# Methodology to Evaluate the Consequence of Hazardous Material Releases from Multiple Tank Cars Involved in Train Accidents

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**ABSTRACT**

Increasing rail hazardous material traffic including petroleum crude oil in North America, and several recent severe release incidents highlight the need to further improve railroad transportation safety. Accurate estimation of the consequence of a release incident is a key element in risk management. This study develops a new methodology for estimating the affected area of a release incident accounting for the number of tank cars releasing, using a sophisticated atmospheric dispersion model on a geographic information system (GIS) platform. The results show a non-linear relationship between the number of cars released and the maximum threat distance. Results show that multiple-car releases may not always be more severe than single car releases. As such, assuming a constant value for a release affected area may not be appropriate for describing a multiple-tank-car released event and its consequences. This research can be used to enable a more accurate risk assessment of railroad hazardous materials transportation, especially to address the potential multiple-tank-car release incidents.

## INTRODUCTION

North American railroads transport more than two million carloads of hazardous materials (hazmat) annually and more than 99.9% of shipments safely reached their destinations (*1, 2*). However, increasing rail hazmat traffic including petroleum crude oil in North America, and several recent severe hazmat release incidents highlight the need to further improve railroad hazmat transportation safety.

An accurate assessment of hazmat release consequence is important in hazmat transportation risk assessment (*3*). Hazmat release consequence modeling is challenging and complex because of different potential evaluation metrics and various affecting factors such as chemical property, volume released, environmental and atmospheric conditions and population density (*4*). Therefore, a flexible and applicable consequence model needs to be developed based on context-specific circumstances and data availability.

As compared with a highway vehicle that usually transport a single tank, a hazmat train may contain a number of tank cars, and can potentially have releases from multiple tank cars in an accident. A better understanding of the consequence of multiple-tank-car releases addresses the unique characteristics of railroad hazmat transportation and enables its more accurate risk assessment. Despite its importance, limited prior research has been conducted to quantify the consequence of multiple-tank-car release incidents (*5*). To advance the body of knowledge in the field, this research develops a new methodology for estimating the affected area given the releases of multiple tank cars using a sophisticated atmospheric dispersion model with a geographic information system (GIS) platform. Using this methodology, the number of affected population can be estimated as a function of the number of tank cars releasing given specific chemical and route characteristics.

The exposition of this paper is structured as follows. First, a literature review is conducted to review the past studies and identify their application and limitations. Next, hazardous materials behaviors in a release incident and their possible consequences are identified. Then, a general approach is developed to address multiple-tank-car release consequence, measured by the number of persons in the affected area. Finally, a case study is used to illustrate the application of the methodology.

## LITERATURE REVIEW

Previous researchers calculated the affected area of a hazmat release incident by using a circular area centered at the release point, assuming a uniformly distributed wind direction (*6*).

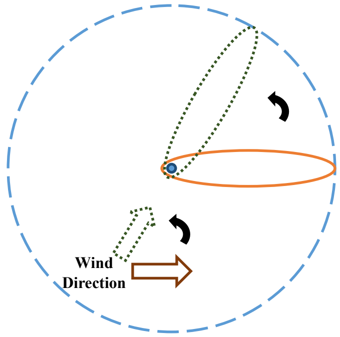


**FIGURE 1 Wind direction effect on area affected**

In a route-specific risk analysis, the population density may change along the route. As such, an estimation of the average population density along a specific route is needed. Usually, a fixed band or buffer with a width equal to the exposure distance is created and used to calculate the average population density corresponding to the exposure area along the route. After that the population affected is determined by multiplying the average population density by the affected area (*7*).

Different models are available to estimate the maximum distance where the concentration is harmful to the general public. One widely used approach is provided by the Emergency Response Guidebook (ERG) by U.S. Department of Transportation (*8*). This guidebook provides initial isolation distance in case of an accident involving specific hazardous materials and it can be used by first responders and planners. Although ERG provides different distances for small (<55 gal.), large (>55 gal.) spills, day and night time (*9*), this model does not consider the effect of the total number of tank cars releasing on the consequence. Therefore, in the case of a multiple-tank-car release the isolation distance could be an over or under estimation.

