Railroad transportation of dangerous goods: Population exposure to airborne toxins

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Abstract

Hazardous materials are potentially harmful to people and environment due to their toxic ingredients. Although a significant portion of dangerous goods transportation is via railroads, prevailing studies on dangerous goods transport focus on highway shipments. We present an analytical framework that incorporates the differentiating features of trains, notably volume and nature of cargo, in the assessment of transport risk. We focus on hazardous materials that are airborne upon an accidental release into the environment. Each railcar is a potential source of release, and hence risk assessment of trains requires representation of multiple release sources in the model. We propose a risk approximation approach, which is not only effective but also robust with regards to the positioning of hazardous cargo in the train. We report on the use of the proposed approach for the assessment of population exposure associated with “Ultra-train” that passes through the city of Montreal everyday.

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1. Introduction

In the wake of the recent catastrophic accidents in Iran and North Korea, risk assessment of railroad transportation of dangerous goods has become a popular concern. United Nations Environment Programme reports 328 fatalities and 460 injuries in Iran, and 161 fatalities and 1300 injuries in North Korea due to explosions [1]. Despite the potentially catastrophic nature of train accidents, an overwhelming

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Table 1
Release incidents involving more than six railcars [8]

<table>
<thead>
<tr>
<th>Incident year</th>
<th>Number of derailed cars</th>
<th>Number of derailed cars carrying dangerous goods</th>
<th>Number of cars released hazardous cargo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>61</td>
<td>19</td>
<td>12</td>
</tr>
<tr>
<td>1990</td>
<td>14</td>
<td>13</td>
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<td>1993</td>
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<td>23</td>
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<td>1996</td>
<td>34</td>
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<td>2000</td>
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<td>18</td>
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<td>2002</td>
<td>17</td>
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<td>39</td>
<td>15</td>
<td>11</td>
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<tr>
<td>2003</td>
<td>50</td>
<td>19</td>
<td>7</td>
</tr>
</tbody>
</table>

The majority of the research on hazardous material (hazmat) transportation focuses on road shipments [2,3]. Although trucks carry a larger share of dangerous goods shipments in many countries, railroad shipments can easily reach comparable levels. In Canada, for example, 48 million tons of hazardous freight was carried via rail while 64 million tons was shipped via trucks in 2000 [4]. There is a need for the development of risk assessment methodologies that incorporate the specific nature of railroad shipments, which we address in this paper.

There are a number of factors that differentiate rail transport from truck shipments. A train usually carries non-hazardous and hazardous cargo together, whereas these two types of cargo are almost never mixed in a truck shipment. Furthermore, a rail tank-car has roughly three times the capacity of a truck-tanker (80 t and 25–30 t, respectively) and the number of hazmat railcars varies significantly among different trains. The resulting variability in the total amount of hazardous cargo needs to be taken into account in assessing the transport risk associated with trains. Also, railroads typically offer much less routing flexibility compared to highway networks.

Another important characteristic of trains, from a risk assessment perspective, is the possibility of incidents that involve multiple railcars. In the United States, there were 11 train derailments during the 1990–2003 period in which more than six railcars were ruptured and released their toxic cargo (see Table 1 for details). Note that this amounts to an average of about one major railroad accident per year. Canada had its share of multiple railcar accidents as well. In December 1999, Canadian National (CN’s) Ultratrain (which constitutes our case study in Section 6) released 2.7 million liters of petroleum products due to the derailment of 35 tank cars just outside Montreal. Thirty cars were seriously punctured and had to be demolished at the accident site [5]. Another well-known accident took place near Toronto in 1979, where chlorine leaking from damaged tank cars forced the evacuation of 200,000 people [6]. Thus, train accidents can have more severe consequences than those involving trucks, mainly due to the higher volumes of hazmats being shipped and the interaction between railcars. Fortunately, empirical evidence suggests that trains have lower accident rates than trucks [7].

Traditionally, hazmat transport risk is defined as the expected undesirable consequence of the shipment i.e., the probability of a release incident multiplied by its consequence. This risk measure is also called the “technical risk” since it requires a detailed assessment of the accident probabilities across the shipment.
route as well as the number of fatalities, injuries and evacuations that would be caused by an incident. Such a detailed analysis can become prohibitive for railroad shipments, since not only the likelihood of the entire train involving in an accident, but also the number and precise locations of the damaged railcars (and their interaction) are relevant. Based on the difficulties in deriving detailed accident probability estimates for railroad shipments, we resort to a more aggregate risk measure in this paper: population exposure. We represent transport risk as the total number of people exposed to the possibility of an undesirable consequence due to the shipment. For example, according to the North American Emergency Response Handbook [9], 800 m around a fire that involves a chlorine tank, railcar or tank-truck must be isolated and evacuated. Therefore, the people within the predefined threshold distance from the railroad are exposed to the risk of evacuation. This fixed bandwidth approach has originally been suggested and used by Batta and Chiu [10] and ReVelle et al. [11]. It is important that, in contrast with the traditional “average” risk measure, population exposure constitutes a “worst-case” approach to transport risk. Therefore, it is particularly suitable for assessing risk as perceived by the public as well as for estimating the required emergency response capability.

