Environmental risk analysis of hazardous material rail transportation

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\textbf{HIGHLIGHTS}

- Comprehensive, nationwide risk assessment of hazardous material rail transportation.
- Application of a novel environmental (i.e. soil and groundwater) consequence model.
- Cleanup cost and total shipment distance are the most significant risk factors.
- Annual risk varies from $20,000 to $560,000 for different products.
- Provides information on the risk cost associated with specific product shipments.

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\textbf{ABSTRACT}

An important aspect of railroad environmental risk management involves tank car transportation of hazardous materials. This paper describes a quantitative, environmental risk analysis of rail transportation of a group of light, non-aqueous-phase liquid (LNAPL) chemicals commonly transported by rail in North America. The Hazardous Materials Transportation Environmental Consequence Model (HMTECM) was used in conjunction with a geographic information system (GIS) analysis of environmental characteristics to develop probabilistic estimates of exposure to different spill scenarios along the North American rail network. The risk analysis incorporated the estimated clean-up cost developed using the HMTECM, route-specific probability distributions of soil type and depth to groundwater, annual traffic volume, railcar accident rate, and tank car safety features, to estimate the nationwide annual risk of transporting each product. The annual risk per car-mile (car-km) and per ton-mile (ton-km) was also calculated to enable comparison between chemicals and to provide information on the risk cost associated with shipments of these products. The analysis and the methodology provide a quantitative approach that will enable more effective management of the environmental risk of transporting hazardous materials.

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1. Introduction

An important aspect of railroad environmental risk management involves tank car transportation of hazardous materials. Initial work addressing environmental risk due to hazardous material rail transportation was presented by Barkan et al. [1]. They conducted a quantitative environmental risk analysis for the Association of American Railroads (AAR) using empirical environmental cleanup cost data from major railroads in the U.S. Anand and Barkan [2] developed geographical probability distributions of soil types and depths to groundwater along rail lines in the U.S. Subsequently, Anand [3] developed a risk analysis model that accounted for railroad accident probabilities, tank car safety performance, chemical characteristics and the variation of different soil types and depths to groundwater at the location of a spill.

Yoon et al. [4] developed a more comprehensive, quantitative screening model to assess light, non-aqueous-phase liquid (LNAPL) infiltration into soils, groundwater transport, and groundwater cleanup time. Hridaya [5] updated the Hazardous Materials Transportation Environmental Consequence Model (HMTECM) developed by Yoon et al. [4] to include a free product recovery module to simulate pumping extraction of low-solubility LNAPL.
from the lens at the groundwater table, and Schaeffer et al. [6] conducted a series of validation and verification analyses of HMTECM.

In this paper, we used HMTECM to estimate the soil and groundwater cleanup costs. We extended the risk analysis model in Anand [2] by developing a more comprehensive groundwater geographic dataset and considered chemical-specific rail transportation routes to determine the exposure to different hydrogeological features along rail lines. We also considered the consequence costs related to potential exposure to human population and train delay. Accident-caused release rate was estimated based on the most common tank car specifications used to transport the set of LNAPLs under consideration, their total annual shipments, and train derailment accident rate. Resultant risk estimates are presented in terms of annual risk, and risk per car-mile (car-km) and per ton-mile (ton-km).

2. Risk analysis methodology

Risk in general can be defined as the product of the probability and the consequences of an event. In the context of railroad hazardous materials transportation, a simplified definition of risk is as follows:

\[ R = \sum_i P_R \times P_{C_i} \times C_i \]  

where \( R \), risk of transporting a hazardous material; \( P_R \), probability or rate of accident-caused release; \( P_{C_i} \), probability of a release impact \( i \) occurring; \( C_i \), consequence level from a release impact \( i \), release impacts to people, property, the environment and other risk receptors.

Fig. 1 shows a generic event tree summarizing the risk analysis framework used in this study. For simplicity, only one branch is expanded at each node. Each of the probability and consequence elements are described in more detail in the following sections.

3. Probability analysis

Accident-caused release rate from a tank car can be defined as follows:

\[ P_R = P_{RA} \times P_A \times M \times \frac{Cap}{Cap'} \]  

where \( P_R \), tank car accident-caused release rate; \( P_{RA} \), conditional probability of a tank car release given the car is derailed in a Federal Railroad Administration (FRA) reportable accident; \( P_A \), tank car derailment rate per car-mile; \( M \), number of car miles; \( Cap \), nominal gallon capacity of a baseline tank car; \( Cap' \), nominal gallon capacity of an alternate-design tank car.

