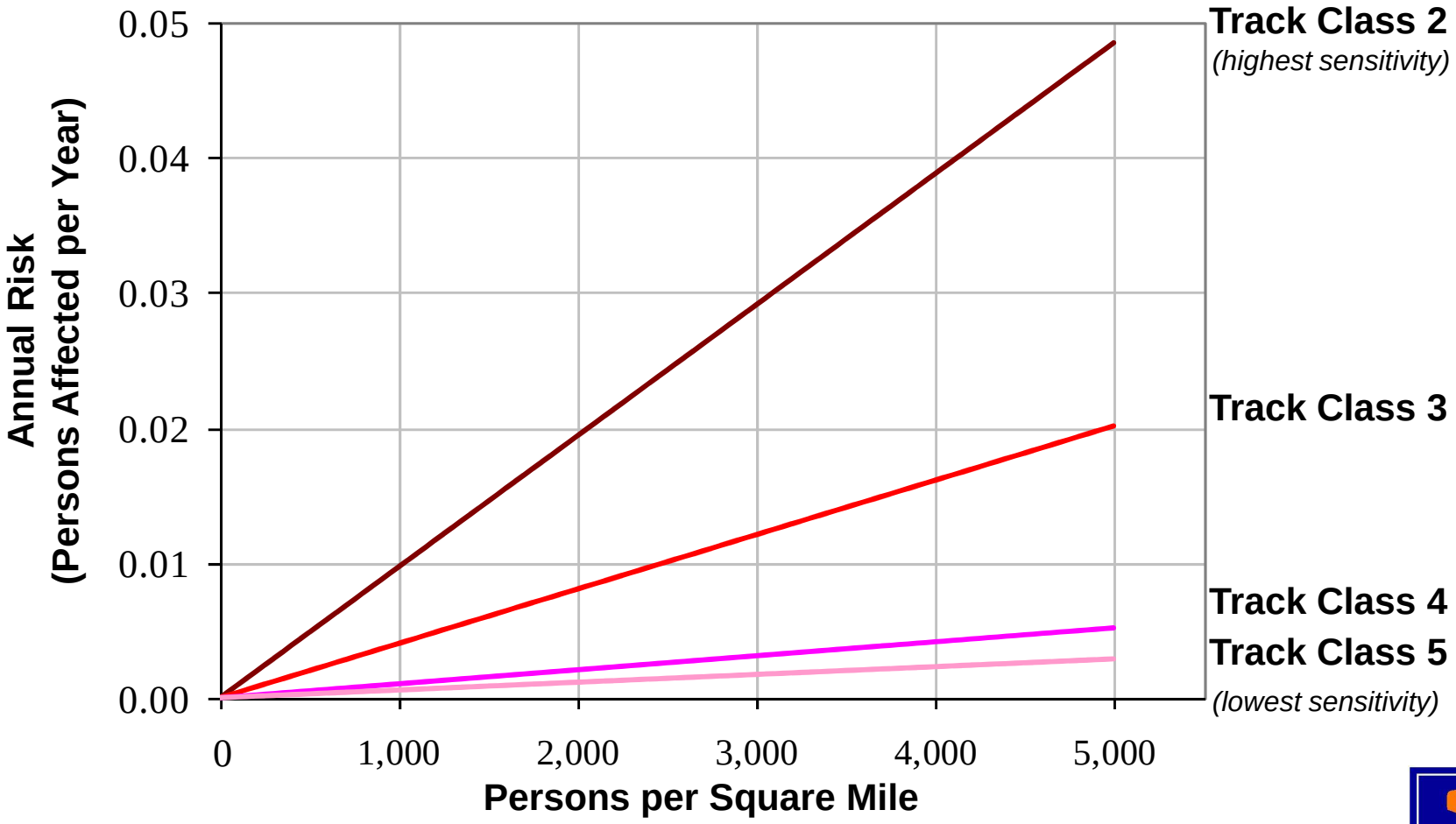


Relationship Between Track Class and Risk Parameters



* Kawprasert, A., and C.P.L. Barkan. **Effects of Train Speed on Hazardous Material Transportation Route Risks.** Accepted for Presentation at the 89th Annual Meeting of the Transportation Research Board, Washington, D.C., 2010.

Effect of Track Class Changes on Risk as Function of Population Density



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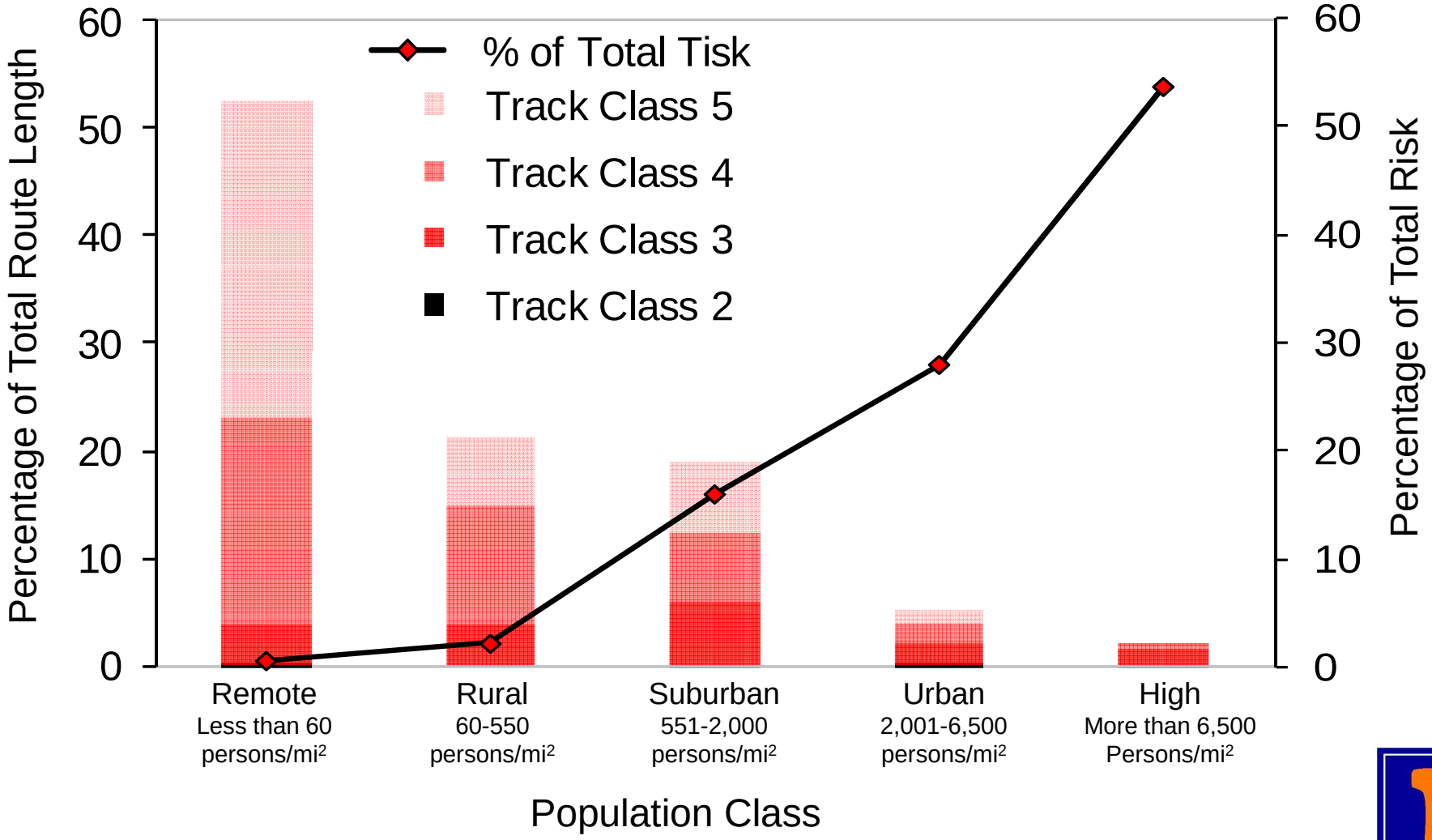
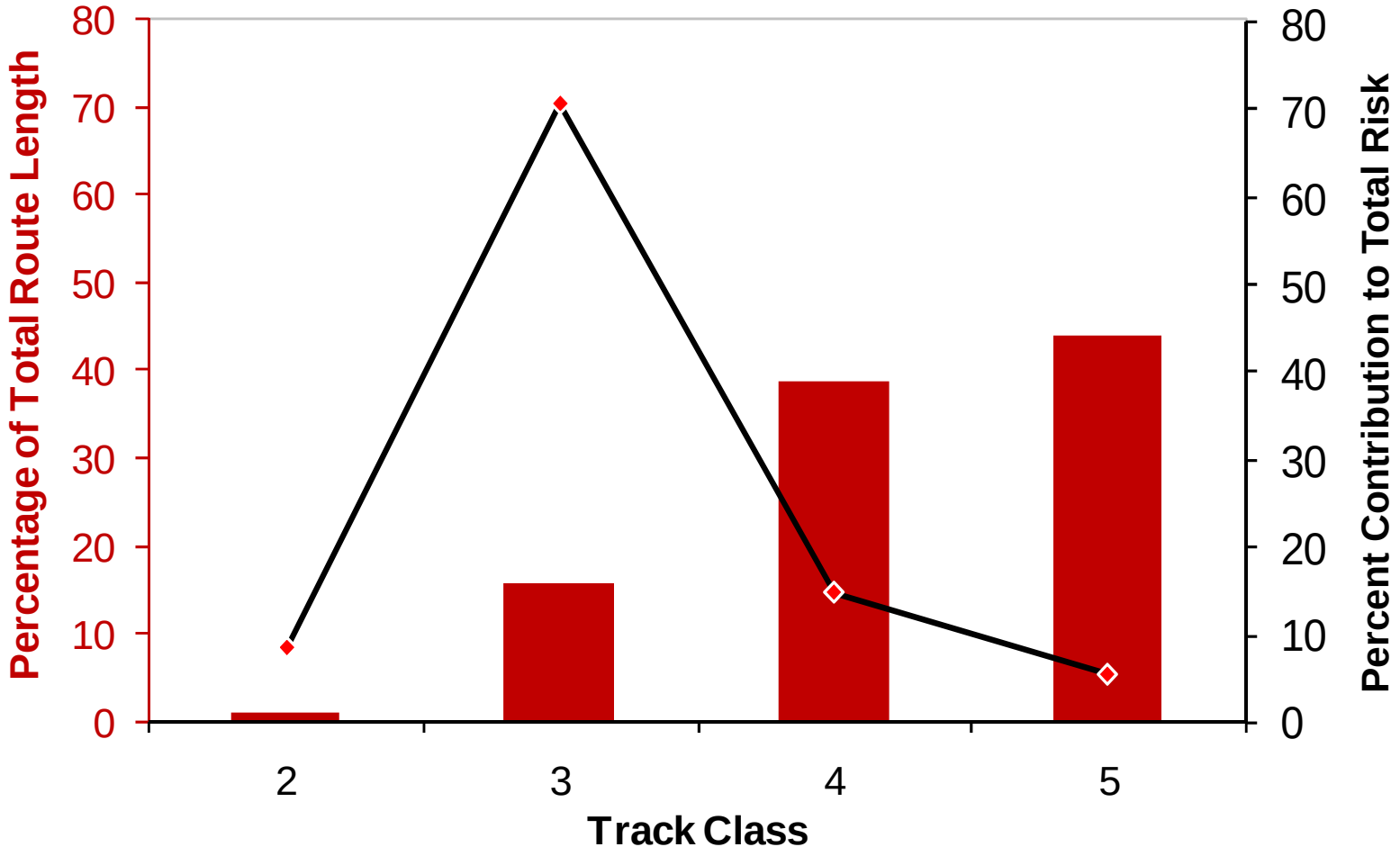
Risk Contribution By Population Density and Track Classes

