# Appendix F.

## Railroad Crude Oil Release Rate Analysis for Route between Roseville and Benicia

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
RAIL TRANSPORTATION AND ENGINEERING CENTER
*RAILTEC*

**Final Report**

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# Railroad Crude Oil Release Rate Analysis for Route between Roseville, CA and Benicia, CA

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## EXECUTIVE SUMMARY

This report describes an analysis of the estimated annual rate of petroleum crude oil train release accidents on the rail route between Roseville, CA and Benicia, CA. Several major risk factors were taken into account, including Federal Railroad Administration track class, method of operation, tank car safety design and traffic exposure. The results show that the expected occurrence of a crude oil train release incident exceeding 100 gallons is approximately 0.009 per year, or an average of about once per 111 years. The portion of the route traversing the Suisun wetland area has an even lower annual risk of a release incident equaling 0.00381, which corresponds to an average interval between incidents of 262 years.

| Type of Tank Car | Annual Crude Oil Train Derailment Rate | Annual Crude Oil Train Release Rate | Average Interval between Release Incidents (Years) |
|---|---|---|---|
| CPC-1232, Non-Jacketed | 0.0189 | 0.00903 | 111 |


## 1. INTRODUCTION

The purpose of this analysis was to estimate the annual release rate of trains transporting petroleum crude oil on the route between Roseville and Benicia, CA. The analysis was conducted based on segment-specific rail infrastructure information and tank car safety design. This study is intended to assist the city of Benicia to understand the risk associated with rail transportation of petroleum crude to the Valero refinery.

## 2. METHODOLOGY

### 2.1. Crude Oil Train Release Rate Model

The occurrence of a crude oil train release incident is the result of a sequence of events that are affected by a number of factors. The following model was used to estimate crude oil train release rate:

$$P(R) = \sum_{i=1}^{N} Z_i S_i L_i P_i(R \mid A) \qquad (1)$$

Where:

P(R) = annual crude oil train release rate

$Z_i$ = train derailment rate per train-mile on the $i^{th}$ segment

$S_i$ = number of trains on the $i^{th}$ segment

$L_i$ = segment length (miles)

$P_i(R|A)$ = probability of at least one tank car releasing per crude oil train derailment

N = number of track segments on the route

## 2.2. Parameters in Risk Analysis

### 2.2.1. Train Derailment Rate, Z

Train derailment rate is the likelihood that a train derails per unit of traffic exposure (e.g., per million train-miles traveled). Average train derailment rate over the 5-year period 2005 – 2009 has previously been estimated using data from the U.S. Department of Transportation, Federal Railroad Administration (FRA) Rail Equipment Accident (REA) database combined with traffic data from the rail industry (Liu, 2013). The FRA database records all accidents that exceed a specified monetary damage cost to on-track equipment, signals, track, track structures, and roadbed (FRA, 2012). Train derailment rate has been shown to vary with infrastructure and operating characteristics such as: Federal Railroad Administration (FRA) track class, method of operation and traffic density (Liu 2013). Higher FRA track classes (corresponding to higher operational speeds and more stringent safety standards) and signaled trackage demonstrate lower derailment rates, compared to lower FRA track classes and non-signaled trackage (Figure 1).

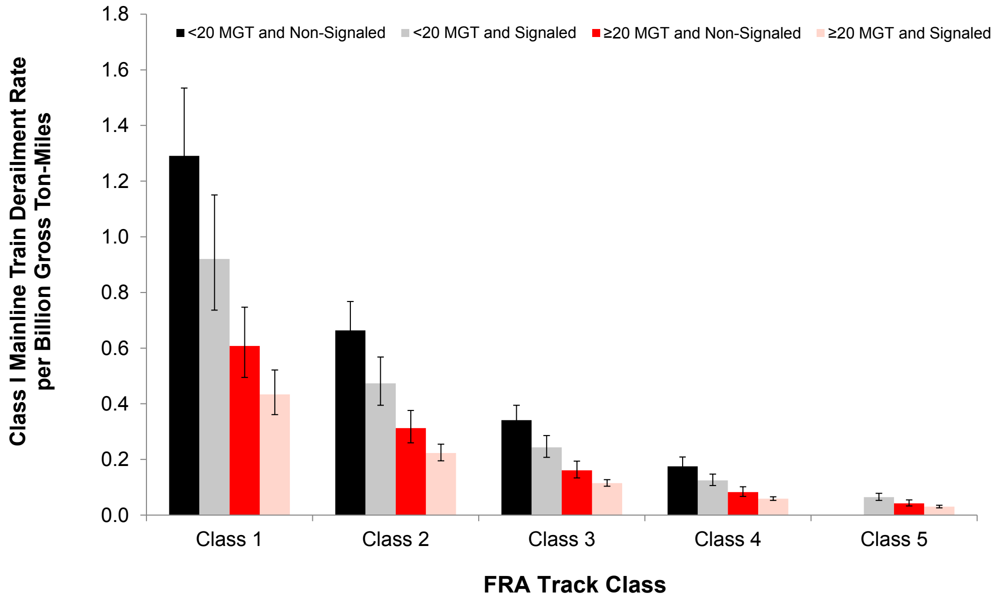


**Figure 1:** Estimated Class I mainline freight-train derailment rates by FRA track class, method of operation and annual traffic density (error bars represent 95% confidence intervals) (Liu 2013)

The train derailment rates presented in Figure 1 were developed using accident data from the FRA Rail Equipment Accident (REA) database, combined with rail industry traffic exposure data. In addition to normalized rates that can be used for comparative purposes they permit absolute rates to be calculated for any particular route and combination of characteristics (Liu 2013). These rates, combined with characteristics specific to the Roseville to Benicia route, were used to estimate the derailment rate on this line as discussed below.

