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Final Report

Consequence Based Route Selection for Hazardous Material Cargo: GIS-Based Time Progression of Environmental Impact Radius of Accidental Spills

(Project # 2012-036S)

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ABSTRACT

The aim of this study was to investigate the transportation networks in order to identify the most suitable routes for transporting hazardous material cargoes. The potential key contribution of the study is the development of a decision tool to assist in comparing and selecting highway routes to transport hazardous materials. This research considered criteria in order to evaluate each link in the transportation network including health risks and cost of delay as a result of an en route accidental release of hazardous materials; as well as proximity to public places, and travel cost. The Gaussian air dispersion model was employed to estimate the extent of health risk protective zones and the possible affected population. Queuing analysis was utilized to calculate delay time and accordingly the associated cost. Public places with high occupation around the road segments were identified and assigned to the road segments. Trucking costs were calculated based on the length of the links and the cost per unit length. After evaluating the networks, the tool then identifies the best route in regards to the criteria using a Multi-Criteria-Decision-Making method. The results of this study can effectively aid decision makers and hazardous materials transportation companies in understanding the conflicting nature of transporting and routing hazardous cargoes in view of the decision criteria for selecting the routes and evaluating possible consequences in case of accidental releases.

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CHAPTER 1: INTRODUCTION

According to the Federal Motor Carrier Safety Administration (FMCSA), hazardous materials are defined as substances that if not regulated, are capable of threat for the population and the environment health, safety or property when transported in commerce (FMCSA, 2006). Hazardous material shipments carried by trucks in the U.S. add up to approximately 1.5 million tons annually, representing about 59.4 % of the total commodity shipments in 2012 with an increase by 27.3 % from 2007 to 2012, yet the trend in hazardous materials volume continues to grow at a rate of 5% per year (U.S. Census Bureau, 2012). Accidents involving hazardous materials are relatively less frequent; yet they are considered as high-consequence incidents because they can cause injuries, death, costly environmental damage and cleanup efforts (Toumazis and Kwon, 2013).

Based on a report by the Federal Motor Carrier Safety Administration (FMCSA), each year about 200 hazardous material trucks are involved in fatal and 5,000 in non-lethal incidents (Craft, 2004). Despite the small number of crashes in comparison to the total number of truck accidents (i.e., the probability of a person in the U.S. to be killed by lightning is three times the probability of being killed by a truck carrying hazardous material accident occurring) (PHMSA, 2010), the threat that hazardous material accidents pose on human health and properties is significant (Craft, 2004). It is estimated that hazardous material highway crashes have a societal cost impact of more than $1 billion a year (Craft, 2004).

The risk of hazardous materials transport through urban transportation networks and highways depends on the characteristics of the hazardous materials being transported in their specified routes. The population living/working around and along the routes used for hazardous materials shipments may suffer from the undesirable consequences of an accident.

Hazardous materials are fundamental components of the United States economy and industry. The economy to a large extent relies on utilization of hazardous materials; including manufacturing, mining, agriculture, construction, and medical and sanitary services (Verter and Kara, 2008). Therefore, consumption of hazardous materials and consequently transportation of such chemicals are inevitable; accordingly, hazardous materials cargo accidents and accidental releases of hazardous materials during transport pose significant risks which needs to be evaluated in view of the road characteristics, land use around the transportation networks, population density, and characteristics of the cargo.

About 90% of hazardous material transportation incidents take place on highways, intersections and junctions of rural/urban roads (approximately one out of five trucks on U.S. highways is a hazardous material truck) (Erkut and Verter 1998). The spillages (or releases to the atmosphere) due to transportation incidents involving road tanker trucks carrying hazardous chemicals on highways, not only create substantial toxic hazards through inhalation of the substances but also pose flammability hazards due to pool fire and flash fire (Chakrabarti and Parikh, 2013). Air pollution increases risks of cancer, respiratory and allergy diseases, it also aggravates the condition of people suffering from such diseases (Jensen et al., 2001).

Over the past three decades, many nations have been involved with research on developing operational strategies to improve transport and disposal of hazardous materials and reduce accidental risks (Rakas et al., 2004); yet, the accidental releases and explosions causing unexpected destructions, injuries and deaths have occurred and continue to happen as results of production, storage or transportation of toxic and explosive chemicals. Public concern regarding accidental explosions and toxic hazards has been increased in the recent years with the increase in chemical use dictated by economic changes (Baker et al., 1983).