3.1. Tank car conditional probability of release and capacity

The chemicals of interest are typically transported in general-purpose DOT 111A100W1 tank cars with 0.4375 in. (1.11 cm) head and shell thicknesses without top fittings protection. We assumed an inside tank diameter of 110.25 in. (2.81 m), and other product specific designs for the base case for each chemical in the analyses in the subsequent sections (Table 1). The set of chemicals represents the most commonly shipped pure LNAPL chemicals that can be analyzed using the HMTECM version used in this study. The conditional probability of release given a tank car is derailed in a mainline accident, \( P_{RA} \), was calculated using the statistical model in Treichel et al. [7]. Tank car payload capacity associated with the baseline designs were estimated using IllITank, a tank car weight and sizing program [8]. For the base-case annual risk estimation in this study, the term \( Cap/Cap' \) is equal to 1.

3.2. Tank car derailment rate

Anderson and Barkan [9] developed estimates of Class 1 railroad mainline freight train and car accident rates based on the FRA safety statistics. In the nationwide risk analysis described here we used
their estimate of average railcar derailment rate per car-mile for \( P_A \):

\[
P_A = 1.28 \times 10^{-7} \quad \text{(standard error} = 6.6327 \times 10^{-8}).
\]

### 3.3. Number of car miles

Annual waybill shipment data from the AAR’s railcar movement database, TeleRail Automated Information Network (TRAIN II) [10], were used to determine sample routes in a typical year used to transport the specific chemicals of interest, and to estimate the average shipment distance. Each waybill record represents origination and destination (O–D) information as well as all intermediate railroads involved in a shipment. Point locations for a specific shipment route from PC*MILER-Rail were then exported to ArcGis, a GIS software from ESRI used for spatial analysis to create the route over the rail network map from the U.S. DOT [11].

The average shipment distance for each chemical based on sample routes mapped was multiplied by the total annual carloads to get the total annual number of car miles (km), \( M \) (Table 2).

### 3.4. Release rate calculation

Accident-caused release rate for each of the chemicals of interest was calculated using Eq. (2) (Fig. 2). This rate represents the “probability” or frequency element in calculating the risk. As methanol and xylenes have the highest total annual car miles, their annual accident-caused release rates are also among the highest.

### 4. Consequence analysis

#### 4.1. Impacts to soil and groundwater

The HMTECM was used to estimate the total cleanup cost given a spill of the chemicals of interest from a tank car involved in an accident. Spill scenarios considered involve three different soil types, \( j \) (sand, silt and clay) and five different depths to groundwater, \( k \) (10, 20, 50, 100 and 200-ft or about 3, 6, 15, 30 and 60-m, respectively).

#### 4.1.1. Environmental consequence model

The HMTECM combines several different modules and sub-modules representing different elements in the spill and environmental cleanup process. Fig. 3 shows the overall model logic and the associated remediation technologies used in the HMTECM [4–6].

#### 4.1.2. Soil and groundwater exposure assessment

We applied GIS spatial analysis methods similar to those used by Anand and Barkan [2]. First we identified the most comprehensive and suitable databases with regard to the geographic distributions of different soil types, depths to ground water and rail line network in the U.S. Then we used the waybill shipment data discussed in Section 3.3 to identify actual routings of chemical shipments of interest. Finally, we used the overlay and clipping spatial analysis methods to develop the probability distributions of soil type and depth to groundwater exposures along the chemical-specific routes.

The CONUS-SOIL database from Miller and White [12] was used to assess the potential exposure level of different soil types. An overlay analysis using the GIS route of each of the chemicals of interest and the soil database was performed to estimate the probability distribution of different soil types (Table 3).

For groundwater exposure analysis, a spatial database of groundwater sites in the continental U.S. was downloaded from the United States Geological Survey (USGS) National Water Information System (NWIS) [13] and several other state-specific groundwater databases [14,15]. The average depth to groundwater for each site was calculated using measurements between 1990 and 2008 to get the approximate representation of the current depth to groundwater distribution. The resultant database contains groundwater depth information from approximately 200,000 sites (Fig. 4).

We conducted a GIS overlay analysis using the route for each chemical of interest and the groundwater database to estimate the probability distribution of depth to groundwater of the chemical-specific routes (Table 4).

The probability distributions of soil type and depth to groundwater in this paper are different than those in Anand and Barkan.
Table 2  
Baseline tank car designs.