Another popular model used to calculate the chemical concentration after a release is the Gaussian Plume Model (GPM) (*6*). The GPM is widely used because it combines a simple and flexible mathematical expression, and realistic results which represent adequately diverse laboratory and field experiments. However, not all the chemical releases can be modeled using GPM. One principal assumption of the GPM is that the chemical gas should be a neutrally buoyant gas, which means that its weight should be considered almost equal to the air weight. However, not all chemicals have weight less than or equal to air. Therefore, those chemicals, grouped as heavy gas chemicals, should be modeled using a heavy gas model instead of GPM (*10*). The heavy gas model (HGM) is applicable to those heavy gas chemicals and is able to better estimate the concentration downwind. In some conditions GPM and HGM will result in similar affected area.

Finally, the utilization of advanced computational fluid dynamics (CFD) techniques may be used to simulate releases in high-complex geometrics environments, such as urban areas. This relatively new technique incorporates finite elements and numerical analysis, and can simulate different scenarios including: isothermal and non-isothermal heavy gas dispersion, confined and unconfined explosions, as well as flammable cloud fire (*11, 12*). Although this sophisticated tool may be more relevant for industrial facility risk analysis, it could be used in future hazmat transportation risk analysis.

## HAZARDOUS MATERIALS BEHAVIORS AND THEIR CONSEQUENCES

Various psychochemical factors affect a chemical's hazard. For instance, some chemicals are more prone to generate a toxic cloud instead of being ignited or exploded (*13*). Different possible scenarios for a release are described below.

First, a basic classification is proposed for every hazardous material as a flammable or nonflammable chemical, and as a toxic or nontoxic chemical (*14*).

**TABLE 1 Product Characteristic and Release Behavior**

| | Flammable | Nonflammable |
|---|---|---|
| Toxic | Multi hazard behavior of chemicals | Jet flow<br>Vapor cloud<br>Evaporation pool |
| Nontoxic | Jet/Pool fire thermal radiation<br>Vapor cloud fire hazard<br>Explosion hazard (BLEVE) | No interest |

If a nonflammable toxic chemical is released from a punctured tank-car, there are three different possible scenarios: jet flow, vapor cloud, and evaporation pool. The first scenario generally occurs when the tank-car is transporting an under-pressured liquefied gas and it has a small puncture as a consequence of the accident. The material is released as a high velocity jet flow to form a mixture of liquid drops and gas (two-phase flow). This two-phase mixture cloud generally behaves first as a heavy gas, flowing downwind like water, until it is diluted enough into the atmosphere, when it behaves like a neutrally buoyant gas, following the traditional Gaussian dispersion model.

The second scenario, vapor cloud, commonly refers to the circumstance that the entire tank car is released almost instantaneously. In such event, the initial isolation area would be circular around the release point, and then the vapor cloud would start moving downwind as a whole, diluting its concentration with the air.

The last scenario for toxic nonflammable chemical is the evaporation pool. In this case, the chemical is released from the tank as liquid phase forming a pool around the tank. Then, the liquid starts evaporating from the pool and a toxic vapor plume is generated. This vapor plume is transported and dispersed by the wind.

For these three scenarios, the affected area is defined using an appropriate Level of Concern (LOC) that represents the concentration level at which the chemical is not dangerous for general public.

On the other hand, if a nontoxic flammable chemical is released from a tank-car, the main concern about the release consequences will be focused on the thermal energy radiated from the release and the overpressure wave from an explosion. There are some possible scenarios: jet/pool fire, vapor cloud explosion, and BLEVE.

