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Probabilistic analysis of the release of liquefied natural gas (LNG) tenders due to freight-train derailments

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ABSTRACT

Liquefied natural gas (LNG) has emerged as a possible alternative fuel for freight railroads in the United States, due to the availability of cheap domestic natural gas and continued pursuit of environmental and energy sustainability. A safety concern regarding the deployment of LNG-powered trains is the risk of breaching the LNG tender car (a special type of hazardous materials car that stores fuel for adjacent locomotives) in a train accident. When a train is derailed, an LNG tender car might be derailed or damaged, causing a release and possible fire. This paper describes the first study that focuses on modeling the probability of an LNG tender car release incident due to a freight train derailment on a mainline. The model accounts for a number of factors such as FRA track class, method of operation, annual traffic density level, train length, the point of derailment, accident speed, the position(s) of the LNG tender(s) in a train, and LNG tender car design. The model can be applied to any specified route or network with LNG-fueled trains. The implementation of the model can be undertaken by the railroad industry to develop proactive risk management solutions when using LNG as an alternative railroad fuel.

1. Introduction

Due to factors including low rolling resistance, large economies of scale, reduced labor costs, and high asset utilization, railroads offer an efficient transportation mode for freight and passengers. While actual energy efficiency varies with train and loading types, on average U.S. freight railroads can move one ton of freight approximately 479 miles using one gallon of diesel fuel (AAR, 2015). Since 1980, railroad energy efficiency has increased by 103 percent (AAR, 2015). Despite railroads' favorable energy efficiency, the cost of locomotive fuel is still the second largest operating expense (labor cost is the highest) for U.S. freight railroads. In 2013, U.S. freight railroads consumed over 3.7 billion gallons of diesel (worth nearly $11.6 billion), accounting for approximately 22.5 percent of total railroad operating expenses (AAR, 2014).

Recently, North American freight railroads have shown renewed interest in evaluating and testing the potential of using Liquid Natural Gas (LNG) as an alternative fuel. LNG is a mixture of natural gas comprised of 98 percent methane, created by cooling natural gas to 260 °F below zero using liquid nitrogen (O'Connor, 1994; Kumar et al., 2010). Railroad companies began to explore the use of natural gas as a locomotive fuel in the 1980s. In the early 1990s, LNG engine technology was first adapted to locomotives. Working with Energy Conversions Inc. of Tacoma, WA, Burlington Northern (BN) Railroad

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developed the first LNG-powered line-haul locomotives, which went into revenue coal service on mainline routes in the Pacific Northwest in 1992 (Ditmeyer, 1993). During the same timeframe, Morrison and Knudson Corp. of Boise teamed up with Caterpillar Inc. to develop a 1200 HP LNG-powered yard switcher designed for use within rail yards and for short local trips (O'Connor, 1994). While proof-of-concept projects like these were successful in demonstrating the feasibility of using LNG trains, the economic drivers were not sufficient at that time to justify the capital investment required for widespread adoption. In addition to the high cost of LNG locomotive purchase and/or retrofitting, the lack of available LNG fueling infrastructure has been a substantial market barrier. However, due to the current abundance of low-cost natural gas, major North American railroads are again exploring the economic feasibility of LNG as a locomotive fuel.

An LNG fuel tender is used to store the fuel for LNG locomotives. Since LNG requires approximately twice as much volume as diesel for the equivalent amount of energy, a tender car is necessary to provide enough storage space (Stolz, 1992). Typically, one LNG tender supplies fuel for two locomotives, both of which are placed adjacent to the tender car (Fig. 1).

At present, at least two tender car design options are being considered by North American railroads, including an ISO tank mounted on a modified flat car or well car (Fig. 1), and a modified tank car fuel tender (Fig. 2). Both LNG tender car options require suitable LNG-refueling stations along rail lines.

Fig. 1. LNG-fueled ES44C4 GE locomotives and ISO-tank tender on flat car (photo by Bob Pickering, used with permission).

Fig. 2. LNG tender used by CN, modified tank car design (Photo by David Schauer, used with permission).

Currently, the regulatory framework is still in development regarding final LNG tender car design standards. Regardless of which design standard is chosen, the safety risk will remain a primary concern for the implementation of LNG-fueled trains. Between 2000 and 2014, there were 6,026 Federal Railroad Administration (FRA)-reportable freight-train derailments on Class I railroad mainlines in the United States (Liu, 2016), many of which resulted in the derailment of locomotives and the railcars adjacent to locomotives. There exists a potential derailment risk of the LNG tender(s).

2. Considerations of using LNG as railroad fuel

Before the railroad industry can embrace the widespread adoption of LNG-fueled locomotives, several key requirements need to be satisfied. These requirements can be arranged into four main categories: (1) economic feasibility; (2) operational feasibility; (3) environmental compliance; and (4) safety (Fig. 3). Railroads and government agencies have begun addressing these requirements as the interest in LNG as a locomotive fuel has resurfaced in the last decade. While the first three categories will be discussed briefly, the objective of this study is to address the safety of LNG-fueled trains, specifically the derailment risk associated with LNG tender cars.

2.1. Economic feasibility

The economic feasibility of using LNG as an alternative locomotive fuel requires a long-term fuel saving resulting from the reduced cost of natural gas compared to diesel fuel. Since the price of natural gas and diesel are both subject to uncertainty, it is difficult to determine whether the price advantage of LNG will be sufficient to justify the high capital investments required for implementation. As extraction methods for natural gas have helped to lower prices for LNG, these same extraction methods have also benefitted the domestic crude oil market, resulting in lower diesel fuel prices and reducing the price advantage of LNG. However, the introduction of LNG as an alternative locomotive fuel would allow railroads to diversify their locomotive fleets, resulting in greater flexibility. Since North American freight railroads presently depend largely on diesel, changes in oil prices can have a substantial economic impact. If LNG locomotives were available, railroads could have the option to make fueling decisions based on the price advantage between diesel and natural gas.

In 2007 BNSF Railway, Union Pacific Railroad, the Association of American Railroads, and California Environmental Associates conducted a study to assess the economic feasibility of LNG as a locomotive fuel (BNSF Railway Company et al., 2007). This study concluded that LNG did not offer a viable solution as a locomotive fuel except in limited special service situations. However, since 2007, the natural gas market has changed drastically and Class I railroads are again considering the use of

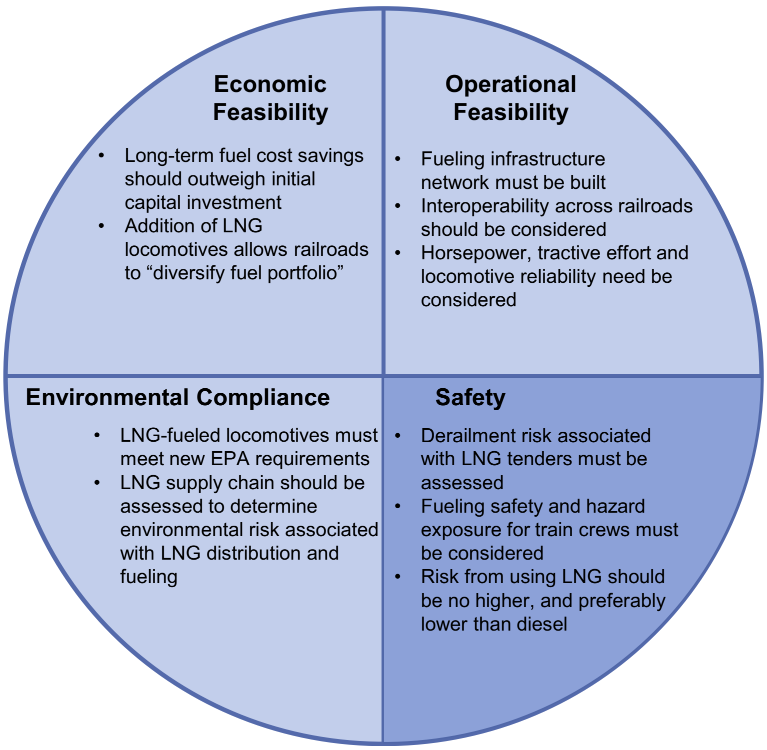

Fig. 3. Key considerations of adopting LNG as an alternative locomotive fuel.

