Effect of Train Speed on Railroad Hazardous Materials Transportation Route Risk Analysis

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ABSTRACT

This paper considers the effect of train speed on railroad hazardous materials transportation risk. A statistical method was developed to estimate the speed-dependent conditional probability of release (CPR) of tank cars involved in accidents with the objective of assessing its effect on risk analysis results. A case study of a representative hazardous materials route was conducted in which risk estimates were developed using conventional, average-speed CPR and compared to the analysis of the same route using speed-dependent CPR. The calculated risk results differed indicating that use of speed-dependent CPR may be an important refinement for accurate calculation of route risk.

The effect of track-class upgrades on risk was also considered. Higher FRA track classes have lower accident rates, but the higher permissible speeds increase CPR if a tank car is derailed in an accident. Consequently, evaluation of the effect of track upgrades must account for both factors to understand the net impact on risk. In the track-class upgrade analysis two scenarios were considered: upgrades without speed increase, and upgrades with speed increase. The increased tank car release rate at the higher speeds permissible on higher track classes was more than offset by the reduction in accident rate for all the track-class upgrade scenarios considered. For the particular route analyzed in the case study, using speed-dependent CPR resulted in a slight increase in the overall risk estimate, and upgrading class-3 track provided the greatest reduction in risk. Such results will be route-specific; however, use of speed-dependent CPR enables more accurate analysis of local risk and provides a better evaluation of risk reduction options that involve changes in operating and track characteristics.

Keywords: risk analysis, rail transportation, hazardous material, train speed, conditional probability of release, Geographic Information System

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INTRODUCTION
Train operating speed is one of the factors affecting the likelihood of a release in railroad accidents involving tank cars transporting hazardous materials. The higher the speed of a derailment, the more cars are likely to derail, and of these the higher the probability that one or more will suffer a release (1). Nevertheless, previous studies have generally simplified this aspect of railroad hazardous materials transportation risk analysis by using a single value for the conditional probability of release (CPR), that does not account for variation in train speed (2, 3, 4, 5). Use of a single value of CPR, independent of train speed simplifies risk analysis, but also implies an average speed of derailment (6). Since this average CPR speed may be higher than actual operating speed in some situations, and lower in others, using it will have the effect of over-estimating release probabilities in lower speed sections, and under-estimating release probabilities in higher speed sections of the route.

The relationship between speed and CPR has previously been considered (7, 8, 9). The most recent study (7) provides estimates for both average-speed and speed-dependent CPR of the tank cars, but only the average-speed CPR accounts for specific safety design features. Earlier works were not specific to tank cars (8), or did not enable application of speed-dependent effects to specific tank car designs (9). In this study, the authors explicitly consider the effects of train speed on hazardous materials transportation risk analysis and develop a technique that enables estimation of speed-dependent CPR for specific tank car designs using published data on safety performance of tank cars in accidents (7) that permits one to apply adjustment factors derived from a group of car types to a specific car type.

Use of tank car design enhancements as options to reduce risk has become more prevalent over the past decade and the model introduced here provides flexibility that enables the effect of these enhancements to be considered using the most up-to-date published data available. Furthermore, the effect of tank car safety design can be integrated with other options.

In this paper, the authors specifically consider the interaction of infrastructure quality, train speed and tank car performance to understand the effect on risk estimates using speed-dependent CPR. A case study is presented using a representative hazardous material transportation route. The results of a risk analysis in which average-speed CPR is used are compared to one using speed-dependent CPR.