The first two scenarios, jet fire and pool fire, are similar to the toxic scenarios jet flow and evaporation pool, respectively. In both cases, the main difference lies in the high flammability of the chemical, which catches on fire immediately after the release started. A jet fire occurs when a pressurized liquid is released as a high velocity two-phase flow and it is immediately burned, like a blowtorch. When the chemical is released forming a pool around the punctured tank and it gets in flame, the result is a pool fire. In both cases, the affected area is where thermal energy radiates from the fire.

A release of flammable chemical sometimes does not result in fire immediately after the accident occurs. In those cases, the chemical starts evaporating and forming a vapor cloud of highly flammable gas. This gas may propagate far away from the released point and if it is exposed to an ignition source (i.e. spark, flame etc.), it can be ignited and generate a flash fire or explosion. The Lower Explosive Limit (LEL) and the Upper Explosive Limit (UEL) affect the size of the flammable area. Every chemical has its own limits and they represent the chemical gas concentration range within the air where the chemical may be burned. If the concentration is below the LEL, there is not enough chemical to combust. Alternatively, if the concentration is above the UEL, there is not enough oxygen to allow the combustion. In general, the affected area will be defined by the LEL boundary.

The last possible scenario that may take place when a nontoxic flammable chemical is released is the Boiling Liquid Expanding Vapor Explosion, also known as a BLEVE event. A BLEVE is usually produced when a tank-car involved in the accident contains a liquefied gas and it is heated by fire until the pressure within the container is higher than the container strength, consequently the chemical is violently released in an explosion. After the explosion, a fireball may occur and even some parts of the container may be launched over surrounding area as projectiles. Although those fragments may represent an important source of damages for surrounding areas, 80% of fragments have been reported at less than 600 feet from the explosion point, which is less than most of the evacuation areas due to thermal radiation or overpressure wave (*15*).

Finally, it is interesting to note that not all the chemical substances are flammable or toxic. Some substances are flammable and toxic, and consequently they have a multi-hazard behavior. Proposed by Raj & Turner (1992) the probability distributions of some selected chemicals with multi-hazard behavior are as follows:

**TABLE 2 Probability of Different Behaviors for Different Products (*14*)**

| Chemical Name | Hazard Type and Chemical Phase | Prob. of Different Behaviors | | | |
|---|---|---|---|---|---|
| | | Toxic Vapor | Pool Fire | Explosion | Vapor Fire |
| Gasoline | Flammable Liquid | 0.00 | 0.90 | 0.05 | 0.05 |
| Liquefied Petroleum Gas (Propane) | Flammable Gas | 0.00 | 0.05 | 0.30 | 0.65 |
| Ethylene Oxide | Poison Gas | 0.50 | 0.10 | 0.20 | 0.20 |
| Chlorine | Poison Gas | 1.00 | 0.00 | 0.00 | 0.00 |

## MULTIPLE TANK-CAR RELEASED CONSEQUENCE EVALUATION

There are two main approaches to evaluate the consequence of multiple tank car releases based on the following two assumptions. The first assumption is that all releases concentrate at one point. The second assumption is that each tank car release has its own concentration center and interacts with other car releases. According to the first assumption, the affected area is a circular area, whereas the second assumption results in a more complicated shape of affected area depending on the interaction among different release points (Figure 2). In this study, the first assumption is used in the dispersion modeling.

1st Approach: Release concentrated in one point

2nd Approach: Every car is a different point of release

**FIGURE 2 Two approaches to calculate multiple tank-car released consequences**

## METHODOLOGY

A new methodology is proposed in this paper to estimate a multiple-tank-car release consequence accounting for specific chemical, route and operational characteristics. The first two steps in this methodology include selecting the hazardous material and identifying its possible release behavior based on the literature. Once the product is selected and its possible behaviors are identified, a simulation tool is used to determine the affected area and the corresponding population potentially affected by the release is calculated using GIS techniques.