LNG-fueled locomotives. By March 2014, five Class I railroads, including BNSF and Union Pacific, were preparing to test natural gas-fueled locomotives, particularly on high-traffic mainlines with high fuel consumption rates (Stagl, 2014). In 2016 the Florida East Coast (FEC) Railroad became the first railroad in North American to begin full system revenue service trials using LNG-powered locomotives (Fig. 1). With LNG plants in both Miami and Titusville, FL the FEC plans to convert their entire 350 mile operation over to LNG-powered trains (Frailey, 2016). Advances in LNG engine technology and an abundance of natural gas have also led railways in other countries (such as Russia) to consider and begin testing LNG-fueled locomotives (Barrow, 2014).

2.2. Operational feasibility

One critical operational requirement necessary for adopting LNG locomotives is the development of an LNG fueling infrastructure. The first LNG production plant built in the US was the Kenai LNG Plant in Alaska, which has operated since 1969, supplying Asian customers by tanker ship (ConocoPhillips, 2014). For the last 40 years, there have been no major LNG production plants in the lower 48 states, until the opening of LNG liquefaction plants in North Dakota in 2014 (Nowatzki, 2014) and the Sabine Pass LNG export plant in Louisiana in 2016 (DiSavino and Chang, 2016). There are currently only about 100 operational LNG production facilities in the world, mostly in China, with about 10–15 plants now operating in the US (IGU, 2015). However, a number of LNG production facilities are currently planned or in construction: Frontier Natural Resources will open a small scale LNG production facility in central Pennsylvania in 2016, REV LNG will begin production at another small-scale LNG facility in 2017 in northeastern Pennsylvania (Business Wire, 2015) and Dominion Resources will open a larger facility in Maryland in 2017, intended for LNG marine exports (Shelor, 2016). Several companies, including GE and Siemens, are also pursuing smaller scale LNG production, which could provide solutions for future locomotive fueling facilities located at railroad terminals. With the recent growth in LNG production and marine exports and increased pipeline exports to Mexico, the U.S. is expected to become a net exporter of natural gas in 2017, which will be the first time this has happened in the U.S. since 1957 (DiSavino and Chang, 2016). These increases in LNG production have led to development of LNG fueling stations for highway vehicles. According to the U.S. Department of Energy Alternative Fuels Data Center, there are currently over 80 such LNG fueling stations in the US open to the public and others installed for private use (DOE 2016). However, despite these improvements, to date the Florida East Coast Railroad has the only known LNG locomotive fueling operation in North America used for revenue service (Frailey, 2016). Therefore, while the technology exists and there are definite signs of growth in the LNG industry, there is still a great need for additional infrastructure investment across the country before LNG-powered locomotives can be implemented on a large scale in the US.

Next, locomotive interoperability across different railroads must be considered. Class 1 railroads currently exchange locomotives between railroads in order to allow cross-country traffic to move more efficiently through interchange points. Union Pacific railroad, for example, estimated that up to 12 percent of the locomotives on its network at any given time were foreign units, owned by another railroad company (BNSF Railway Company et al., 2007). If LNG is not adopted by multiple railroads across the industry, all at the same time, railroads would not be able to exchange locomotives as they do now, reducing the incentive for the development of fueling infrastructure.

Other operational considerations are related to the chemical nature of LNG as a locomotive fuel. Since LNG has a lower energy density than diesel (Kumar et al., 2010), LNG engines are not as energy efficient as diesel (Meyer et al., 2011). Additionally, LNG is subject to venting losses during fueling operations and/or through boil-off as the LNG warms and expands inside the tender. One study estimated up to 12 percent of the LNG fuel was lost due to venting and boil-off for a prototype LNG switcher locomotive (TIAX, 2010). Using a larger LNG tender may require less frequent fueling, and the increased fuel capacity will allow trains to travel greater distances between fueling. However, the time required to fuel the LNG locomotives will most likely be longer than is required for diesel locomotives (Vantuono, 2014).

2.3. Environmental compliance

In 2001, the Commission of the European Communities identified natural gas to be the most promising alternative fuel for reducing transportation emissions in the medium-long term, with hydrogen energy being most promising in the very long term (European Commission, 2001). Compared to other alternative fuels, natural gas was identified as a more suitable substitute because it is readily available at a competitive price and it uses technology that is already widely available (Arteconi et al., 2010). While initial studies concluded that LNG-fueled locomotives would produce greater greenhouse gas (GHG) emissions than diesel (BNSF Railway Company et al., 2007), new engine technology has reduced greenhouse gas emissions for LNG conversion kits, leading to greater potential for environmental compliance. New solutions are now available to meet EPA locomotive emissions requirements, including GE's NextFuel™ Natural Gas Retrofit Kits for Tier 2+/Tier 3 EPA emissions (GE, 2013). Furthermore, using the trucking industry for comparison, total lifecycle GHG emissions for LNG are estimated to be nearly equivalent to that of diesel emissions (Meyer et al., 2011) or even lower (Kumar et al., 2010). In one lifecycle analysis, GHG emissions for LNG-powered heavy-duty vehicles were estimated to be 10% less than that of diesel when LNG was procured directly from a regasification terminal (Arteconi et al., 2010). While the use of LNG as an alternative fuel has been shown to increase emissions of CH_4 (methane) and N_2O (nitrogen dioxide) compared to diesel, the conversion to LNG also results in a much larger reduction in CO_2 emissions. One study found an estimated 13% overall reduction of CO_2 equivalent GHG emissions during combustion in heavy-duty vehicles (Graham et al., 2008). While the production and liquefaction of

LNG do produce methane emissions, this value has been estimated to be very small: about 0.17% of the gas produced (Tamura et al., 2001). The current value is about one sixth lower than was previously estimated, as field surveys indicated that methane emissions are either returned to the fuel line or burned off in flares at LNG plants before discharging. Gas leaks from equipment were found to be minimal.

As LNG locomotive developments continue, additional research will be needed to assess the LNG fueling supply chain specific to the North American railroad market, and to incorporate the potential for leakage and/or spills resulting in the release of methane into the atmosphere. If LNG locomotives are implemented on a large scale, the additional handling of LNG to supply fueling facilities and to refuel locomotives will provide the potential for new sources of GHG emissions that may be more potent than current emissions resulting from diesel. Specifically, the potential increase in CH_4 and N_2O emissions should be considered when designing LNG locomotives and locomotive fueling facilities in order to minimize such emissions.

2.4. Safety

While other studies have explored the economics, operational feasibility, and environmental compliance of LNG, little work has been published addressing the safety factors related to LNG-powered train operations. Furthermore, the authors are unaware of any published research specifically addressing the derailment risk of LNG tenders under specified operating characteristics. This paper aims to develop a normative methodological framework that enables evaluation of the potential risk based on recent railroad safety statistics.