In the second part of the paper, the importance of using CPR adjusted for speed is highlighted by further considering its utility as part of an assessment of the effect of track-class upgrade on risk. Upgrading track has been shown to be correlated with the reduction of certain types of accidents and consequently risk (8). However, if the upgrade is also intended to allow increased operating speeds, it may increase the probability of release if an accident does occur (1, 7). CPR and accident rate are the two principal elements in hazardous materials transportation risk analysis. Considering each as a function of speed enables more accurate estimation of route-specific risk. This also facilitates proper consideration of the benefit of infrastructure improvement. Two scenarios were analyzed: track upgrade without a speed increase, and upgrade with a speed increase. The degree of risk reduction varies with these options and consideration is given to which offers the greatest safety benefit for the problem analyzed.
REVIEW OF RISK ANALYSIS METHODS

Hazardous materials transportation risk can be quantitatively expressed as the frequency of a release incident multiplied by the consequence of that release. In this study, frequency is a product of: annual per car-mile-rate of tank car involvement in an FRA-reportable derailment on mainline track, number of shipments, total mileage from origin to destination and the conditional probability of release given that a tank car derails. The consequence of a release incident is the impact of the released material and is affected by product characteristics, quantity and rate of spillage, atmospheric conditions and the population density along the route analyzed.

The consequence can be expressed using several metrics. In this study the authors used the number of persons who might potentially be affected due to a hazardous material release from a tank car in accordance with the product-specific recommendations in the U.S. Department of Transportation (DOT) Emergency Response Guidebook (ERG) (10, 11). The consequence can be estimated by multiplying the affected area using the ERG recommended evacuation distances by the population density within the affected area.

The risk model calculated using the method described above is the annual expected number of persons who might be evacuated or sheltered in place due to a hazardous materials release. Specifically, risk is calculated from the product of: accident rate, traffic volume measured in car-miles, tank car CPR, the probability distribution of release sizes, the affected area corresponding to the release size, and the population density in the affected area summed over all segments on the route.

The risk model in Eq. (1) incorporates these segment-specific parameters and gives the estimate of risk associated with shipments of hazardous materials on the route.

\[
S = \sum_{i=1}^{n} \sum_{j=1}^{k} Z_i V_i L_i R_i P_j A_j D_i
\]

where

- \( S \) = annual risk (persons affected per year)
- \( Z_i \) = rate of tank car involvement in an FRA-reportable derailment (cars derailed per car-mile)
- \( V_i \) = annual shipments (carloads per year)
- \( L_i \) = length of track segment (mile)
- \( R_i \) = conditional probability of release given that a tank car derails
- \( P_j \) = conditional probability of a specific scenario \( j \) given that there is a hazardous material release from a derailed tank car
- \( A_j \) = affected area corresponding to a specific release scenario per the U.S. DOT ERG recommendation (square mile)
- \( D_i \) = average population density along track segment (persons per square mile)
- \( i \) = track specific segment
- \( n \) = total number of segments along the route considered
- \( j \) = specific release scenario (e.g. spill size, fire involvement, time of day)
- \( k \) = total number of scenarios considered
CASE STUDY
The authors consider a typical, representative route as part of the distribution network of a particular hazardous material on the North American rail network. The distance from origin to destination is 1,400 miles and is comprised of 598 segments with an average segment length of 2.34 miles. These track segments correspond to links in the FRA rail transportation network obtained from the Bureau of Transportation Statistics (12). The authors assumed 100 annual carloads over the entire route using a non-insulated, DOT-111A100W1 tank car with 7/16 inch tank thickness and no special safety design features beyond the DOT minimum requirements.

For some materials, consideration of multiple release scenarios may be appropriate. However, based on expert opinion of the manufacturer of the product and the objectives of this study, use of a single release scenario was satisfactory. Thus, the major factors affecting risk in this analysis are: product characteristics, track-class-specific accident rate, shipment volume, tank car safety design, operating speed, and population exposure along the route.

The case study is used to analyze the effects of train speed on the route risk estimate, and the contribution of various other factors to the risk, including population density and FRA track class. In addition, the case study is used to illustrate the merit of using speed-dependent CPR in an assessment of the effect of track infrastructure upgrade on risk reduction. These will be discussed in more detail in the subsequent sections.