<table>
<thead>
<tr>
<th>Commodity name</th>
<th>Average shipment distance (miles)</th>
<th>(km)</th>
<th>Annual carloads</th>
<th>Annual car miles</th>
<th>Annual car km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylonitrile</td>
<td>486</td>
<td>782</td>
<td>2892</td>
<td>1,406,133</td>
<td>2,262,946</td>
</tr>
<tr>
<td>Benzene</td>
<td>435</td>
<td>700</td>
<td>3543</td>
<td>1,541,225</td>
<td>2,480,355</td>
</tr>
<tr>
<td>Butyl acrylates</td>
<td>714</td>
<td>1149</td>
<td>4077</td>
<td>2,910,782</td>
<td>4,684,438</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>470</td>
<td>756</td>
<td>4331</td>
<td>2,036,186</td>
<td>3,276,916</td>
</tr>
<tr>
<td>Ethanol</td>
<td>737</td>
<td>1186</td>
<td>4091</td>
<td>2,910,782</td>
<td>4,684,438</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>758</td>
<td>1220</td>
<td>1163</td>
<td>881,173</td>
<td>1,418,107</td>
</tr>
<tr>
<td>Ethyl acrylate</td>
<td>564</td>
<td>908</td>
<td>1151</td>
<td>649,216</td>
<td>1,044,809</td>
</tr>
<tr>
<td>Methanol</td>
<td>918</td>
<td>1477</td>
<td>17,814</td>
<td>16,361,224</td>
<td>26,330,772</td>
</tr>
<tr>
<td>Methyl methacrylate</td>
<td>725</td>
<td>1167</td>
<td>5437</td>
<td>3,944,250</td>
<td>6,347,639</td>
</tr>
<tr>
<td>Styrene</td>
<td>810</td>
<td>1304</td>
<td>3216</td>
<td>2,604,849</td>
<td>4,192,088</td>
</tr>
<tr>
<td>Toluene</td>
<td>928</td>
<td>1493</td>
<td>9950</td>
<td>9,234,437</td>
<td>14,861,349</td>
</tr>
<tr>
<td>Vinyl acetate</td>
<td>810</td>
<td>1304</td>
<td>6210</td>
<td>5,033,087</td>
<td>8,099,948</td>
</tr>
<tr>
<td>Xylenes</td>
<td>928</td>
<td>1493</td>
<td>9950</td>
<td>9,234,437</td>
<td>14,861,349</td>
</tr>
</tbody>
</table>

Fig. 3. Flowchart of the HMTECM logic.

[2] since our methodology considers the routes of each chemical of interest instead of the overall national rail network. In addition, we used a more comprehensive, multi-year historical average of groundwater data from about 2000 sites instead of 166 data points within approximately a one-year period in Anand and Barkan [2].

4.1.3. Expected total cleanup cost

For a specific spill volume, the expected total cleanup cost, $C_{ave}$, can be calculated as follows:

$$C_{ave} = \sum_{j,k,l} P_j \times P_k \times P_l \times C_{j,k}(Q_l)$$

where $C_{ave}$, expected total cleanup cost; $P_j$, probability of a spill occurred on soil type $j$; $P_k$, probability of a spill occurred at $k$ ft depth to groundwater; $P_l$, probability of a release size $l$ per release size category in (7) given a tank car released its content; $C_{j,k}(Q_l)$, cleanup cost estimate from HMTECM with $Q_l$ spill volume for $j$ soil type and $k$ ft depth to groundwater; $Q_l$, average release quantity with release size $l$ = average percentage tank capacity lost for release size $l \times$ tank car capacity.

The HMTECM was used to estimate the cleanup cost for all possible release size, soil and depth to groundwater scenarios (Fig. 5). The highest expected cleanup costs correspond to chemicals with the lowest solubility in water which require longer groundwater cleanup time.
Table 3: Distribution of soil types along chemical-specific rail routes.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Percentage of rail route on soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sand</td>
</tr>
<tr>
<td>Acrylonitrile</td>
<td>49.6%</td>
</tr>
<tr>
<td>Benzene</td>
<td>44.1%</td>
</tr>
<tr>
<td>Butyl acrylates</td>
<td>53.9%</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>55.7%</td>
</tr>
<tr>
<td>Ethanol</td>
<td>59.3%</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>56.7%</td>
</tr>
<tr>
<td>Ethyl acrylate</td>
<td>48.2%</td>
</tr>
<tr>
<td>Methanol</td>
<td>60.7%</td>
</tr>
<tr>
<td>Methyl methacrylate</td>
<td>56.3%</td>
</tr>
<tr>
<td>Styrene</td>
<td>53.3%</td>
</tr>
<tr>
<td>Toluene</td>
<td>56.7%</td>
</tr>
<tr>
<td>Vinyl acetate</td>
<td>53.5%</td>
</tr>
<tr>
<td>Xylenes</td>
<td>52.8%</td>
</tr>
</tbody>
</table>

Fig. 4: Post-1990 depths to groundwater distribution.

4.2. Population exposure

The total population exposed given a spill of a chemical of interest can be estimated as follows:

\[ Pop_c = Area_c \times PopDensity_c \]  

(4)

where \( Pop_c \), total population exposure due to a spill of chemical \( c \); \( Area_c \), chemical-specific hazard footprint area; \( PopDensity_c \), average population density along a chemical-specific route.

