

Risk Analysis of Transporting Crude Oil by Rail

Methodology and Decision Support System

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In 2014, there were around 500,000 carloads of petroleum crude oil on the U.S. railroad network, an 80-fold increase since 2005. A spate of crude oil release incidents has attracted national attention to railroad transportation safety. A practical probabilistic risk analysis model to estimate the in-transit risk of transporting crude oil by rail in unit trains on main lines is described. The goal of the research for the model was to provide methods and tools for optimal safety risk management of rail transport of crude oil and other hazardous materials. The model accounts for track segment specific characteristics, including segment length, FRA track class, method of operation, and annual traffic density; train-specific characteristics such as train length, train speed, and tank car safety design; and population density along each segment. The risk model estimates segment-specific risk that is measured by the expected number of affected persons. Also, the model estimates the average interval between release incidents. The model is implemented into a decision support tool that automates risk calculation, interpretation, and visualization. The methodology and implementation tool developed can be adapted to specific train configurations on any given railroad network.

The United States is experiencing a boom in the production of petroleum crude oil from shale. Consequently, the rail transport of petroleum crude oil has increased dramatically. Since 2005, the volume of rail transport of crude oil has increased 80-fold, from around 6,000 carloads in 2005 to around 500,000 carloads in 2014 (1). Although more than 99.99% of railroad crude oil shipments safely reached their destinations (2), a release incident may have potentially significant consequences. A notable example is the Lac-Mégantic crude oil train derailment in Canada in July 2013, which claimed 47 fatalities and resulted in thousands of evacuees and millions of dollars in damages (3). To effectively and efficiently manage the risk of rail transport of crude oil, an accurate and implementable risk management solution is useful for both private and public sectors.

RESEARCH OBJECTIVES AND SCOPE

The objective of this study was to develop an implementable, practical risk analysis model for rail transport of petroleum crude oil in unit trains on main tracks. A crude oil release incident, albeit at a

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Transportation Research Record: Journal of the Transportation Research Board, No. 2547, Transportation Research Board, Washington, D.C., 2016, pp. 57–65. DOI: 10.3141/2547-09

relatively low probability, may cause considerable consequences, especially when an incident occurs in populated or environmentally sensitive areas. In this paper, the risk model estimates the probability of a train derailment–caused crude oil unit-train release incident as well as the consequences of that release (e.g., measured by the affected population in the evacuation area). The specific objectives of this paper include

1. To develop a probabilistic risk analysis model that will quantify the likelihood and consequence of a crude oil release incident, accounting for route-specific and train-specific characteristics;
2. To implement the risk analysis methodology into a geographic information system (GIS)–based decision support tool that automates risk calculation, interpretation and visualization; and
3. To propose future research directions and technical roadmaps for risk management of rail transport of crude oil and other hazardous materials.

The paper begins with a comprehensive literature review, followed by model development and implementation. After that, the paper introduces a decision support tool that calculates and visualizes location-specific crude oil release risk. Finally, the paper provides its principal findings and describes possible future research directions.

LITERATURE REVIEW

Event Chain of a Hazardous Materials Release

A train accident–caused hazardous materials release results from a chain of events (Figure 1). Several factors affect the occurrence of each event. The literature has discussed the effects of certain risk factors through context-specific risk models.

The literature focuses on five areas of risk factor research:

1. Train derailment rate,
2. Number of cars derailed,
3. Number of tank cars derailed,
4. Number of tank cars releasing contents, and
5. Release consequences.

Each area is explained in detail in the following subsections.

Train Derailment Rate

Derailment is a common type of freight train accident in the United States (5). Most major hazardous materials releases occurred in