ESTIMATION OF PARAMETERS AFFECTING RISK
FRA track-class-specific accident rates were used in this study (13). Track speed reflects FRA track class, which has been shown to be correlated with railroad accident rates (8). The authors used railroad timetable speeds to infer the FRA track class and other local operating restrictions for all segments along the route. The next step is to estimate CPR given that a tank car is derailed in an accident. The relationships developed by Treichel et al (7) were used to determine the CPR of the particular design of tank car considered in this study. Since CPR is also affected by train accident speed (1, 7, 8, 9), the authors adjusted it according to the timetable speed for each track segment. The authors calculated the speed-dependent CPR using the procedure described in the following section.

To estimate the consequences of a release, the authors used Geographic Information System (GIS) software, ArcGIS Desktop 9.2, to create the shipment route using the U.S. DOT national rail network (12). An overlay analysis of the population distribution along the rail network was conducted using census tract data from the ESRI Data & Maps, Electronic Database (14) and a buffer representing the exposure area was created. This was the area within the radius from track center equal to the U.S. DOT ERG maximum evacuation distance for the material considered. Then, the average population density of the affected area corresponding to each track segment was determined.

The procedure used to estimate and measure risk is similar to that described in previous papers (2, 6), except that this paper focuses on refining the method to understand the effect of speed-dependent CPR.
SPEED-DEPENDENT CONDITIONAL PROBABILITY OF RELEASE

Treichel et al. (7) described lading loss probability based on the four major cause-specific loss events as:

\[ P = P(R_h \cup R_s \cup R_t \cup R_b) \]  

where \( P \) = the probability of an event that a tank car released its contents given that it derailed in an accident 
\( R_h \) = an event that contents lost was attributed to head damage 
\( R_s \) = an event that contents lost was attributed to shell damage 
\( R_t \) = an event that contents lost was attributed to top fitting damage 
\( R_b \) = an event that contents lost was attributed to bottom fitting damage

The cause-specific loss events have very low correlations (7) so the authors assumed that \( R_h, R_s, R_t, \) and \( R_b \) are independent. Therefore:

\[ P = 1 - P^c \]  

\[ = 1 - P(R_h^c \cap R_s^c \cap R_t^c \cap R_b^c) \]  

\[ = 1 - P(R_h^c)P(R_s^c)P(R_t^c)P(R_b^c) \]  

\[ = 1 - [1 - P(R_h)][1 - P(R_s)][1 - P(R_t)][1 - P(R_b)] \]

where \( c \) = the complement of an event

Let \( R \) equal the conditional probability of release given that a tank car derailed in an accident, unadjusted for speed, and \( R_h, R_s, R_t, R_b \), the CPR attributed to head, shell, top fitting, and bottom fitting, respectively, so that:

\[ R = 1 - (1-R_h)(1-R_s)(1-R_t)(1-R_b) \]  

where \( R \) = tank car CPR, unadjusted 
\( R_h \) = CPR from head, unadjusted 
\( R_s \) = CPR from shell, unadjusted 
\( R_t \) = CPR from top fittings, unadjusted 
\( R_b \) = CPR from bottom fittings, unadjusted

Speed-dependent CPR was calculated by multiplying the unadjusted CPR by the speed-adjustment factors. This adjustment can be made to the CPR associated with each specific source of release, i.e.,

\[ R' = 1 - (1-R_h J_h)(1-R_s J_s)(1-R_t J_t)(1-R_b J_b) \]  

\[ \text{where} \quad R' = \text{tank car CPR, adjusted for speed} \]  
\( J_h \) = speed-adjustment factor for CPR from head 
\( J_s \) = speed-adjustment factor for CPR from shell 
\( J_t \) = speed-adjustment factor for CPR from top fittings 
\( J_b \) = speed-adjustment factor for CPR from bottom fittings
To determine the speed-adjustment factors in Eq. (5), the authors first developed the relationships between train speed and CPR for each release source using the proportion of tank cars losing lading from each source. The authors used statistical software, SAS 9.1, to fit a simple linear regression equation with zero intercept to the published data on tank car safety performance (7) (Figure 1). A simple linear regression was used without weighting by the number of observations at each speed, consistent with a similar analysis by Treichel et al. (7). The fitted functions are shown below and the corresponding test statistics are summarized in Table 1.