As the FRA considers the approval of LNG as a locomotive fuel, it is requiring Class 1 railroads to perform comprehensive safety analyses to identify the inherent safety risks. In a letter to BNSF Railway in May 2013, the FRA stated that these analyses must address the following (USDOT, 2013):

- The design of the natural gas tender, including the crashworthiness of the packaging, as well as all connections to the locomotives being fueled.
- The placement and operation of a tender containing LNG and operating as a potential ignition source adjacent to an occupied locomotive.
- The ability of first responders to identify the contents of the tender vehicle in the event of an accident.
- The heat leak rate into the LNG storage tank (including the effect of sloshing) and the consequent pressure buildup inside the tank.
- The release of flammable vapors into the atmosphere to relieve tank pressure.
- Mechanical issues related to the equipment.

To adequately address the primary safety concern of derailment risk, the scope of this paper is to develop a methodology that can be adapted to any specific route or network with LNG trains in the future when the needed information is available. Because Class I railroads are still testing and evaluating the use of LNG-fueled trains, there is little information available regarding specific routing and traffic volume. Also, since the infrastructure for fueling LNG locomotives has not yet been well developed, this paper does not seek to address safety risk related to fueling. Finally, due to data limitations, specific hazards to train crews on LNG trains were not considered.

3. Scope and intended contributions of the study

This paper focuses on modeling the derailment and release probability of LNG tenders on main tracks, accounting for a variety of track and train characteristics. When the probability of LNG tender derailment is understood, better decisions can be made regarding the crashworthiness, placement, and operation of the tender car, as well as the potential consequences of an explosion due to a derailment. The mainline accident data for this paper comes from the Rail Equipment Accident (REA) of the FRA; the introduction of the FRA safety database will be presented in Section 5.1. In addition, we reviewed relevant literature and identified useful information that can be used to evaluate LNG tender derailment and release probability.

The main contribution of this paper is the development of a generalized methodology that can estimate LNG tender derailment and release probability, accounting for a variety of factors (FRA track class, method of operation, annual traffic density, train length, speed, the number and positions of LNG tenders and LNG tender release probability). To our knowledge, this is the first model specific to LNG tender derailment analysis. The model can be implemented into a decision support tool that potentially aids the railroad industry in evaluating the risk given any LNG train configurations on any specified route or network. The model encompasses a number of parameters, such as train derailment rate and derailment severity (number of vehicles derailed). We attempted to calibrate each parameter based on the best information available to us. When no information was available, we used the most recent information in the literature. Prior research aimed at modeling each individual parameter; however, an integration of these parameters through a probabilistic approach in the context of LNG tender derailment analysis was not found in the literature.

As an initial study into the probability of an LNG tender car release incident, this research attempts only to address the hazard to the public in the event of a derailment. Future work will consider the risk to train crews and hazards at fueling facilities. The remainder of this paper is structured as follows. Sections 4 and 5 introduce a model to quantify LNG tender car release probability due to freight-train derailments on mainlines. Section 6 develops a numerical example to illustrate model application, accounting for location-specific infrastructure characteristics and different train configurations. Section 7 discusses the principal findings and the implications of this research with respect to the potential use of LNG as an alternative railroad fuel. Section 8 proposes potential future research directions.

4. Methodology

4.1. Event chain of LNG tender car derailment and release

The derailment and release of an LNG tender car are the result of a chain of events (Fig. 4).

Due to certain accident causes (e.g., track failures, equipment defects, or human errors), a train may be involved in an accident. Train accident likelihood is affected by infrastructure quality, method of operation, traffic density, railroad type, and traffic exposure (Liu, 2013; Liu et al., 2016). After a train accident occurs, a number of locomotives or railcars may be derailed, depending on accident speed, accident cause, point of derailment (the position of the first car derailed), and train length (the total number of locomotives and railcars in a train) (Anderson, 2005; Saccomanno and El-Hage, 1989, 1991; Bagheri et al., 2011; Liu et al., 2013). Whether a derailed LNG tender car releases its contents may be affected by its safety design, accident speed, and other accident characteristics.

4.2. LNG tender derailment and release probability

4.2.1. Train accident probability, $P_i(A)$

When undertaking a shipment on a specified route, a train traverses a number of track segments. A train accident may occur on any segment. The probability that a train accident occurs on the ith segment of a route is the probability that there is no accident on all the prior segments (segment 1, 2, ..., i − 1) combined with the probability that a train accident occurs when passing the ith segment alone. Fig. 5 illustrates accident occurrence scenarios.

For one train shipment, the probability that a train accident occurs on the ith segment of a route can be calculated as:

$$P_i(A) = \left[\prod_{j=1}^{i-1}(1 - m_j)\right] m_i \tag{1}$$

where

$P_i(A)$ = train accident probability on the ith segment of a route (no accident on all the prior segments),
m_i = train accident probability when passing the ith segment alone.

When m_i is small, it is approximately equal to the product of traffic exposure (e.g., ton-mile or train-mile) and accident rate per unit of traffic exposure (Liu et al., 2011):

$$m_i \approx Z_i T_i \tag{2}$$

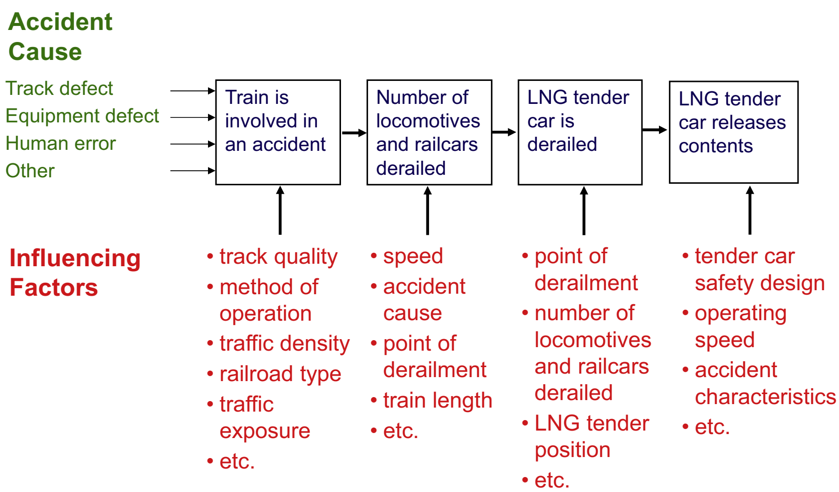

Fig. 4. Event chain leading to an LNG car derailment and release.

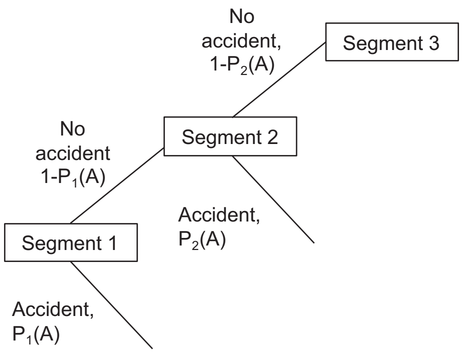

Fig. 5. Illustration of the event tree of a train accident on a route (partial).

where

Z_i = train accident rate per unit of traffic exposure,
T_i = traffic exposure.