Table 4: Distribution of depth to groundwater along chemical-specific rail routes.

<table>
<thead>
<tr>
<th>Depth to groundwater range in ft (m)</th>
<th>&lt;5 (2)</th>
<th>&gt;5 (2) to &gt;15 (5)</th>
<th>&gt;15 (5) to &gt;25 (8)</th>
<th>&gt;25 (8) to &lt;75 (23)</th>
<th>&gt;75 (23) to &lt;125 (38)</th>
<th>&gt;125 (38)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average depth to groundwater k in ft (m)</td>
<td>0</td>
<td>10 (3)</td>
<td>20 (6)</td>
<td>50 (15)</td>
<td>100 (30)</td>
<td>200 (60)</td>
</tr>
<tr>
<td>Acrylonitrile</td>
<td>15.38%</td>
<td>27.88%</td>
<td>11.54%</td>
<td>28.85%</td>
<td>6.73%</td>
<td>9.62%</td>
</tr>
<tr>
<td>Benzene</td>
<td>13.79%</td>
<td>31.90%</td>
<td>6.90%</td>
<td>25.86%</td>
<td>6.03%</td>
<td>15.52%</td>
</tr>
<tr>
<td>Butyl acrylates</td>
<td>7.12%</td>
<td>24.34%</td>
<td>8.61%</td>
<td>27.34%</td>
<td>10.86%</td>
<td>21.72%</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>18.87%</td>
<td>32.08%</td>
<td>7.55%</td>
<td>26.42%</td>
<td>5.66%</td>
<td>9.43%</td>
</tr>
<tr>
<td>Ethanol</td>
<td>7.02%</td>
<td>24.16%</td>
<td>13.20%</td>
<td>29.78%</td>
<td>8.99%</td>
<td>16.85%</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>5.77%</td>
<td>16.03%</td>
<td>11.54%</td>
<td>33.33%</td>
<td>9.62%</td>
<td>23.72%</td>
</tr>
<tr>
<td>Ethyl acrylate</td>
<td>6.99%</td>
<td>11.89%</td>
<td>10.49%</td>
<td>37.06%</td>
<td>10.49%</td>
<td>23.08%</td>
</tr>
<tr>
<td>Methanol</td>
<td>14.31%</td>
<td>27.36%</td>
<td>10.51%</td>
<td>24.46%</td>
<td>7.43%</td>
<td>15.94%</td>
</tr>
<tr>
<td>Methyl methacrylate</td>
<td>7.44%</td>
<td>26.03%</td>
<td>9.92%</td>
<td>24.38%</td>
<td>10.33%</td>
<td>21.90%</td>
</tr>
<tr>
<td>Styrene</td>
<td>14.71%</td>
<td>20.32%</td>
<td>10.43%</td>
<td>27.81%</td>
<td>9.36%</td>
<td>17.38%</td>
</tr>
<tr>
<td>Toluene</td>
<td>12.73%</td>
<td>22.12%</td>
<td>10.61%</td>
<td>28.18%</td>
<td>9.09%</td>
<td>17.27%</td>
</tr>
<tr>
<td>Vinyl acetate</td>
<td>16.03%</td>
<td>22.76%</td>
<td>7.69%</td>
<td>26.60%</td>
<td>8.33%</td>
<td>18.59%</td>
</tr>
<tr>
<td>Xylenes</td>
<td>7.46%</td>
<td>20.52%</td>
<td>11.94%</td>
<td>29.85%</td>
<td>8.96%</td>
<td>21.27%</td>
</tr>
</tbody>
</table>

Fig. 5: Expected total cleanup cost ($) given a spill.

4.2.1. Hazard exposure model

The U.S. DOT Emergency Response Guidebook [16] hazard exposure model was used to estimate the consequence of a chemical release to a human population. All of the chemicals of interest in this study are classified as flammable liquids by the U.S. DOT. The ERG model suggests an initial isolation and protective distance of one half mile (805 m) in all directions for spills of all the chemicals considered in this study.

4.2.2. Population density

A spatial buffer was created along chemical-specific routes. The size of the buffer was based on the affected area in the DOT ERG [16]. The buffer for each chemical was then overlaid on the U.S. census tract map from ESRI Data and Maps [17] to estimate the proportion of different population density levels [18] along the routes for each chemical (Table 5).

4.2.3. Expected population evacuation cost

The exposure area was multiplied by the average population density along a chemical-specific route to estimate the total population exposed to a potential release incident. The associated evacuation cost was assumed to be $225 per person per day for food and lodging, based on a court-approved settlement related to a railroad chemical release incident [19]. Analysis of the U.S. DOT Pipeline and Hazardous Materials Safety Administration (PHMSA) incident statistics for railroad release accidents indicated that the average evacuation period involving a release of a flammable liquid is approximately one day [20], so our analysis assumed this value.
Table 5
Distribution of population densities along chemical-specific rail routes.

