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Analysis of railroad tank car releases using a generalized binomial model

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ABSTRACT

The United States is experiencing an unprecedented boom in shale oil production, leading to a dramatic growth in petroleum crude oil traffic by rail. In 2014, U.S. railroads carried over 500,000 tank carloads of petroleum crude oil, up from 9500 in 2008 (a 5300% increase). In light of continual growth in crude oil by rail, there is an urgent national need to manage this emerging risk. This need has been underscored in the wake of several recent crude oil release incidents. In contrast to highway transport, which usually involves a tank trailer, a crude oil train can carry a large number of tank cars, having the potential for a large, multiple-tank-car release incident. Previous studies exclusively assumed that railroad tank car releases in the same train accident are mutually independent, thereby estimating the number of tank cars releasing given the total number of tank cars derailed based on a binomial model. This paper specifically accounts for dependent tank car releases within a train accident. We estimate the number of tank cars releasing given the number of tank cars derailed based on a generalized binomial model. The generalized binomial model provides a significantly better description for the empirical tank car accident data through our numerical case study. This research aims to provide a new methodology and new insights regarding the further development of risk management strategies for improving railroad crude oil transportation safety.

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1. Introduction

The United States is experiencing an unprecedented boom in the production of petroleum crude oil and natural gases from shale, driven by technological advances in hydraulic fracturing and horizontal drilling. This has consequently led to a significant rise in the rail transport of petroleum crude oil. In 2014, there were over 500,000 carloads of petroleum crude oil transported over U.S. rail network, up from 9500 in 2008, or a 5300% increase (Barkan et al., 2015) (Fig. 1). The fast-growing crude oil traffic puts railroad safety under the national spotlight, especially in the wake of a chain of crude oil release incidents in 2013 and 2014, such as those in Lac-Mégantic, Canada in July 2013; Aliceville, Alabama in November 2013; Casselton, North Dakota in December 2013; and Lynchburg, Virginia in April 2014.

Differing from roadway transport of hazardous materials, which usually involves a single tank trailer, a train may carry multiple tank cars loaded with hazardous materials. In particular, railroads promote the use of unit-trains (a unit-train may contain 50 to over 100 loaded hazardous materials cars) to transport crude oil as a means of achieving greater transportation efficiency (AAR, 2015). In view of continual growth in railroad crude oil traffic, a proper risk management becomes a high priority for railroad carriers, regulators, shippers and related stakeholders (CRS, 2014).

In railroad hazardous materials transportation risk analyses, the number of tank cars releasing per train accident is an important variable (Glickman et al., 2007; Bagheri et al., 2011, 2012, 2014; Liu et al., 2014). Previous studies were almost exclusively based upon the same assumption that tank car releases in the same train accident are mutually independent. Based on this assumption, a binomial (or Poisson binomial) model was developed to estimate the number of tank cars releasing per accident, given the total number of tank cars derailed. However, it is possible that there exists interdependency between tank car releases within the same train accident, due to the interactive effects of derailed tank cars that are coupled together in the same block, or due to certain common accident conditions. If such dependency exists, it will affect the estimation of the probability of a large, multiple-car release incident. To our knowledge, there is no prior research that specifically focused on modeling dependent tank car releases within the same accident.

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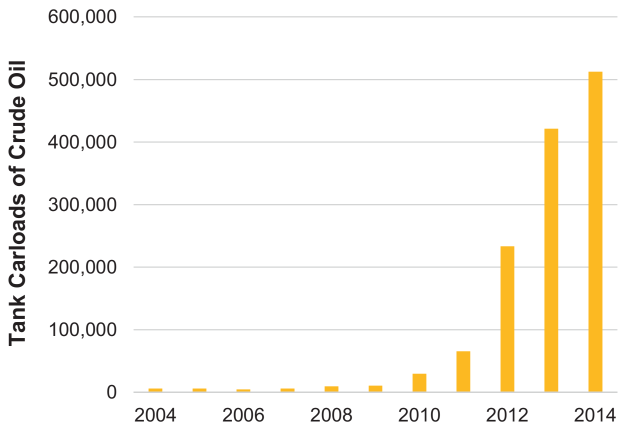

Fig. 1. Traffic of rail transport of petroleum crude oil on U.S. Class I railroads. *Source*: Association of American Railroads, adapted from Barkan et al. (2015).

To narrow this knowledge gap, we first formulate each railroad tank car release as a Bernoulli variable and analyze their sum using a generalized binomial model. Next, we present a numerical example to illustrate the application of the new model, with comparison to the previous binomial model. Finally, we discuss the implications of this study with respect to rail safety policy and practice. The methodology developed in this paper can be expanded to a larger risk management framework for improving the safety of rail transport of crude oil and other hazardous materials.