Historically, there have been numerous accidents that have led to explosions, health threats and property damages. For example, an explosion of vapor cloud occurred in Naples, Italy in 1985 in a fuel storage containing gasoline, diesel fuel and fuel oil. The accident originated form a spill during a filling operation and the outcome fire lasted for over a week destroying all the buildings and facilities in surrounding areas (Maremonti et al., 1999). In Bangkok, Thailand, 1990, a truck carrying LPG crashed and overturned and led to the discharge of 5 tons LPG, a vapor cloud was created and a flash fire explosion caused 68 death and over 100 injuries beside considerable property damages. Another incident happened in East St. Louis, Illinois, in 1973; an accident in Saint Herblain, France, 1991; a fire and explosion in Crescent City, Illinois, in 2008, and many other examples of similar incidents (Beroggi, 1994). The detailed hazardous material accidents in the U.S. are available in the Appendix, which shows the accidents involving gasoline with the amount of release more than 5,000 gallons.

In the literature, several studies focused on hazardous material transport through employing/introducing methodologies and techniques. For instance, Das et al., (2012) created a framework for risk assessment of transportation of hazardous wastes in respect to the population involved. Ronza et al., (2007) proposed an event tree in an attempt to predict the probability of ignition of hydrocarbon spills based on statistical data. In another study, Van Aerde et al., (1988) utilized a model to predict the impact of a spill followed by an accident during transport, taking into account the atmospheric condition, time of accident and thermodynamic properties of the material shipped. Analysis and categorization of the available studies on hazardous material cargo incidents showed that a significant portion of the studies have focused on risk analysis and route selection. Research regarding the risk associated with hazardous material transport is quite extensive (Leonelli et al., 2000; Glickman et al., 2007; Zografos and Androutsopoulos, 2008; Reniers et al., 2010; Toumazis and Kwon, 2013; Kang et al., 2014; Saat et al., 2014; Chakrabarti and Parick, 2013b; Van Raemdonck et al., 2013).

Several studies have focused on routing of the hazardous material cargos; the key approach was taking into account scheduling, location, and perhaps high risk routes and nods (Beroggi, 1994; Guo and Verma, 2010; Karkazis and Boffey, 1995; Erkut, 1995; Frank et al., 2000; Leonelli et al., 2000; Gunasekera and Edwards, 2003; Bubbico et al., 2004; Carotenuto et al., 2007; Singh et al., 2011; Mahmoudabadi and Seyedhosseini, 2013). In the studies which focused on routing the hazardous freights, the common criterion used was the risk associated with the transport of hazardous goods (Zografos and Davis, 1989; Lepofsky et al., 1993; Jacobs and Warmerdam, 1994; Giannikos, 1998; Leonelli et al., 2000; Frank et al., 2000; Fabiano et al., 2005; Akgün et al., 2007; Sadjadi, 2007; Dadkar et al., 2008; Zografos and Androutsopoulos, 2008; Bonvicini and Spadoni, 2008; Bianco et al., 2009; Guo and Verma, 2010; Pradhananga et al., 2010; Das et al., 2012; Mahmoudabadi and Seyedhosseini, 2013; Chakrabarti and Parikh, 2013; Cappanera and Nonato, 2014). However, other criteria were also utilized to either identify or select the best possible route for hazardous material cargoes, such as cost associated with property damage (Lepofsky et al., 1993; Zografos and Davis, 1989); travel distance (Leonelli et al., 2000; Kazantzi et al., 2011; Das et al., 2012; Cappanera and Nonato, 2014); and, travel time (Zografos and Davis, 1989; Lepofsky et al., 1993; Jacobs and Warmerdam, 1994; Frank et al., 2000; Sadjadi, 2007; Dadkar et al., 2008; Zografos and Androutsopoulos, 2008; Pradhananga et al., 2010; Mahmoudabadi and Seyedhosseini, 2013; Cappanera and Nonato, 2014). There are also studies that focused on risk equity (Zografos and Davis, 1989; Bianco et al., 2009).