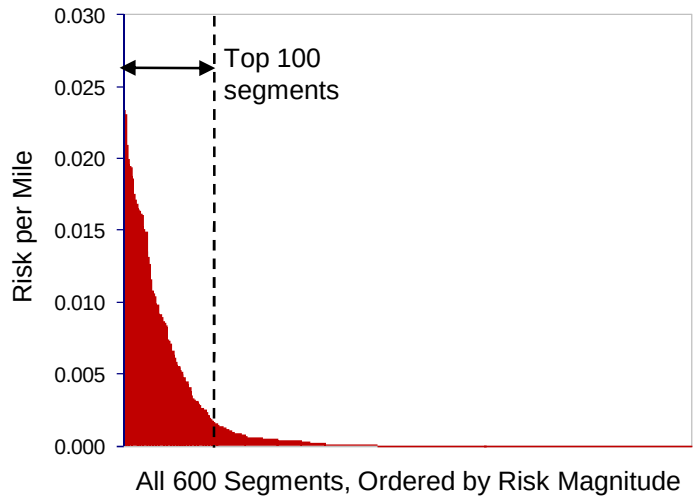


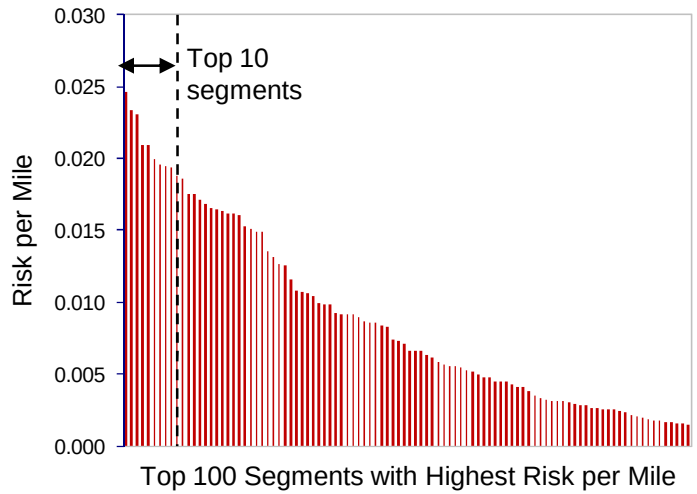
Risk Contribution By Track Classes



Effects of Infrastructure Improvement:
Segment-specific Risk Analysis

- Analyze two scenarios: with and without speed increase after track upgrade
- Distributions show that small percentages of route length contribute a large proportion of risk[1].
- For clarity, we will examine changes in risk of top ten segments with highest risk per mile for each track class.
- Consider three scenarios separately
  - Upgrade all class 2 to class 3
  - Upgrade all class 3 to class 4
  - Upgrade all class 4 to class 5





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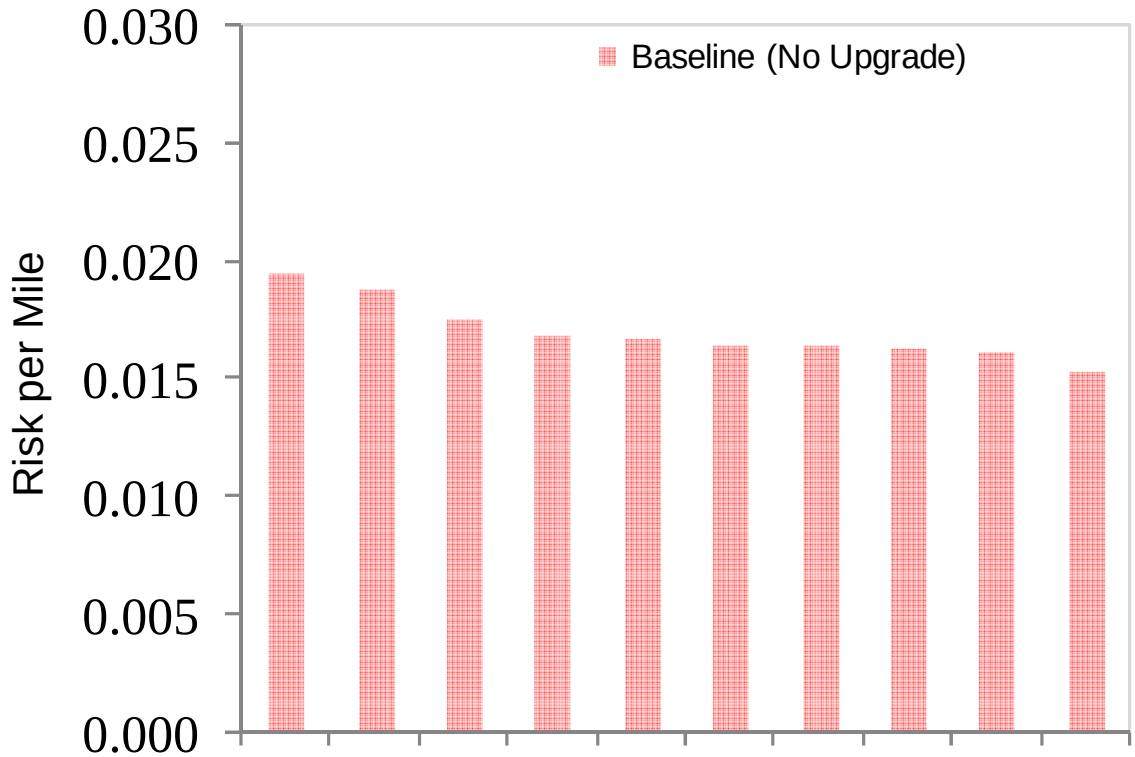
Effects of Infrastructure Improvement and Train Speed on Segment-specific Risk