Furthermore, because m_i is sufficiently small,

$$\prod_{j=1}^{i-1}(1 - m_j) \approx 1 \tag{3}$$

Based on Eqs. (1)–(3), train accident probability on the ith segment of a route is approximately equal to the product of train accident rate per unit of traffic exposure and the traffic volume, that is:

$$P_i(A) \approx Z_i T_i \tag{4}$$

4.2.2. Probability of an LNG tender derailment, $P_i(D|A)$

After a train accident occurs, each locomotive or railcar may derail, either when it is the first vehicle derailed, or when it becomes a "victim" in a block of derailed vehicles. Throughout this paper, the generic use of "cars" refers to all vehicles (including railcars and locomotives), unless specifically stated otherwise. The position of the first vehicle derailed is called the point of derailment (POD) (Saccomanno and El-Hage, 1989, 1991). The POD information was recorded in the FRA REA database. Note that the POD may not necessarily be the car that initiates the derailment. For example, a car with a mechanical failure may derail and drag the car(s) adjacent to it. However, the FRA database records neither the derailment progression direction nor the position of each derailed car. Since the POD is defined as the first car in a sequence of cars derailed, all other derailed cars will be behind the POD. Saccomanno and El-Hage (1989, 1991) originally developed a position-dependent railcar derailment probability (Eq. (5)). This paper adapts this equation in the context of LNG tender derailment analysis, based on more recent train safety data.

$$PD_i(j) = \sum_{k=1}^{j}\left\{POD_i(k) \times \sum_{x=j-k+1}^{L-k+1} PN_i(x)\right\} \tag{5}$$

where

$PD_i(j)$ = probability of derailment for a vehicle at the jth position of a train on the ith segment,
$POD_i(k)$ = point-of-derailment probability for the kth position of a train on the ith track segment,
$PN_i(x)$ = probability of derailing x vehicles in a train accident on the ith segment,
L = train length (total number of vehicles in a train).

Eq. (5) indicates that, for the LNG tender to be involved in the derailment, the number of vehicles derailed in a train accident must equal or exceed the number of cars between the POD (including the POD) and the LNG car. Both POD and the total number of cars derailed per accident follow stochastic distributions (Bagheri et al., 2011; Liu et al., 2014), the distributional parameters of which can be estimated based on the FRA REA database. In Section 5, we will detail the estimation of the POD distribution and the number of vehicles derailed.

4.2.3. Release probability of a derailed LNG tender, $CPR_i(R|D)$

The release probability of a derailed LNG car (denoted as $CPR_i(R|D)$) reflects its safety performance. For example, when $CPR_i(R|D)$ is 0.2, there is a 20 percent chance that a derailed LNG car would release if derailed in a train accident. The release probability of a derailed LNG tender may be affected by tender car safety design and other circumstances. Given the release probability of a derailed LNG tender car, the probability of an LNG tender release is:

$$PR_i(j) = PD_i(j) \times CPR_i(j) \tag{6}$$

where

$PR_i(j)$ = release probability of an LNG tender at the jth position of a train on the ith segment,
$CPR_i(j)$ = conditional probability of release (CPR) of a derailed LNG tender.

The probability that at least one LNG tender releases can be estimated using the following equation:

$$R_i = \left\{1 - \prod_j [1 - PR_i(j)]\right\} \tag{7}$$

where

R_i = LNG train release probability on the ith segment.

Route-specific LNG tender release frequency is approximately the summation of all the segment-specific release probability since segment-specific release probability is very small.

$$R = M\sum_{i=1}^{N} R_i \tag{8}$$

where

R = annual LNG tender release frequency on a route,
N = the total number of track segments on a route,
M = annual number of LNG-fueled trains on the route.

The model accounts for both track-specific and train-specific factors. For each track section, we consider FRA track class, method of operation and annual traffic density. These factors were found to be correlated with train derailment rate (Liu, 2013; Liu et al., 2016). Given each track section, train-related factors (train length, speed, number and placement of LNG tenders) affect position-dependent LNG derailment probability. In order to calculate the probability of an LNG tender release incident, a number of parameters are needed, including:

(1) Train accident rate, Z_i.
(2) Point of derailment, $POD_i(K)$.
(3) Probability distribution of the number of locomotives and railcars derailed, $PN_i(X)$.
(4) Conditional probability of release of a derailed LNG tender car, $CPR_i(j)$.

5. Parameter estimation

5.1. Train accident rate, Z_i

The FRA requires all railroads operating in the United States to submit detailed reports of all accidents that exceed a monetary threshold for damages to track infrastructure, equipment, and signals. The FRA compiles the submitted accident reports into the Rail Equipment Accident (REA) database that records information on the type, cause, cost, and contributing factors of each accident (FRA, 2011). Using this database supplemented by other data, a number of studies have been conducted to estimate train accident rate, measured by the number of train accidents normalized by a certain traffic exposure, such as train-miles, car-miles, or gross ton-miles (Nayak et al., 1983; Anderson and Barkan, 2004; Liu et al., 2016).

Derailments are the most frequent type of FRA-reportable, mainline accidents (Liu et al., 2012). Previous research has focused on derailment rate. Nayak et al. (1983) published the first study to identify a correlation between train derailment rate and FRA track class. A higher track class has a greater maximum allowable speed, thereby requiring more stringent track safety and maintenance standards (Anderson and Barkan, 2004). The correlation between FRA track class and train derailment rate was validated and updated in later studies (Treichel and Barkan, 1993; Anderson and Barkan, 2004). Recently, the single-factor train derailment rate research was advanced by a multivariate analysis that accounts for two additional affecting factors, namely the method of operation (i.e., non-signaled track versus signaled track) and annual traffic density level measured below or above 20 million gross tons (MGT) (Liu, 2013; Liu et al., 2016). That study found that all three factors (FRA track class, method of operation, and annual traffic density) are significantly correlated with train derailment rate (Eq. (9)). The analysis showed that, when all other factors are equal, a higher FRA track class is associated with a lower derailment rate; signaled track has a lower derailment rate than non-signaled track; and higher traffic density trackage has a lower derailment rate. Liu et al. (2016)'s analysis was based on the data between 2005 and 2009. In recognition of declining train derailment rates (Liu, 2015), a temporal adjustment factor is used to extrapolate future derailment rate. Liu (2015) found an average of 5.6 percent annual declining rate in Class I mainline freight-train derailment rate from 2000 to 2014. Assuming that this trend continues, a statistical model can be used to estimate the freight-train derailment rate now and in the near future (Eq. (9)).

$$Z = \exp(0.9201 - 0.6649X_{trk} - 0.3377X_{moo} - 0.7524X_{den})(1 - 5.6\%)^{T_i - 2009} \tag{9}$$

where

Z = estimated freight-train derailment rate per billion gross ton-miles,
X_{trk} = FRA track class (1–5),
X_{moo} = method of operation (1 for signaled, 0 for non-signaled),
Xd_{en} = annual traffic density level (1 for $\geqslant$20 MGT, 0 for <20 MGT),
T_i = year (for example, T_i is equal to 2014 for the year 2014).

Although the derailment rate estimates above were based on the best information available to us, there are several limitations in the current study that call for future research. First, it would be advantageous to update previous derailment rate analyses using current safety and traffic data and accounting for additional possible affecting factors (mechanical or human). This effort will require extensive data from the railroad industry. Second, in addition to derailments, there could be other types of train accidents that may affect LNG tender safety. Future research can be developed to analyze other accident types (e.g. train collisions, grade crossing incidents) by contributing factors, to better understand potential safety hazards posed to LNG tender.