The implementation of this methodology is based on the dispersion model that estimates the affected area combined with a GIS tool to compute the number of persons in the affected area. The dispersion model is implemented in the software called Area Locations of Hazardous Atmospheres (ALOHA) jointly developed by U.S. Environmental Protection Agency's Office of Emergency Management (OEM) and National Oceanic and Atmospheric Administration Office of Response and Restoration (NOAA). The ALOHA software includes the aforementioned GPM and HGM models. It is able to calculate the threat zone based on the characteristics of the released product, release behavior, weather conditions and tank car design information. The tool also accounts for the amount of release, thereby can be used to estimate the affected area of multiple-tank-car release incidents.

Like any simulation tool, ALOHA has certain limitations (e.g., only applicable to flat terrain) and has been considered conservative in some studies (*16*). However, it is still one of the most popular tools extensively used by government agencies and previous researchers (*6, 17-19*). This paper uses this tool to illustrate the concept and potential application of multiple-tank-car release evaluation methodology. In the future, the methodology can be adapted with any or more advanced dispersion tools.

First, the ALOHA software is used to estimate threat zones associated with several different behaviors and types of a hazardous chemical release, including toxic gas clouds, fires, and explosions. Then, a weighted average threat distance is estimated based on the probability distribution of hazard type for the same chemical. A GIS tool is used to estimate the number of persons in the affected area by multiplying the affected area by average population density along each segment (*20-22*). Although there are other consequence metrics such as property damage, environmental impact and service disruption, population in the affected area is widely used in the prior research (*23, 24*), and is used in this paper.

In the next section, a case study is developed to illustrate the application of the methodology. We use a number of graphical and tabular illustrations to better communicate the principal results.

## CASE STUDY

The scope of the case study is to estimate the population affected due to a multiple-tank-car release of propane on an actual, anonymous route (Figure 4). The graph also illustrates the distribution of population density along this route. Point A represents a highly populated metropolitan city and Point B represents a medium-population city. On average, population density is relatively low along the route.

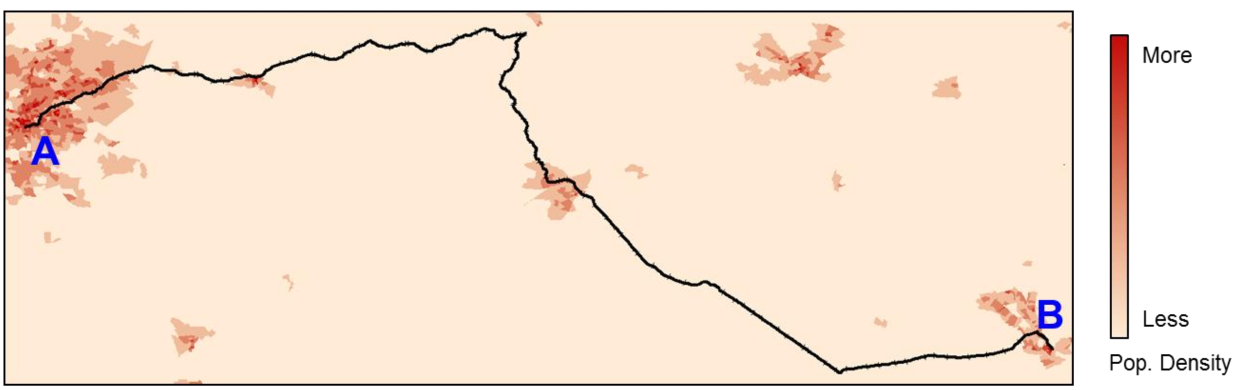


**FIGURE 3 Route map and population distribution**

Without detailed weather information, this study uses the worst-case scenario. It is assumed that atmospheric stability class is F (from a scale A to F), low wind speed (~5 mph), and night time. The train contains ten DOT 112 tank cars transporting propane under pressure (*25*). The cars are completely full and they will release all the content. A hole of 8 by 8 inches is considered for every car punctured. The size of the hole is assumed to be equivalent to a rail section.

A summary table with the main parameters taken for this example is presented below.