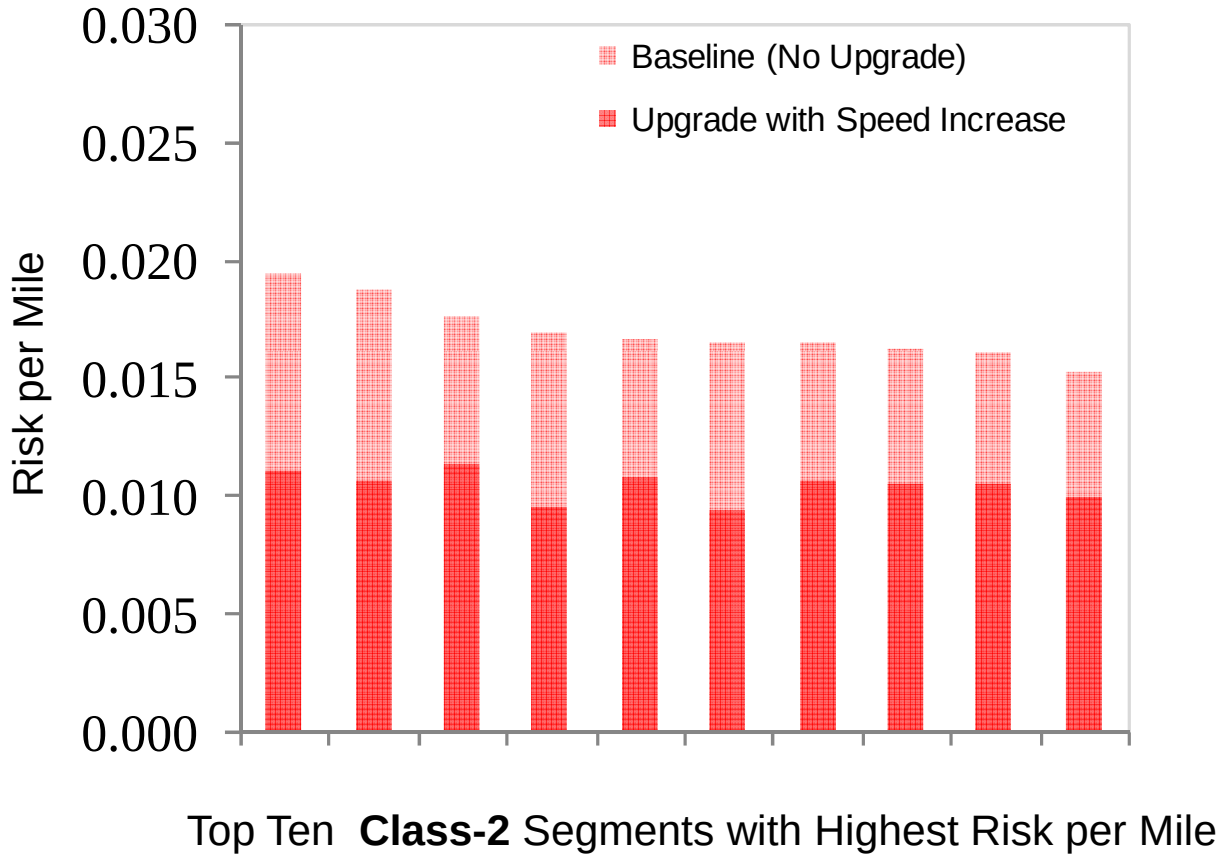
Class-2 Segments: Baseline (No Upgrade)



Top Ten **Class-2** Segments with Highest Risk per Mile

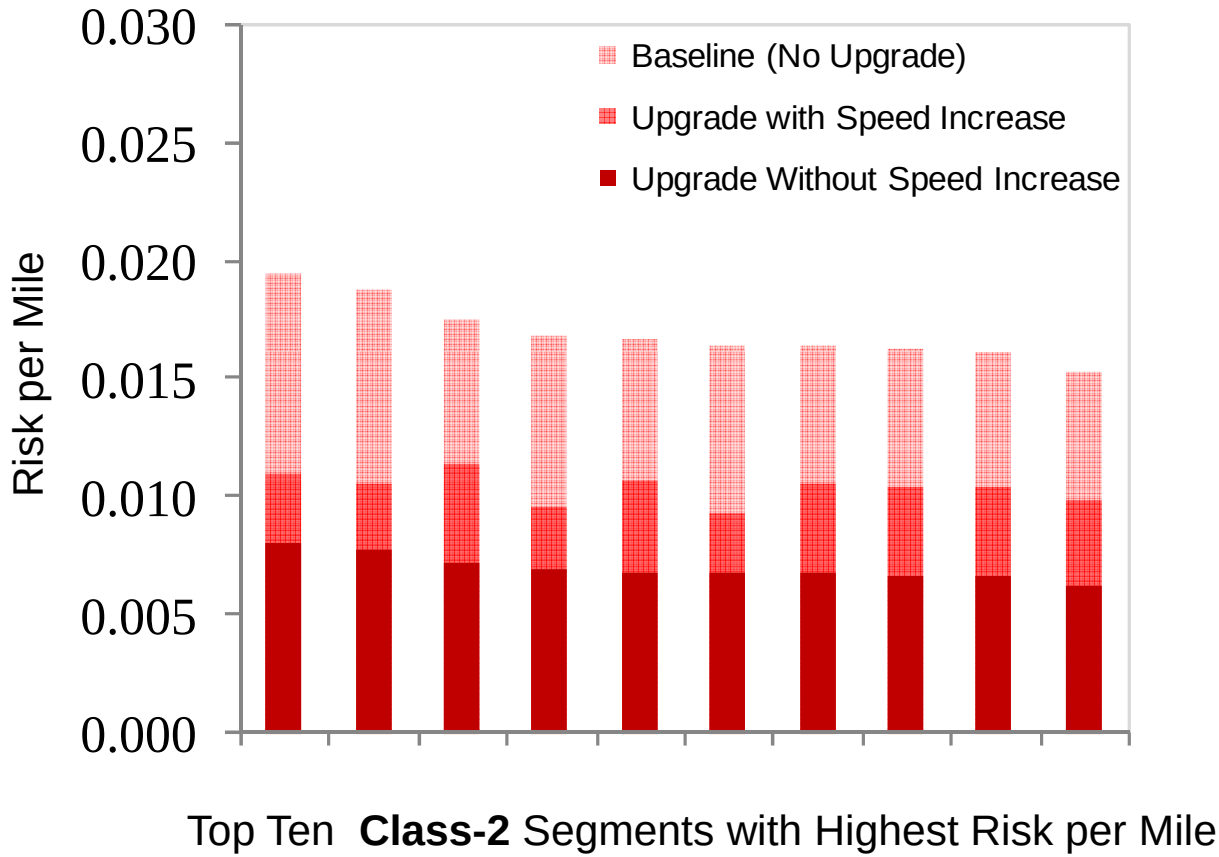
Effects of Infrastructure Improvement and Train Speed on Segment-specific Risk

Class-2 Segments Upgraded to Class 3 (With Speed Increase)



Effects of Infrastructure Improvement and Train Speed on Segment-specific Risk

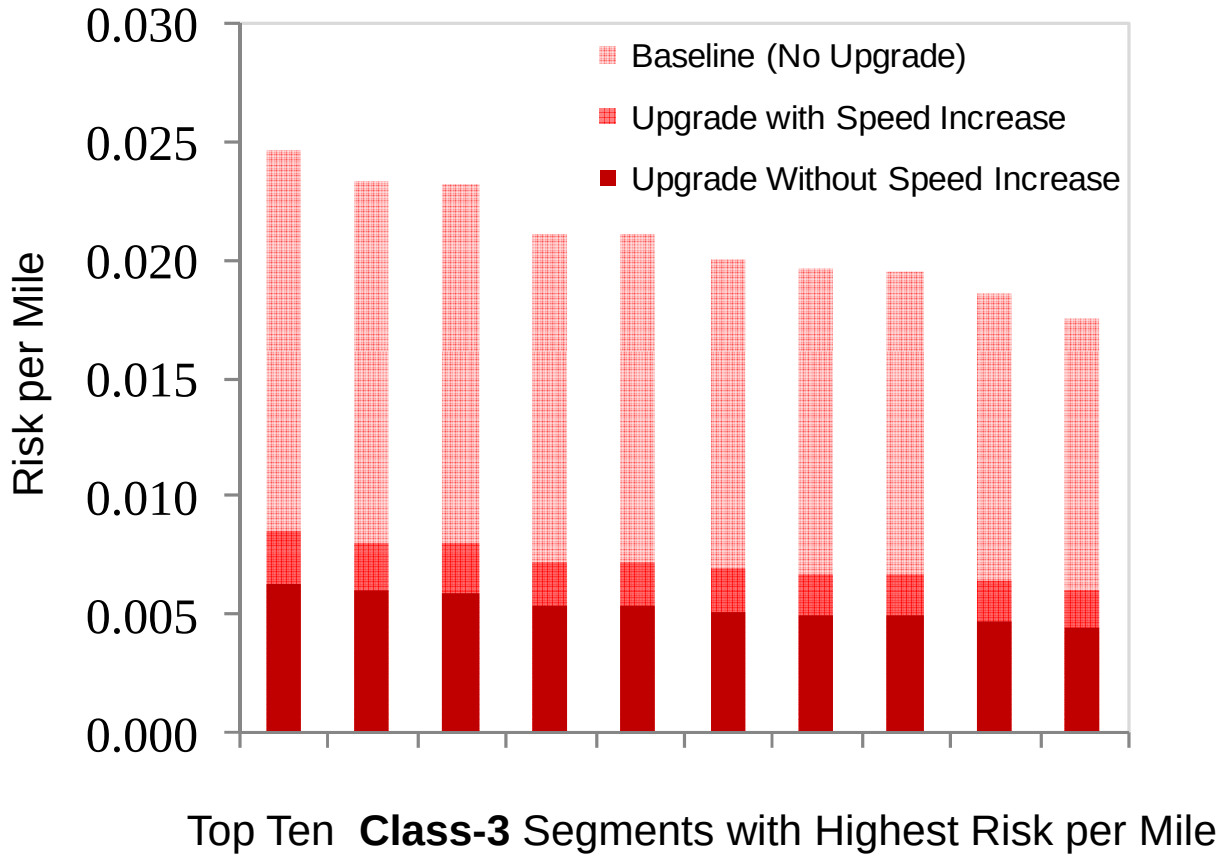
Class-2 Segments Upgraded to Class 3 (Without Speed Increase)



- Class-2 segments represent a small proportion in the route. Therefore, risk reduction by upgrading them will not be much.