5.2. Point of derailment, $POD_i(K)$

Point-of-derailment (POD) is the position of the first vehicle (locomotive or railcar) derailed. The first vehicle (generally the lead locomotive) is frequently the POD in a train derailment (Anderson, 2005; Liu et al., 2014). Previous studies have found that the POD affects the number of vehicles, given all else being equal (Saccomanno and El-Hage, 1989, 1991; Anderson, 2005; Bagheri et al., 2011, 2012, 2014; Liu et al., 2013, 2014). To account for different train lengths, the normalized POD (NPOD) was calculated by dividing POD by train length (Saccomanno and El-Hage, 1989, 1991). Several probability distributions (Beta, Normal, Logistic, Weibull, Uniform, Gamma) were evaluated to fit the NPOD data. The goodness-of-fit of a fitted NPOD distribution was evaluated using the Kolmogorov-Smirnov (K-S) test. In the Kolmogorov-Smirnov (K-S) test, the P-value evaluates the goodness of fit of empirical data compared to a theoretical distribution. If the P-value is larger than 0.05, the distribution chosen to fit the data may be acceptable. The "best-fit" for the NPOD distribution (all accident causes combined) is a Beta (0.6793, 0.8999) based on 3812 FRA-reportable Class I railroad freight-train mainline derailments from 2002 to 2011 (P-value = 0.48). Given a train length L, the probability that the POD is at the kth position, POD(k), can be estimated using the following equation (Liu et al., 2014):

$$POD(k) = F\left(\frac{k}{L}\right) - F\left(\frac{k-1}{L}\right) \tag{10}$$

where

POD(k) = POD probability at the kth position of a train,
F( ) = cumulative density distribution of the fitted normalized POD distribution,
L = train length (total number of cars in a train).

For example, for a 100-car train (L = 100), the estimated POD (k = 1) is 0.040, and POD (k = 2) is 0.024, from the fitted Beta distribution. It is interpreted that there is 4.0 percent chance that the derailment initiates from the first vehicle in a train (i.e., lead locomotive), and a 2.4 percent chance that the derailment initiates from the second car. Each car may be the POD, though with differing probabilities. Depending on the POD, train length and speed, the total number of vehicles derailed can be estimated as detailed in the following section.

5.3. Total number of vehicles derailed, $PN_i(x)$

Although the total damage costs of a train accident are sometimes used as a metric of accident severity, the number of locomotives or railcars derailed is a better metric for the analysis of railroad safety risk analysis because of its relationship with accident kinetic energy (Barkan et al., 2003; Liu et al., 2014). The total number of cars derailed is affected by accident cause (Saccomanno and El-Hage, 1989, 1991; Bagheri et al., 2011; Liu et al., 2013), accident speed (Nayak et al., 1983; Saccomanno and El-Hage, 1989, 1991; Liu et al., 2013), train length (Saccomanno and El-Hage, 1989, 1991; Liu et al., 2013), and point of derailment (Saccomanno and El-Hage, 1989, 1991; Liu et al., 2013). The statistical model for estimating train accident severity was first developed by Saccomanno and El-Hage (1989, 1991), and subsequently modified by Anderson (2005) and Bagheri et al. (2011), respectively. The probability distribution of the number of vehicles derailed given the POD can be estimated as (Liu et al., 2014):

$$PN_i(x) = \frac{\frac{\exp(z)}{1+\exp(z)}\left[\frac{1}{1+\exp(z)}\right]^{x-1}}{1-\left[\frac{1}{1+\exp(z)}\right]^{L-k+1}} \tag{11}$$

$$\mathrm{Z} = \mathrm{a} + b \times \ln(\mathrm{S}) + \mathrm{c} \times \ln(\mathrm{L_r}) + \mathrm{d} \times \mathrm{I(POD)} \tag{12}$$

where

$PN_i(x)$ = The probability that X vehicles derailed given the POD at the kth position of a train (K = 1, 2, 3, . . . , L) on the ith segment,
S = accident speed (mph),
L = train length (total number of vehicles in a train, including locomotives),
L_r = residual train length, defined as the number of vehicles between the POD and the train end (L_r = L − K + 1),
I(POD) = 1 if the POD is a locomotive or a loaded railcar, 0 otherwise,

a = 2.1426 (parameter coefficients a, b, c and d were based on FRA-reportable Class I railroad freight-train derailment data between 2002 and 2011, for all accident causes combined. The parameter coefficients were fitted using a nonlinear regression model described in Anderson (2005)),
b = −0.8104,
c = −0.3836,
d = −0.3688.

Previous studies found that a higher accident speed is correlated with a larger number of cars derailed, given all else being equal (Saccomanno and El-Hage, 1989, 1991; Bagheri et al., 2011). As mentioned earlier, the maximum operating speed delineates FRA track class, which was found to be correlated with train derailment rate (Liu, 2013; Liu et al., 2016). While a higher-speed track segment may have a lower train derailment rate due to higher track engineering and safety standards, once a train derailment occurs, it may likely cause more cars derailed. The model in this paper accounts for the effects of both FRA track class and accident speed on LNG tender derailment probability.

5.4. LNG tender release probability, CPR(R|D)

The probability that a derailed LNG tender car releases some of its contents in an accident will be affected by its safety design and other factors. The Railway Supply Institute and the Association of American Railroads have been collecting data on tank car safety performance in accidents since the 1970s. They have published a number of reports analyzing the probability of a release for different tank car designs. LNG tender car designs are still in the development stage but they have some important design elements in common with tank cars. We are unaware of any published statistics regarding tender safety performance in accidents, so we used published tank car statistics (Treichel et al., 2006) to develop approximate estimates.

Despite the common design features with tank cars, there are also elements that differ. Few tank cars (if any) have the exact configuration of inner and outer tank thickness as is being considered for LNG tenders. However, there are tank cars in which the total thickness of the tank plus its external jacket or head shield are similar. Under the assumption that the effect of total thickness on the probability of a puncture can be considered approximately additive, we can calculate estimates using the tank car data. For this paper, we consider an LNG tender with 0.5-in. internal tank thickness and approximately 0.56-in. external tank (jacket) thickness. Based on this we can estimate the LNG tender CPR assuming the combined equivalent thickness of the tank shell and head as 1.06 in. Using this approach, and accounting for different tank car CPRs for the tank head and shell and the effect of the thickness of the 11-gauge jacket, it yields a CPR value of approximately 0.06 for LNG tenders in FRA-reportable accidents on mainlines.

Other factors contributing to the uncertainty in the estimate are differences in the tender's fittings design, and its placement adjacent to a locomotive, both of which are unlike conventional tank cars. Nevertheless, the estimate is reasonable and sufficient for the objectives of this paper. The RSI-AAR Tank Car Project is currently developing more up-to-date statistical estimates of tank car safety performance using newer data and more sophisticated statistical techniques. When they are available, these forthcoming results can be used to update the CPR of LNG tender described above.

6. Numerical example

In this section, we present a numerical example to illustrate the methodology described above. For illustrative purposes, we develop a generic calculation method for estimating LNG derailment and release probability given various track and train characteristics. The average train length (number of railcars) for bulk traffic is between 86 and 112 (Cambridge Systematics, 2007). In this paper, we assume an average of 100 vehicles per train (including railcars, LNG tender, and locomotives). Based on route characteristics and a desired horsepower-to-trailing ton ratio, locomotive configurations may differ. We consider five possible LNG train configurations that may be used:

(1) Two locomotives in the front of the train.
(2) Four locomotives in the front of the train.
(3) Two locomotives in the front and two in the rear of the train.
(4) Four locomotives in the front of the train and two in the rear of the train.
(5) Two locomotives in the front, two in the middle, and two in the rear.