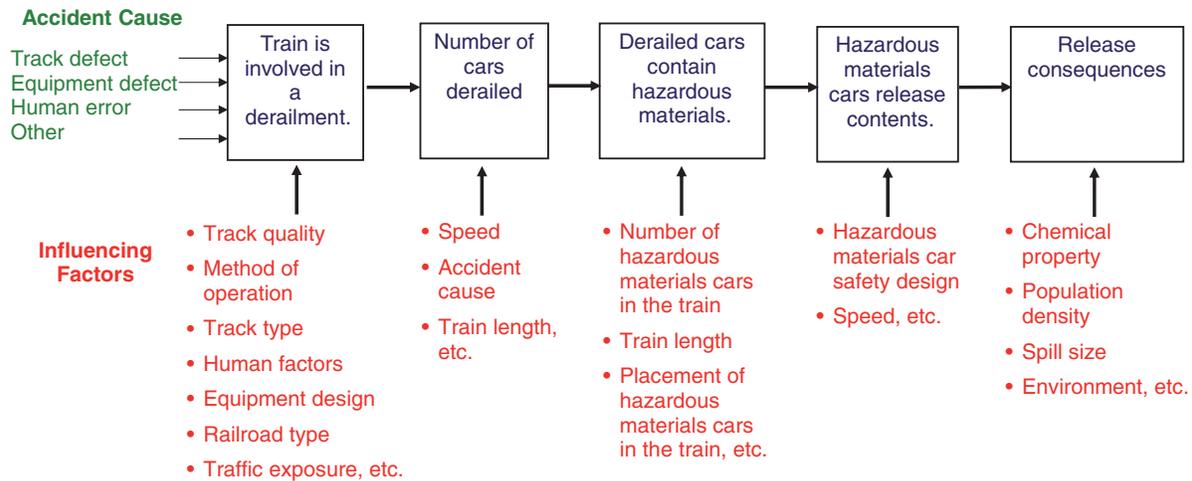


FIGURE 1 Event chain of a railroad hazardous materials release incident (4).

train derailments (6). Train derailment rate, defined as the number of accidents normalized by traffic exposure, is a proxy for train derailment likelihood. Train derailment rate correlates with FRA track class (7, 8), the method of operation, and annual traffic density (9). The latest industrywide study found that all three factors (FRA track class, method of operation, and traffic density) significantly affect train derailment rate (9).

Number of Railcars Derailed

The number of cars derailed is related to accident kinetic energy and has been used to measure train derailment severity (6). Several studies have investigated the effects of train derailment severity factors, such as accident speed (6, 10–13); point of derailment (the position of the first car derailed) (10, 11); train length (10, 11); and accident cause (5, 6, 8, 12).

Number of Tank Cars Derailed

If a train carries both tank cars and other types of cars, the probability that a tank car will derail depends on the amount and placement of tank cars in a train (14). Glickman et al. estimated the number of tank cars derailed based on a hyper-geometric distribution assuming that tank cars were randomly placed throughout a train (15). Bagheri, Saccomanno et al. (14, 16) and Bagheri et al. (17) estimated the number of tank cars derailed given their positions in a train using a derailment profile approach. Liu et al. considered different types of derailed tank cars using a multivariate hypergeometric model (4). The derailment of a crude oil unit train would typically derail crude oil tank cars, except for those with only locomotives or buffer cars derailed (buffer cars separate locomotives and tank cars).

Number of Tank Cars Releasing Contents

The conditional probability of release (CPR) of a derailed tank car measures tank car safety performance. The CPR for a specific tank car depends on tank car design features (18, 19), derailment speed (20), and derailment severity (21).

Release Consequences

The release consequence can be evaluated by several metrics, such as the number of casualties and evacuees, property damage, traffic delays, environmental impact, litigation, business loss, and other factors. The affected area is subject to many variables, such as chemical properties, quantity released, rate of release, meteorological conditions, and local terrain (22). The U.S. Department of Transportation's *Emergency Response Guidebook* recommends that emergency responders determine initial isolation and protective action distances for specific chemicals and scenarios of release (23). According to the recommended evacuation distance, GIS techniques were used to estimate the affected population (24, 25).

Risk Modeling Research

Some studies used a so-called car-specific model to calculate railroad transportation risk (20, 26, 27). This model uses the average tank car derailment rate, regardless of train-specific characteristics, such as train length or tank car positions in a train. The car-specific risk model is suited to a preliminary, high-level risk assessment in the absence of detailed train-related information. However, this model does not account for the probability of an incident involving the releases of multiple tank cars. To address the limitations of car-specific risk models, Bagheri, Saccomanno et al. (14, 16) and Bagheri et al. (17) developed a more sophisticated train-specific risk model that accounts for train length, derailment speed, accident cause, point of derailment, and tank car positions in a train. Their model assumes that all of the derailed tank cars have equal release probabilities. That work was later extended by Liu et al. by incorporating heterogeneous release probabilities of different tank car safety designs (4).

Risk analysis models are often used to evaluate and compare risk mitigation strategies. The literature has largely focused on an individual risk reduction option, including infrastructure upgrade (12), rolling stock condition improvement (28), speed reduction (20), tank car safety design enhancement (19), routing (27), placement of tank cars in a train (14, 16, 17, 29), and emergency response (26). There is little research regarding the optimal integration of multiple risk reduction strategies, except in work by Lai et al., which is based on a simplified car-specific risk model (30).