Effects of Infrastructure Improvement and Train Speed on Segment-specific Risk

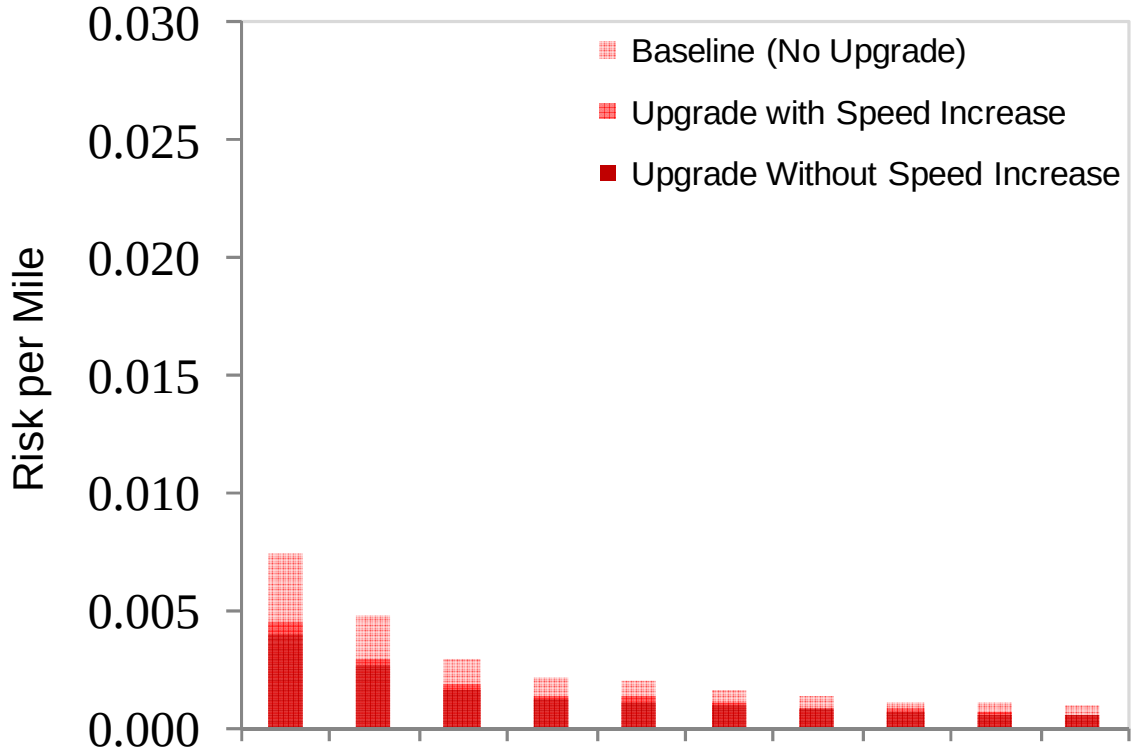
Class-3 Segments Upgraded to Class 4



- For the representative route, upgrading class-3 segments to class 4 may be the most suitable option since it offers the greatest risk reduction.

Effects of Infrastructure Improvement and Train Speed on Segment-specific Risk

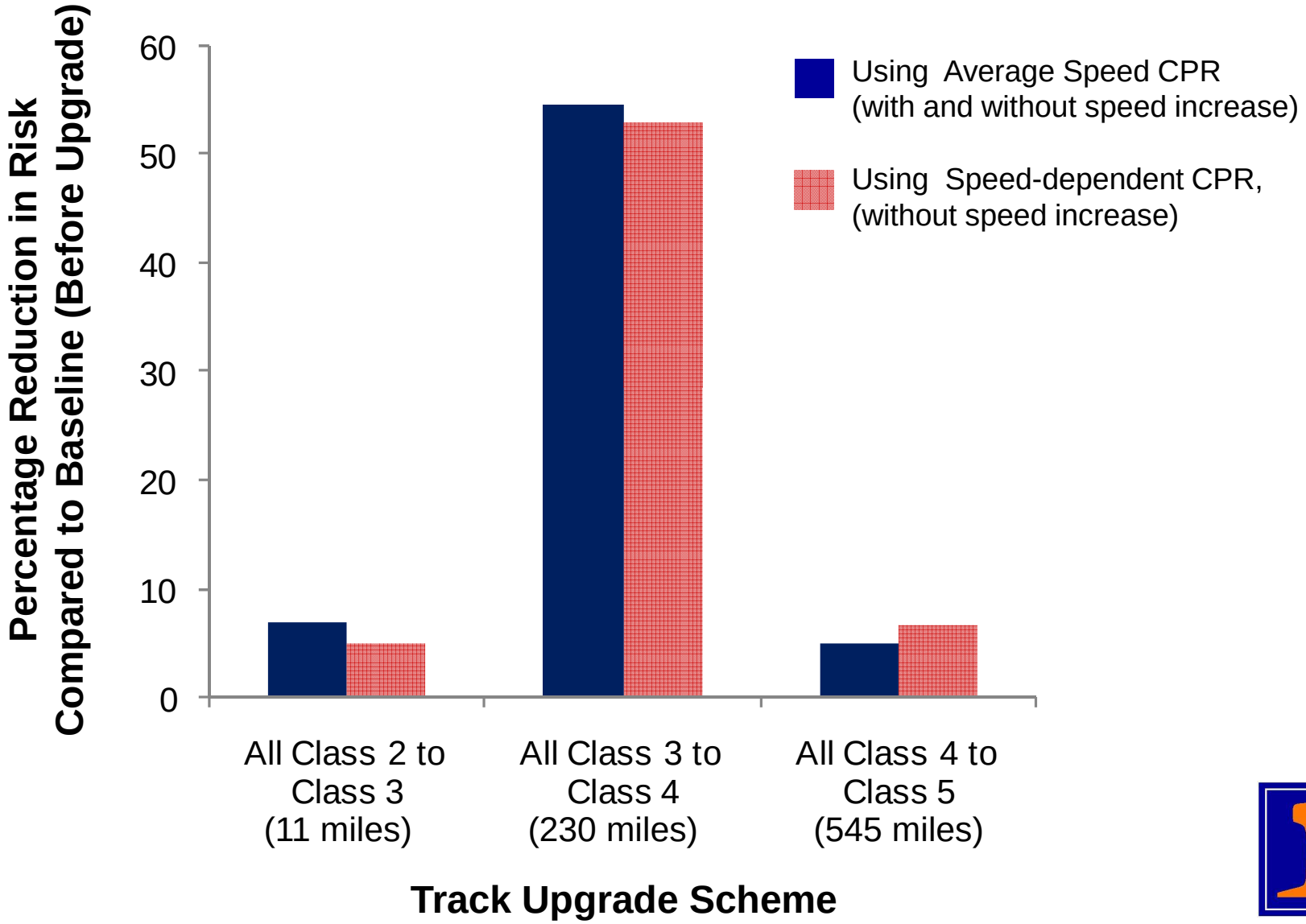
Class-4 Segments Upgraded to Class 5



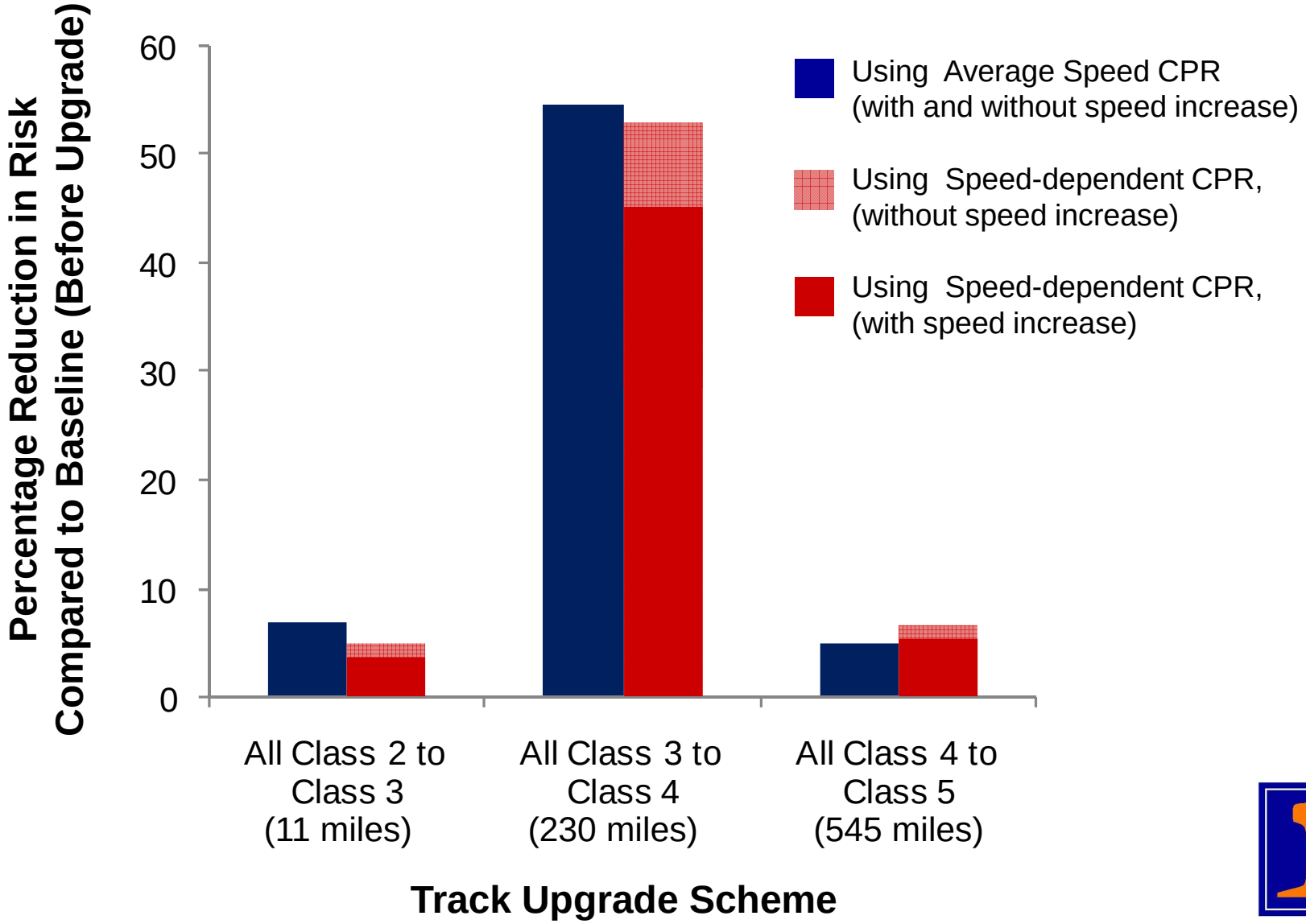
Top Ten **Class-4** Segments with Highest Risk per Mile

- Track classes 4 and 5 represent the highest proportion in the route but upgrading class 4-segments to class 5 gives a little reduction in risk.