For each set of two locomotives, one LNG tender is located between them. For example, if there are two locomotives in the front of a train, the LNG tender is at the 2nd position. When there are four locomotives in the front of the train, one LNG tender is located at the 2nd position and the other at the 5th position. Using this pattern, the other configurations can be determined by locating the LNG tenders at the 2nd, 5th, 51th and/or 99th positions of the train. It is assumed that each locomotive weighs 200 tons, and each fully loaded railcar and LNG tender car weighs 143 tons. The methodology can be adapted to other train configurations and loadings.

Position-dependent vehicle derailment probability can be estimated using Eq. (5). Given train length (100 vehicles in this example), vehicle derailment probability varies by derailment speed (Fig. 6). The four selected speeds (25, 40, 60 and 80 mph) represent the maximum allowable operating speed by FRA track classes 2–5, respectively. For example, when the speed is 40 mph and there are six locomotives (two in the front, two in the middle, and two in the rear), the derailment probabilities of three LNG tenders are 0.06273, 0.16501 and 0.03889, respectively. Using a similar approach, we can estimate the probability of LNG tender derailment accounting for other train configurations and/or accident speeds.

Due to a lack of information regarding the actual LNG fleet, railroad network with LNG-fueled trains and LNG tender design & release probability, we estimate the normalized release probability per train-mile, under different operating scenarios. Based on the analysis above (Section 5.4), we set the LNG release probability to be 0.056 ($CPR(R|D) = 0.056$). Based on the actual LNG tender release probability and affected population values, the estimated release probability can be adjusted accordingly. Using the adapted matrix, railroads could estimate their route-specific or network-specific LNG tender car derailment and release probability. Table 1 is a sensitivity analysis in which we consider 20 track-related scenarios and five train configurations. The accident speed is conservatively assumed to be the FRA-track-class-specific maximum allowable speed. The table can be modified when other scenarios or factors are accounted for.

As expected, Table 1 shows that a higher number of LNG locomotives (and tenders) on a train results in a higher probability of LNG release in a derailment. However, when comparing different locomotive configurations on a train, release probability changes with the location of the LNG tender. In general, the results follow the position-dependent vehicle derailment probability shown in Fig. 6. For example, given a train with four LNG locomotives, locating all four locomotives in the front of the train (Table 1b) results in a higher probability of release than locating two locomotives in the front and two locomotives in the rear (Table 1c), given the same track characteristics. For a train with six locomotives, placing four locomotives in the front and two locomotives in the rear (Table 1d) has a lower probability of release per derailment than having two locomotives in the front, two in the middle, and two in the rear (Table 1e), on FRA track classes 2–5. This is due to the higher vehicle derailment probability for vehicles positioned in the center of the train, compared to those in the front or rear.

To further illustrate these data, Fig. 7 shows the release probability of LNG tenders on a typical Class I railroad mainline (signaled track, FRA track classes 2–5, with greater than 20 MGT per year). In general, given the same train configuration,

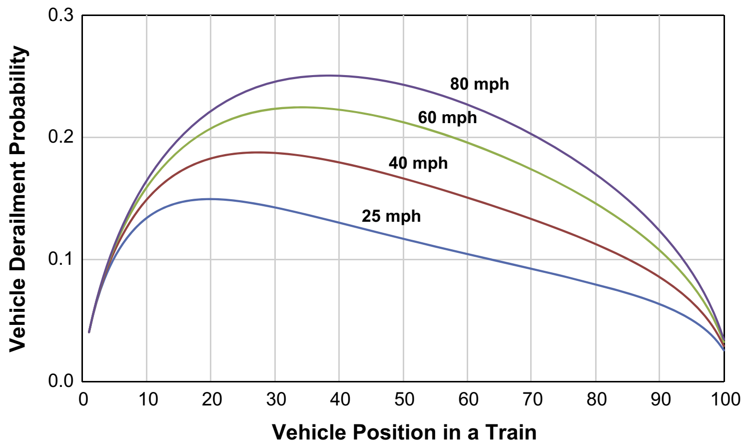

Fig. 6. Position-dependent vehicle derailment probability in a FRA-reportable freight-train derailment on mainlines (assuming 100 vehicles in a train).

Table 1
Sensitivity analysis of normalized tender derailment and release probability on mainlines in the year 2015.

FRA track class	Method of operation	Annual traffic density	Train derailment rate per train-mile	Probability of at least one tender release in a train derailment	Release probability per train-mile
(a) Two locomotives in the front of the train (with LNG tender at the 2nd position of the train)					
1	Non-Signaled	<20 MGT	1.32E−05	0.00332	4.37E−08
2	Non-Signaled	<20 MGT	6.77E−06	0.00347	2.35E−08
3	Non-Signaled	<20 MGT	3.48E−06	0.00351	1.22E−08
4	Non-Signaled	<20 MGT	1.79E−06	0.00354	6.34E−09
5	Non-Signaled	<20 MGT	9.21E−07	0.00356	3.28E−09
1	Non-Signaled	⩾20 MGT	6.20E−06	0.00332	2.06E−08
2	Non-Signaled	⩾20 MGT	3.19E−06	0.00347	1.11E−08
3	Non-Signaled	⩾20 MGT	1.64E−06	0.00351	5.77E−09
4	Non-Signaled	⩾20 MGT	8.44E−07	0.00354	2.99E−09
5	Non-Signaled	⩾20 MGT	4.34E−07	0.00356	1.54E−09
1	Signaled	<20 MGT	9.39E−06	0.00332	3.12E−08
2	Signaled	<20 MGT	4.83E−06	0.00347	1.67E−08
3	Signaled	<20 MGT	2.48E−06	0.00351	8.73E−09
4	Signaled	<20 MGT	1.28E−06	0.00354	4.52E−09
5	Signaled	<20 MGT	6.57E−07	0.00356	2.34E−09
1	Signaled	⩾20 MGT	4.43E−06	0.00332	1.47E−08
2	Signaled	⩾20 MGT	2.28E−06	0.00347	7.89E−09
3	Signaled	⩾20 MGT	1.17E−06	0.00351	4.11E−09
4	Signaled	⩾20 MGT	6.02E−07	0.00354	2.13E−09
5	Signaled	⩾20 MGT	3.10E−07	0.00356	1.10E−09
(b) Four locomotives in the front of the train (with LNG tenders at the 2nd and 5th positions of the train)					
1	Non-Signaled	<20 MGT	1.33E−05	0.00815	1.08E−07
2	Non-Signaled	<20 MGT	6.83E−06	0.00915	6.25E−08
3	Non-Signaled	<20 MGT	3.51E−06	0.00949	3.33E−08
4	Non-Signaled	<20 MGT	1.81E−06	0.00970	1.75E−08
5	Non-Signaled	<20 MGT	9.29E−07	0.00981	9.11E−09
1	Non-Signaled	⩾20 MGT	6.25E−06	0.00815	5.10E−08
2	Non-Signaled	⩾20 MGT	3.22E−06	0.00915	2.94E−08
3	Non-Signaled	⩾20 MGT	1.65E−06	0.00949	1.57E−08
4	Non-Signaled	⩾20 MGT	8.51E−07	0.00970	8.26E−09
5	Non-Signaled	⩾20 MGT	4.38E−07	0.00981	4.29E−09
1	Signaled	<20 MGT	9.47E−06	0.00815	7.72E−08
2	Signaled	<20 MGT	4.87E−06	0.00915	4.46E−08
3	Signaled	<20 MGT	2.50E−06	0.00949	2.38E−08
4	Signaled	<20 MGT	1.29E−06	0.00970	1.25E−08
5	Signaled	<20 MGT	6.62E−07	0.00981	6.50E−09
1	Signaled	⩾20 MGT	4.46E−06	0.00815	3.64E−08
2	Signaled	⩾20 MGT	2.29E−06	0.00915	2.10E−08
3	Signaled	⩾20 MGT	1.18E−06	0.00949	1.12E−08
4	Signaled	⩾20 MGT	6.07E−07	0.00970	5.89E−09
5	Signaled	⩾20 MGT	3.12E−07	0.00981	3.06E−09
(c) Two locomotives in the front and two in the rear of the train (with LNG tenders at the 2nd and 99th positions of the train)					
1	Non-Signaled	<20 MGT	1.33E−05	0.00460	6.10E−08
2	Non-Signaled	<20 MGT	6.83E−06	0.00528	3.61E−08
3	Non-Signaled	<20 MGT	3.51E−06	0.00568	1.99E−08
4	Non-Signaled	<20 MGT	1.81E−06	0.00604	1.09E−08
5	Non-Signaled	<20 MGT	9.29E−07	0.00628	5.84E−09
1	Non-Signaled	⩾20 MGT	6.25E−06	0.00460	2.87E−08
2	Non-Signaled	⩾20 MGT	3.22E−06	0.00528	1.70E−08
3	Non-Signaled	⩾20 MGT	1.65E−06	0.00568	9.40E−09
4	Non-Signaled	⩾20 MGT	8.51E−07	0.00604	5.14E−09
5	Non-Signaled	⩾20 MGT	4.38E−07	0.00628	2.75E−09
1	Signaled	<20 MGT	9.47E−06	0.00460	4.35E−08
2	Signaled	<20 MGT	4.87E−06	0.00528	2.57E−08
3	Signaled	<20 MGT	2.50E−06	0.00568	1.42E−08
4	Signaled	<20 MGT	1.29E−06	0.00604	7.78E−09
5	Signaled	<20 MGT	6.62E−07	0.00628	4.16E−09
1	Signaled	⩾20 MGT	4.46E−06	0.00460	2.05E−08
2	Signaled	⩾20 MGT	2.29E−06	0.00528	1.21E−08
3	Signaled	⩾20 MGT	1.18E−06	0.00568	6.71E−09
4	Signaled	⩾20 MGT	6.07E−07	0.00604	3.66E−09
5	Signaled	⩾20 MGT	3.12E−07	0.00628	1.96E−09
(d) Four locomotives in the front of the train and two in the rear of the train (with LNG tenders at the 2nd, 5th and 99th positions of the train)					
1	Non-Signaled	<20 MGT	1.34E−05	0.00942	1.26E−07
2	Non-Signaled	<20 MGT	6.88E−06	0.01096	7.54E−08
3	Non-Signaled	<20 MGT	3.54E−06	0.01165	4.12E−08