In this paper, we focus on railroad transportation of hazmats that become airborne in the event of an accidental release, such as chlorine, propane and ammonia. Airborne toxins can travel long distances due to wind and expose large areas to health and environmental risks. We use the Gaussian plume model (GPM) in estimating spatial distribution of the toxic concentration level. Concentration increases with release rate of hazmat, whereas it decreases with distance from the accident site and wind speed. At a given distance from a release source, the maximum concentration is observed at the downwind location. We use the immediately dangerous to life and health (IDLH) concentrate levels of the hazmat being shipped in determining the threshold distances for fatality and injuries [12]. In estimating the population exposure, we adopt the worst-case approach by assuming least favorable weather conditions and focusing on maximum concentrate levels. Also, our population exposure estimates are based on the derailment and rupture of all railcars with hazardous cargo, which constitute a real possibility (see the 1996 and 2000 incidents in Table 1). Less conservative exposure scenarios can be easily incorporated in the parameter settings of the risk assessment methodology presented in Section 3.

The originality of our model is in its ability to estimate the exposure zone around the railroad as a function of volume (and type) of hazmats on the train. Thus, the model extends the fixed bandwidth approach to population exposure, which is more suitable for truck shipments. We show that the multiple release-source nature of train accidents can be effectively captured by using a railcar referencing mechanism. We also present a risk approximation procedure that is robust to train make-up i.e., length of the train as well as the type and positioning of its hazardous cargo. The remainder of this paper is organized as follows: Section 2 presents an overview of the relevant literature. Section 3 describes the use of a GPM for the assessment of railroad transport risk, and Section 4 discusses the insights provided by the proposed model. Section 5 presents an approximation method for railroad transport risk. Section 6 reports on an application of the proposed methodology in the province of Quebec, Canada. Finally, Section 7 provides some concluding comments.

2. Literature review

Although railroad transportation has been a popular area of research (see [13], for a comprehensive survey), the literature on the use of trains for hazmat shipments is rather sparse. In this section, we present
an overview of the most relevant threads of research. Early academic studies focused on the impact of spills in the vicinity of the accident site. Analyzing past data on train derailments, Glickman and Rosenfield [14] derived and evaluated three forms of risk: the probability distribution of the number of fatalities in a single accident, the probability distribution of total number of fatalities from all the accidents in a year, and the frequency of accidents that result in any given number of fatalities. Glickman [15] showed that rerouting of trains with (or without) track upgrades can reduce risk. The trade-off between the societal and individual risks of hazmat shipments is addressed in Saccomanno and Shortreed [16]. Recently, Barkan et al. [17] undertook a study to identify proxy variables that can be used to predict circumstances most likely to lead to a hazmat release accident. They concluded that the speed of derailment and the number of derailed cars are highly correlated with hazmat release.

Over the past three decades, railroad industry has spent considerable effort in reducing the frequency of tank car accidents as well as the likelihood of releases in the event of an accident. To this end, the Association of American Railroads, Chemical Manufacturers Association and Railway Progress Institute formed an inter-industry task force in the early 1970s [18]. Unfortunately, the activities of this voluntary task force largely ceased in about 1994, and most of their internal reports were never publicized and considered proprietary to the sponsoring organizations [19,20]. More recent industry initiatives have focused on improving the tank car safety at the design stage. By studying the risks associated with non-pressurized materials, Raj and Pritchard [21] report that the DOT-105 tank car design constitutes a safer option than DOT-111. Barkan et al. [22] showed that tank cars equipped with surge pressure reduction devices experienced lower release rates than those without this technology.

A number of studies focused on the comparison of rail and road as alternative modes for hazmat transport, and no consensus has been reached with respect to the safer option. Glickman [23] concluded that the accident rate for significant spills (when release quantities exceed 5 gal or 40 pounds) is higher for for-hire truck tankers compared to rail tank cars, whereas rail tank cars are more prone to small spills. Saccomanno et al. [7] pointed out that differing volumes complicate comparison between the two transport modes, and showed that the safer mode varies with the hazmat being shipped. Leeming and Saccomanno [24] report on a case study in England, which involves the handling of chlorine by a major industrial facility with two options for delivery (i.e., rail and road). They found out that the two options do not differ significantly in terms of total risk, although rail shipments pose more risk to the residents around the facility. Kornhauser et al. [25] present a case study of DuPont’s Mississippi facility, wherein they conclude that railroad is a safer option than highway to ship anhydrous ammonia. The difference in shipment volumes between the two transport modes, however, was handled through a linear adjustment factor.