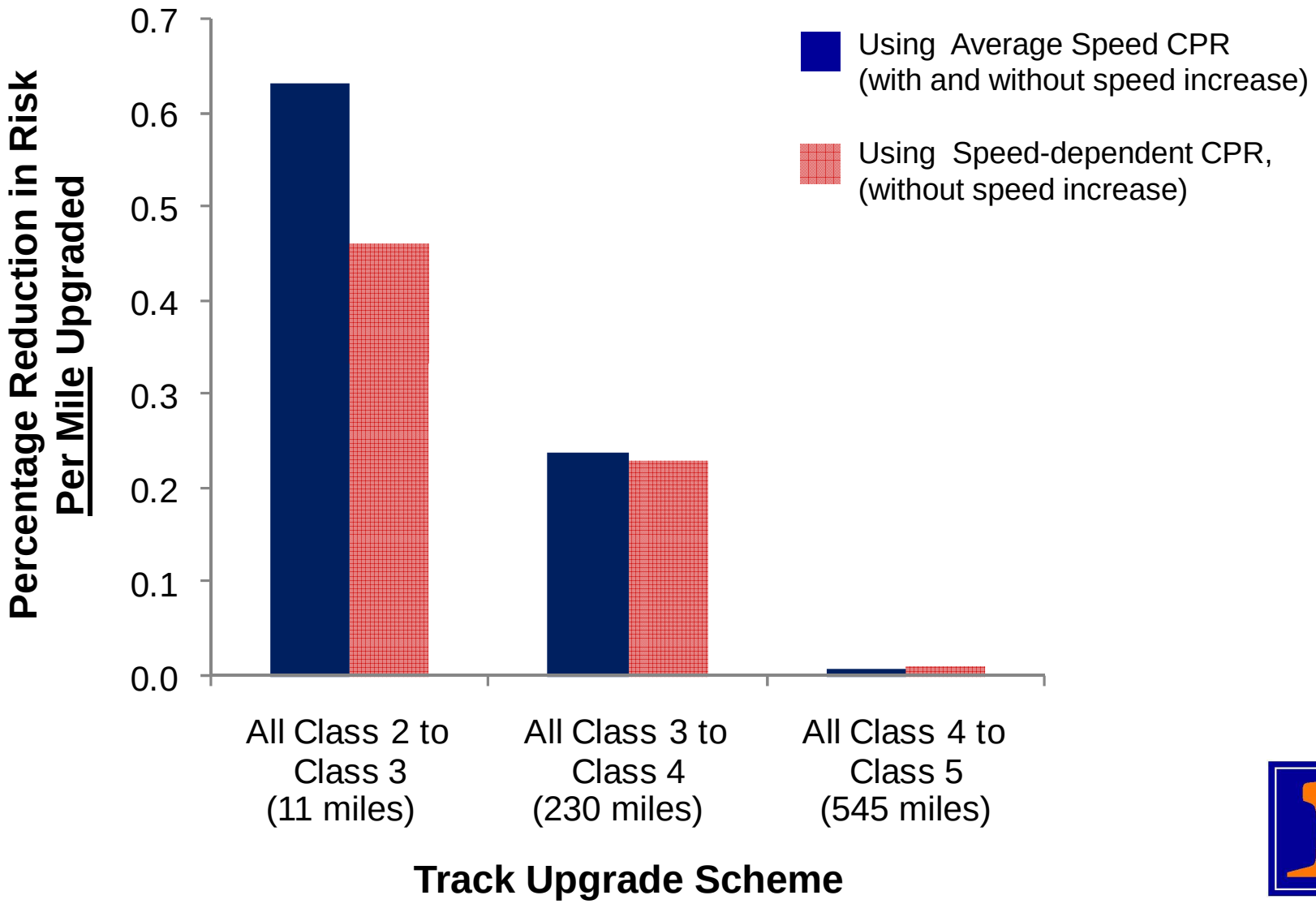
Effects of Infrastructure Improvement and Train Speed on Route-specific Risk



Effects of Infrastructure Improvement and Train Speed on Route-specific Risk



Effects of Infrastructure Improvement and Train Speed on Route-specific Risk



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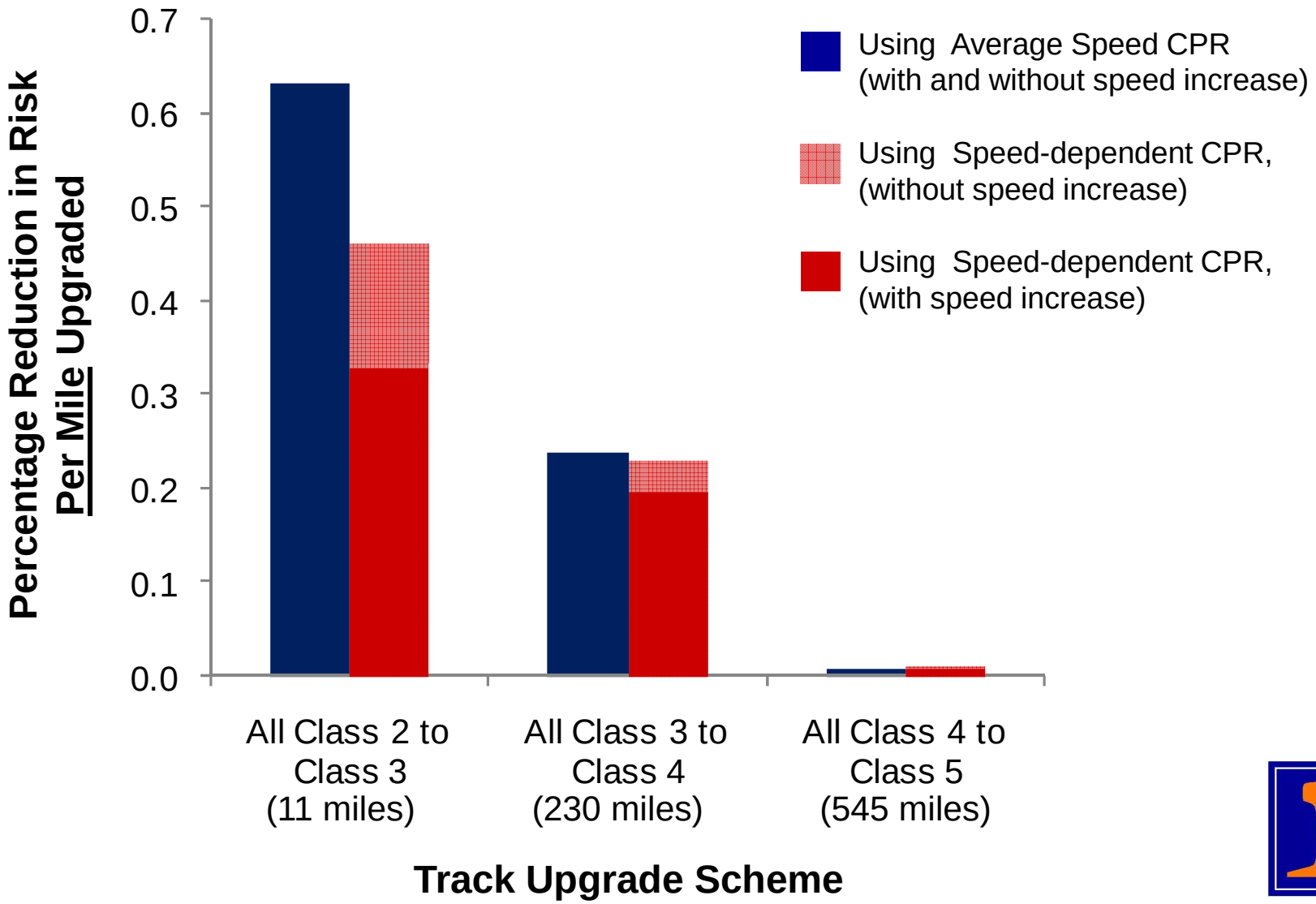


Options for Railroad Track Infrastructure Improvement to Reduce Hazardous Materials Transportation Risk

- We identified a particular track class that gives the highest risk reduction.
- Next step is to identify the locations in the network where upgrade may be considered to obtain the most safety benefits possible. In this regard, one may consider:
  - Mathematical programming
  - Simulation
  - Graphical technique
  - Expert opinion
- The model and techniques presented here are primarily intended to illustrate the application of speed-dependent CPR in risk management and analyses.
- Therefore, the results may not represent the best (actual) practice regarding track maintenance or upgrade.

Investment Selection Problem for Railroad Track Infrastructure Improvement

Mathematical Programming (Mixed-Integer Nonlinear Problem: MINLP)

$$\textit{Minimize Annual Risk, } S = \sum_{i=1}^{n} V_i Z_i (L_i - U_i + U_i) W_i D_i A_i$$

subject to

$$\sum_{i=1}^{n} U_i \le X \quad \rightarrow \text{Resource}$$

$$U_i = C_i L_i, \quad \forall i \quad \rightarrow \text{Upgrade length}$$

$$Z_i = T_i - C_i M_i, \quad \forall i \quad \rightarrow \text{Accident rate}$$

$$W_i = R_i - C_i (R_i - Q), \quad \forall i \quad \rightarrow \text{Speed-dependent CPR}$$

And

$$C_i = 1 \quad \textit{if upgrade}$$
$$= 0 \quad \textit{otherwise} \quad \rightarrow \text{Decision}$$

where

S = annual risk (persons affected per year)

V_i = shipments (carloads)

A_i = affected area (square mile)

W_i = final value of speed-dependent CPR

D_i = average population density (persons per sq. mi.)