### 2.2.2. Probability of at Least One Car Releasing in a Crude Oil Train Derailment

The probability of at least one tank car releasing per crude oil train derailment can be estimated using the following equation:

$$P(R \mid A) = 1 - (1 - CPR)^D \tag{2}$$

Where:

D = number of crude oil cars derailed per train derailment

CPR = conditional probability of release of a derailed or damaged tank car

The median number of cars derailed per FRA-reportable, freight-train derailment on Class I mainlines was six (Liu et al. 2013). In this analysis, we assumed that all derailed cars are crude oil tank cars (D = 6). The conditional probability of release (CPR) represents tank car safety performance in an accident and was estimated based on the latest statistics developed by the Railway Supply Institute (RSI) – Association of American Railroads (AAR) Railroad Tank Car Safety Research and Test Project. The RSI-AAR Tank Car Project analysis accounts for tank car safety design features and accident characteristics.

The car that will be used to transport the petroleum crude on this route is the enhanced safety specification tank car referred to by AAR as CPC-1232 (Figure 2). The safety features affecting its performance in accidents are summarized in Table 1. The RSI-AAR Tank Car Safety Project has calculated that the probability of releasing more than 100 gallons ($CPR_{(>100)}$) if a car of this design is derailed in an FRA-reportable accident is 0.103 (AAR-ASLRA 2013).

**Table 1** Summary of CPC-1232 Tank Car Safety Features Affecting Performance in Accidents

- 0.5" thick tank manufactured of TC-128 steel
- Half-height head shield
- Top fittings (rollover) protection
- Bottom fittings protection
- Double-shelf couplers
- High-capacity pressure relief valve

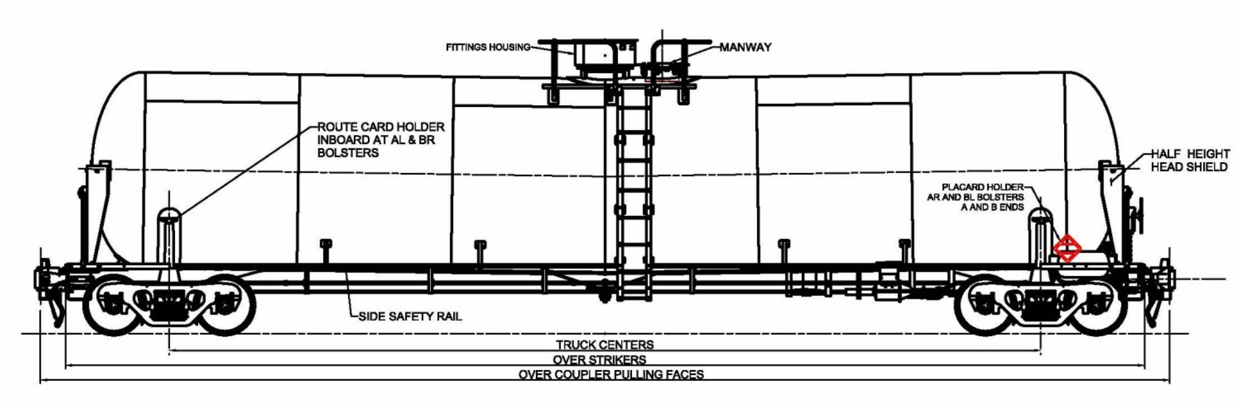


**Figure 2:** Diagram of CPC-1232 compliant tank car design

Using Equation (2), we estimated the probability of at least one tank car with the CPC-1232 design characteristics releasing if a crude oil train were to derail (Table 2). For example, if a crude oil train containing CPC-1232, non-jacketed tank cars is derailed, there is a 48% chance that this derailment will result in at least one tank car release.

**Table 2** Probability of at least one tank car releasing per crude oil train derailment (assuming six tank cars derailed per derailment)

| Type of Tank Car | $CPR_{(>100)}$ | P(R\|A) |
|---|---|---|
| CPC-1232, Non-jacketed | 0.1030 | 0.4791 |

## 3. RESULTS

### 3.1. Route Information

The Roseville to Benicia route is 69-miles long with signaled trackage that is mostly FRA class 5 with some class 3 track (Table 3).