A variety of air dispersion models have been proposed for transport risk assessment. The most comprehensive study thus far is carried out by Hwang et al. [26], who used a Lagrangian-integral dispersion model to estimate impact zones for six toxic-by-inhalation materials. In analyzing the chlorine-handling facility mentioned above, Leeming and Saccomanno [24] made use of dense-gas dispersion model to estimate the impact areas stemming from each possible release scenario. The GPM, however, is by far the most popular dispersion model used by micro-meteorologists, air pollution analysts, and regulatory agencies [27,28]. In his 1999 book, Arya states that GPM-based models have received “official blessing” from state and federal regulatory agencies in the US and their use has been recommended in official regulatory guidelines [29]. For example, the 1996 Guidelines on Air Quality Models by the US Environmental Protection Agency (EPA) recommends the use of nine standard air quality models for specific regulatory applications, which are mostly based on Gaussian formulations with empirical dispersion parameterization schemes [30].
Patel and Horowitz [31] were the first to use the GPM, coupled with a geographical information system (GIS), for risk assessment of road shipments. In an effort to develop closed-form expressions, they assumed that dispersion parameters are equal to one. They devised a numerical method to determine the minimum risk path under four scenarios: specific wind direction, uniform average wind direction, maximum concentration wind direction and wind-rose averaged wind directions and speeds. Patel and Horowitz [31] focused on the technical risk by assessing the total expected contaminant concentration due to a potential spill. Recently, Zhang et al. [32] modeled the probability of an undesirable consequence as a function of the concentration level and, again, used the expected consequence representation of transport risk. They adopted a raster GIS framework that approximates the plane with a set of discrete points (i.e., pixels). This enabled the authors to compute the concentrate levels without having to make the linearity assumption as in [31] that essentially ignores atmospheric stability conditions. The method proposed in [32], however, assumes a pre-specified wind direction and speed.

In summary, the prevailing studies on railroad transportation of dangerous goods overwhelmingly focus on accident risk, whereas exposure risk has not been well studied in this context. Furthermore, GPM-based dispersion models—that constitute a potentially effective means of estimating the exposure zone due to a rail shipment—have only been developed for highway shipments. In the next section, we develop a risk assessment methodology to fill this gap in the literature.

3. Risk assessment framework for railroad shipments

The use of a fixed bandwidth approach, that implicitly assumes a standard hazmat volume, is inappropriate for estimating the number of people put at risk due to railroad shipments. The number and location of railcars with hazardous cargo vary considerably among trains. Consequently, it is important to define the boundary of impact area as a function of the volume of hazmat being shipped. A train including one propane tank-car, for example, exposes an individual living 1 km from the railroad to minor injury risk, whereas the same individual would be exposed to fatality risk due to a train with 21 propane tank-cars. This can be explained by the considerable increase in the toxic concentration level at the individual’s location due to the additional 20 railcars. We define exposure in terms of the level of toxic material concentration, which we estimate using GPM. We consider an individual “exposed” to a certain undesirable consequence, if the imposed toxicity is at (or higher than) the associated IDLH level.

We first adapt the standard GPM to represent a single railcar (release source). Then, we extend the model to represent train shipments, which typically involve multiple release-sources. Assuming that the release-source and the impact point are at zero elevation, our single railcar model is as follows:

\[
C(x, y) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp \left(-\frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right),
\]

where \(C(x, y)\) is the concentration level (ppm) at impact point \((x, y)\) in steady-state, \(Q\) the release rate of pollutant (mg/s), \(u\) the average wind-speed (m/s), \(\sigma_y\) the horizontal dispersion coefficient (m), \(\sigma_z = ax^b\), \(\sigma_y = cx^d\), \(x\) the downwind distance from the source (m), and \(y\) the crosswind (perpendicular) distance from the source (m).