**TABLE 3 Summary of Parameters for ALOHA**

| Parameter | Value in ALOHA |
|---|---|
| Hazardous material | Propane |
| Stability class | F |
| Time | Night |
| Wind speed | 5 mph |
| Air temperature | 60 F |
| Humidity | 50 % |
| Tank Car | DOT112 |
| Volume Tank-Car | 33,600 gallons |
| Temperature Tank-Car | Ambient Temperature |
| Hole size | 8x8 in (64 $in^2$) |

The first step of the methodology is identifying the different possible behaviors of the hazmat being studied. For this example, the product selected is propane, one of the top ten chemicals in term of carloads transported by rail in North America (*1*). Propane is considered a highly flammable material transported usually under pressure in liquid form.

Nowadays, crude oil and petroleum derivatives are experiencing a huge increase in rail transportation volumes in the U.S. In addition, they have been involved recently in some tragic incidents, receiving more public attention such as in Lac Megantic, QB and Parkers Prairie, MN, both in 2013. Due to limited data about crude oil properties, it could not be adequately modeled using ALOHA. By contrast, propane has standard properties, already included in the ALOHA chemical library. Furthermore, the fact that this material is highly flammable and it is transported under pressure assures diverse potential behaviors in case of a release.

Propane may have three different released behaviors (Table 2). It may be released as a jet fire, explosion, and BLEVE or flash fire. By definition, jet fire and BLEVE events should be considered only for one car because their effects cannot be combined when more than one car is involved. However, pool fire, explosion, and flash fire depend on the number of cars released, which means, if two cars are involved in the accident and they are releasing the content as a pool fire, the area affected would be greater than if only one car is involved.

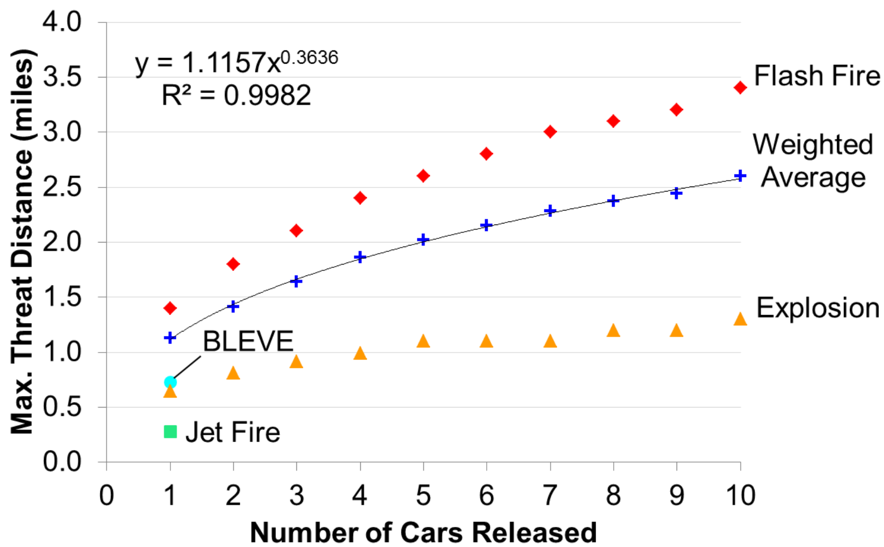


**FIGURE 4 Relationship between number of cars released and threat distance for propane**

Figure 5 illustrates the distribution of maximum threat distance for every scenario from one up to ten cars released, and for each different behavior. As explained above, BLEVE and jet fire events are only considered for one car released. The weighted average is also plotted and approximated by a nonlinear function. The analysis shows that flash fire could represent the behavior with the greatest maximum threat distance, affecting more than 3 miles distance for 10 cars released. By comparison, jet fire would have a relatively smaller affected.

The affected area information using the ALOHA software is implemented into GIS tool to calculate the number of persons affected. The distribution of population affected by one car released along the route is shown below.