**FIGURE 1** Proportion of Non-pressure Tank Cars Releasing vs. Speed for Releases From A) Heads, B) Shells, C) Top Fittings, and D) Bottom Fittings.
TABLE 1  Parameter Estimates of the Linear Speed-CPR Models

| Model  | Estimate of Regression Coefficient, β | Standard Error | t-value | Pr > |t| | R²    |
|--------|--------------------------------------|----------------|---------|------|-----|--------|
| Y_h = β_hX | 0.00786                              | 0.00044925     | 17.49   | <0.0001 | 0.9622 |
| Y_s = β_sX | 0.00674                              | 0.00061609     | 10.94   | <0.0001 | 0.9089 |
| Y_t = β_tX | 0.00460                              | 0.00072981     | 6.30    | <0.0001 | 0.7677 |
| Y_b = β_bX | 0.00150                              | 0.0031975      | 4.69    | 0.0005  | 0.6468 |

Y_h = 0.00786X                          (6)
Y_s = 0.00674X                          (7)
Y_t = 0.00460X                          (8)
Y_b = 0.00150X                          (9)

where

Y_h = proportion of non-pressure cars releasing from heads, corresponding to train speed X
Y_s = proportion of non-pressure cars releasing from shells, corresponding to train speed X
Y_t = proportion of non-pressure cars releasing from top fittings, corresponding to train speed X
Y_b = proportion of non-pressure cars releasing from bottom fittings, corresponding to train speed X
X = train speed (mph)

In the next step, the authors used the data in Treichel et al (7) to calculate the weighted average train speeds for releases from tank head, shell, top fittings and bottom fittings, which were, 38.5, 41.2, 28.7, and 35.5 mph, respectively. These average speeds were then substituted into Eqs. (6) through (9) to determine the proportion of cars releasing from each source, yielding the following values for the non-insulated 111A100W1 considered here, Y_{ha} = 0.30260, Y_{sa} = 0.27753, Y_{ta} = 0.13178, and Y_{ba} = 0.05330, respectively.

Speed-adjustment factors were then determined by dividing the proportion of non-pressure cars releasing at a particular speed by the proportion of cars releasing corresponding to weighted average speed, e.g. J_h = Y_h/Y_{ha} and so on. The speed-adjustment factors, applicable to non-pressure cars were:

J_h = 0.02597X                          (10)
J_s = 0.02429X                          (11)
J_t = 0.03491X                          (12)
J_b = 0.02814X                          (13)

The cause-specific CPRs for the particular tank car considered were estimated, using the data from Treichel et al (7), as: \( R_h = 0.0799, \) \( R_s = 0.1092, \) \( R_t = 0.1577, \) \( R_b = 0.0625. \) Using Eq. (4), the average-speed (unadjusted) CPR for this tank car is 0.3527. Substituting the values of cause-specific CPRs into Eq. (5), the speed-dependent CPR was estimated as follows:

\[ R' = 1 - [(1-0.0799J_h)(1-0.1092J_s)(1-0.1577J_t)(1-0.0625J_b)] \]  (14)
Figure 2 shows the speed-dependent CPRs, compared to the average-speed CPR of the non-insulated 111A100W1 tank car considered. This method can be adapted for any other type of tank car for which suitable data are available (7).

**FIGURE 2** Estimated Conditional Probability of Release Dependent on Speed for the Tank Car Considered (DOT-111A100W1).

**EFFECTS OF TRAIN SPEED ON RISK**
The authors evaluated the effects of train speed by comparing risk estimates calculated using speed-dependent CPR, with the baseline case in which average-speed CPR was used. Use of speed-dependent CPR yields an annual risk of 1.428 persons affected per year, compared to 1.291 if average-speed CPR is used, an 11% difference. Further detail regarding the effect of speed-dependent CPR can be seen by comparing the risk profiles calculated using speed-dependent versus average-speed CPRs (Figure 3A).