<table>
<thead>
<tr>
<th>Population class</th>
<th>Remote ≤ 20 (8)</th>
<th>Rural &gt;20 (8) to ≤100 (38)</th>
<th>Suburban &gt;100 (38) to ≤1000 (385)</th>
<th>Urban &gt;1000 (385) to ≤3000 (1154)</th>
<th>High &gt;3000 (1154) to ≤10,000 (3845)</th>
<th>Extremely high &gt;10,000 (3845)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average population density (people/mile² (people/km²))</td>
<td>10 (4)</td>
<td>60 (23)</td>
<td>550 (211)</td>
<td>2000 (769)</td>
<td>6500 (2499)</td>
<td>10,000 (3845)</td>
</tr>
<tr>
<td>Acrylonitrile</td>
<td>11.45% 44.61%</td>
<td>30.39%</td>
<td>9.26%</td>
<td>4.13%</td>
<td>0.16%</td>
<td></td>
</tr>
<tr>
<td>Benzene</td>
<td>28.20% 38.24%</td>
<td>23.07%</td>
<td>7.04%</td>
<td>3.35%</td>
<td>0.11%</td>
<td></td>
</tr>
<tr>
<td>Butyl acrylates</td>
<td>29.07% 35.31%</td>
<td>24.02%</td>
<td>7.29%</td>
<td>3.91%</td>
<td>0.40%</td>
<td></td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>20.64% 39.51%</td>
<td>28.95%</td>
<td>7.73%</td>
<td>2.95%</td>
<td>0.23%</td>
<td></td>
</tr>
<tr>
<td>Ethanol</td>
<td>34.26% 31.14%</td>
<td>22.21%</td>
<td>7.56%</td>
<td>4.31%</td>
<td>0.50%</td>
<td></td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>28.67% 32.03%</td>
<td>25.45%</td>
<td>8.23%</td>
<td>4.97%</td>
<td>0.65%</td>
<td></td>
</tr>
<tr>
<td>Ethyl acrylate</td>
<td>26.63% 41.85%</td>
<td>22.04%</td>
<td>6.13%</td>
<td>3.10%</td>
<td>0.24%</td>
<td></td>
</tr>
<tr>
<td>Methanol</td>
<td>45.54% 27.12%</td>
<td>17.67%</td>
<td>5.83%</td>
<td>3.56%</td>
<td>0.28%</td>
<td></td>
</tr>
<tr>
<td>Methyl methacrylate</td>
<td>24.93% 36.09%</td>
<td>25.95%</td>
<td>8.10%</td>
<td>4.50%</td>
<td>0.44%</td>
<td></td>
</tr>
<tr>
<td>Styrene</td>
<td>28.24% 35.11%</td>
<td>23.95%</td>
<td>7.87%</td>
<td>4.40%</td>
<td>0.43%</td>
<td></td>
</tr>
<tr>
<td>Toluene</td>
<td>37.44% 31.19%</td>
<td>20.20%</td>
<td>7.06%</td>
<td>3.81%</td>
<td>0.30%</td>
<td></td>
</tr>
<tr>
<td>Vinyl acetate</td>
<td>31.66% 34.52%</td>
<td>22.21%</td>
<td>7.26%</td>
<td>4.00%</td>
<td>0.35%</td>
<td></td>
</tr>
<tr>
<td>Xylenes</td>
<td>37.55% 31.80%</td>
<td>20.05%</td>
<td>6.53%</td>
<td>3.84%</td>
<td>0.23%</td>
<td></td>
</tr>
</tbody>
</table>

Table 6
Expected evacuation costs.

<table>
<thead>
<tr>
<th>Commodity name</th>
<th>PopDensity, (people/mile²)</th>
<th>Pop, (people)</th>
<th>Expected evacuation cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylonitrile</td>
<td>665</td>
<td>257</td>
<td>522</td>
</tr>
<tr>
<td>Benzene</td>
<td>532</td>
<td>202</td>
<td>410</td>
</tr>
<tr>
<td>Butyl acrylates</td>
<td>596</td>
<td>230</td>
<td>468</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>554</td>
<td>214</td>
<td>435</td>
</tr>
<tr>
<td>Ethanol</td>
<td>626</td>
<td>242</td>
<td>492</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>715</td>
<td>276</td>
<td>562</td>
</tr>
<tr>
<td>Ethyl acrylate</td>
<td>497</td>
<td>192</td>
<td>391</td>
</tr>
<tr>
<td>Methanol</td>
<td>494</td>
<td>191</td>
<td>388</td>
</tr>
<tr>
<td>Methyl methacrylate</td>
<td>665</td>
<td>257</td>
<td>522</td>
</tr>
<tr>
<td>Styrene</td>
<td>642</td>
<td>248</td>
<td>504</td>
</tr>
<tr>
<td>Toluene</td>
<td>553</td>
<td>214</td>
<td>434</td>
</tr>
<tr>
<td>Vinyl acetate</td>
<td>586</td>
<td>226</td>
<td>460</td>
</tr>
<tr>
<td>Xylenes</td>
<td>537</td>
<td>207</td>
<td>422</td>
</tr>
</tbody>
</table>

The expected evacuation costs in a release incident involving the chemicals of interest were estimated accordingly (Table 6).