Knowledge Gaps in the Literature

Much crude oil is shipped in unit trains, which usually have at least 50 and sometimes more than 100 cars, consisting of a single commodity. A unit-train accident can potentially cause the derailment and release of a large number of tank cars. To date, there is limited research on an integrated practical crude-by-rail risk model that encompasses all principal risk factors and risk mitigation strategies. Furthermore, there are few decision support tools available to automate complex risk assessment and communication processes, thus constraining the implementation of research in the practice. This research aims to narrow those knowledge gaps by developing a practical crude-by-rail risk analysis model based on up-to-date railroad risk research and safety statistics.

RISK ANALYSIS METHODOLOGY

This paper focuses on risk analysis of crude oil transported in unit trains. Ongoing effort is under way to adapt the current risk model to other train types. In this paper, the risk is defined as the expected consequence, measured by a product of the probability and consequence of a release incident (27):

$$R_i = P_i \times C_i \quad (1)$$

where

R_i = crude oil train release risk on the i th segment per train shipment,

P_i = probability of a crude oil release incident on the i th segment per train shipment, and

C_i = consequence of a release incident on the i th segment.

Segment-specific release probability (P_i) is estimated as a product of train accident probability, and the conditional probability that the train accident results in at least one tank car releasing crude oil:

$$P_i = P_i(A)P_i(R|A) \quad (2)$$

where $P_i(A)$ is train accident probability on the i th segment per train shipment and $P_i(R|A)$ is the probability that a derailed crude oil train causes at least one tank car releasing

Crude oil train accident probability, $P_i(A)$, can be estimated with the following equation (31):

$$P_i(A) = Z_i L_i \exp(-Z_i L_i) \approx Z_i L_i \quad \text{if } Z_i \text{ is sufficiently small} \quad (3)$$

where Z_i is train accident rate per mile and L_i is segment mileage.

Assuming that there are D crude oil tank cars derailed in a train accident, the probability of at least one tank car releasing crude oil is estimated by a binomial distribution assuming that the release probabilities of different tank cars in the same train accident are statistically independent:

$$P_i(R|A) = 1 - (1 - \text{CPR}_i)^{D_i} \quad (4)$$

where CPR_i is the average conditional probability of release of a derailed tank car on the i th segment and D_i is the average number of crude oil tank cars derailed per accident on the i th segment.

On the basis of Equations 2 to 4, route-specific crude oil train release risk is expressed as

$$R = \sum_{i=1}^N \{Z_i L_i [1 - (1 - \text{CPR}_i)^{D_i}] C_i\} \quad (5)$$

where R is total route risk per train shipment and N is the number of track segments on the route.

The annual route risk is equal to a multiplication of the risk per train shipment (R) and annual number of trains on the route (denoted as Q). The model focuses on main-line risk, without an explicit consideration of the risk in yard (32). Although main-line train accidents account for a significant proportion of the risk, future research can include the risk in other sectors, thus providing a system-level risk assessment.

To estimate main-line transportation risk, the following parameters are needed:

- Train accident rate (Z),
- Segment mileage (L),
- CPR of a derailed crude oil tank car,
- Number of crude oil tank cars derailed per accident (D), and
- Release consequence (C).

The following section leverages the latest train safety data to develop statistical estimators of those parameters. Where certain proprietary data are not available, the most relevant literature is used. Model users can update the results based on specific infrastructure, train, and operational information available to them.

PARAMETER ESTIMATION

Train Accident Rate, Z_i

The majority of hazardous materials release incidents occurred in train derailments (6). The latest freight train derailment rates were developed as a function of FRA track class, method of operation, and annual traffic density (9). That study was based on data from 2005 to 2009. In recognition of declining train derailment rates (31), a temporal adjustment factor is used to extrapolate future derailment rate. Liu found an average of 5.6% annual declining rate in Class 1 main-line freight train derailment rate from 2000 to 2014 (31). Assuming that this trend continues, a statistical model can be used to estimate freight train derailment rate now and in the near future. The development of a three-factor derailment rate and a temporal adjustment factor have been detailed in Liu (9, 31) and thus are not repeated here.

$$Z = \exp(0.9201 - 0.6649X_{\text{trk}} - 0.3377X_{\text{moo}} - 0.7524X_{\text{den}}) \times (1 - 5.6\%)^{T_i - 2009} \quad (6)$$

where

Z = estimated freight train derailment rate per billion gross ton miles;

X_{trk} = FRA track class (1 to 5);

X_{moo} = method of operation (1 for signaled track territory; 0 for nonsignaled);

TABLE 1 Average Portion of Railcars Derailed, by Train Length and Speed: U.S. Class 1 Railroad Main-Line FRA-Reportable Freight-Train Derailments, 2000 to 2014

Train Speed (mph)	Train Length (total number of cars)	Number of Train Derailments	Average Portion of Railcars Derailed per Derailment
20–30	50–70	167	0.126
	71–90	253	0.093
	91–110	346	0.097
	111–130	260	0.081
31–40	50–70	105	0.159
	71–90	161	0.134
	91–110	187	0.117
	111–130	184	0.110
41–50	50–70	97	0.212
	71–90	169	0.149
	91–110	200	0.124
	111–130	193	0.132

X_{den} = annual traffic density level (1 for ≥ 20 million gross tons; 0 for < 20 million gross tons); and
 T_i = year (e.g., T_i is equal to 2014 for year 2014).