In estimating the steady-state concentration level at point \((x, y)\), the model assumes that the release rate and atmospheric conditions remain constant over the period of dispersion. Although the steady-state conditions are rarely reached, this is a common assumption—particularly reasonable during the first hour.
of release [33,34]. The release rate, $Q$, depends on container volume, hazmat type and rupture diameter. We use ALOHA [28], a popular software among North American regulatory agencies including EPA, US Department of Transportation and Transport Canada, to calculate the release rate. Although ALOHA can also be used for estimating the concentration level, $C(x, y)$, its results are only reliable within 1 h of the release event, and 10 km from the release source. In order to assess the population exposure under worst-case conditions, the highest release rate is incorporated in the model by assuming a 24 in rupture at the bottom of the railcar (The impact of non-worst case conditions is discussed in Section 4 through an analysis of smaller rupture sizes). Dispersion coefficients $\sigma_y$ and $\sigma_z$ are determined by atmospheric stability category and the downwind distance, $x$, to the release source. Pasquill and Smith [35] and more recently Arya [29] provide the values of dispersion parameters $a$, $b$, $c$ and $d$ based on atmospheric stability category. Each atmospheric category is determined by a combination of factors such as solar radiation, cloud-cover and humidity; and it is compatible with a range of wind speeds. Minimum wind speed, under any atmospheric category, results in the maximum concentration at all points in a plane. Thus, we focus on the minimum possible wind speed under the neutral atmospheric conditions i.e., 2.5 m/s. At a given (Euclidean) distance from the release source, the maximum concentration level is observed at the downwind point, where crosswind distance $y = 0$. Thus, the maximum concentrate level at (downwind) distance, $x$, from a release source is:

$$C(x) = \frac{Q}{\pi \mu \sigma_y \sigma_z}.$$  

(2)

The two shaded areas in Fig. 1 depict two zones of a Gaussian plume footprint from a single release source, when the wind is blowing east. The two zones represent areas where toxicity is higher than a pre-specified concentration level e.g., the IDLH level associated with a certain undesirable consequence. The inner zone corresponds to higher exposure to hazmat transport risk, while the outer to non-severe exposure. We address the uncertainty in wind direction by rotating the footprint around the release source, which constructs two concentric circles. (An alternative way is incorporation of the variance of risk as suggested by Sivakumar and Batta [36].) Consequently, the furthest point from the release source, where threshold concentration level is attained, defines radius of the circle (e.g., point $P$ in Fig. 1). This constitutes the most conservative approach to transport risk, since the concentrate level at any point on the circle cannot be higher under any plausible wind direction. The two concentric circles in Fig. 1 represent the severe and
non-severe impact areas under wind direction uncertainty. Conceivably, there may be prevailing winds along some segments of the train’s route. If, for example, wind only blows within the east and north directions along a track segment, then only the upper-right quarters of the danger circles need to be used for estimating population exposure. It is important that, in contrast with the fixed bandwidth approach, the radius of each impact area in Fig. 1 varies with the release rate.

Now, we extend the basic GPM to incorporate multiple release-sources. In Fig. 2, assuming that the 11-railcar train is travelling east, $F$ and $L$ denote the first and last railcars with hazardous cargo, respectively. $M$ is the point with equal amount of hazmats on both sides, which we call hazmat-median of the train. For trains with an even number of hazmat railcars, $M$ is midpoint of the two hazmat railcars at the center of hazardous cargo. Note that $M$ and $D$, the middle of the train, do not necessarily refer to the same point. $P_1$, $P_2$ and $P_3$ are equidistant from $M$. In Fig. 2, the five hazmat railcars are blocked at the back of the train.

Pasquill and Smith [35] and Arya [29] suggested that pollution from an array of sources with an arbitrary distribution of position and strength of emission can be modeled by superposing the patterns of pollution from these sources, and hence aggregating the resulting contamination at each impact point. In Fig. 2, when the wind is blowing east, $P_1$ constitutes a downwind location where crosswind distance $y = 0$ for all railcars. In the event of a major incident that ruptures all five railcars with hazardous cargo, the total concentrate level at $P_1$ would be sum of the concentrate levels associated with each railcar, which can be estimated via (2). The three curves in Fig. 3 depict total concentration at $P_1$ as a function of distance to $F$, $M$ and $L$, respectively. Consider a fixed reference point at $x = 0$. As the train travels east, $F$, $M$ and then $L$ pass by the reference point. Thus, Fig. 3 also shows the upward shift in concentrate level as a result of the train’s movement. Note that contaminant toxicity increases much faster at impact points closer to the train.
When the wind is blowing northeast in Fig. 2, P2 is downwind from M and it has positive crosswind distances (i.e., \( y > 0 \)) to the other four railcars. Therefore, the maximum concentration at P2 cannot exceed that of P1. Similarly, the maximum concentration at P3, which is attained when the wind is blowing north, is less than that of P1. Thus, P1 is the maximum concentration point among all the locations equidistant from M. When the distance from hazmat-median of an 11-railcar propane block is 1500 m, for example, the concentrate levels at P2 and P3 are 95.8% and 95.5%, of the maximum level, respectively. This difference decreases with distance and increases with the number of hazmat railcars.