Table 1 (*continued*)

FRA track class	Method of operation	Annual traffic density	Train derailment rate per train-mile	Probability of at least one tender release in a train derailment	Release probability per train-mile
4	Non-Signaled	<20 MGT	1.82E−06	0.01219	2.22E−08
5	Non-Signaled	<20 MGT	9.36E−07	0.01253	1.17E−08
1	Non-Signaled	⩾20 MGT	6.30E−06	0.00942	5.94E−08
2	Non-Signaled	⩾20 MGT	3.24E−06	0.01096	3.55E−08
3	Non-Signaled	⩾20 MGT	1.67E−06	0.01165	1.94E−08
4	Non-Signaled	⩾20 MGT	8.57E−07	0.01219	1.04E−08
5	Non-Signaled	⩾20 MGT	4.41E−07	0.01253	5.52E−09
1	Signaled	<20 MGT	9.54E−06	0.00942	8.99E−08
2	Signaled	<20 MGT	4.91E−06	0.01096	5.38E−08
3	Signaled	<20 MGT	2.52E−06	0.01165	2.94E−08
4	Signaled	<20 MGT	1.30E−06	0.01219	1.58E−08
5	Signaled	<20 MGT	6.68E−07	0.01253	8.36E−09
1	Signaled	⩾20 MGT	4.50E−06	0.00942	4.24E−08
2	Signaled	⩾20 MGT	2.31E−06	0.01096	2.53E−08
3	Signaled	⩾20 MGT	1.19E−06	0.01165	1.39E−08
4	Signaled	⩾20 MGT	6.12E−07	0.01219	7.45E−09
5	Signaled	⩾20 MGT	3.15E−07	0.01253	3.94E−09
(e) Two locomotives in the front, two locomotives in the middle, and two in the rear (LNG tenders are at the 2nd, 51st and 99th position of the train)					
1	Non-Signaled	<20 MGT	1.34E−05	0.00765	1.02E−07
2	Non-Signaled	<20 MGT	6.88E−06	0.01173	8.07E−08
3	Non-Signaled	<20 MGT	3.54E−06	0.01487	5.26E−08
4	Non-Signaled	<20 MGT	1.82E−06	0.01779	3.24E−08
5	Non-Signaled	<20 MGT	9.36E−07	0.01975	1.85E−08
1	Non-Signaled	⩾20 MGT	6.30E−06	0.00765	4.82E−08
2	Non-Signaled	⩾20 MGT	3.24E−06	0.01173	3.80E−08
3	Non-Signaled	⩾20 MGT	1.67E−06	0.01487	2.48E−08
4	Non-Signaled	⩾20 MGT	8.57E−07	0.01779	1.53E−08
5	Non-Signaled	⩾20 MGT	4.41E−07	0.01975	8.71E−09
1	Signaled	<20 MGT	9.54E−06	0.00765	7.30E−08
2	Signaled	<20 MGT	4.91E−06	0.01173	5.76E−08
3	Signaled	<20 MGT	2.52E−06	0.01487	3.75E−08
4	Signaled	<20 MGT	1.30E−06	0.01779	2.31E−08
5	Signaled	<20 MGT	6.68E−07	0.01975	1.32E−08
1	Signaled	⩾20 MGT	4.50E−06	0.00765	3.44E−08
2	Signaled	⩾20 MGT	2.31E−06	0.01173	2.71E−08
3	Signaled	⩾20 MGT	1.19E−06	0.01487	1.77E−08
4	Signaled	⩾20 MGT	6.12E−07	0.01779	1.09E−08
5	Signaled	⩾20 MGT	3.15E−07	0.01975	6.21E−09

Notes: The normalized values in the five tables above were based on an assumption of a 100-vehicle train (including locomotives), the release probability of a derailed LNG tender being 0.056. When actual LNG tender release probability and release consequence are available, the matrix shall be modified accordingly.

trains on higher FRA track classes have a lower release probability per train-mile. This is because the lower train derailment rate on a higher track class more than offsets the increased vehicle derailment probability due to a higher speed (a higher track class has a higher maximum operating speed). Additionally, the location of the LNG locomotives and tenders within the train affects release probability.