There is also substantial research on designing road networks for hazardous materials, where the evaluation criteria were defined for specific assessment (e.g., Kara and Verter, 2004; Erkut and Gzara, 2008, Zhang et al., 2000, Frank et al., 2000, Zografos and Androutsopoulos, 2005, Gzara, 2013, Das et al., 2012, Kang et al., 2014). However, most of the studies have focused only on travel cost through link length, in some cases risk also was taken into account for network assessment/design. In the field of hazardous material network design, the design term refers to selection of suitable segments within an existing network of roads, as designing a new transportation network for hazardous goods and freight is not cost effective; hence, it is not considered as an option.

Transport of hazardous materials involves different parties including shippers, carriers, manufactures, residents, governments and emergency responders, each with different priorities in view of the criteria and objectives being considered. One of the most referred criterions in transportation of hazardous materials is travel cost. Travel cost is important for evaluating the economic advantages and savings to carriers and shippers, as well as the consumers. However, the lowest cost route may pass through densely populated areas posing high health risks to people in case of an accidental release. On the other hand, one consideration that has not been well studied in the field of hazardous materials transport is the burden that accidents involving hazardous materials pose on transportation networks due to congestions and traffic delays. In the literature, delays that affect the delivery of the hazardous good have been considered; however, the traffic delays within the transportation network and the impact on the users of these routes have not been addressed.

PROJECT OBJECTIVES

This research aimed to:

1. Investigate hazardous material cargo crashes in an attempt to predict the outcomes of such accidents;
2. Estimate the expected concentrations of chemicals released air after the hazardous material releases, to further identify the health impact radius;
3. Develop criteria to be taken into account for routing of trucks carrying hazardous materials;
4. Assess suitability of transportation networks for transporting hazardous materials;
5. Provide a network of recommended route segments in regards to path evaluation criteria; and
6. Identify the hazardous material cargo routing options using a Multi-Criteria-Decision-Making technique in an attempt to reduce potential adverse impacts of accidental releases of hazardous materials during transport.

The results of this research can be used for routing hazardous material cargoes, not only to minimize risks of transportation accidents which impact human health and safety, but also to avoid transportation congestions, while make the suggested routing options appealing to the carriers by finding economically viable routes.

ROUTE SELECTION CRITERIA

Many studies focused on routing the hazardous material trucks considering different criteria. In several studies, risk was the main criteria to be taken into account in selection of the transport paths. In many other studies, travel cost as a matter of distance, time and fuel consumption was another most referred criteria in the field of routing the hazardous material cargoes. Table 1 presents detailed criteria, which have been documented in the literature.

The proposed criteria used by this study were health risk, proximity to public places, trucking expenses and delay costs. Health risk and trucking cost are not new criteria in cargo route selection problems in the literature, so that the majority of the studies considered this criteria in their evaluations. On the other hand, delay cost as a criterion in selection of the best route for truck tankers, was found to be new and not been used in the field of hazardous material transport routing studies. In the event of an accident, accident cost includes property damage, fatality and injuries, while the delay cost corresponds to the expense that is forced onto the other users of the transportation system. Moreover, considering vulnerable public places such as daycares, hospitals and schools as a matter of numerating the places around each road segment and assigning the numbers to the links is a novel feature. The approach of this study is comprehensive and innovative, as it considers four important evaluation criteria for assessment of transportation networks. The method developed can be used to identify the route which is most favorable for transporting hazardous materials depending on location, time of day, crash history, and traffic characteristics.

Table 1. Common criteria in hazardous cargo truck route selection studies.

Author	Year	Risk	Damage	Travel time (cost)	Distance (cost)	Number of vehicle	Risk (cost)	Risk (special people)	Risk equity
Zografos and Davis	1989	✓	✓	✓				✓	
Lepofsky et al.	1993	✓		✓					
Jacobs and Warmerdam	1995	✓		✓					
Giannikos	1998	✓							✓
Frank et al.	2000	✓		✓					
Leonelli et al.	2000	✓			✓		✓		
Fabiano et al.	2005	✓							
Akgün et al.	2007	✓							
Sadjadi	2007	✓		✓					
Bonvicini and Spadoni	2008	✓							
Zografos and Androutsopoulos	2008	✓		✓					
Dadkar et al.	2008	✓		✓					
Bianco et al.	2009	✓							✓
Pradhananga et al.	2010	✓		✓		✓			
Guo and Verma	2010	✓							
Chakrabarti and Parikh	2011	✓							
Kazantzi et al.	2011	✓			✓				
Das et al.	2012	✓			✓				
Mahmoudabadi and Seyedhosseini	2013	✓		✓					
Chakrabarti and Parikh	2013	✓							
Cappanera and Nonato	2014	✓		✓	✓				