There are limited historical data to statistically evaluate crude oil train derailment rate by various factors. Therefore, this research used the average derailment rate of all freight trains as a proxy for crude oil train derailment rate. The underlying assumption is that there is no statistical difference of derailment rate between hazardous materials trains and other types of trains. A similar assumption has been used in previous studies (8, 14). Future research is needed to better understand crude oil train accident rate and its affecting factors.

Average Number of Crude Oil Tank Cars Derailed, D_i

The FRA rail equipment accident database records the number of railcars derailed (both loaded and empty) and the total number of railcars in a train (33). Table 1 presents the average portion of railcars derailed per freight train derailment based on the data from 2000 to 2014.

For example, for train derailments occurring at speeds between 31 and 40 mph, and with 91 and 110 cars in length, an average of 11.7% of railcars in this train may derail. The use of Table 1 is

illustrated as follows. If a 100-car crude oil unit train derails at 40 mph, an average of 11.7% of tank cars might derail. Within these parameters, around 12 tank cars are expected to derail (100×0.117). This categorical statistical analysis provides a high-level estimation of the number of tank cars derailed in a unit train. Depending on questions of interest, some other researchers developed more complex position-dependent railcar derailment probability models (10, 11, 14, 16, 17). Those models are useful for risk analysis of a manifest train shipment when specific tank car positions are known. Incorporation of position-dependent tank car derailment probability for risk analysis of manifest crude oil trains is the next step of this research.

Conditional Probability of Release of a Derailed Crude Oil Tank Car, CPR_i

The Railway Supply Institute (RSI) and the Association of American Railroads (AAR) developed industrywide tank car CPR statistics. AAR published the average CPR estimate by tank car design (34) (Table 2). For example, if a nonjacketed 111A100W1 (7/16-in. tank thickness) derails, its release probability is 0.196. Given 100 cars of this type derailed, an average of approximately 20 tank cars are expected to release. By contrast, the release probability of a jacketed CPC-1232 car (7/16-in. tank thickness) is reduced to 0.046. The U.S. Department of Transportation recently issued a final specification for the new tank car standard, which is DOT-117 [Hazardous Materials: Enhanced Tank Car Standards and Operational Controls for High-Hazard Flammable Trains, PHMSA-2012-0082 (HM-251), 2015] (it is TC-117 in Canada). Table 2 summarizes different tank car specifications and the corresponding CPR values.

If a unit train contains multiple types of crude oil tank cars with different CPRs, the weighted average CPR for the train can be estimated when tank cars are randomly distributed throughout a train:

$$CPR_{ave} = \frac{\sum_{k=1}^K CPR_k Q_k}{\sum_{k=1}^K Q_k} \tag{7}$$

where

- CPR_{ave} = average CPR for the train,
- CPR_k = CPR for the *k*th type of tank car,
- Q_k = number of the *k*th tank car in a train, and
- K = total types of tank car.

TABLE 2 Tank Car Design Specifications and Conditional Probability of Release (34)

Tank Car Design	Head Thickness (in.)	Shell Thickness (in.)	Jacket	Head Shields	Top Fittings Protection	Conditional Probability of Release ^a
Conventional, nonjacketed	0.4375	0.4375	No	None	No	0.196
Conventional, jacketed	0.4375	0.4375	Yes	None	No	0.085
Nonjacketed CPC-1232	0.5000	0.5000	No	Half height	Yes	0.103
Jacketed CPC-1232	0.4375	0.4375	Yes	Full height	Yes	0.046
DOT-117	0.5625	0.5625	Yes	Full height	Yes	0.029

^aThe CPR of a tank car in this table is for a release of more than 100 gal.