These differences in estimated risk when speed-dependent CPR is used are specific to the characteristics of the particular route analyzed in this case study. In general, the effect on risk estimates will depend on the distribution of speeds along a route. Specifically, routes with a larger percentage of higher-than-average-speed trackage will tend to have increased risk estimates when speed-dependent CPR is used, and those with a lower percentage will tend to have reduced risk estimates.

In previous work, it was found that a large percentage of risk along a route was attributable to a small percentage of its length (6). In the case study described here, the 100 segments with the highest risk per mile (Figure 3B) accounted for 18% of route length but 92% of the risk. Of these segments, all but 22 had higher estimated risk when speed-dependent CPR was used compared to average-speed CPR. Interestingly, these 22 segments were among the very highest risk segments in the entire analysis, accounting for 2% of route length but 23% of the total risk. By contrast to the overall risk analysis results for the route, use of the speed-dependent CPR for these segments resulted in lower risk estimates than when average-speed CPR was used.
It is not surprising that use of speed-dependent CPR resulted in higher overall risk estimates in the case study considered because the segments with higher than average speeds comprised a majority of the overall route length, i.e. 1% for speed 11-25 mph (track class 2), 16% for speed 26-40 mph (track class 3), 39% for speed 41-60 mph (track class 4), and 44% for speed 61-70 mph (track class 5). FRA regulations permit operation of freight trains up to 80 mph on class-5 track (15); however, 70 mph is a more typical maximum speed and was the case for the route studied. The maximum speed for "Key trains" is 50 mph (16) but the particular hazardous material considered in this study does not affect Key train status. For the purposes of this study, maximum permissible speeds from railroad timetables were used to infer FRA track class and were assumed to represent the operating speeds on each track segment.
A potential drawback of using timetable speeds to infer track class is that some segments may actually have higher quality track and correspondingly lower accident rates than would be assumed based on inferences from timetable speed. In some circumstances, railroads may be maintaining trackage to a higher standard than required by the track safety regulations for the particular speed shown in the timetable. If information is available on actual maintenance standards and operating speed, this can be formally incorporated into the risk model allowing more accurate estimates of accident rate for these segments.

Even in the absence of such information, use of speed-dependent CPR instead of average-speed CPR provides more accurate risk estimates because it better reflects the particular operating characteristics of a route and their effect on risk. Such refinement is particularly important for comparison of the risk associated with different route alternatives, e.g. a shorter route passing through urban areas with lower train speed vs. a longer route that goes through less populated areas where trains may operate at higher speeds. Such considerations are germane to railroads and the U.S. DOT when considering the results of route risk assessments as required under HM-232E (17).

**RISK CONTRIBUTION BY POPULATION DENSITY AND TRACK CLASSES**

The authors analyzed the contributions to risk by different population density groups, using both average-speed and speed-dependent CPRs to understand their effects on risk estimates with respect to different population densities for the representative route. Track segments that are located in highly populated areas contribute a large proportion of route risk. For example, those segments located in areas where population density exceeds 6,500 persons per square mile represent the smallest proportion of the total route length but account for the largest percentage of the risk when the speed-dependent CPR is used (Figures 4A and 4B).

For the route considered, use of speed-dependent CPR yields higher risk estimates for all population density groups (solid line), compared to when average-speed CPR is used (dashed line) (Figure 4A). The difference between risk estimates for the two CPRs is largest for the highest density group, and smallest for the lowest density group. However, when the contribution is expressed as a percentage of total route risk instead of an absolute estimate; use of speed-dependent CPR results in a lower contribution for the highest population density group, relative to average-speed CPR (Figure 4B).