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CHAPTER 2: RESEARCH APPROACH

Road segments for each route were evaluated (quantitatively) and the route options were compared based on the suitability of the road segments within the transportation network. The following four criteria were considered in development of the network assessment tool:

1. Health risks due to exposure after accidental releases,
2. Delay costs,
3. Trucking expenses, and
4. Proximity to vulnerable areas.

The approach used in this study is an interactive and flexible tool, written in Python programming language, capable of executing analyses on the transportation network of any given area of interest, provided by the user, for assessing the suitability of the road links for transporting hazardous materials. Evaluations, calculations and analyses are conducted by one time execution of the program and the outputs are obtained in the form of maps and tables. Figure 1 presents the overall methodology used in developing the route assessment tool.

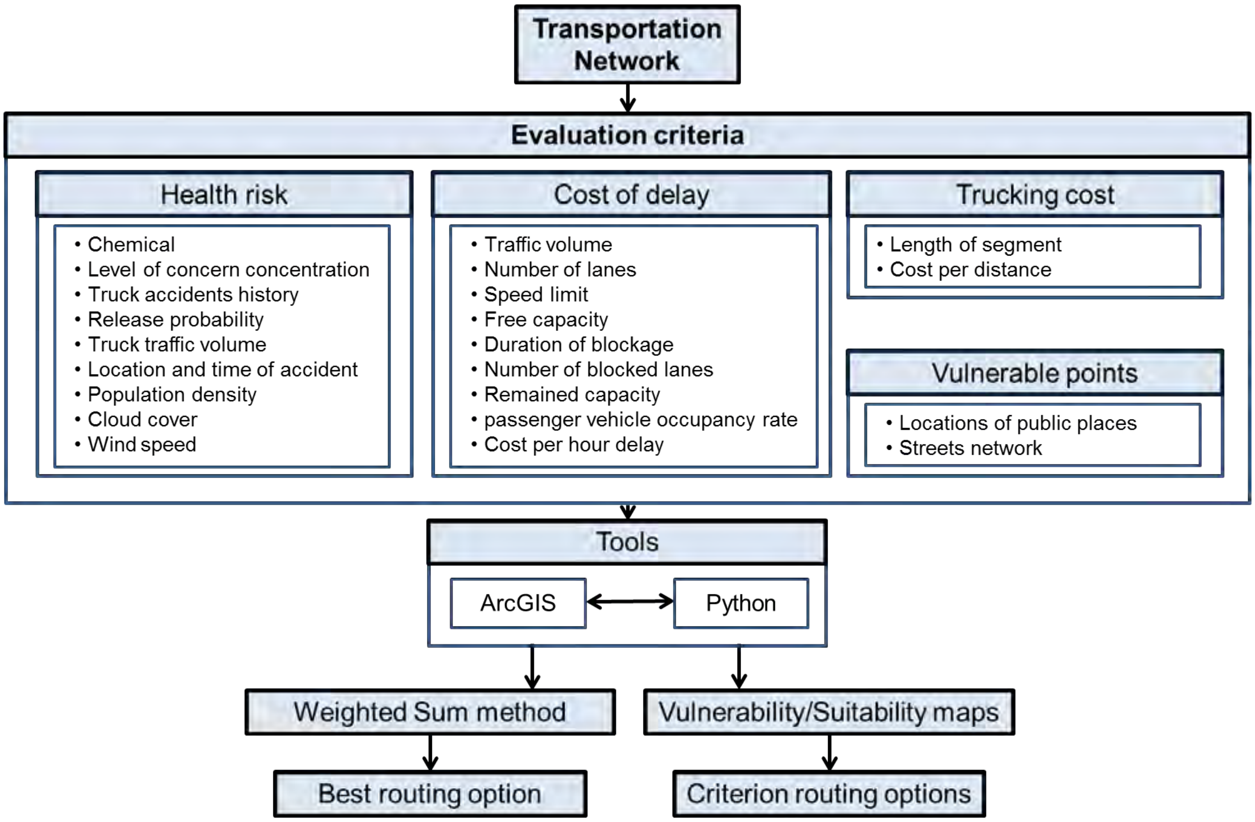

Figure 1. Methodology of the hazardous cargo transportation network assessment tool