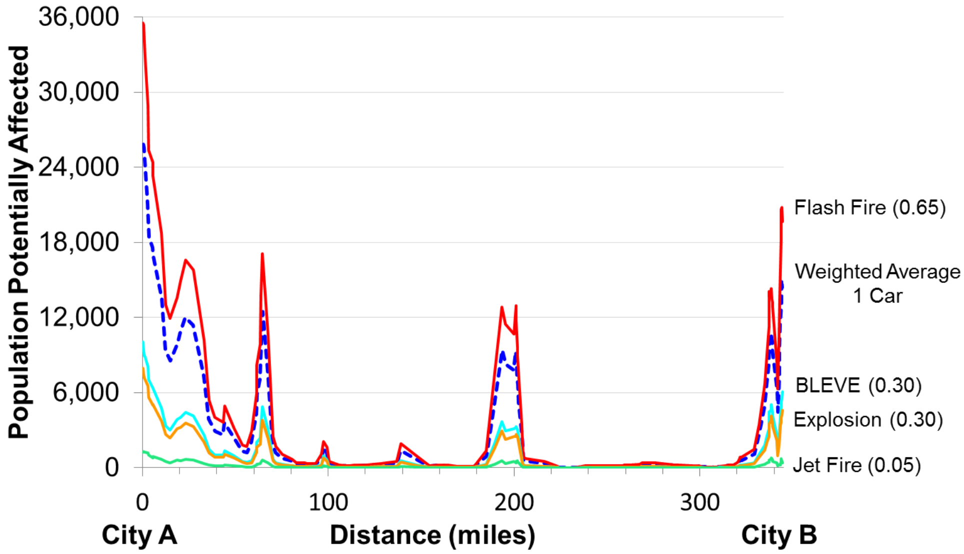


**FIGURE 5 Distribution of population potentially affected by 1 car released along the route**

Figure 6 shows the change of population distribution along the route. The weighted average is represented by a dash line. The “consequence hot spots” can be identified as three population cores. Two areas practically unpopulated along this particular route can be identified as well. This graph may be used by companies or regulators pursuing a better understanding of how the consequences of a multiple-tank-car release are distributed along a route and where they may focus their efforts to mitigate potential damages given a release.

The previous figure only shows the population distribution in case of one car release. If the same process is repeated for every scenario, the distribution of consequence of multiple tank-car releases can be estimated (Figure 7).