**Table 3** Train derailment rate and mileage by FRA track class (signaled track territory)

| FRA Track Class | Train Derailment Rate Per Million Train-Miles | Percent of Mileage |
|---|---|---|
| 1 | 3.10 | 1.9% |
| 2 | 1.67 | 0.0% |
| 3 | 0.84 | 18.5% |
| 4 | 0.41 | 0.0% |
| 5 | 0.20 | 79.6% |
| Weighted Average | 0.37 | |

The mileage-weighted average train derailment rate over the entire route is 0.37 derailments per million train miles (calculation below):

3.10 × 1.9% (class 1) + 1.67 × 0% (class 2) + 0.84 × 18.5% (class 3) + 0.41 × 0% (class 4) + 0.20 × 79.6% (class 5) = 0.37 train derailment rate per million train-miles

### 3.2. Annual Train Release Rate

We calculated annual crude oil train derailment and release rates from Roseville to Benicia using the particular characteristics of the route and the methodology described above (Table 4). The annual train release rate on this route is 0.00903, which corresponds to an expected interval between release incidents of approximately once per 111 years of operation (1/0.00903).

**Table 4** Annual train derailment and release rates

| | |
|---|---|
| Train Derailment Rate per Million Train-Miles | 0.37 |
| Crude-Oil Train Release Rate per Million Train Miles | 0.18 |
| Annual Crude Oil Train Derailment Rate | 0.0189 |
| Probability of Train Derailments Involving Releases | 0.4791 |
| Annual Crude Oil Train Release Rate | 0.00903 |
| Average Interval between Release Incidents (Years) | 111 |

The route risk presented represents the entire route from Roseville to the Valero terminal in Benicia. We were also able to develop an estimate of the risk of a derailment and release on the portion of the route traversing the Suisun wetlands area (Figure 3). Using the same methodology we were able to estimate that the annual train release rate is 0.00381, which corresponds to an average interval between release incidents of 262 years.

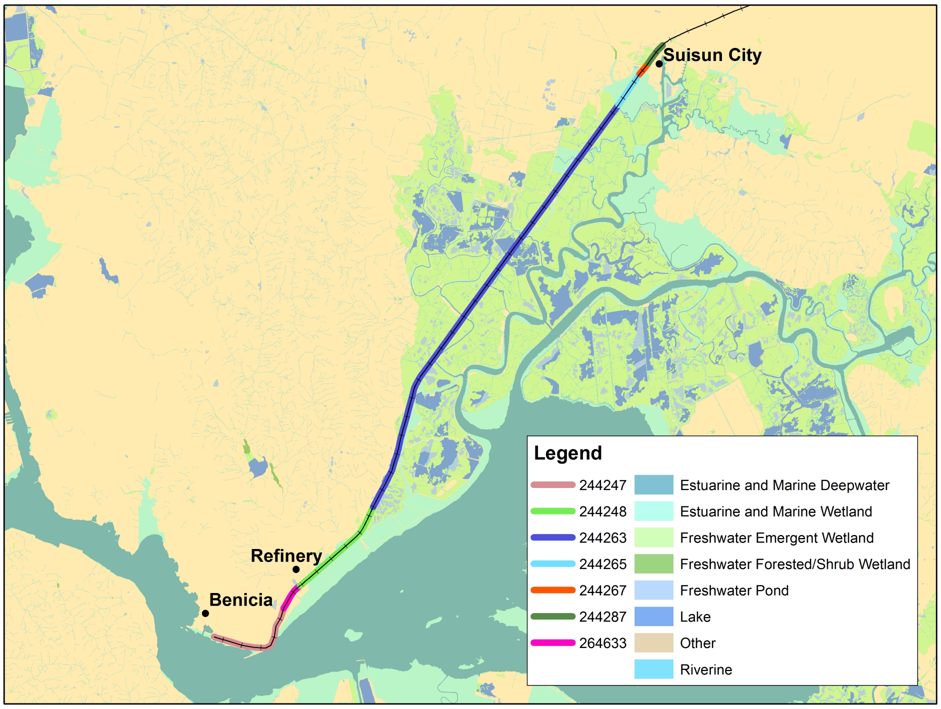


**Figure 3:** Rail route traversing the Suisun wetland area

### 3.3. Discussion & Interpretation

The risk estimates described here are probably conservative, i.e. they may tend to over estimate the risk for several reasons. The railroad industry's hazardous materials release accident rate has declined in the years since the rate estimates were developed (2005 – 2009) (Figure 4). Thus the average rate calculated over that time interval is probably higher than if the same rate were calculated using more current data. More broadly, the railroads' accident rate has been declining for decades and this trend is likely to continue due to continued investment in infrastructure and various new technologies that are being developed to improve operating safety. Furthermore, the accident rates used in this analysis do not take into account the effect of various additional safety practices specific to rail transportation of petroleum crude oil that are being implemented (AAR, 2014; Union Pacific, 2014). The risk analysis described here did not account for any of these potential reductions in accident rate.