EXPOSURE HEALTH RISK CRITERIA AND QUANTIFICATION

The hazards in risk assessments are usually considered as acute toxicity, flammability, thermal radiation, blast wave and missile damage (Alp, 1995) (Inanloo and Tansel, 2015). Risk is a measure of the probability and severity of threat to a receptor due to acute exposure to hazardous material fumes. Acute Exposure Guideline Levels (AEGLs) were developed to the risk to human health causing by exposure to once-in-a-lifetime, or rare airborne chemicals. In order to quantify the health risk of inhalation of spilled chemicals, AEGL-3 was taken into account as the threshold concentration for health impact radius identifications (EPA, 2015). AEGL-3 represents “the airborne concentration (expressed as ppm or mg/m3) of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death" (EPA, 2015). Having the impact radius calculated, the number of people within the threat zone was estimated as the consequence of the accident.

The health risks due to the inhalation of hazardous chemicals after an accidental release was calculated by Equation 1 below:

$$\text{Risk} = \text{Frequency} \times \text{Consequences} \quad (1)$$

Accident frequency can be estimated from the number of similar events occurring per year and the consequences can be expressed from different perspectives (i.e., impacted population, fatalities, size of the impacted area, environmental impacts) (Inanloo et al., 2015). The procedure used for estimating the different components of the risk factors are described below.

Accident Frequencies

In order to calculate the accident frequency, as defined in the Highway Safety Manual (HSM, 2000), the normalized value of the crash frequency with exposure (the degree to which a road user is exposed to traffic risks) was calculated. Exposure in 100 million vehicle miles traveled was calculated by Equation 2. Crash rate was acquired by the Equation 3 (HCM, 2000).

$$\text{EXPO}=\text{AADT} \times 365 \times \text{number of years} \times \text{total segment length } 100{,}000{,}000 \quad (2)$$

$$\text{Crash rate}=\text{Total crash count} \text{EXPO} \quad (3)$$

where, EXPO is the exposure to accidents and AADT is the annual average daily traffic. In this study, AADT for trucks was considered to represent the frequency of truck accidents. The total crash count was estimated by identifying accidents involving trucks within a search radius around each segment of the transportation network. The probability of chemical releases in accidents involving trucks was based on the statistics of hazardous material accidents, as the percentage of the accidents, which led to chemical releases to the number of total hazardous material accidents. According to PHMSA, 27.3% of the hazardous material accidents result in chemical releases (Battelle, 2001).

Consequence Analysis

In order to identify and quantify the health impact buffer zones around the road segments, AEGL-3 concentration for one hour exposure of the released chemical was taken into account; through plug the concentration threshold into Equation 4 and find the farthest distance that the certain concentration would be perceived. The proposed tool developed by this study is provided with a dictionary of AEGLs for commonly carried hazardous materials, with the capability of selection between the substances, as the thresholds differ from a chemical to the other. Therefore, the impact radius also varies by the change in the level of concern concentrations (Inanloo et al., 2014).

(4)

where, x, y and z are the distance downwind and crosswind and vertical directions, respectively. C (x, y, z) is the concentration of the substance at (x, y, z) location from the spill at time t after the release. Q is the release quantity and σx, σy σz are the standard deviations of concentrations distributions in different directions (σx, σy are considered equal). u is the wind speed and h is the effective stack height.

The concentrations were calculated for downwind direction without any deviations from the centerline of the wind, and on the ground level. The standard deviations vary depending on the atmospheric condition and the distance downwind. The coefficients in Table 2 were used in order to calculate the standard deviations. However, the stability of atmosphere needed to be identified prior this step.

Table 2. Equations used for , , and calculations (Slade, 1968).