An example calculation of the normalized value is illustrated as follows. If a track section has FRA track class 4, signals and annual traffic density above 20 MGT, its estimated train derailment rate is 6.12E−07 per train-mile. If there are four locomotives in the front of the train and two in the rear of the train (with LNG tenders at the 2nd, 5th and 99th positions of the train), at the maximum speed of 60 mph on track class 4, the position-dependent derailment probabilities for the three LNG tenders are 0.063 (2nd position), 0.110 (5th position) and 0.045 (99th position). Assuming that the release probability of a derailed tender is 0.056, the probability of at least one tender release is $1\text{-}(1–0.063 \times 0.056) \times (1–0.110 \times 0.056) \times (1–0.045 \times 0.056) = 0.01219$, using Eq. (7). Based on train derailment rate and the probability of LNG release in a train derailment, the normalized release probability per train-mile is $6.12\text{E}{-}07 \times 0.01219 = 7.45\text{E}{-}09$ (Table 1d).

In the example above, the rear of a train has a lower vehicle derailment probability than other positions. For example, at the 99th position, the vehicle derailment probability is 0.045 at a derailment speed of 60 mph. By comparison, the 2nd, 5th and 51st positions of the train have a derailment probability of 0.063, 0.110, 0.211, respectively. A similar observation was made for other accident speeds. This finding was consistent with the prior research (Bagheri et al., 2011; Liu et al., 2014). Therefore, the LNG tender car in the rear of a train is associated with a lower derailment probability. Note that this paper focuses on the risk posed to LNG tender cars in freight-train derailments. This analysis does not account for train collisions. Collisions comprise approximately 5% freight-train accidents on mainlines (Liu et al., 2012; Liu, 2016). In addition, railroads are implementing an advanced train control system called positive train control (PTC), especially on the high-density lines where the LNG tender is most likely to be used. This will substantially reduce the incidence of collisions. Thus, the omission of collisions in this analysis may have a limited effect on the risk estimates.

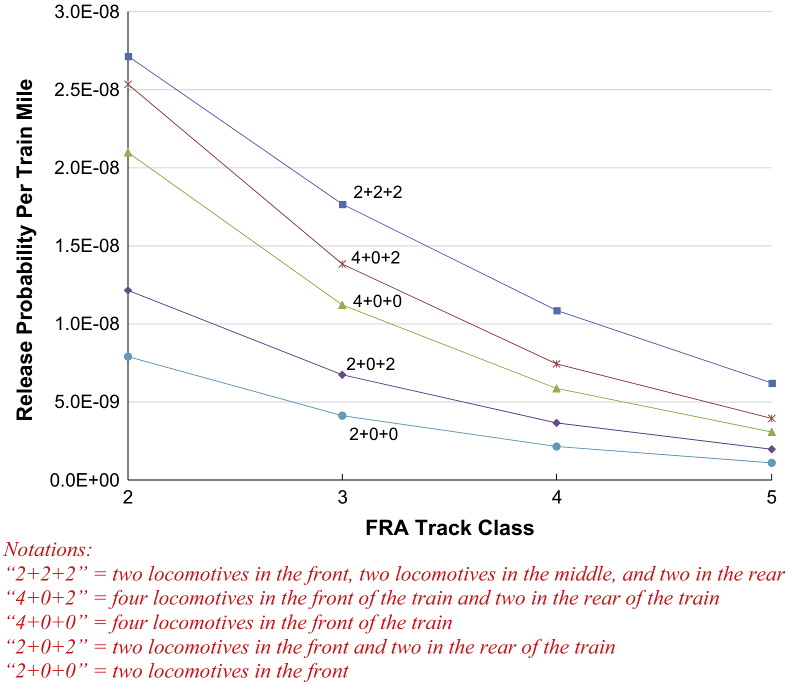

Fig. 7. Probability of LNG tender release per train-mile by FRA track class with various train configurations on signaled mainline with more than 20 MGT annual traffic density.

To illustrate the use of the matrix above, consider the following example. According to a previous study (Liu, 2013; Liu et al., 2016), 48 percent of ton-miles on Class I railroads were on signaled track, FRA track class 4, with annual traffic density above 20 MGT. Assume LNG locomotives are operating on a high fuel-consumption route, consisting of FRA Class 4 signaled track with an annual traffic density above 20 MGT, using a six-locomotive LNG train (with four locomotives in the front and two locomotives in the rear). In this case, the normalized release probability is 7.45E−09 per train-mile (Table 1d). It is assumed that the section is 10 miles long. If there are 300 LNG-fueled trains per year, the annual traffic volume of LNG trains is 3000 train-miles. Using this train/locomotive configuration on this particular section, the annual LNG tender release frequency is 2.24E−05 (7.45E−09 × 3000). It is interpreted that there is an average of 0.002% chance of an LNG tender release incident per year on this 10-mile track section.

Using a similar approach, given traffic volume, train characteristics, LNG tender design, route-specific or network-specific risk can be determined using a step-by-step procedure:

1. Determine the route or network for analysis. Categorize traffic volume (train-miles) by FRA track class, method of operation and annual traffic density.
2. Determine train configuration, including train length, the number and positions of locomotives and LNG tenders. The scenario-specific release probability matrix can be calculated based on specified input variables.
3. Given specified track and train characteristics, calculate normalized release probability per train-mile, based on the table above (other similar matrices can be developed for different train lengths). Based on the normalized value and the traffic volume within each scenario of track characteristics, the total release probability within each scenario can be assessed. Finally, the summation of scenario-specific release probability generates the total frequency on the entire route or network.

7. Concluding remarks

The principal contribution of this paper is the development of a generalized methodology that can estimate LNG tender derailment and release probability accounting for a variety of factors such as FRA track class, method of operation, annual traffic density, train length, speed, the number and positions of LNG tenders and LNG tender release probability. The model can be implemented into a decision support tool that potentially aids the railroad industry in evaluating the risk given any LNG train configuration on any specified route or network. As part of a larger effort to model all-hazard risk associated with the use of LNG on freight railroads, the LNG tender derailment risk can be linked to other types of risk (e.g. risk to the train crew, fueling facility risk, the risk of transporting fuel to fueling stations) and ultimately can contribute to a better understanding of the safety implications of using LNG as an alternative fuel on North American railroads.

8. Suggested future research directions

Due to data limitations, there are several topics that were not discussed in depth in this paper but can be analyzed in future research.

- Future research can account for fueling station risk as well as the risk of using trains to transport LNG to the fueling station, or as shipments in general revenue service.
- Consider the capital and operational costs due to the use of LNG-powered locomotives including LNG locomotive purchase (or retrofit) and maintenance cost; fueling station construction and maintenance cost; evaporation or burn-off losses from LNG storage; and operational efficiency loss due to lower interoperability.
- This research focuses on LNG tender risk from a train derailment, which accounts for a major source of danger. Future research can be developed to account for other types of accidents, such as train collisions and grade-crossing incidents.
- While the location of the LNG locomotives and tenders within a train affects release probability, it also affects train handling and operations. Future research can incorporate other operational considerations (e.g. grade, curvature, switching requirements, train handling) to determine the preferred train configuration for a given route.
- Future research can also address crew safety, which will require a better understanding of leak detection capabilities and potential modifications to locomotive cabs intended for crew protection.
- LNG locomotive lifecycle assessment of greenhouse gas emissions.
- Development of a comprehensive comparison between LNG and diesel, accounting for their economic, environmental, operational and safety implications.
- Previous studies (e.g. Verma, 2011; Toumazis and Kwon, 2013) estimated hazardous materials transportation risk in rail or roadway. The next step of this paper can be to estimate the consequences of a potential release from LNG-fueled trains to calculate its transportation risk.

These future research efforts can inform the FRA and the railroad industry in developing policies, practices, and new technology to balance operational safety and efficiency, economic competitiveness, and environmental stewardship when considering LNG as an alternative fuel.

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