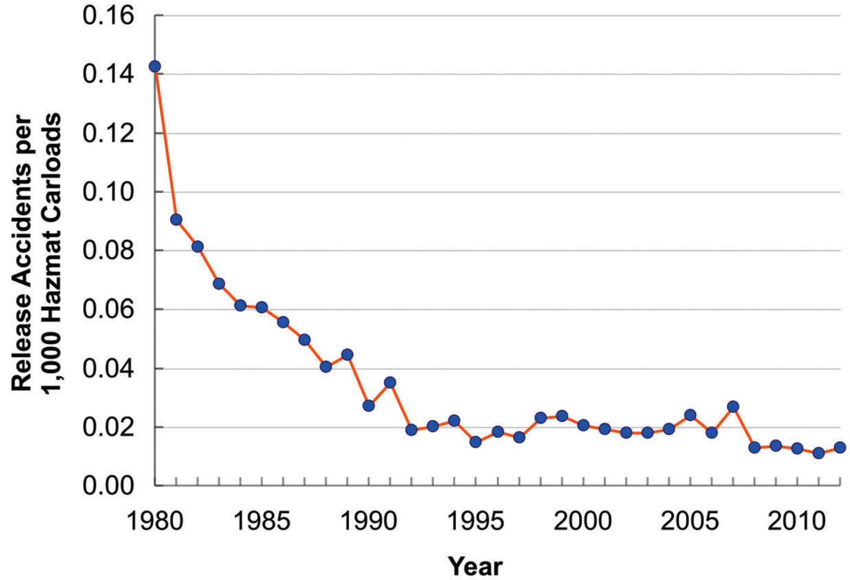


**Figure 4:** Railroad accident hazardous materials release rate 1980 – 2012
(FRA data, presented in Barkan et al 2013)

Another factor potentially causing an over estimate of the risk are possible changes in the safety design of tank cars use to transport petroleum crude oil. We assumed that the tank cars would conform to the current, AAR non-insulated CPC-1232 design. This is an industry standard agreed to in 2011 that exceeds current federal regulatory requirements for DOT 111 tank cars transporting crude oil. However, a possible result of the current federal rule-making (PHMSA, 2013) would be a requirement to use tank cars that conform to an even safer design at some point in the future, further reducing the risk.

### 3.4. Relative Risk Compared to Motor Vehicle Transport

Using the analysis described above, the estimated crude oil train release rate per million train-miles is 0.18 ($0.00903\times10^6/50552$) (Table 4). By comparison, the average estimated rate of police-reported highway accidents is 4.04 per million vehicle miles (NHTSA 2012). Thus the occurrence of a crude oil train derailment and release on the Roseville to Benicia is approximately 22 times less likely than a highway accident on a per mile-traveled basis. Considered on an annual basis, in 2012 the average U.S.

driver traveled 14,000 miles, and was 6.3 times more likely to be involved in a motor vehicle accident and 1.9 times more likely to be involved in an accident involving injuries or fatalities, than a release incident on the Roseville to Benicia route.

## 4. Summary

The major factors understood to affect railroad hazardous materials releases were quantitatively analyzed. These include Federal Railroad Administration track class, method of operation, tank car safety design and traffic exposure. The results show that the expected occurrence of a crude oil train release incident exceeding 100 gallons between Roseville and Benicia is approximately 0.009 per year, or an average of about once per 111 years. The portion of the route traversing the Suisun wetland area has an even lower annual risk of a release incident equaling 0.00381, which corresponds to an average interval between incidents of 262 years.

## REFERENCES CITED

Association of American Railroads (AAR) 2014. Freight Railroads Join U.S. Transportation Secretary Foxx in Announcing Industry Crude by Rail Safety Initiative. https://www.aar.org/newsandevents/Press-Releases/Pages/Freight-Railroads-Join-U-S-Transportation-Secretary-Foxx-in-Announcing-Industry-Crude-By-Rail-Safety-Initiative.aspx#.U4-PmcYYWkR (accessed 4 June 2014).

Association of American Railroads and American Short Line Railroad Association (AAR-ASLRRA) 2013. Comments on Docket No. PHMSA-2012-0082: Hazardous Materials: Rail Petitions and Recommendations to Improve the Safety of Railroad Tank Car Transportation (RRR).

Barkan, C.P.L., M.R. Saat, F. González, III and T.T. Treichel 2013. Cooperative Research in Tank Car Safety Design, TR News 286: 12-19, Transportation Research Board of the National Academies, Washington, DC.

Center for Chemical Process Safety (CCPS) (1995). Guidelines for chemical transportation risk analysis. Center for Chemical Process Safety of the American Institute of Chemical Engineers, New York.

Federal Railroad Administration (2012). Railroad Equipment Accident/Incident Reporting Threshold 1957–2011. FRA, U.S. Department of Transportation, Washington, DC. http://www.fra.dot.gov/eLib/details/L03622 (accessed 4 June 2014).

Liu, X. (2013). Optimal strategies to improve railroad train safety and reduce hazardous materials transportation risk. Ph.D. Dissertation, Department of Civil and

Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL.

Liu, X., M.R. Saat, X. Qin, C.P.L. Barkan (2013). Analysis of U.S. freight-train derailment severity using zero-truncated negative binomial regression and quantile regression. Accident Analysis and Prevention 59: 87–93.

National Highway Traffic Safety Administration (NHTSA) 2012. Traffic Safety Facts 2012: A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System, National Highway Traffic Safety Administration, National Center for Statistics and Analysis, U.S. Department of Transportation, Washington, DC.

Pipeline and Hazardous Materials Administration (PHMSA) 2013. Docket No. PHMSA-2012-0082, Hazardous Materials: Rail Petitions and Recommendations to Improve the Safety of Railroad Tank Car Transportation (RRR), September 6, 2013, 78 Federal Register 54: 849-861.

Union Pacific 2014. Crude-by-Rail Voluntary Safety Operating Practices https://www.uprr.com/newsinfo/attachments/media_kit/safety/crude_by_rail_safety_practices.pdf (accessed 4 June 2014).