2. Literature review

Each derailed tank car containing hazardous materials has one of two outcomes: release or no release. The release of each derailed tank car can be viewed as a Bernoulli variable, whose Bernoulli probability is referred to as the conditional probability of release (CPR) (Barkan et al., 2007; Barkan, 2008). The total number of tank car releases in a train accident can be viewed as the sum of a series of Bernoulli variables. If the Bernoulli variables are independent and identically distributed (IID), their sum follows a binomial distribution (Ross, 2007). Previous studies almost exclusively used a binomial model to estimate the number of tank cars releasing given the number of tank cars derailed (e.g., Nayak et al., 1983; Glickman et al., 2007; Bagheri et al., 2011, 2012, 2014). Liu et al. (2014) extended the prior work by accounting for heterogeneous, independent tank car releases based on a Poisson binomial model.

However, we are unaware of any published study yet to consider the total number of *dependent* tank car releases in a train accident. This paper aims to narrow this knowledge gap by proposing a new generalized binomial model.

3. Methodology

The release of each derailed tank car is a Bernoulli variable. Let D_i denote the release of the ith derailed tank car in a train. The Bernoulli probability (denoted as P_i) measures tank car safety performance in an accident (Barkan et al., 2007; Barkan, 2008) (Table 1).

Table 1
Outcomes of a derailed tank car in a train accident.

	Bernoulli variable (D_i)	Probability
Release	1	P_i
No release	0	$1 - P_i$

If there are n tank cars derailed in a train accident, the total number of tank cars releasing (denoted as R) is expressed as:

$$R = \sum_{i=1}^{n} D_i \tag{1}$$

If the releases of individual derailed tank cars are independent and identically distributed, the total number of releases, R, follows a binomial distribution (Nayak et al., 1983; Glickman et al., 2007; Bagheri et al., 2011, 2012, 2014). When the D_i's are non-identical but independent, R follows a Poisson binomial distribution (Liu et al., 2014). In this paper, we analyze the probability distribution of total number of dependent tank car releases, given the total number of tank cars derailed.

First, we define the dependencies among tank car releases within the same accident. We assume that the release probability of the ith derailed tank car within all tank cars derailed depends on the total number of cars releasing prior to it (Eq. (2)):

$$P(D_i = 1 | D_1, D_2, \ldots, D_{i-1}) = P(D_i = 1 | D_1 + D_2 + \cdots + D_{i-1}) \tag{2}$$

This assumption indicates that whether a derailed tank car releases depends on the total number of tank cars releasing prior to the car in question, regardless of which of the prior cars have released. This total-kinetic-energy-related assumption appears to agree with the prior railroad engineering research (Barkan et al., 2003; Liu et al., 2011, 2012). For all the tank cars derailing prior to the ith car ($D_1, D_2, \ldots, D_{i-1}$), the total number of their releases would range from 0 to $i-1$. For illustration simplicity, we use the following notation, originally developed by Yu and Zelterman (2002):

$$C_n(s) = P(D_1 = 1 | D_1 + D_2 + \cdots + D_{n-1} = s - 1 \tag{3}$$

where $C_n(s)$ = the conditional probability that the nth derailed tank car would release, given that there are $(s-1)$ tank cars releasing prior to it ($s \geq 1$).

We also define that $C_1(1) = P(D_1 = 1)$. Let $P_n(s)$ represent the probability of releasing s tank cars out of n derailed tank cars, that is:

$$P_n(s) = P(D_1 + \cdots + D_n = s) \tag{4}$$

Based on the Law of Total Probability (Ross, 2007), we have

$$\begin{aligned} P_n(S) = \; & C_n(s-1) P(D_1 + \cdots + D_{n-1} = s - 1) \\ & + [1 - C_n(s)] P(D_1 + \cdots + D_{n-1} = s) \end{aligned} \tag{5}$$

Eq. (5) can be re-written in an equivalent but more concise way:

$$P_n(S) = C_n(s-1) P_{n-1}(s-1) + [1 - C_n(s)] P_{n-1}(s) \tag{6}$$

Eq. (6) provides a recursive algorithm to calculate the probability mass function (PMF) of the number of dependent tank car releases (s) given the number of tank cars derailed (n). If $n - 1 < s$, $P_{n-1}(s)$ is 0. $P_n(0)$ can be calculated as a complementary probability of $P_n(s \geq 1)$. To explicitly describe the dependency structure among Bernoulli variables, Yu and Zelterman (2002) proposed the following $C_n(s)$ based on a medical research study. In the context of railroad safety, this particular type of dependency structure takes into account the number of tank cars derailed, which is a proxy related to train accident kinetic force and, correspondingly, to the degree of severity (Barkan et al., 2003). Therefore, this paper starts with this dependency structure. In future research, the recursive algorithm proposed in Eq. (6) can be adapted to other possible dependency structures:

$$C_n(s) = \frac{\alpha s + p}{n\alpha + 1} \tag{7}$$

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