Analogous to the single release-source case, it is possible to estimate the exposure around the train by rotating the maximum concentration point, P1, around the hazmat-median, M. Therefore, we use the hazmat-median as the reference point for the train. This assures consistency among the maximum concentrate levels under opposite wind directions, when hazmat railcars are blocked. If another point were used as reference, the concentrate levels at the opposite downwind locations from the hazmat railcar block would be different. Take, for example, F as an alternative reference point. Since all the railcars are behind F, the total concentrate level at a certain downwind distance will be higher when the train is moving upwind. Because the amount of hazardous cargo on both sides of M is the same, it constitutes the best option for a reference point.

Thus, the maximum concentrate level at distance \( x \) from the hazmat-median of an \( n \)-railcar hazmat block is

\[
C_n(x) = \frac{Q}{\pi u a c x^b x^d} + \frac{Q}{\pi u a c (x-l)^b (x-l)^d} + \frac{Q}{\pi u a c (x+l)^b (x+l)^d} + \cdots + \frac{Q}{\pi u a c (x-nl/2)^b (x-nl/2)^d} + \frac{Q}{\pi u a c (x+nl/2)^b (x+nl/2)^d},
\]

(3)

where \( l \) denotes the length of each railcar. In the next section, we present a number of insights obtained via the above model.
4. The nature of railroad transport risk

Evidently, the definition of the worst-case scenario is at the core of population exposure estimates, and hence it is a possible source of contention among various stakeholders in hazmat transport risk. For example, it is plausible that a 24 in rupture on all damaged hazmat railcars, which we use in the analyses above, could be deemed extremely unlikely. Nonetheless, widespread acceptance of the population exposure estimates can be achieved by establishing their robustness to reasonable changes in the worst-case parameter settings. To illustrate this, we provide a parametric analysis of the impact of rupture size on exposure levels. Focusing on the instances with equal damage to all hazmat railcars, Fig. 4 depicts the total concentrate levels induced by 6, 12 and 24 in ruptures in a 5-railcar propane block. It is important that the concentrate curve associated with 12 in ruptures is very close to the curve due to 24 in ruptures. This can be explained by the small difference between the release rates from an 80 t railcar for these two rupture sizes: 2600 and 2670 pounds/s, respectively. Our analysis also showed that all concentrate curves representing the scenarios with either 12 or 24 in ruptures on each of the five railcars fall within the top two curves in Fig. 4. The concentrate curve is below the 12 in curve only when there is a 6 in rupture on one or more of the railcars. This is due to the significant decline in the release rate for small ruptures i.e., 693 pounds/s for a 6 in rupture. Consequently, as long as all the stakeholders can be convinced that none of the hazmat railcars would have a small rupture in the worst-case, 24 in constitutes a robust parameter setting in the model.

We now turn to an analysis of the impact of train make-up on the exposure levels. Using (3), we first address the question “How does the impact area vary with the positioning of a given number of hazmat railcars in the train?” Along the lines of the case study in Section 6, we will use a 68-railcar train for illustrative purposes.

A comparison between two alternative configurations of the train that includes 20 tank-cars of propane provides some insight. In Fig. 5, “20 Cars” represents the concentration curve associated with a block of 20 propane tank-cars at the center of the train, whereas “20 Cars-S” is obtained by placing a 10 tank-car block at each end of the train. “20 Cars-S” causes less contamination only at downwind distances of less than 180 m. This is because the people who are “too close” to the hazmat-median of “20 Cars-S” are exposed only to the 10 tank-car block at the back of the train. Given that the train is 612 m long, the peak concentrate level at 306 m from $M$ is clearly due to the 10 tank-car block at the front of the train. Note that, however, the area within 180 m of $M$ is extremely vulnerable to small changes in wind direction.
Fig. 5 shows that blocking hazmat railcars, as in “20 Cars”, imposes less transport risk as one moves away from the train.

Perhaps a more important question is “How does the exposure zone vary with the number of railcars?” To address this, we assume the hazmat railcars are blocked. Fig. 6 depicts the maximum concentrate levels as a function of distance for 30-, 68- and 120-railcar hazmat blocks.

As expected, concentration curve shifts upward as the number of hazmat railcars increases. Consequently, the curve associated with 68 railcars lies within the area defined by the 30-railcar and 120-railcar blocks. At points closer to the train, contaminants accumulate at a higher rate than the increase in the number of hazmat railcars. At 1000 m, for example, the concentrate level due to 120 railcars is 4.7 times that of 30 railcars.