For example, if a unit train has 70 jacketed CPC-1232 crude oil cars (7/16-in. tank thickness) (its CPR is 0.046) and 30 conventional jacketed cars (7/16-in. tank thickness) (its CPR is 0.085), the weighted average CPR for the train is $(0.046 \times 70 + 0.085 \times 30) / (70 + 30) = 0.058$. AAR published CPR statistics were based on 26-mph train derailment speed (21). This paper used a linear speed-dependent adjustment factor to extrapolate the CPRs at other speeds. This paper assumes that as the speed increases, the estimated CPR will increase by the same percentage based on a previous study (20). RSI and AAR are anticipated to publish a new study that explicitly quantifies the effect of speed on the CPR. However, that study was not publicly available at the time of the writing of this paper. The upcoming tank car safety statistics can be used in a revised risk model in future research.

Release Consequence, C_i

Population in the affected area was often used in previous studies (35, 36). The hazard exposure model in the U.S. Department of Transportation’s Emergency Response Guidebook recommends a 0.5-mi-radius circle as the affected area for a fire caused by flammable hazardous materials releases (23). Once the affected area is determined, the number of people affected can be estimated by multiplying the size of the affected area by the average population density within the affected area.

RESEARCH IMPLEMENTATION

A GIS-based decision support system was developed to implement the risk analysis methodology as described. This tool, called Crude Oil by Rail Risk Analyzer (CBR-Risk), has three major modules (Figure 2) as follows.

Input Module

The user provides crude oil route information including the origin, destination, and several enroute stations. Where the actual proprietary crude oil route information is unavailable, the tool generates the shortest path to connect all of these locations by using Dijkstra’s algorithm (37). Generally, the more enroute stations that a user provides, the better the generated path could represent the actual crude oil route. In addition, the user also provides train-specific information, including the annual number of crude oil unit trains on a route, amount of each type of crude oil tank cars in a train, and tank car safety specifications. In addition to data privacy, certain information may not be available for some segments. In these cases, proper assumptions need to be made to conduct a preliminary risk analysis. The methodology can be modified in accordance with the best available information.

Calculation Module

On the basis of train- and route-specific inputs, the calculation module automates risk calculation, on both the segment level and the route level, using the methodology presented in the section on risk analysis methodology.

Output Module

The risk analysis results are displayed on a GIS interface. The high-risk locations that cumulatively account for 80% of the total route risk are displayed. When the user clicks each segment, a pop-up table will display segment-specific risk information (Figure 2).

An accurate risk assessment requires carrier-specific network and traffic information, which is typically not publicly available. To

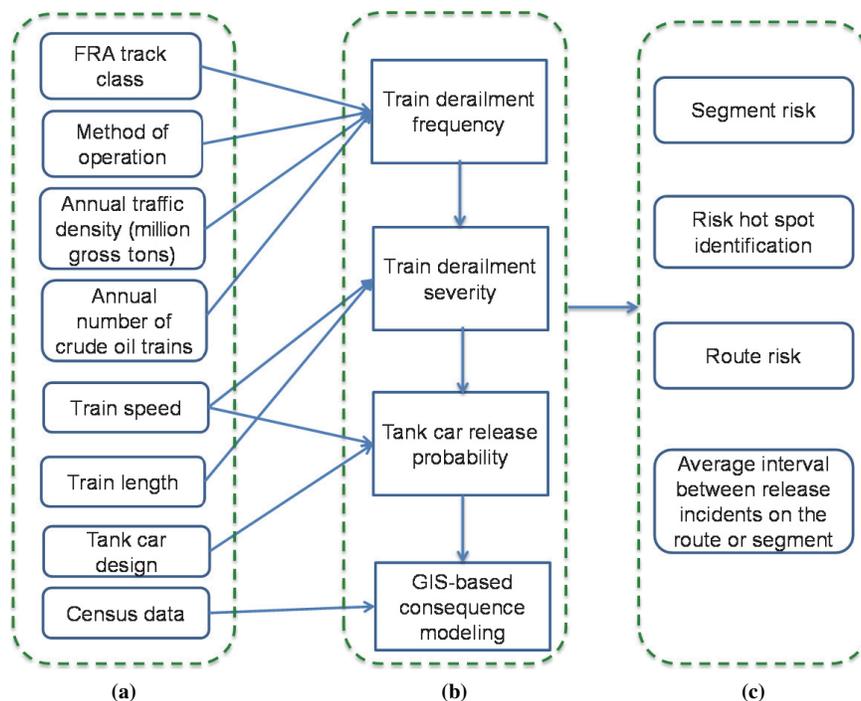


FIGURE 2 Implementation tool input and output.

verify and illustrate the technical feasibility of the model, the current CBR-Risk tool is built on hypothetical railroad infrastructure information. Consequently, the risk values presented in the following numerical example are for illustration only. Railroad carriers interested in using the tool should incorporate their network and operational information.