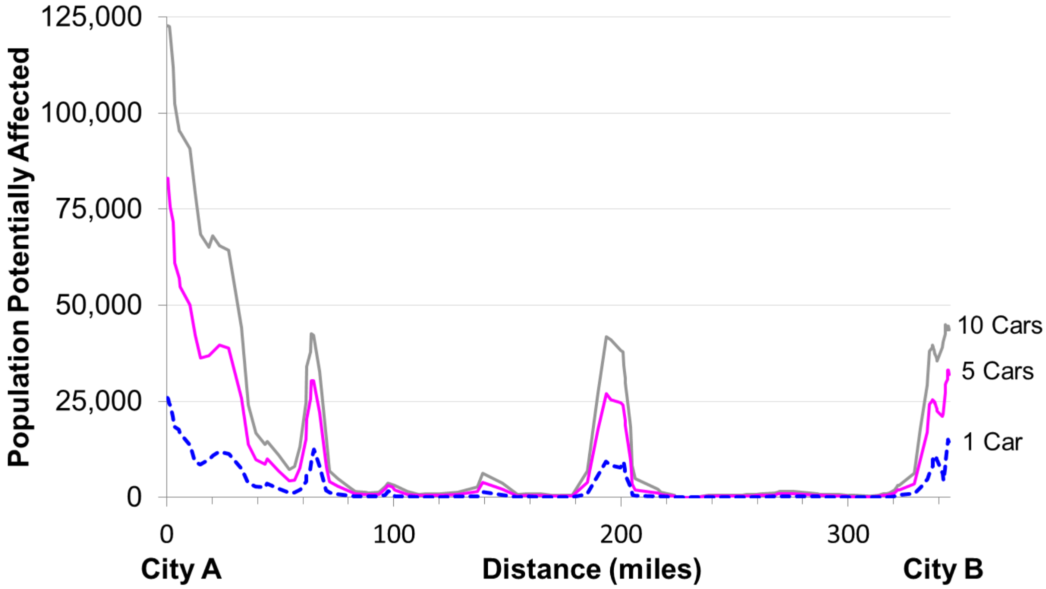


**FIGURE 6 Distribution of population potentially affected by multiple tank-car released along the route**

There are certain areas where no matter how many cars are released, almost the same number of population would be affected. However, at the high-population locations, the difference in volume released could significantly affect the level of population affected.

In addition, a small proportion of the route accounts for the majority of the risk. In this 10-car release example, 8% of the total miles accounts for 50% of the total potential population affected by the release (Figure 8).

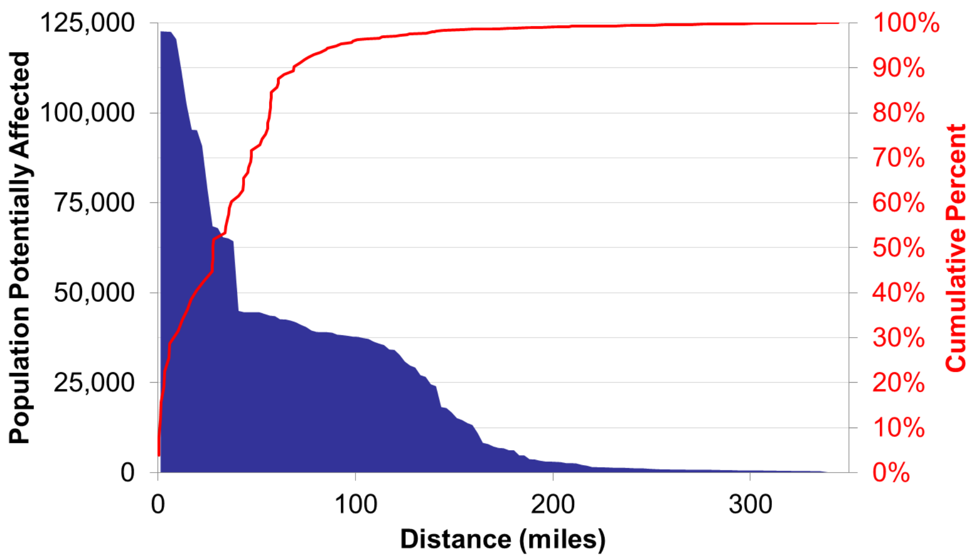


**FIGURE 7 Cumulative distribution of population potentially affected by 10 cars released along the route**

## CONCLUSION

This analysis highlights the importance of performing a more detailed consequence estimation study for multiple-tank-cars release events. This analysis shows the relationship between the number of cars involved in the released incident and the maximum threat distance as well as the affected area. This relationship follows a power equation, which demonstrates that assuming a linear relationship is not accurate and may overestimate the affected distance.

This work may also help locating the most sensitive areas along a route in case of a release incident. As shown in Figure 8, the affected population along a route is concentrated on a small part of the total route. Thereby, railroads, planners, and regulators may identify and prioritize areas to implement risk mitigation strategies.

## FUTURE DIRECTIONS

According to the consequence definition, the magnitude of an accident is directly influenced by external factors as weather and topography. However, at this initial stage of this work, those aspects have been assumed as worst case scenario on flat terrain. In addition, consequences may also consider environmental damage and properties loss as well. A future stage of this study may include those consequence metrics.

Further step for performing a risk analysis would include calculating the probability of occurrence associated with every release scenario such as the probability of having only one car released, two cars released, or more. Although probability calculation is out of the scope of this current work, both, probability and consequence, are needed to estimate the total risk for a specific route.

**ACKNOWLEDGEMENTS**

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