The IDLH levels for propane exposure are 4,200,000 ppm for fatality and 600,000 ppm for injuries [12]. Since concentrate curves monotonically decrease with distance (see Fig. 6), toxic concentration remains higher than a specified IDLH level until a threshold distance. The people within this threshold face the possibility of suffering the associated undesirable consequence. In Table 2, we provide the severe and non-severe threshold distances for the three hazmat blocks under consideration. For each configuration, these two thresholds define three concentric regions around the train i.e., the fatality zone, the injury zone and the non-exposure zone (where the concentration is less than 600,000 ppm). Consequently, the exposure level is a step function of distance despite the continuous nature of concentration. An individual
Table 2
Threshold distances (in meters) as a function of $n$

<table>
<thead>
<tr>
<th>Threshold distance</th>
<th>No. of hazmat railcars</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Severe zone</td>
<td>1238</td>
</tr>
<tr>
<td>Non-severe zone</td>
<td>4466</td>
</tr>
</tbody>
</table>

would be indifferent to changes in the number of hazardous railcars in a train as long as the resulting adverse consequence remains unaltered. For instance, an individual residing at 1500 m from the train would be indifferent between 68 and 120 railcars because of being exposed to the fatality risk in both cases (Table 2 shows that the severe zone for a 68-railcar block is up to 2041 m). This individual, however, would certainly prefer a 30-railcar block (as opposed to the 68 or 120 railcar train) since the exposure reduces to the non-severe level as a result of the reduction in the number of hazardous railcars. In general, an individual will be indifferent between two trains of different lengths as long as there is no change in unfavorable consequence. But the same individual will prefer a single exposure from a longer train (say 120 hazmat railcars) to multiple exposures from shorter trains (two trains with 60 hazmat railcars), as long as the adverse consequence stemming from the two train lengths is identical.

Table 2 (and Fig. 6) show that threshold distance increases with the number of hazardous railcars in the train, which we denote by $n$. We also observe that the rate of increase in the threshold distance is consistently less than that of $n$. For example, the fatality threshold for $n = 30$ is 1238 m, whereas it is 3015 m for $n = 120$. This translates into a 143% increase in the threshold distance for the severe zone when the number of hazmat railcars is quadrupled. Focusing on a 120 railcar shipment for illustration; the choice among $n = 30$ and 120 blocks involves a trade-off between exposing the people within 1238 m to fatality risk four times and exposing those within the 3015 m only once. The total population exposure associated with each alternative depends on the spatial distribution of population density around the tracks. Clearly, the number of people within the larger zone is 143% higher, when population density within 3015 m is constant.

The above observations relate to the concept of equity in the spatial distribution of transport risk. Gopalan et al. [37] pointed out that equity can be improved by the use of alternate routes for a shipment. Although this is plausible for highway shipments, the sparse railroad network in North America does not present many routing options. This leaves train make-up as a primary determinant of risk equity. Given a certain demand to be shipped, the use of fewer trains would lead to an increase in the exposure zone while reducing the number of times people close to the tracks are exposed. When the railroad passes through a large region with uniform population density, this would spread exposure over a larger populace that improves equity according to the established measures e.g., the Gini Coefficient [38,39].

5. Approximating the maximum concentration level

The typical cross-length of a Gaussian plume is 2–3 km, while the separation distance of consecutive railcars is around 10 m. This implies a substantial overlap of Gaussian plume footprints emanating from hazmat railcars positioned anywhere in the train. Therefore, (3) lends itself to the following approximation
Table 3
Percent error due to approximation

<table>
<thead>
<tr>
<th>Threshold distance</th>
<th>No. of hazmat railcars</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Severe zone (%)</td>
<td>0.81</td>
</tr>
<tr>
<td>Non-severe zone (%)</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 4
Threshold distances (in meters) under random positioning of hazmat railcars

<table>
<thead>
<tr>
<th>Threshold distance</th>
<th>5 Hazmat railcars</th>
<th>11 Hazmat railcars</th>
<th>21 Hazmat railcars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approximate</td>
<td>1341</td>
<td>2204</td>
<td>3417</td>
</tr>
<tr>
<td>Average</td>
<td>1366</td>
<td>2213</td>
<td>3422</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>60</td>
<td>41</td>
<td>33</td>
</tr>
</tbody>
</table>

that can be used as a practical means to estimate the exposure levels:

\[
\overline{C}_n(x) = n \times \frac{Q}{\pi a c x^b x^d},
\]

where \( n \) is the number of identical release sources with rate \( Q \). This amounts to assuming that all the hazardous cargo is located at the hazmat-median of the train. In the remainder of this section, we show that (4) is not only reliable for estimating the threshold distances, but also robust in terms of train make-up.