NUMERICAL EXAMPLE

This section presents a step-by-step procedure for using the CBR-Risk tool to assess route-specific crude oil transportation risk, based on an example in the state of New York. On the basis of a study published by the New York State government (38), the Buffalo–Syracuse–Albany route is presented as an example. For model illustration, it is assumed that the Buffalo–Syracuse–Albany route has 500 crude oil unit trains per year and each train has 100 crude oil tank cars. For the purpose of comparison, it is assumed that all of the tank cars are conventional nonjacketed DOT-111 tank cars (7/16-in.) cars. It is assumed that the train speed on this route is 30 mph. On the basis of these assumptions and segment-specific FRA track class; method of operation; and traffic density (hypothetical values are used here because the actual information is proprietary to the railroad), the CBR-Risk tool automatically calculates segment-specific risk and the corresponding recurrence intervals between release incidents (Figure 3).

It shows that annual crude oil release risk on this route in the year 2015 under the previously mentioned assumptions would be 0.0138 (expected number of persons affected), equaling to one incident every 84 years. In addition to the route risk estimator, a risk curve was also presented (Figure 4). The risk curve depicts the probability distribution of the affected population (consequence) on the studied route. For example, Figure 4 shows that the annual probability of affecting

1,000 or more people because of a possible release is around 6 out of 1 million ($6.0E-6$) on the studied route.

Furthermore, segment-specific risk distribution was analyzed to understand risk variation by population density and other factors (Figure 5). The segment risk is ranked in a descending order. It shows that at some segments, high population densities contribute to high risk estimates, while some other densely populated locations still have low risks owing to low crude oil release probabilities that are attributable to better infrastructure or operational conditions.

Finally, the route risk is interpreted in terms of the recurrent period (years) between release incidents by tank car design and traffic volume on the same route (Table 3). The analysis shows that higher annual traffic volume will increase the risk and shorten the incident recurrence interval. By contrast, an enhanced tank car design can reduce the risk and increase the interval between release incidents. For example, if all tank cars conform to DOT-117 specifications, given 500 trains per year, the release interval would increase to 172 years, compared with 84 years when all tank cars are conventional non-jacketed DOT-111. The absolute interval values are hypothetical because of hypothetical railroad network data.

DISCUSSION OF RESULTS

This section discusses how this research can contribute to the body of knowledge and how it can potentially be applied to practice.

Implications for Literature

This research aims to develop a practical risk analysis model suited to rail transport of crude oil and other flammable liquids in unit