Some urban-area segments do not experience the reduction in estimated risk when speed-dependent CPR is used because in the case study these segments had speeds higher than average. On the other hand, some segments in non-urban areas had lower risk when speed-dependent CPR was used because of speed restrictions on these segments. Figures 4A and 4B also show that the majority of the representative route is class-4 and class-5 track. Most of these segments are located in moderate to low population density areas. Class 3-segments, however, are more evenly distributed over different population classes, from the lowest to the highest density.

The higher-track-class segments do not contribute much risk despite their greater percentage of route length. By contrast, the lower-track-class segments contribute a larger percentage of total route risk due to a combination of accident rate and population densities associated with them, despite the lower CPRs.

Using the speed-dependent CPR yields a lower estimate of risk on class-2 track but higher estimates for classes 3, 4 and 5 (Figure 4C). When the percentage contribution to total risk is considered (Figure 4D), use of the speed-dependent CPR results in a lower percentage of risk on track classes 2 and 3, and larger percentages from classes 4 and 5, compared to when average-speed CPR is used. This analysis based on the representative route illustrates that the use of speed-dependent CPR takes into account the effect of differential operating speeds on risk for each categorical variable considered: population density, and track class.
In the context of this discussion, it is useful to consider the ratio of the percentage of total risk to the percentage of route length. For the route analyzed, this risk:route length ratio based on speed-dependent CPR was 8.6, 4.4, 0.4, and 0.1, for track classes 2, 3, 4, and 5, respectively. Although class-2 track has the highest risk contribution per track mile, the overall contribution from class-2 is not as high as that of class-3 track due to the small percentage of class-2 track on the route. Since class-3 track contributes the largest percentage of risk on this route, measures to reduce this are likely to have the greatest overall effect. In the next section, the authors consider the effects of infrastructure upgrade on risk and illustrate how use of speed-dependent CPRs enables better assessment of the safety benefits of track infrastructure upgrade.
EFFECTS OF INFRASTRUCTURE UPGRADE

In the case study, the authors considered the effect of upgrading all class-2, class-3, and class-4 segments to the next higher class, i.e. to classes 3, 4, and 5, respectively, as three distinct upgrade options. The authors first considered the effect of track-class upgrade strictly as a means of reducing accident rate and consequently risk, and therefore assumed that operating speeds were held constant after track upgrades. Upgrading classes-2, 3 and 4 track to the next higher class yielded a 5%, 53%, and 7% reduction in risk, respectively. Upgrading class-3 segments offered the greatest reduction in risk, primarily because of the relatively large reduction in accident rate combined with a fairly large percentage of the route.

Track upgrade principally affects track-caused accidents; however, not all track-related accidents are affected in the same way by track-class upgrades. Furthermore, there are a wide variety of potential accident causes (18). Non-track-related causes may have no relationship, or only an indirect one with track class. Some accident causes, notably certain ones attributable to equipment failures such as broken wheels or axles, may actually increase with track-class upgrades if operating speed also increases. Hence, increasing track class only affects the likelihood of some types of accidents, and the functional relationship between each of these accident causes and track class varies. When one also considers that different accident causes have differing relationships with the likelihood of a derailed hazardous materials car suffering a release (1) it further complicates calculation of the effect of track-class upgrades on risk reduction. Further research on both the statistical and causal relationships between track class and accident frequency and severity is needed to improve quantitative assessment of the effect of changes in infrastructure quality on safety and risk. Until such research is completed and comprehensive data on critical infrastructure parameters is generally available, track class remains the best proxy statistic for estimating track quality, derailment rate and ultimately risk.

COMBINED EFFECTS OF INFRASTRUCTURE AND TRAIN SPEED

In this section, the relationships between track class, accident rate, and speed-dependent CPRs are examined. It was assumed that train speeds increase in accordance with track-class upgrades. That is, trains are assumed to operate at the maximum normal operating speed corresponding to the upgraded track classes. Therefore, for each segment, the accident rate will be reduced due to the track-class upgrade, but tank car CPR will increase because of the higher speed (Figure 5). The overall release rate, which is the product of accident rate and CPR (in this example, a non-insulated 111A100W1), is dominated by the former, and thus also declines. The difference in magnitude of release rate between consecutive track classes is the smallest for track classes 4 and 5.