Table 3 depicts the percent error in the threshold distances for 30-railcar, 68-railcar and 120-railcar propane blocks computed via (4). The error is defined as the percent deviation from the corresponding values in Table 2. Note that the approximate model estimates all the threshold distances within an error margin of 1.26%. The approximate concentrate level shifts upward proportionately to the number of hazmat railcars. However, as mentioned in the previous section, the percent increase in the actual concentrate level is more than the percent increase in \( n \) at points close to the train. Consequently, accuracy of (4) increases with distance and decreases with the number of hazmat railcars. At 1000 m, for example, the approximation errors associated with the severe zone for 30 and 68 propane cars are 1.14% and 7.11%, respectively. These errors reduce to 0.45% and 3.64% at 1600 m from hazmat-median of the train. Nevertheless, the approximation errors near the train are inconsequential since the concentrate levels are very high, making a severe consequence almost certain.

In order to analyze robustness of the approximate model with respect to positioning of the hazmat railcars in a train, we considered three cases: 5, 11, and 21 propane tank-cars in a train with 68 railcars. Transport Canada regulations stipulate that the first and last five railcars in a non-unit train cannot carry hazardous cargo [6]. Thus, 100 train make-ups were generated for each case by randomly positioning the hazardous cargo among the 6th and 63rd railcars. Table 4 shows the (statistics associated with) non-severe threshold distances as well as the approximations. Given \( n \), (4) estimates the same distance for all random train make-ups, since all hazmat is aggregated at the hazmat-median. The accurate calculation of total concentrate level, however, needs to incorporate the actual distance to each hazmat railcar. To illustrate
this, consider a train make-up with hazardous cargo in the 6th, 11th, 15th, 37th and 63rd railcars. The hazmat-median, in this example, is the 15th railcar. Note that the hazmat-median will remain the same if the hazardous cargo in the 63rd railcar was moved to the 38th railcar, whereas the actual toxicity level at downwind distances from the train will change as a result. Thus, the average threshold distances of 100 random train make-ups for each of the three cases are depicted in Table 4.

The approximation error is within 2% for all three cases. This enables us to surmise that the approximate model remains effective under uncertainty regarding the positioning of hazmat railcars in the train. Also, the approximate model performs better as the number of hazmat railcars increases. This can be explained by the reduction in variance of the threshold distance as hazardous content of the train increases. The distances in Table 4 are calculated at downwind locations assuming that the train is traveling east, as in Fig. 2. If the train is traveling in the opposite direction, the average threshold distances will be slightly different, whereas the approximate distance will remain the same.

6. Assessment of the “Ultra-train” shipments

In this section, we present a case study that makes use of the proposed methodology in the province of Quebec, Canada. Every day, CN runs a train from Ultramar’s refinery near Quebec City to its terminal in Montreal. This 68 tank-car train, which CN calls the “Ultra-train”, is devoted to finished petroleum products such as, gasoline, diesel, jet fuel and propane. Ultra-train uses the CN main-line, which is the southern route in Fig. 7a. The public is sensitized to the Ultra-train shipments due to a 1999 accident near Mont-Saint-Hilaire that killed two CN employees. A popular newspaper [40] pointed out that if the derailment occurred in a residential area, rather than an industrial zone, its impact could have been much worse. Consequently, there is considerable concern with the circuitous nature of the current route in the city of Montreal, which is depicted in Fig. 7b.

According to a report commissioned by the EPA [41], bulk evaporation is typically quite high for refined petroleum products e.g., 90–100% for gasoline. The report also suggests that these products can be modeled as neutrally buoyant gases, although their vapors are heavier than air. The content of Ultra-train varies daily, and the information regarding its cargo is not publicly available. Propane is shipped as a liquefied gas, which becomes airborne immediately after an accidental release. Gasoline, on the other hand, is initially released as a liquid, which results in a spill (puddle formation), and then evaporates gradually. In the absence of more detailed information, we modeled the entire cargo as a propane shipment that enabled us to derive conservative estimates of population exposure. The other model parameters are set as described in Section 3.

Currently, CN is using a single threshold distance of 800 m in their risk assessment as per the suggestion in [9]. Our model, however, indicates that the fatality threshold distance for the Ultra-train is 2 km, whereas people within 7.7 km of the railroad are exposed to injury risk. [42] provides the technical documentation for the values of initial isolation and protective action distances in the 2000 Emergency Response Guidebook [9]. These values are calculated using a number of hypothetical scenarios, and corresponding safe distances with chemical concentration below hazard level are determined. Spill size and the presence of multiple sources of release are the two reasons (plus the different atmospheric parameters) to account for the difference in the threshold distance as computed here and the one specified in [9]. Large spill size in [9] means anything more than 55 gal, whereas in our computation 80 t (per rail tank car) of hazmat is released and hence modeled for exposure level calculations (perfect worst-case
scenario). Secondly, for propane, [9] presents values based on spill-size (and day/night variants) without considering multiple sources of release as in the event of a hazmat-unit train. In contrast we have used specific number of release sources to calculate aggregate concentration levels and threshold distances. Our results and analysis imply that the method used by CN grossly underestimates the population exposure risk and hence the danger posed by the Ultra-train.