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## Education

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| **Ph.D.** | **1987** | **Biology - State University of New York at Albany**<br>Quantitative ecology, stochastic optimization modeling, experimental design, statistical analysis |
| **M.S.** | **1984** | **Biology - State University of New York at Albany**<br>Behavioral ecology, social behavior, optimality theory, statistical analysis |
| **B.A.** | **1977** | **Goddard College, Plainfield, VT**<br>Ecology and environmental studies |

## Post-Doctoral Employment

University of Illinois at Urbana-Champaign, Urbana, IL

- 2010 – Present: Executive Director – Rail Transportation and Engineering Center (RailTEC)
- 2009 – Present: Professor
- 2001 – 2009: Associate Professor (granted tenure 2004)
- 2006 – Present: George Krambles Faculty Fellow
- 1998 – 2010: Director – Railroad Engineering Program
- 1998 - 2001: Senior Scientist

Association of American Railroads, Washington, DC

Research & Test and Safety & Operations Departments

- 1988 – 1998: Director - Risk Engineering
- 1995 – 1997: Senior Manager
- 1990 – 1994: Manager
- 1989 – 1990: Assistant Manager
- 1988 – 1989: Environmental Scientist

Smithsonian Environmental Research Center, Edgewater, MD

- 1987 - 1988: Postdoctoral Research Fellow

## PROFESSIONAL SUMMARY

Christopher P.L. Barkan is a professor in the Department of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign (UIUC) where he has been employed since 1998. Prior to that he was Director of Risk Engineering at the Association of American Railroads (AAR) where he was employed for ten years in their Research & Test and Safety & Operations Departments. At the AAR he had principal responsibility for the railroad industry's cooperative research programs in environment, hazardous materials and tank car safety. His current research interests are in railroad transportation safety and risk analysis, train derailment analysis, hazardous materials transport, tank car safety, energy efficiency, rail capacity, railroad infrastructure and operating economics, and the development and cost-effectiveness of new rail technologies. He has supervised six Ph.D. students and 29 M.S. students, all of them in rail engineering and transportation subjects. He is also Director of the National University Rail (NURail) Center, a consortium of seven colleges and universities focused on rail research and education funded by the US DOT Research and Innovative Technology Administration. He continues to serve the rail industry as Director of the AAR Affiliated Lab at UIUC, and Deputy Director of the Railway Supply Institute-AAR Railroad Tank Car Safety Research and Test Project. Dr. Barkan is an author or editor of more than 100 railroad-engineering papers, reports, chapters or books on a range of topics. He and his students have won several awards for research presented at international conferences and papers published in peer-reviewed journals. He has been an invited speaker at conferences, universities and corporations throughout North America, as well as Europe and Asia.

## QUALIFICATIONS AND RELEVANT EXPERIENCE

**University of Illinois at Urbana-Champaign**

1998 – Present, *Department of Civil & Environmental Engineering*

*Professor 2009 to present*
*Associate Professor 2001 – 2009*
*Senior Scientist 1998 – 2001*

Dr. Barkan's research at UIUC encompasses railroad transportation safety and risk analysis, hazardous materials transport, railroad energy efficiency, rail line and terminal capacity, railroad infrastructure and operating economics, and the development and cost-effectiveness of new rail technologies. Dr. Barkan teaches courses in railroad transportation engineering, railway signaling and operation, shared rail corridor engineering and operation, and advances in rail technology. Since coming to the University of Illinois, he and his colleagues have expanded the rail curriculum from one course to twelve, the largest of any North American university. He is also working with colleagues at other colleges and universities, leading efforts to expand rail transportation and engineering academic programs and opportunities nationwide.

2010 – Present, *Executive Director, Rail Transportation & Engineering Center (RailTEC)*
1998 – 2010, *Director, Railroad Engineering Program*

In addition to his research and teaching activities at UIUC, Dr. Barkan has served as director of UIUC's railroad engineering program since 1998. With the formation of RailTEC in 2010, this responsibility was expanded to encompass all rail engineering and transportation research and academic activities at UIUC. He promotes and coordinates the development of the rail curriculum and supports faculty and students conducting research on a wide range of topics to improve rail safety, reliability and efficiency.

1998 – Present, *Director, Association of American Railroads Affiliated Laboratory*

Dr. Barkan directs the rail-industry sponsored research activities at UIUC, serving as Director of the AAR Affiliated Laboratory at UIUC. He maintains frequent contact, coordination and collaboration with the railroad research staff at the Transportation Technology Center Inc. in Pueblo, Colo., and with AAR headquarters staff in Washington, D.C., as well as senior engineering and technical staff and the major North American railroads and the rail supply industry.

1990 – Present, *Deputy Director, Railway Supply Institute - Association of American Railroads Railroad Tank Car Safety Research and Test Project*

Dr. Barkan has served as Deputy Director of the RSI-AAR Railroad Tank Car Safety Research and Test Project for over 20 years. The RSI-AAR Tank Car Project is a cooperative program of the tank car and railroad industries conducting research on improving tank car safety. In this role he has been extensively involved in statistical, engineering, safety and risk analyses evaluating railroad tank car transportation of hazardous materials on behalf of the two project sponsor organizations and their members. The results of this work are extensively used by industry and government stakeholders concerned with tank car safety improvement.