4.3. Train delay

In the event of a derailment, through traffic train at the location of the accident may be disrupted. The length of the delay depends on the severity of a derailment. The density of the rail line affects the possible number of trains delayed due to a release incident. Schafer and Barkan [21] estimated the single-train delay cost per train-hour, which includes car, locomotive, fuel and crew labor costs. In this paper, we used the equation from Schafer and Barkan [21] to estimate multiple-train delay cost:

\[ C_{delay} = T_C + \sum_{n=1}^{m} (T - nt)c \]  

where \( C_{delay} \) = total train delay cost for multiple trains; \( T \) = total delay hours due to a release incident; \( c \) = cost of delay per train-hour ($233.32); \( T \) = hours per train arrival = 53.33/MGT; MGT, annual million tonnage; \( m \) = number of following trains delayed = \( T/t \).

Based on railroad industry expert opinion, we assumed a release incident involving the chemicals of interest would increase the delay in reopening a rail line following an accident by an average of 24 h (\( T = 24 \)). Chemical-specific routes were used to estimate the distribution of different rail line traffic density (Table 7). The expected total train delay cost given a release incident was estimated by totaling the product of the delay cost for each traffic density category with the probability of each category (Table 8). The higher the average annual density for a chemical-specific route, the greater the estimated train delay cost.

4.4. Total consequence cost calculation

Total expected consequence cost, the sum of soil and groundwater cleanup, evacuation and train delay costs, for each of the chemicals of interest were calculated (Fig. 6). This cost represents the total expected consequence in the event of a release in calculating the risk.

5. Risk estimation

The annual risk was estimated by multiplying the accident-caused release rate in Fig. 2 by the total consequence cost in Fig. 6 (Fig. 7).

5.1. Risk profile

The annual risk presented above represents the expected impact from a release incident at any given location along a
chemical-specific route, in which the weighted averages of soil type, depth to groundwater, population class and traffic density are incorporated. In order to get a better perspective on the overall risk problem, the rate of occurrence and impact for all possible release scenarios (Fig. 1) can be illustrated using a risk profile [22]. Fig. 8 shows an example risk profile for methanol.

6. Discussion

6.1. Current risk scenarios

This paper provides a quantitative analytical approach to estimate the risk cost of transporting hazardous materials by rail. The estimated annual risk associated with the chemicals under consideration ranged from approximately $20,000–560,000 and the risk cost per car-mile (car-km) ranged from 1.0 (0.6) to 4.4 (2.8) cents. The annual risk and the risk per car-mile (car-km) vary by factors of 28 and 4, respectively. These reflect current practices in transporting the chemicals of interest. The annual risk estimates account for chemical-specific hazard, tank car design, route-specific characteristics and annual accident exposure based on the total number of shipments. The risk per car-mile estimates have the traffic effect normalized to focus on chemical hazard, tank car safety design, and route specific characteristics affecting risk.

The risk estimates provide a single number to represent the expected consequence per year, per car-mile (car-km) or ton-mile (ton-km). Consequences for all possible events are weighted by their probabilities of occurrence (Eq. (1)). In addition to expected values for risk it may also be useful to consider the likelihood of the range of possible consequences especially low probability-high consequence events. Risk profiles provide additional perspective in evaluating the risk by specifying the probability or rate of occurrence of incidents over a range of consequence levels.

6.2. Main factors affecting disparities in risk estimates

Several factors affect the risk and the magnitude of its severity (Eqs. (1)–(5)). For the chemicals studied here the variation in safety performance of the baseline tank car designs is minimal (Table 1). However, higher variation in total car miles (km) among different chemicals leads to significant differences in their annual accident-caused release rate (Table 2 and Fig. 2). In estimating the consequence cost, chemicals that are less soluble in water, in general, have higher soil and groundwater cleanup cost because of longer remediation time. In terms of evacuation cost, chemicals transported along routes with higher-density population result in higher consequence costs. However, since more than 50 percent of shipments are mainly transported across remote and rural areas (Table 5), the variation in evacuation cost is minimal. Meanwhile, train delay cost only accounts for between three to eight percent of