The authors examined each individual segment to understand the change in risk as a result of track infrastructure upgrade and speed increase. Figure 6 shows the distribution of segment-specific risk per mile for three cases for each track class: 1) the baseline case (no upgrade), 2) upgrade to a higher class without increase in speed, and 3) upgrade to a higher class with a speed increase. Speed-dependent CPRs were used in all scenarios. For clarity, only the top ten segments with the highest risk per mile, ordered by the baseline risk, are shown. These charts indicate that upgrading class-3 segments to class 4 yields the largest reduction in risk, while upgrading class-4 track to class 5 offers little reduction in risk for the representative route. Furthermore, the difference between segment risk per mile when speed is held constant, compared to when speed is increased, is highest for the case in which class-2 segments are upgraded to class 3. The magnitude of difference varies because of the different initial operating speeds on each segment (Figure 6A). Overall, use of speed-dependent CPR enables individual consideration of both of the factors affecting risk in this case, the reduction in accident rate due to the upgraded track class, and the increase in CPR due to the higher operating speed.
FIGURE 5  Relationship between Track Classes, Accident Rates, Speed-dependent CPRs, and Release Rates for the Tank Car Considered (DOT-111A100W1).

FIGURE 6  Effects of Infrastructure Upgrade and Speed on Risk Reduction for the Top 10 Segments with the Highest Risk per Mile
A) Class 2 Upgraded to Class 3, B) Class 3 Upgraded to Class 4, and C) Class 4 Upgraded to Class 5.
DISCUSSION
When risk estimates for each of the scenarios analyzed in the case study are summarized, several results can be discerned (Table 2).

<table>
<thead>
<tr>
<th>Track Class</th>
<th>Total Distance Upgraded (Miles)</th>
<th>Accident Rate (Cars Derailed per Year)</th>
<th>Release Rate (Releases per Year)</th>
<th>Annual Risk (Persons Affected per Year)</th>
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<tr>
<td></td>
<td></td>
<td>Using Average-speed CPR</td>
<td></td>
<td>Using Speed-dependent CPR</td>
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<tr>
<td>Class 2</td>
<td>11</td>
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<td>0.0065</td>
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<tr>
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<td>0.0033</td>
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<tr>
<td>Class 4</td>
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<td>0.0125</td>
<td>0.0044</td>
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<table>
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<th>Track Class</th>
<th>Total Distance Upgraded (Miles)</th>
<th>Accident Rate (Cars Derailed per Year)</th>
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<th>Annual Risk (Persons Affected per Year)</th>
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<td>With Speed Increase</td>
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Percent Reduction from Baseline

<table>
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<th>Track Class</th>
<th>Total Distance Upgraded (Miles)</th>
<th>Accident Rate (Cars Derailed per Year)</th>
<th>Release Rate (Releases per Year)</th>
<th>Annual Risk (Persons Affected per Year)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Using Average-speed CPR</td>
<td></td>
<td>Using Speed-dependent CPR</td>
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<td></td>
<td></td>
<td>Without Speed Increase</td>
<td>With Speed Increase</td>
<td>Without Speed Increase</td>
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</table>

Percent Reduction per Mile Upgraded

First, in the consideration of track infrastructure upgrades, there are different opportunities for risk reduction based on the distribution of track classes on the route and the differential effects on risk reduction with respect to each track class. Upgrading the lowest track class provides the highest risk reduction per track mile; however, it represents the smallest proportion of the route so that it does not offer much opportunity to reduce risk. On the other hand, upgrading class-3 track segments to class 4 provides the highest risk reduction overall despite these segments not representing the largest percentage of the route compared to other track classes.
Second, use of speed-dependent CPR allows speed effects on different routes to be properly accounted for, whereas use of average-speed CPR does not. Furthermore, speed-dependent CPR is necessary for proper evaluation of the effect of track-class upgrades on risk: with or without speed increase.