2012 – Present, *Director, National University Rail (NURail) Center*

Dr. Barkan is the Director of the NURail Center, a new, rail-focused, Tier-1 University Transportation Center funded by the U.S. Department of Transportation - Research and Innovative Technology Administration. In 2011, he formed led the consortium of seven colleges and universities that developed the successful proposal for the NURail Center that was awarded in early 2012 and renewed in 2013.

The principal objectives of the NURail Center are to improve and expand U.S. academic rail education, research, workforce development and technology transfer. Rail education is being enhanced through development of new, full-semester courses, continuing education programs and on-line educational opportunities. The NURail consortium selected "Shared rail corridors" as the central theme of its research program and is developing a series of strategic development plans in key areas related to the center theme, including: Integrated rail vehicle-infrastructure design, dynamics and interaction; Railroad safety and risk; Rail network capacity analysis and planning; Urban, regional and high-speed passenger rail implementation; Multi-modal freight transportation; and Rail transport funding, finance, community and economic development . These topics are critically important to sustaining and expanding U.S. freight railroad transportation excellence while at the same time developing commuter and intercity passenger rail.

1988 – 1998, *Association of American Railroads - Research and Test Department and Safety and Operations Department*

From 1988 through 1998, Dr. Barkan was employed in positions of increasing responsibility by the Association of American Railroads in Washington, DC. For most of this time he had principal responsibility for direction and management of the railroad industry's cooperative research programs in environment, hazardous materials transportation risk and tank car safety. In this position he worked extensively on research projects with major railroads, the railway tank car industry, chemical and petroleum shippers, government agencies in the U.S. and Canada and other organizations concerned with improving railroad environmental and safety performance.

## Selected Recent Publications

### Peer-Reviewed Journal Articles

Liu, X., M.R. Saat, C.P.L. Barkan 2014. Probability analysis of multiple-tank-car release incidents in railway hazardous materials transportation (Accepted with revisions) Journal of Hazardous Materials.

Saat, M.R., Werth, C.J., Schaeffer D.,Yoon, H., Barkan, C.P.L. 2014. Environmental risk analysis of hazardous material rail transportation. Journal of Hazardous Materials 264: 560-569.

Dingler, M.H., Y-C. Lai, and C.P.L Barkan. 2013. Effect of train-type heterogeneity on single-track heavy haul railway line capacity. In-Press, Journal of Rail and Rapid Transit.

Dingler, M.H., Y-C. Lai, and C.P.L. Barkan. 2013. Mitigating train-type heterogeneity on a single-track line. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 227: 140-147.

Liu, X., M.R. Saat, C.P.L. Barkan and X. Qin 2013. Analysis of U.S. freight-train derailment severity using zero-truncated negative binomial regression and quantile regression. Accident Analysis and Prevention 59: 87–93.

Liu, X., M.R. Saat and C.P.L. Barkan 2013. Integrated risk reduction framework to improve railway hazardous materials transportation safety. Journal of Hazardous Materials 260: 131-140.

Liu, X., M.R. Saat and C.P.L. Barkan 2013. Safety-effectiveness of integrated risk reduction strategies for rail transport of hazardous materials. Transportation Research Record - Journal of the Transportation Research Board 2374: 102-110.

Lovett, A., G. Munden, M.R. Saat and C.P.L. Barkan 2013. High-speed rail network design and station location evaluation: a model and sensitivity analysis. Transportation Research Record - Journal of the Transportation Research Board 2374: 1-8.

Rapp, C.T., M.C. Dersch, J.R. Edwards, C.P.L. Barkan, B. Wilson and J. Mediavilla 2013. Measuring concrete cross-tie rail seat pressure distribution with matrix-based tactile surface sensors. Transportation Research Record - Journal of the Transportation Research Board 2374: 190-200.

Saat, M.R., C.J. Werth, D. Schaeffer, H. Yoon and C.P.L. Barkan 2013. Environmental risk analysis of hazardous material rail transportation. Accepted, Journal of Hazardous Materials.

Sogin, S.L., Y-C Lai, C.T. Dick and C.P.L. Barkan 2013. Comparison of capacity of single- and double-track rail lines. Transportation Research Record - Journal of the Transportation Research Board 2374: 111–118.

Zeman, J.C., J.R. Edwards, D.A. Lange and C.P.L. Barkan 2012. Hydraulic pressure cracking in rail seats of concrete crossties. ACI Materials Journal 109: (6) 639-646.

Liu, X, M.R. Saat and C.P.L. Barkan 2012. Analysis of major causes of train derailments and their effect on accident rates. Transportation Research Record - Journal of the Transportation Research Board 2289: 154-163.

Marruffo, A., H. Yoon, D.J. Schaeffer, C.P.L. Barkan, M.R. Saat and C.J. Werth 2012. NAPL source zone depletion model and its application to railroad-tank-car spills. Ground Water 50: 627–632.

Lai, Y-C, A. Kawprasert, C.Y. Lin, M.R. Saat, C.H. Liang and C.P.L. Barkan 2011. Integrated optimization model to manage risk of transporting hazardous materials on railroad networks. Transportation Research Record - Journal of the Transportation Research Board 2261: 115-123.