Z_i = final value of accident rate (per car-mile)

L_i = length of the track segment (mile)

U_i = length of the track segment to be upgraded

X = maximum upgrade length (mile)

C_i = decision variable

T_i = accident rate (per car-mile)

M_i = absolute difference between the original accident rate and the new rate in which track segment is upgraded to a higher class

R_i = original speed-dependent CPR

Q = speed-dependent CPR for the upgraded segment

C_i = decision variable for track segment *i*

n = total number of segments in the route

i = track segment ID

Solution Approaches to Route Infrastructure Upgrade Selection Problem

- Solve RMINLP to obtain lower bound then trial for feasible solutions
- Use MINLP solvers
  - AlphaECP (Westerlund and Pörn)
  - BARON (Sahinidis and Tawarmalani)
  - COINBONBIN (Bonami et al.)
  - DICOPT (Vecchietti and Grossmann)
  - SBB (GAMS)
- Simplify the problem and solve as Mixed-integer Programming (MIP)
  - Need to pre-process the data
- Use simulation

Solutions Comparison

Consider upgrading class 3 track segments to one higher class under a budget equivalent to 50 mile-upgrade

Scenario / Solver Used	Route Risk	Percent Reduction
Before Improvement (Baseline)	0.7786	
After Improvement		
▪ AlphaECP	0.4739	39.1%
▪ BARON	0.4739	39.1%
▪ COINBONMIN	0.4739	39.1%
▪ COINIPOPT	0.4712	39.5%*
▪ DICOPT	0.4741	39.1%
▪ SBB	0.4718	39.4%

- Solving MINLP generally requires longer computation time.
  → up to half an hour for this particular problem
- Depending on the problems and the solvers used, global minimum may not be guaranteed.

*RMINLP

Generalized Model

Mixed-Integer Programming (MIP)

$$\textit{Minimize Annual Risk}, S = \sum_{i=1}^{n} S_i$$

subject to

$$\sum_{i=1}^{n} C_i L_i \le X \quad \rightarrow \text{Resource}$$

$$S_i = \tilde{R}_i - C_i d_i, \quad \forall i \quad \rightarrow \text{Segment risk}$$

And

$$\left.\begin{aligned} C_i &= 1 \quad \textit{if upgrade} \\ &= 0 \quad \textit{otherwise} \end{aligned}\right\} \rightarrow \text{Decision}$$

where

S_i = segment risk (persons affected per year)

L_i = length of the track segment (mile)

X = maximum upgrade length (mile)

$\acute{R}_i$ = segment risk before upgrade

d = reduction in risk if segment is upgraded to a higher class

C_i = decision variable for track segment *i*

n = total number of segments in the route

i = track segment ID

Consider upgrading class 3 track segments to one higher class under a budget equivalent to 50 mile-upgrade

- Route risk before upgrade = 0.7786
- Route risk after upgrade = 0.4706*
- Percentage reduction = 39.6%

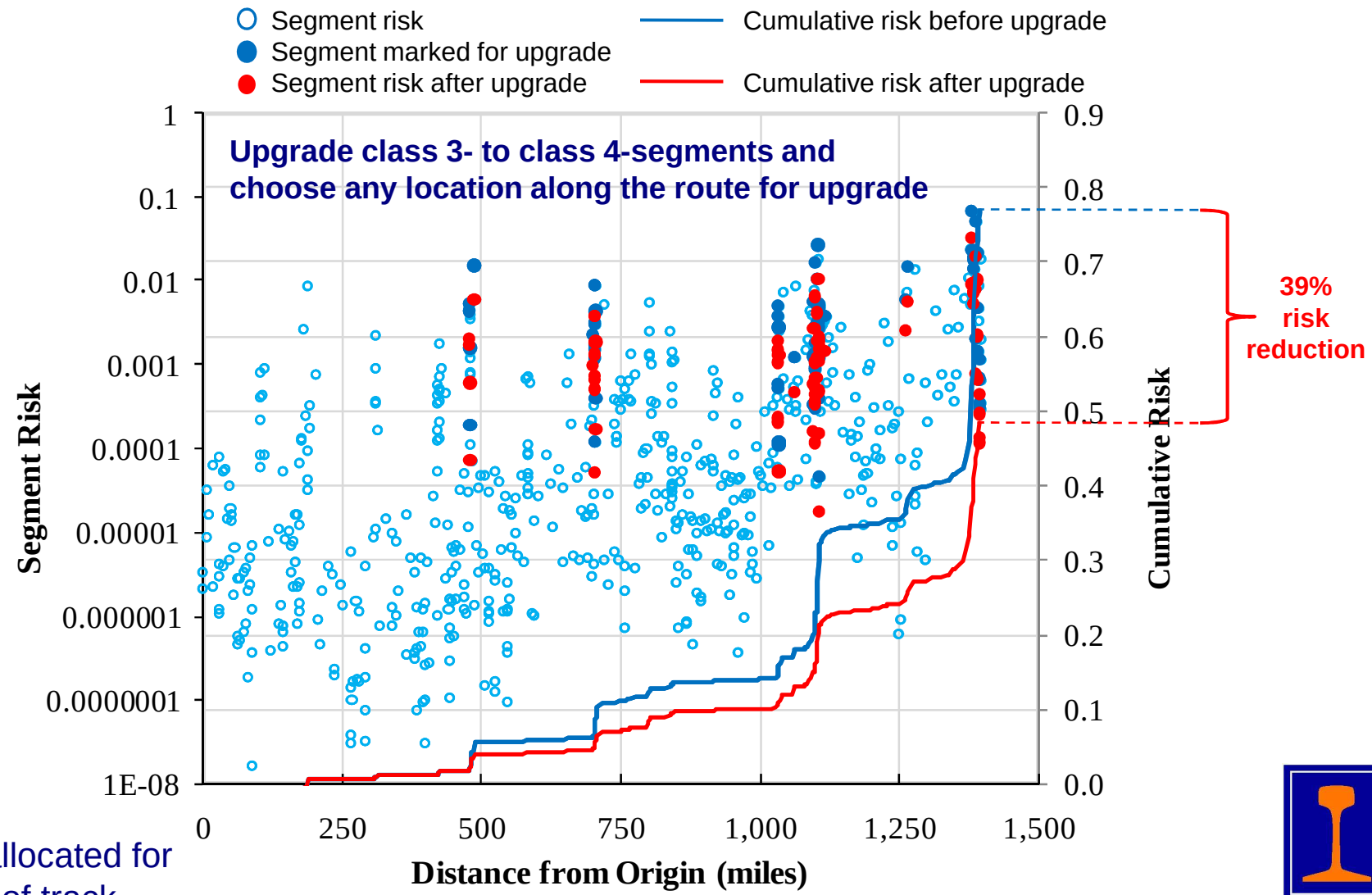
*GAMS/CPLEX MIP solution

Different Strategies of Track Infrastructure Upgrade for Risk Reduction

- Track infrastructure investment selection problem can be applied to various scenarios.
  - Upgrade lower-class track vs. higher class track
  - Upgrade one track class vs. multiple track classes
  - Upgrade any segments vs. contiguous segments

- Following are illustrations for three cases:
  - Upgrade class 3- to class-4 segments at any location
  - Upgrade class 3- to class-4 segments in one particular area
  - Upgrade class 4-segments or lower at any location

Graphical Representation of Risk Reduction by Railroad Track Infrastructure Improvement