Third, for the representative route, use of speed-dependent CPR yields annual risk estimates slightly higher than the average-speed CPR does. This is because the majority of the route has higher-than-average track speeds. This result will vary depending on route-specific characteristics.

Fourth, upgrading track class with the commensurate speed increase actually reduces risk relative to the baseline case. This is because the incremental effect of the lower accident rate due to the higher track class, more than offsets the slight increase in CPR due to the higher speed.

Completing the analyses used to illustrate the effect of speed-dependent CPR on risk estimates required several assumptions. As mentioned, for track-class upgrades with speed increase, it was assumed that trains would operate at the maximum allowable speed corresponding to the upgraded track class. This will result in higher-speed estimates than would actually be used on some segments, thus overestimating risk for these. Inferring track class based on timetable speed may not always represent actual maintenance conditions for some track segments, also resulting in over-estimation of risk. For both of these circumstances, if data for actual operating speed are available, they can be incorporated into the model and use of speed-dependent CPR will make such adjustments more accurate. Additionally, the relationships developed to estimate speed-dependent conditional probability of release in this study do not account for other possible speed-dependent effects such as number of cars derailed or spill size distribution; but, these factors can also be incorporated into the model if suitable data are available.

The intent of this research was to develop a general method to calculate speed-dependent CPR using published data on railroad tank cars. The authors then used a case study to compare several different scenarios that affect, or are affected by speed, in order to gain insight into the effect of using speed-dependent CPR on estimates of safety and risk. Analysis of these scenarios is not meant to suggest that these are necessarily the most cost-effective approaches to risk reduction. Instead, the methodology presented here is intended to describe and illustrate the utility of speed-dependent CPR and how to incorporate it into safety and risk analysis calculations. The scenarios considered here include upgrading track class both with and without speed increases. Either scenario would entail considerable additional capital and maintenance expense (19). Rational consideration of these options would require data on their incremental cost, and ideally, information on the cost-effectiveness of other options that might also affect risk. This would enable informed decisions about when and where risk reduction options should be implemented and which are the most cost-effective.

CONCLUSIONS
In this paper, the authors present a technique to incorporate the effects of different train speeds on accident rate and CPR and incorporate both of these into a hazardous materials transportation risk analysis model. The relationship was developed to estimate speed-dependent CPR thereby allowing more accurate estimates of route risk. Although previous work has addressed various aspects of this question (1, 7, 8, 9), the method for calculating speed-dependent CPR described
here can be used to develop estimates for specific tank car designs, which was not previously possible. Additionally, the statistics and methodology presented here are based on the most up-to-date, published data on tank car performance in accidents. The utility of speed-dependent CPR is illustrated using a case study of track infrastructure upgrades in which the authors analyze the effects of train speed and track improvement independently and together to assess their effect on route risk. Different options in a track infrastructure upgrade problem are considered to determine the option that may provide the greatest reduction in risk for the particular route studied.

Previous work has not explicitly considered the nature or extent of the effect on risk estimates of using average-speed CPR versus speed-dependent CPR. Although use of average-speed CPR may often be appropriate for national or system wide estimates of risk, it does not satisfactorily account for differences in operating characteristics when comparing routes. Different routes will almost certainly have differing speed distributions and population exposure. Use of average-speed CPR can lead to both under- and over-estimates of overall risk along the route, and at specific locations along the route. Both of these may affect risk management decisions; therefore, the ability to more accurately calculate them is important. In addition, use of speed-dependent CPR affects the ability to quantitatively assess the effect of certain types of track infrastructure upgrade as illustrated in the case study. The speed-dependent CPR calculation methodology and its application to risk analysis models should enable more accurate risk calculations, not only for route risk comparisons, but also for assessment and evaluation of the benefits of infrastructure improvements that affect operating speed.

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REFERENCES