Lai, Y-C. and C.P.L Barkan. 2011. Comprehensive decision support framework for strategic railway capacity planning. ASCE Journal of Transportation Engineering 137: 738-749.

Liu, X, C.P.L. Barkan and M.R. Saat 2011. Analysis of derailments by accident cause: Evaluating railroad track upgrades to reduce transportation risk. Transportation Research Record - Journal of the Transportation Research Board 2261: 178–185.

Saat, M.R, and C.P.L. Barkan 2011. Generalized railway tank car safety design optimization for hazardous materials transport: addressing the trade-off between transportation efficiency and safety. Journal of Hazardous Materials 189: 62–68.

Schlake, B.W., C.P.L. Barkan and J.R. Edwards 2011. Train delay and economic impact of in-service failures of railroad rolling stock. Transportation Research Record - Journal of the Transportation Research Board. 2261: 124-133.

Dingler, M.H., Y-C. Lai and C.P.L. Barkan 2010. Effects of communications-based train control and electronically controlled pneumatic brakes on railroad capacity. Transportation Research Record - Journal of the Transportation Research Board 2159: 77-84.

Kawprasert, A. and C.P.L Barkan. 2010. Effect of train speed on risk analysis of transporting hazardous materials by rail. Transportation Research Record - Journal of the Transportation Research Board 2159: 59-68.

Schlake, B.W., S. Todorovic, J.R. Edwards, J.M. Hart, N. Ahuja, and C.P.L Barkan. 2010. Machine vision condition monitoring of heavy-axle load railcar structural underframe components. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit (Special Issue on Heavy Haul and Innovative Development) 224: 499-511.

Dingler, M.H., Y-C. Lai, and C.P.L. Barkan 2009. Impact of train type heterogeneity on single-track railway capacity. Transportation Research Record - Journal of the Transportation Research Board. 2117: 41–49

Kawprasert, A. and C.P.L Barkan 2009. Communication and interpretation of results of route risk analyses of hazardous materials transportation by railroad. Transportation Research Record - Journal of the Transportation Research Board 2097: 125-135.

Lai, Y-C., and C.P.L. Barkan 2009. Enhanced parametric railway capacity evaluation tool. Transportation Research Record - Journal of the Transportation Research Board. 2117: 33-40.

Ouyang, Y., X. Li, Y-C. Lai, C.P.L. Barkan, and A. Kawprasert 2009. Optimal locations of railroad wayside defect detection installations. Computer-Aided Civil and Infrastructure Engineering 24: 1–11.

Peltier, D.C. and C.P.L. Barkan 2009. Characterizing and inspecting for progressive epoxy debonding in bonded insulated rail joints, Transportation Research Record - Journal of the Transportation Research Board. 2117: 85-92.

Yoon, H., Werth, C.J., Barkan, C.P.L., Schaeffer, D.J. and Anand, P. 2009. An environmental screening model to assess the consequences to soil and groundwater from railroad-tank-car spills of light non-aqueous phase liquids. Journal of Hazardous Materials 165: 332-344.

Barkan, C.P.L. 2008. Improving the design of higher-capacity railway tank cars: optimizing the trade-off between weight and safety. Journal of Hazardous Materials 160: 122-134.

Kawprasert, A. and C.P.L. Barkan 2008. Effects of route rationalization on hazardous materials transportation risk. Transportation Research Record - Journal of the Transportation Research Board 2043: 65-72.

Schafer, D.H. and C.P.L. Barkan 2008. Relationship between train length and accident causes and rates. Transportation Research Record - Journal of the Transportation Research Board 2043: 73-82.

## Conference Proceedings Papers and Presentations - 2013

Atanassov, I., C.T. Dick and C.P.L Barkan. 2013. Incremental Capacity of Single to Double Track with Variable and Sparse Siding Spacing. Presented at the 2013 INFORMS Conference, Minneapolis, MN, October 2013.

Caughron, B.M., C. T. Dick and C.P.L. Barkan. 2013. A Project Selection Model for Improving Running Time on Passenger Rail Corridors. In: Proceedings of the American Railway Engineering and Maintenance-of-Way Association Annual Conference, Indianapolis, Indiana, September 2013.

Caughron, B.M., C. T. Dick and C.P.L. Barkan. 2013. A Project Selection Model for Improving Running Time on Passenger Rail Corridors. Presented at the ASME Joint Rail Conference, Knoxville, TN, April 2013.

Chadwick, S.G., C.T. Dick, M.R. Saat and C.P.L. Barkan. 2013. Statistical Modeling of Freight Train Derailments at Highway-Rail Level Crossings. In: 2013 World Congress on Railway Research, Sydney, Australia, November 2013.

Chadwick, S.G., M.R. Saat, C.T. Dick and C.P.L. Barkan. 2013. Decreasing Derailment Occurrence and Severity at Highway-Rail Grade Crossings. In: Proceedings of the American Railway Engineering and Maintenance-of-Way Association Annual Conference, Indianapolis, Indiana, September 2013.

do Carmo, T.B., J.R. Edwards, R.G. Kernes, B.O. Andrawes and C.P.L Barkan. 2013. Analysis of the Shear Behavior of Rail Pad Assemblies as a Component of the Concrete Sleeper Fastening System. In: 2013 World Congress on Railway Research, Sydney, Australia, November 2013.