### Table 7

<table>
<thead>
<tr>
<th>Distribution of rail line traffic densities along chemical-specific rail routes.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic density</td>
</tr>
<tr>
<td>category in MGTkm (MGTkm)</td>
</tr>
<tr>
<td>0.1 (0.1)–4.9 (7.2)</td>
</tr>
<tr>
<td>Average traffic density in MGTkm (MGTkm)</td>
</tr>
<tr>
<td>Acrylonitrile</td>
</tr>
<tr>
<td>Benzene</td>
</tr>
<tr>
<td>Butyl acrylates</td>
</tr>
<tr>
<td>Cyclohexane</td>
</tr>
<tr>
<td>Ethanol</td>
</tr>
<tr>
<td>Ethyl acetate</td>
</tr>
<tr>
<td>Ethyl acrylate</td>
</tr>
<tr>
<td>Methanol</td>
</tr>
<tr>
<td>Methyl methacrylate</td>
</tr>
<tr>
<td>Styrene</td>
</tr>
<tr>
<td>Toluene</td>
</tr>
<tr>
<td>Vinyl acetate</td>
</tr>
<tr>
<td>Xylenes</td>
</tr>
</tbody>
</table>

### Table 8

<table>
<thead>
<tr>
<th>Expected total train delay costs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical</td>
</tr>
<tr>
<td>Acrylonitrile</td>
</tr>
<tr>
<td>Benzene</td>
</tr>
<tr>
<td>Butyl acrylates</td>
</tr>
<tr>
<td>Cyclohexane</td>
</tr>
<tr>
<td>Ethanol</td>
</tr>
<tr>
<td>Ethyl acetate</td>
</tr>
<tr>
<td>Ethyl acrylate</td>
</tr>
<tr>
<td>Methanol</td>
</tr>
<tr>
<td>Methyl methacrylate</td>
</tr>
<tr>
<td>Styrene</td>
</tr>
<tr>
<td>Toluene</td>
</tr>
<tr>
<td>Vinyl acetate</td>
</tr>
<tr>
<td>Xylenes</td>
</tr>
</tbody>
</table>
annualized risk profile for rail transportation of methanol.

FIG. 8. Risk profile for rail transportation of methanol.

Fig. 7. Estimated (a) annual risk, (b) risk per car-mile and (c) risk per ton-mile.

The environmental consequence model, HMTECM, used in this study focuses on soil and groundwater cleanup. Analysis of damages to natural resources such as surface water bodies, and other associated hazards from airborne pollutants would require different type of models. Inclusion of these would increase the environmental consequence cost, but no satisfactory model presently exists to be used in the context of railroad hazardous material transportation risk. In addition, the HMTECM is currently limited to pure LNAPLs; however, a recent work enhances the model so it can be used to evaluate chemical mixtures [23]. This will enable risk analysis of many other important hazardous materials transported by rail such as gasoline, diesel fuel, denatured alcohol, etc.

Evacuation cost was the only metric considered to assess population exposure in this analysis. For other chemicals that present a more acute hazard to human health and safety, the use of a more detailed hazard consequence model may be appropriate for some types of questions in which estimation of the statistical distribution of potential injuries and fatalities is necessary. The statistical value of life or injury concept could then be used to estimate the associated cost of casualties [24].

Estimated train delay cost in this study considered the extra costs related to locomotives, railcars, fuel and crew when multiple trains are delayed after a release accident. In the event of a longer track outage, railroads may need to reroute whole trains, or certain carloads, either over their own network or via other railroads, leading to additional costs.

An important consequence element also not included in this study is litigation cost. Due to the confidential nature of this information, quantitative data on settlement costs is generally not available in the public domain. Based on a survey of major rail accidents involving hazardous materials between 1982 and 1992, Dennis [25] estimated legal settlement expenses accounted for 56% of the total cost of release incidents, compared to about 40% for environmental costs and other expenses. If this ratio is still relevant then it would be possible to estimate total costs by calculating a factor to multiply the consequence costs estimated in this study.