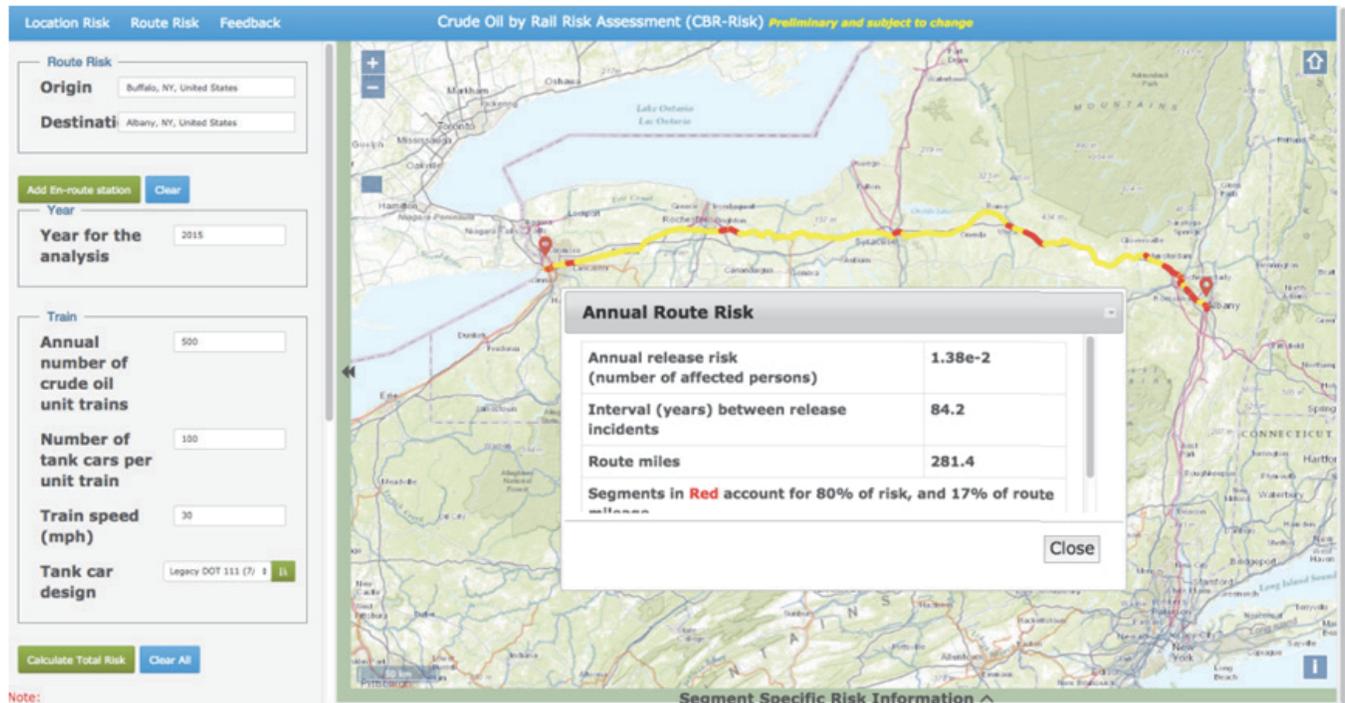


FIGURE 3 Screenshot of CBR-Risk tool used in numerical example.

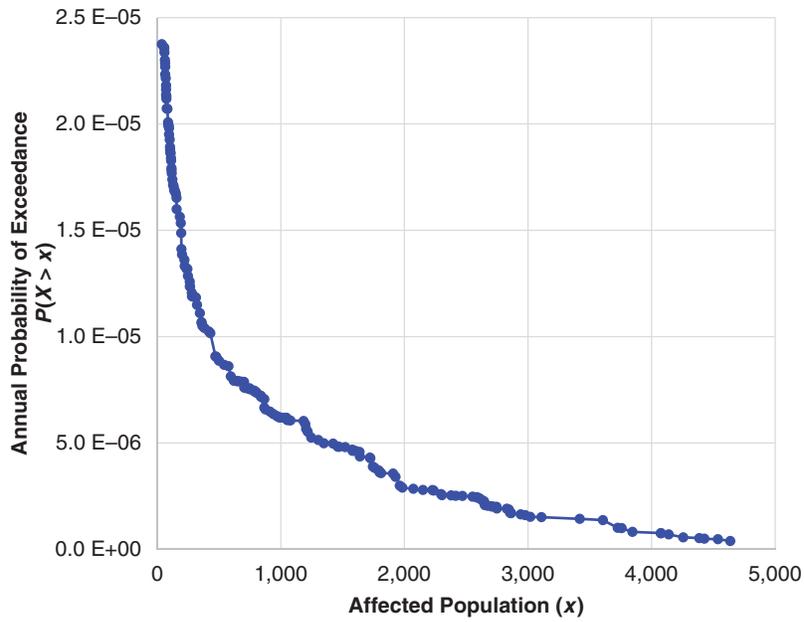


FIGURE 4 Risk curve on studied route.

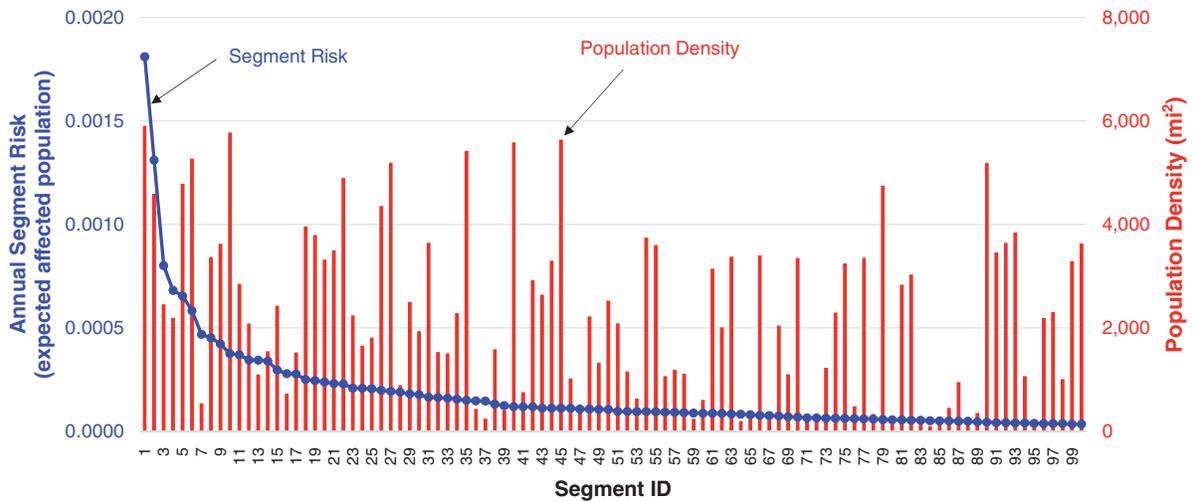


FIGURE 5 Segment risk and population density distributions, in which risk is ranked in descending order and the top 100 segments are displayed.