Greve, M.J., C.T. Rapp, M.S. Dersch, J.R. Edwards, C.P.L. Barkan, J. Mediavilla and B. Wilson. 2013. Quantification of Concrete Sleeper and Elastic Fastening System Demands Utilizing Concrete Sleeper Rail Seat Contact Area. In: 2013 World Congress on Railway Research, Sydney, Australia, November 2013.

Lin, C-Y., M.R. Saat and C.P.L Barkan. 2013. Causal Analysis of Passenger Train Accidents on Freight Rail Corridors. In: 2013 World Congress on Railway Research, Sydney, Australia, November 2013.

Liu, X., M.R. Saat, and C.P.L. Barkan. 2013. A Framework for Evaluating Cost-effectiveness of Accident Prevention Strategies Under Uncertainty. In: Proceedings of the Transportation Research Board Annual Meeting, Washington, DC, January 2013

Liu, X., C.T. Dick, A.H. Lovett, M.R. Saat and C.P.L. Barkan. 2013. Seasonal Effect on the Optimization of Rail Defect Inspection Frequency. In: Proceedings of the ASME 2013 Rail Transportation Division Fall Technical Conference, Altoona, PA, October 2013.

Liu, X., C.T. Dick, A.H. Lovett, M.R. Saat and C.P.L. Barkan. 2013. Optimization of Rail Defect Inspection Frequency. Presented at the 2013 INFORMS Conference, Minneapolis, MN, October 2013.

Liu, X., M.R. Saat and C.P.L Barkan. 2013. Integrated Risk Management Framework for Improving the Safety of Hazardous Materials Transportation by Rail. In: 2013 World Congress on Railway Research, Sydney, Australia, November 2013.

Liu, X., M.R. Saat and C.P.L. Barkan. 2013. Analysis of Major Derailment Causes on Heavy Haul Railways in the United States. In: Proceedings of the 10th International Heavy Haul Association Conference, New Delhi, India, February 2013.

Liu, X., M.R. Saat and C.P.L. Barkan. 2013. Safety Effectiveness of Integrated Accident Prevention Strategies. In: Proceedings of the ASME Joint Rail Conference, Knoxville, TN, April 2013.

Lovett, A.H., C.P.L. Barkan and C.T. Dick. 2013. An Integrated Model for the Evaluation and Planning of Railroad Track Maintenance. In: Proceedings of the American Railway Engineering and Maintenance-of-Way Association Annual Conference, Indianapolis, Indiana, September 2013.

Lovett, A.H., M.R. Saat, C.T. Dick, C. Ruppert and C.P.L. Barkan. 2013. Development of an integrated railroad track maintenance model. In: 2013 World Congress on Railway Research, Sydney, Australia, November 2013.

Shih, M.-C., C.T. Dick and C.P.L Barkan. 2013. Optimal Siding Location Model. Presented at the 2013 INFORMS Conference, Minneapolis, MN, October 2013.

Shurpali, A.A., J.R. Edwards, R.G. Kernes, X. Liu, D.A. Lange and C.P.L. Barkan. 2013. Investigation of material improvements to mitigate the effects of abrasion mechanism of concrete crosstie rail seat deterioration (RSD) In: Proceedings of the Transportation Research Board Annual Meeting, Washington, DC, January 2013.

Shurpali, A.A., R.G. Kernes, J.R. Edwards, M.S. Dersch, D.A. Lange and C.P.L. Barkan. 2013. Investigation of the Mechanics of Rail Seat Deterioration (RSD) and Methods to Improve the Abrasion Resistance of Concrete Sleeper Rail Seats. In: Proceedings of the 10th International Heavy Haul Association Conference, New Delhi, India, February 2013.

Sogin, S., C.T. Dick, Y-C. Lai and C.P.L. Barkan. 2013. Analyzing the Incremental Transition from Single to Double Track Railway Lines. In: Proceedings of the International Association of Railway Operations Research (IAROR) 5th International Seminar on Railway Operations Modelling and Analysis, Copenhagen, Denmark, May 2013.

Van Dyk, B.J., C.T. Rapp, M.S. Dersch, J.R. Edwards, C.J. Ruppert, Jr. and C.P.L. Barkan. 2013. Evaluation of Existing Loading Environment in North America for Improved Concrete Sleepers and Fastening Systems. In: 2013 World Congress on Railway Research, Sydney, Australia, November 2013.

Van Dyk, B.J., J.R. Edwards, C.J. Ruppert Jr. and C.P.L. Barkan. 2013. Considerations for Mechanistic Design of Concrete Sleepers and Elastic Fastening Systems in North America. In: Proceedings of the 10th International Heavy Haul Association Conference, New Delhi, India, February 2013.

Van Dyk, B.J., M.S. Dersch, J.R. Edwards, C.J. Ruppert Jr. and C.P.L. Barkan. 2013. Quantifying Shared Corridor Wheel Loading Variation Using Wheel Impact Load Detectors. In: Proceedings of the ASME Joint Rail Conference, Knoxville, TN, April 2013.