We use ArcView, a popular Geographical Information System, and Avenue Programming Language to generate the corresponding exposure zones around the CN main-line. Then, we overlay these zones on the population centers (i.e., the polygons in Fig. 7a) and identify the intersection areas. The total number of people in the severe zone is 492,195, whereas the population within the non-severe zone is 986,206. In total, Ultra-train exposes about 1.5 million people to varying degrees of transport risk.

During our analysis of the existing railroad network, we identified two alternative routes for Ultra-Train. The “shortcut link” allows for a detour from the CN main-line via a north turn upon entering the island of Montreal (see Fig. 7b), which results in a 16 km reduction in inner-city travel. The “northern route”, however, avoids the island of Montreal almost entirely by entering from northeast (see Fig. 7a). Using our model, we also assessed the transport risk associated with these two routes. If the shortcut link is used, the number of people in the severe zone will reduce 36% and there will be a 24% reduction in the exposure to non-severe consequences. The use of northern route, however, will result in a 57% reduction in both fatality and injury exposures. The northern route is only 3.4% longer than the current route, whereas the shortcut link provides a 5.6% reduction in travel distance. The primary reason for CN to continue using its main-line, which has much higher population exposure, is track quality. The company is deterred from using either of the two alternate routes by the significant capital outlay required for track upgrades and installation of monitoring equipment.

The large amount of refined petroleum products shipped through the city of Montreal on a daily basis is a significant concern for the emergency response planners in Quebec. The analysis in Section 4 shows that a reduction in the volume of hazmats will not pay off in terms of the resulting decrease in the threshold distance. If the number of tank-cars in Ultra-train is halved, for example, the threshold distance of the current severe zone will decrease only 9%. In this case, CN will have to run two 34 tank-car trains daily in order to satisfy Ultramar’s demand. Each shipment exposes 437,176 people to fatality risk, and hence total exposure in the severe zone will increase 78% due to the use of 34 tank-car trains. Due to the non-linearity
of concentrate curve, the impact is less drastic within the non-severe zone: threshold distance for injuries decreases 38%, which puts 619,099 people at injury risk and results in a 26% increase in exposure to non-severe consequences. These numbers are based on the assumption that these two trains reach their destination, without an accident, using the mainline route.

The net effect of a hazmat release is a function of both the severity of the accident and the follow-up efforts of the emergency response team. It is interesting to note that emergency response planners are more concerned with the number of people within the exposure zone than the total exposure. Clearly, this amounts to ignoring the number of times an individual is exposed to a certain risk. A common response to hazmat incidents is evacuation of the impact area around the site of accidental release. Reducing the impact area of an accident, through decreasing the volume of hazmat involved, certainly makes emergency response planning easier. Therefore, emergency response planners in Quebec prefer any reduction in the length of Ultra-train despite the associated increase in population exposure.

7. Concluding remarks

This paper presents a risk assessment methodology for railroad transportation of dangerous goods. Focusing on hazmats that are airborne on release, we represent exposure zone as a function of the volume of hazmat shipped and the make-up of the train. The definition of exposure in terms of concentrate level enables us to model the reduction in transport risk with distance from the railroad. In addressing the multiple release-source nature of train accidents, we propose the use of hazmat-median of the train as a reference point, which also provides a solid basis for approximating the threshold distances for different consequences. In setting parameters of the model, we adopt a worst-case approach to transport risk—although the model can easily incorporate less conservative incident scenarios. This allows us to incorporate the uncertainty in wind direction by using concentration levels on downwind points to generate danger circles.

The proposed methodology provides valuable insights with regards to the nature of railroad transport risk. Most notably, we point out the conflict of interest among the people living nearby railroad tracks and those who are not in the immediate vicinity. Given a certain amount of hazmat to be shipped, increasing the amount of hazardous cargo on each train would favor the former group. We also establish that, in general, blocking hazmat railcars would reduce population exposure. Although we assumed neutral atmospheric stability in this paper, additional computational experiments show that the overall results do not change under other stability conditions. Application of the methodology for assessment of Ultra-train’s transport risk enabled us to validate our insights.

There are a number of future research directions. First, the proposed methodology can be extended to incorporate accident probabilities. This requires a solid understanding of how accident probability varies with train make-up. Since catastrophic train accidents are very rare events, validation of such a probabilistic model against accident data constitutes a formidable challenge. Second, the development of a methodology to analyze the cost-risk trade off in the context of railroad shipments would be a significant contribution. This would certainly facilitate negotiation between the railroad companies and regulator towards mitigating the public and environmental risks associated with trains. Finally, the increasing popularity of multimodal transportation calls for the development of an integrated risk assessment methodology that incorporates both railroad and highway shipments.
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