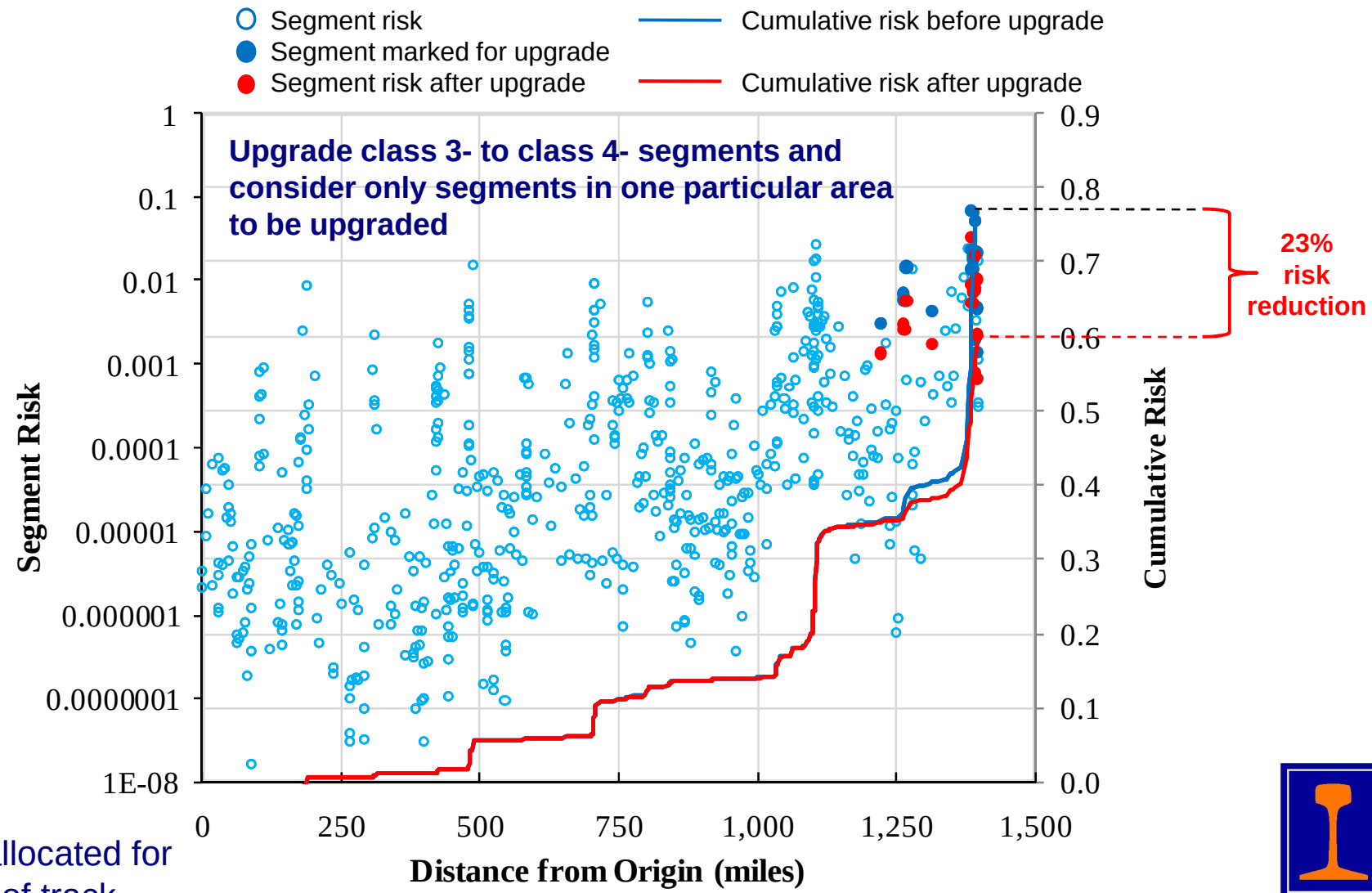


Budget allocated for 50 miles of track

Adapted from Kawprasert and Barkan (2009)

Alternate Policy for Investment Selection Problem:

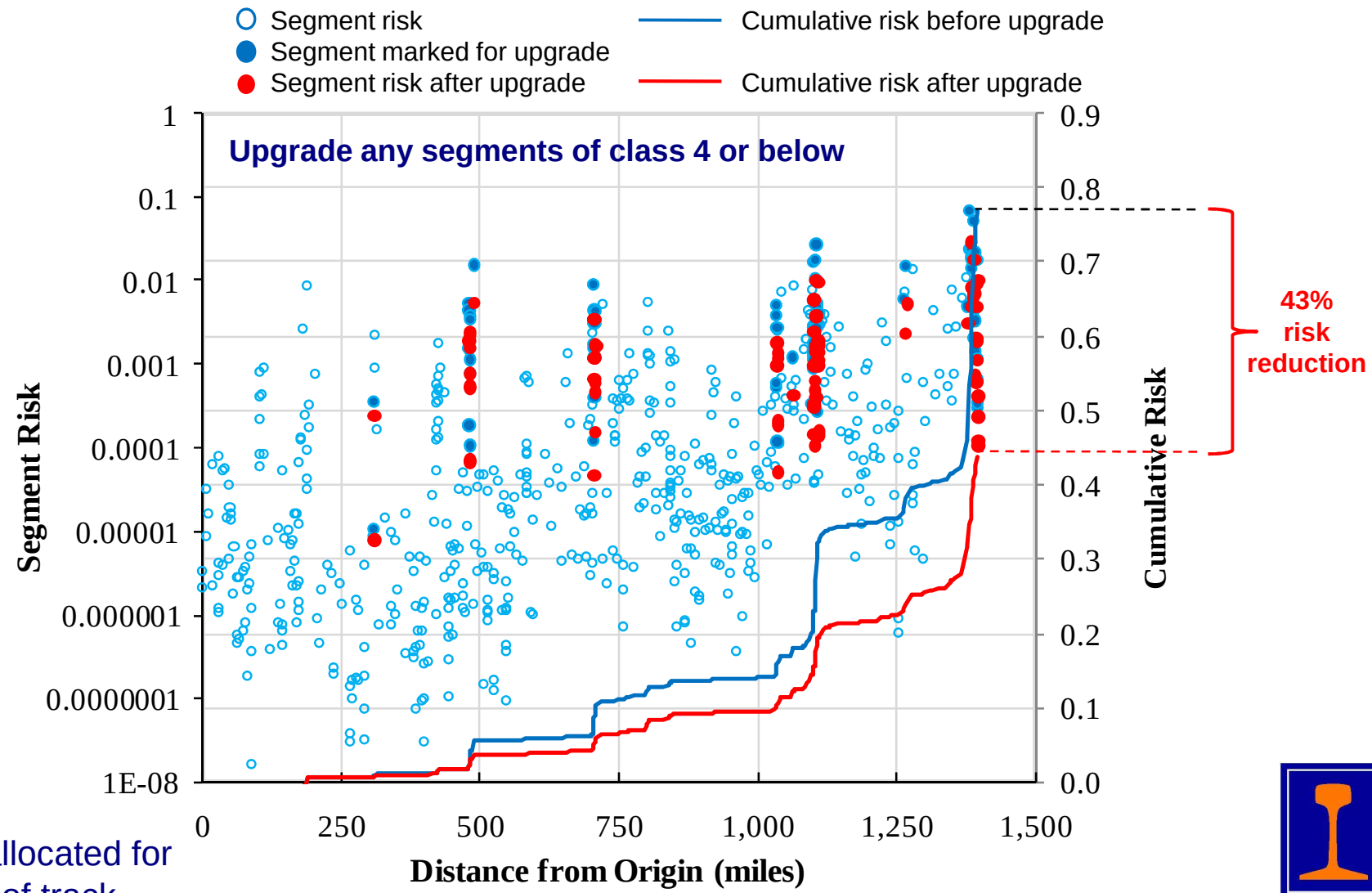
Focus on One Particular Area



Budget allocated for 50 miles of track

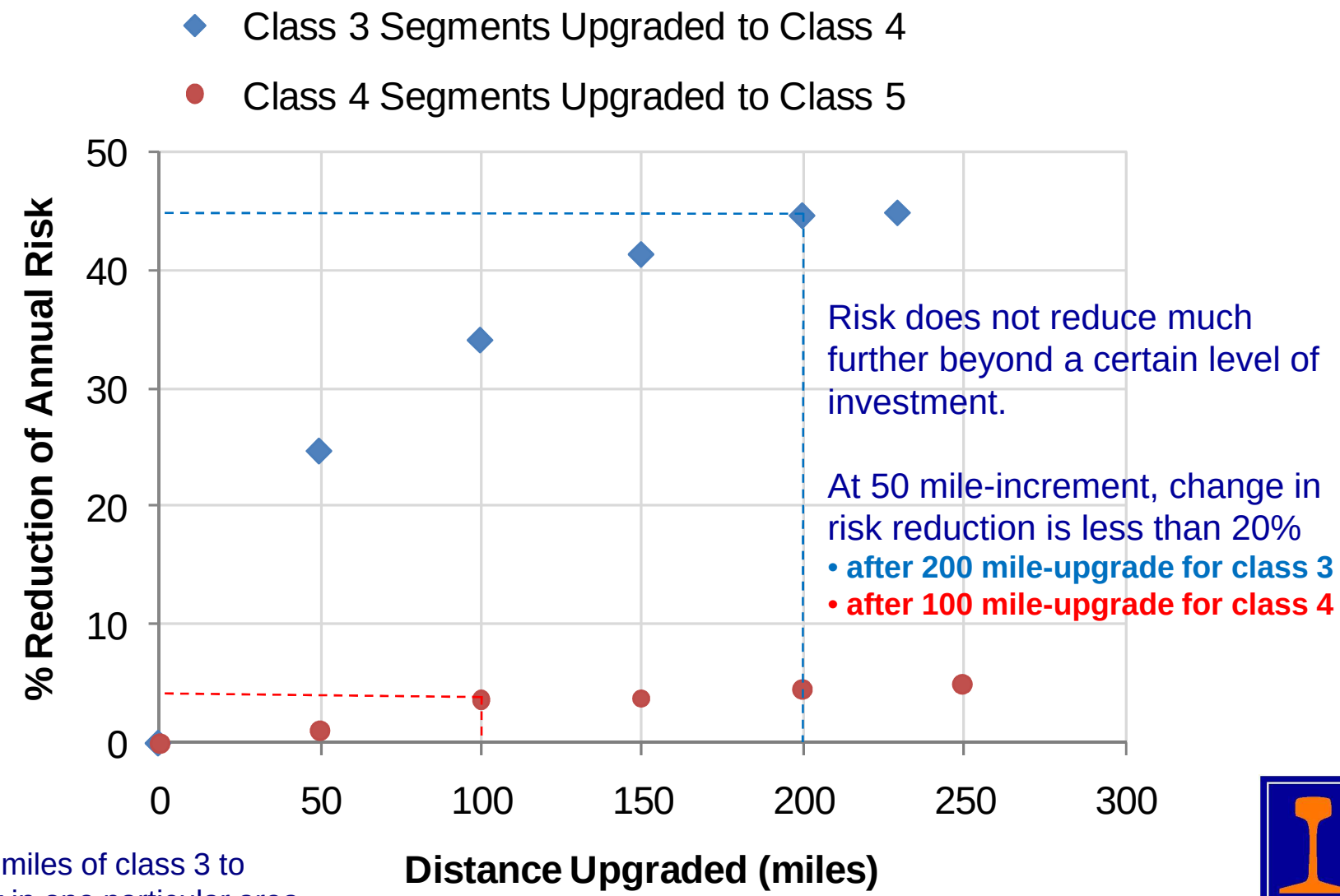
Alternate Policy for Investment Selection Problem:

Upgrade Class 4 Segments or Lower at Any Location



Budget allocated for 50 miles of track

Sensitivity Analysis of Investment Level on Risk Reduction



Upgrade 50 miles of class 3 to class 4 track in one particular area

Consideration of Infrastructure Upgrade Cost

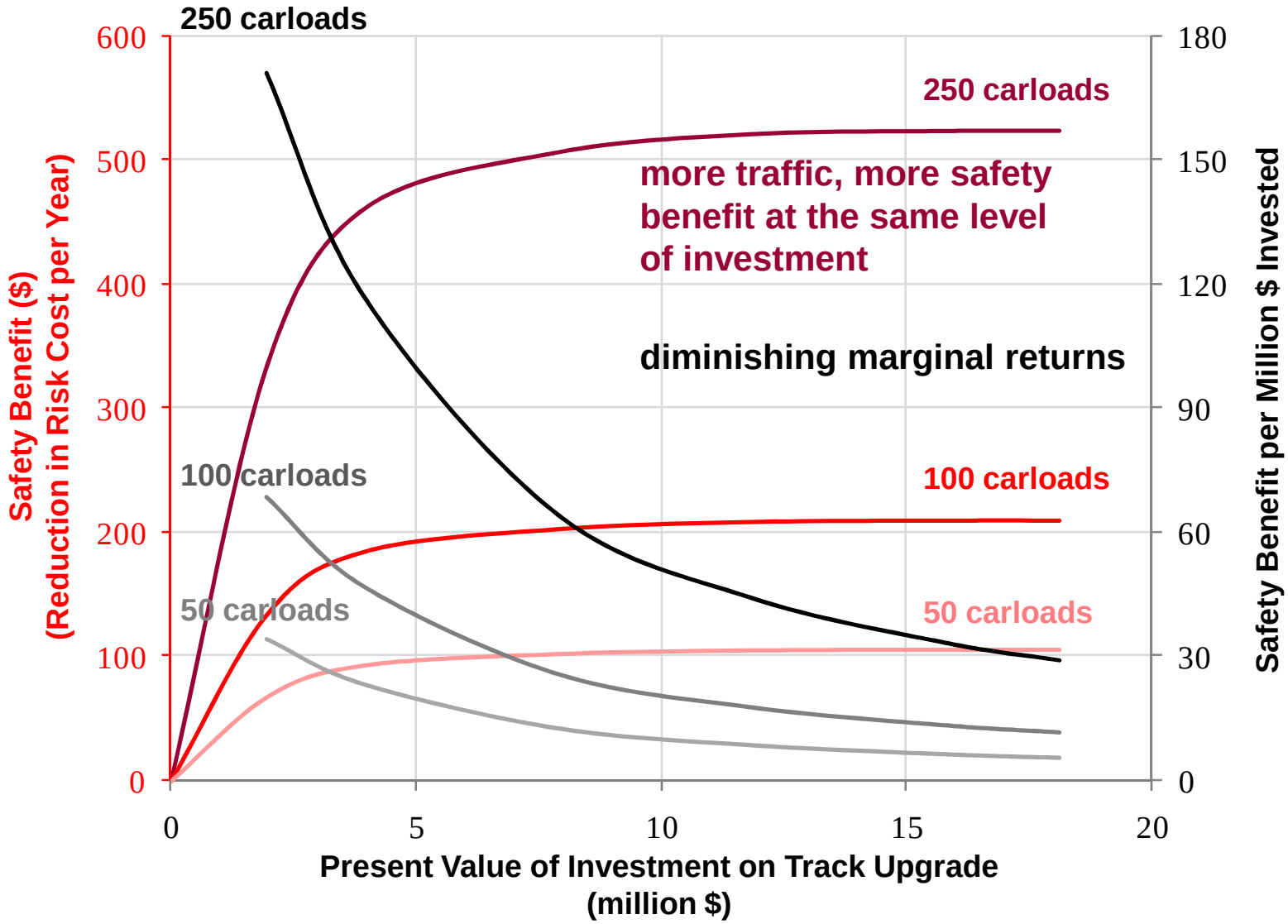
- Assume track upgrade cost: $600,000 per mile[1]
- Evacuation cost: $200 per person per day[2]
- Evacuation period: 72 hours (3 days)
- Discount rate: 7%[3]
- Track service life: 30 years

[1] Rounded from $632,833. Daniels, L. E. Track Maintenance Costs on Rail Transit Properties. TCRP Web-Only Document 43, Transit Cooperative Research Program, Transportation Research Board of the National Academies, September 2008.

[2] Pipeline and Hazardous Materials Safety Administration (PHMSA), U.S. Department of Transportation. **PIH Tank Car NPRM - Regulatory Impact Analysis,** March 2008.

[3] Office of Management and Budget (OMB). **Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs,** Circular No. A-94, October, 1992.

Safety Benefit of Route Infrastructure Improvement As a Function of Investment Level and Traffic



Summary

- The conventional approach in which average speed CPR is used failed to account for the effect of operating changes (such as speed increase) as a result of track infrastructure improvement.
- To overcome the above, we presented a speed-dependent CPR that also helps improve accuracy of local risk estimates.
- We illustrated its application by considering route infrastructure improvement problem.
- Analyses take into account the combined effects on risk from the reduction in accident rate and the increase in CPR as a result of infrastructure improvement.

Summary (cont'd)

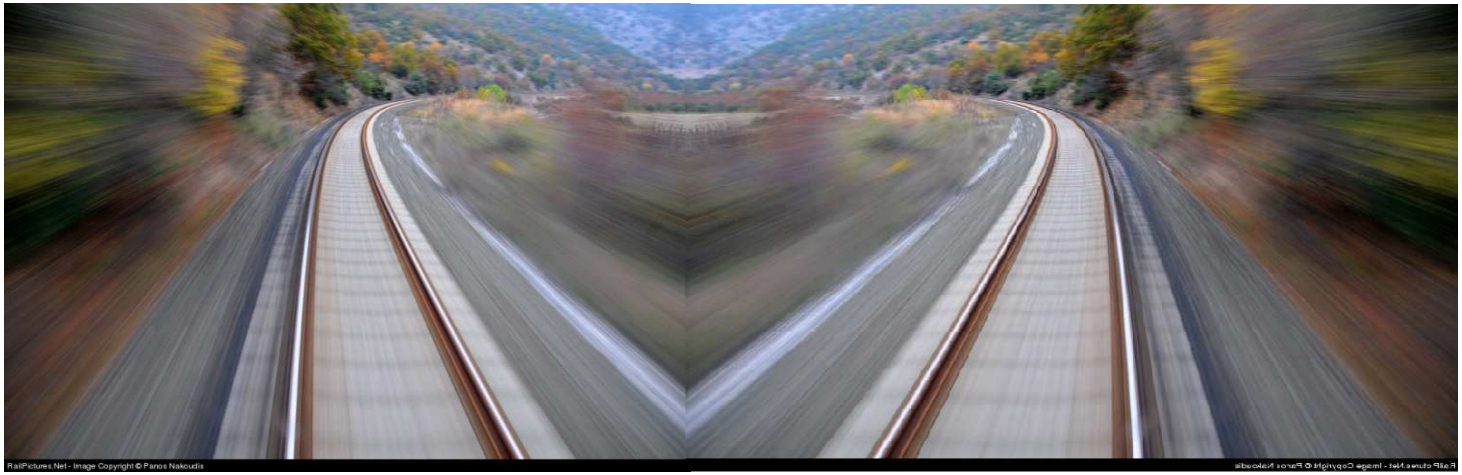
- Based on the case study of the representative shipment network, upgrading class 3 track to class 4 gives the greatest risk reduction compared to upgrading other track classes.
- The route infrastructure upgrade selection model helps determine the locations for track upgrade that potentially gives the greatest reduction in hazardous material transportation risk.
- Different upgrade strategies were illustrated.
  - Upgrade a particular class track that offers the highest risk reduction
  - Upgrade contiguous segments in one area
  - Upgrade any segments in any location
- Sensitivity analysis shows that risk does not reduce much further beyond a certain level of investment on track upgrade.
- The safety benefit from in terms of risk reduction progressively decreases as more investment is put on infrastructure improvement.
- At the same level of investment, the more traffic operated on track, the more safety benefit from route infrastructure improvement.

Limitations of the Study

- Speed-dependent CPR was developed based on 1965-1995 accident data. An update study to incorporate more recent statistics is planned.
- Timetable speeds were used in the case study, while actual operating speed or impact speed can be different.
- Differential track upgrade costs were neglected.
- Track infrastructure improvement only reduces a certain types of accident. It may be considered in conjunction with other measures.
- The model may not represent the actual practice regarding track maintenance or upgrade scheme. It does not capture other physical characteristics such as track geometry, grade and curvature.
- More detailed analysis on cost implications and economic benefits may help justify track infrastructure improvement compared to other risk reduction options.

Ongoing Research

- We are improving the estimation of the speed-dependent CPRs by considering a more up-to-date accident statistics.
- Detailed analyses on track infrastructure upgrade costs and risk cost elements are being carried out.
- These elements will enhance the applicability of route infrastructure improvement selection model and allow a better cost-benefit analysis of this risk reduction option.



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Thank you for your kind attention

Please feel free to send me an email for more questions or comments