TABLE 3 Average Interval Between Release Incidents by Annual Number of Crude Oil Trains and Tank Car Design

Annual Number of Crude Oil Trains	Conventional Nonjacketed DOT-111	Jacketed CPC-1232	DOT-117
300	140	217	287
500	84	130	172
1,000	42	65	86

NOTE: Average interval between release incidents is in years.

trains. Previous studies developed several hazardous materials transportation risk models. The majority of previous models focused on a single railroad tank car release for toxic-inhalation-hazard materials, except Bagheri, Saccomanno et al. (14, 16) Bagheri et al. (17) and Liu et al. (4) that can analyze multiple-car release probabilities. Built on the existing work, this research aims to bring two contributions to the literature. First, this research incorporates the latest train and tank car safety statistics in crude oil transportation risk analysis that accounts for specific train and track characteristics. Second, this research provides a general methodological framework for evaluating crude-by-rail risk via unit-train shipments. One unique aspect of unit-train transport of hazardous materials is the potential for a multiple-tank-car release. This paper provides insights into the probability of a crude oil train

release given multiple tank cars derailed and possibly releasing contents.

Implications for Practice

One practical deliverable of this research is a GIS-enabled risk management decision support tool that automates all the analytical procedures. This tool can potentially be linked to a railroad-specific safety management system to permit an expedited screening of location-specific risk. Another important use of the tool is to identify, evaluate, compare, and prioritize potential risk mitigation strategies. This would address the optimal investment strategies to improve crude-by-rail safety in a cost-justified manner in the future. Public entities like municipalities could use this tool when no other alternative tool is available. They would need a proper level of cooperation from carriers if possible.

SUGGESTED FUTURE RESEARCH

Because the current study is limited by the availability of information, intensive future research might be conducted as follows:

1. The tool requires actual crude oil rail network information (e.g., crude oil route information, segment-specific FRA track class, method of operation, and annual traffic density). This information needs to be provided by railroad carriers. Since acquiring this information is beyond the scope of this study, caution should be used when employing the current tool to make risk-based decisions.
2. The current analysis focuses on unit-train shipments of crude oil. Ongoing effort is under way to adapt the model to manifest trains when tank car positions are given.
3. This research focuses on releases caused by mechanical damage incurred by tank cars in train accidents, without accounting for releases resulting from thermal tear, a process by which a fire impinging on the tank causes the steel to weaken (1). Accounting for thermal-tear-caused tank car release risk is the next step of this work.
4. The risk analysis tool can evaluate and compare different risk mitigation strategies. Accident prevention strategies affect train accident rates, and tank car safety design improvement reduces the probability of tank car release following derailment. An integrated crude oil transportation risk management system is needed to optimize the allocation of limited resources on multiple risk reduction options—either alone or in combination—accounting for their respective safety benefits and costs (39, 40).
5. Finally, risk assessment involves the estimators of several input parameters. The statistical variances of these parameter estimators affect the variance of the risk estimator (41). The variance of risk estimator might be quantified by either statistical inference methods or Monte Carlo simulation approaches (42).

CONCLUSIONS

A variety of infrastructure, train, and operational characteristics affect crude-oil-by-rail transportation risk. This paper describes a risk analysis model to integrate these factors to estimate transportation risk in unit trains on main lines. The methodology is packaged into a GIS-based decision support tool that automates risk calculation, visualization, and interpretation processes. The methodology

and implementation tool can potentially assist decision makers in development of risk-informed policies and practices to manage the risk of rail transport of crude oil and other hazardous materials.

ACKNOWLEDGMENTS

This project was funded by the Center for Advanced Infrastructure and Transportation, an Office of the Assistant Secretary for Research and Technology, U.S. Department of Transportation—designated National University Transportation Center, at Rutgers, the State University of New Jersey. The author's work also was funded in part by the Department of Civil and Environmental Engineering and the School of Engineering, both at Rutgers. The author thanks Todd Treichel of the Railway Supply Institute—Association of American Railroads Railroad Tank Car Safety Research and Test Project for helpful comments on a draft version of this paper.

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The author is responsible for all views and analyses presented in this paper. At present, the CBR-Risk tool can be used only for methodology demonstration in the absence of detailed proprietary crude oil network information. A specific user can modify the tool based on the user's own information with the author's assistance. The current tool shall not be used for any commercial or legal purposes.

The Standing Committee on Transportation of Hazardous Materials peer-reviewed this paper.