6.4. Risk model applications

6.4.1. Evaluating shipment risk cost

The risk estimates are useful to evaluate the relative risk of transporting different chemicals. In this paper, the risk was analyzed at a national-wide level; however, the same framework can be used to evaluate the risk of transporting a chemical along a particular rail corridor or between an origin and destination. The Surface Transportation Board (STB) is considering incorporating risk cost into their formula for determination of freight transport costs, which in

<table>
<thead>
<tr>
<th>Compound</th>
<th>Annual Cost (M)</th>
<th>Risk (Car-Mile)</th>
<th>Risk (Ton-Mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>559,830</td>
<td>4.4 (2.8)</td>
<td>0.045 (0.031)</td>
</tr>
<tr>
<td>Xylenes</td>
<td>409,531</td>
<td>4.0 (2.5)</td>
<td>0.041 (0.028)</td>
</tr>
<tr>
<td>Methyl Methacrylate</td>
<td>149,898</td>
<td>4.0 (2.5)</td>
<td>0.040 (0.027)</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
<td>141,525</td>
<td>3.9 (2.4)</td>
<td>0.038 (0.026)</td>
</tr>
<tr>
<td>Styrene</td>
<td>123,185</td>
<td>3.8 (2.4)</td>
<td>0.036 (0.025)</td>
</tr>
<tr>
<td>Toluene</td>
<td>103,501</td>
<td>3.3 (2.1)</td>
<td>0.034 (0.023)</td>
</tr>
<tr>
<td>Ethanol</td>
<td>78,194</td>
<td>2.6 (1.6)</td>
<td>0.028 (0.019)</td>
</tr>
<tr>
<td>Benzene</td>
<td>52,337</td>
<td>2.0 (1.2)</td>
<td>0.027 (0.018)</td>
</tr>
<tr>
<td>Butyl Acrylates</td>
<td>46,410</td>
<td>2.0 (1.2)</td>
<td>0.021 (0.015)</td>
</tr>
<tr>
<td>Ethyl Acrylate</td>
<td>35,024</td>
<td>1.8 (1.1)</td>
<td>0.021 (0.014)</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>20,229</td>
<td>1.0 (0.6)</td>
<td>0.019 (0.013)</td>
</tr>
</tbody>
</table>
turn has implication for the rates railroads can charge (74 FR 248). The risk model presented in this paper can be used to perform such calculations for the risk elements covered here.

6.4.2. Evaluating cost effectiveness of alternate design tank cars

The use of a more robust tank car safety design reduces \( P_{R \text{RA}} \) and thus the risk. Saat [26] presented an approach to evaluate the cost effectiveness of different alternate tank car designs in hazardous material service. It accounted for chemical-specific hazard and consequent risk and cost. The risk model in this paper can be used to assess the benefit in terms of reduction in risk due to use of different tank car safety designs.

6.4.3. Evaluating alternate routes

The risk model presented in this paper can also be used to evaluate the effect of alternate routes for transporting hazardous materials by rail. Rerouting affects the levels of exposure to both human populations and the environment. In certain cases, rerouting to avoid higher population density or environmentally sensitive areas may reduce risk. However, rerouting decisions may also affect the total shipment distance, and the quality of track used. Longer shipment distances will increase “M” in Eq. (2) which in turn may increase accident-caused release rate and risk. Similarly, transporting chemicals using lower quality track may increase \( P_A \) and thus increase risk. All these factors can be accounted for using the model presented here to compare both the expected risk and risk profiles for route alternatives.

6.4.4. Increase emergency response preparedness

The use of GIS in assessing risk exposure offers detailed route-specific information that can be used to increase emergency response preparedness. This is especially useful when the risk model presented here is used to evaluate micro-level risk by analyzing specific track segments along a route. Track segments with higher risk may justify extra preparation or investment in mitigation capability. In addition, different products and different environmental features may call for different types of preparations in terms of equipment, training or allocation of expertise.

6.4.5. Evaluating infrastructure improvement

Detailed track-segment specific GIS analysis can also be used to prioritize locations along a rail network for infrastructure improvement and maintenance. It may be justified to allocate resources to focus on track improvement near environmentally sensitive areas, high-density populations or high-density traffic. Each of these affects the environmental cleanup cost, evacuation cost and train delay cost, respectively, in estimating the total possible consequence from a release incident. Infrastructure improvement can also potentially reduce the likelihood of a train accident in the first place by reducing \( P_A \) in Eq. (2).

7. Conclusions

This paper provides a quantitative analytical approach to estimate the risk cost of transporting hazardous materials by rail. Focusing on the risk to the environment, a novel environmental consequence model was used to estimate soil and groundwater cleanup costs. GIS analysis was used to account for distributions of different soil types and depths to groundwater along chemical-specific routes. Possible human population exposure to estimate evacuation cost was also considered together with train delay cost. Besides accounting for route-specific characteristics affecting the risk, this model accounts for chemical-specific hazard, tank car design and annual accident exposure based on the total number of shipments.

This model can be used as a framework to incorporate risk cost in freight rate determination, and to evaluate risk reduction options including tank car safety design enhancements, route alternatives and infrastructure improvement. These reflect a variety of changes in practices that may offer opportunities to reduce risk. A major challenge is to understand the inter-relationships among different factors, that is, how changes in one affect another. Additionally, the cost-effectiveness of addressing these different factors will vary, relative to the others at both a system and scenario-specific level.

Acknowledgements

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