Stability class	(m)	(m)
Open country conditions		
A	$0.22x(1+0.0001x)^{-1/2}$	$0.20x$
B	$0.16x(1+0.0001x)^{-1/2}$	$0.12x$
C	$0.11x(1+0.0001x)^{-1/2}$	$0.08x(1+0.0002x)^{-1/2}$
D	$0.08x(1+0.0001x)^{-1/2}$	$0.06x(1+0.0015x)^{-1/2}$
E	$0.06x(1+0.0001x)^{-1/2}$	$0.03x(1+0.0003x)^{-1}$
F	$0.04x(1+0.0001x)^{-1/2}$	$0.016x(1+0.0003x)^{-1}$
Urban conditions		
A-B	$0.32x(1+0.0004x)^{-1/2}$	$0.24x(1+0.001x)^{1/2}$
C	$0.22x(1+0.0004x)^{-1/2}$	$0.20x$
D	$0.16x(1+0.0004x)^{-1/2}$	$0.14x(1+0.0003x)^{-1/2}$
E-F	$0.11x(1+0.0004x)^{-1/2}$	$0.08x(1+0.00015x)^{-1/2}$

Stability of atmosphere corresponds to the ability of the air molecules in creating vertical movements. These motions generate the ability of dilution of chemical particles in the air. The more and faster the movements, the quicker the dilution of the substance in the atmosphere is, and accordingly, less health impacts can be expected, as the chemical would not stay in the atmosphere long enough to cause irritation and health problems. Atmospheric conditionscan be represented by stability classes; as a function of wind speed, solar radiation, and/or cloud cover; as summarized in Table 3.

Table 3. Urban stability categories (Ludwig et al., 1976).

Surface wind velocity ($m\ s^{-1}$)	Daytime Solar elevation angle >15°			Opaque cloud cover ≥ 9/10 day or night or solar elevation angle ≤ 15°	Night time cloud cover	
	Strong insolation	Moderate insolation	Slight insolation		≥ 5/10	≤ 4/10
< 2	A	B	B	D	E	E
2-3	A	B	C	D	D	E

3-5	B	C	C	D	D	D
5-6	C	C	D	D	D	D
> 6	C	D	D	D	D	D

To identify the stability classes of atmosphere, data maps of cloud cover, as well as, wind speed over the case study area were obtained. Wind speed data were used to pinpoint the related row in Table 3 to further select the stability classes based on the solar radiation or/and the cloud cover. The cloud cover data was used to identify the sky cover proportion in a scale of 10 (1 corresponding to clear skies and 10 to completely covered by clouds) to further relate the atmospheric stability classes during nighttime or for the cases with solar radiation angles of less than 15 degrees.

The solar radiation (solar elevation angle) was identified based on equations from Astronomical Algorithms book (Meeus, 1991). Based on the equations, the coordinate of the study area, as well as, the time of day/night and the date at the time and location of the accident are taken into account to calculate the solar elevation angle (to be used in Table 3). Deepending on the location and time of the accident the solar angle would vary (i.e.,as in Egypt vs. Canada; or as in early morning vs. noon or evening). The proposed model by this research is capable of identifying the time and date of the study area at the time of running the tool, which, leads to a location and time based recognition of solar radiation characteristics.

The tool, taking into account the time of evaluations, recognizes whether the transport/accident happens during daytime or night time, so that, it can select which columns of Table 3 are applicable to the case. Having calculated and identified the parameters (wind speed, solar elevation angel and cloud cover), the stability class of atmosphere is identified according to the table.

After determining the stability class, the standard deviations are calculated based on the equations provided in Table 2. In this study, open county conditions were taken into account for the worst case scenarios for estimating the impact radius, as urban areas may prevent vapour clouds from propagation due to urban obstructions. Based on the stability classes of atmosphere, the tool selects the corresponding equations for the standard deviation calculations.

Wind direction and speed were considered as constant during the calculations, disregarding any changes in the parameters over time. However, in reality these parameters would change during the day and night.

Based on the assumptions of Gaussian dispersion equation, particles disperse by the power of wind and toward downwind direction, and there are no chemical particles transmitted upwind. Although, the distance calculated by the suggested model of this study is from the release location to downwind direction with no deviations towards other directions (vertical or horizontal), in order to take into account any changes in the direction of the wind, the predicted health impact radius was used as a buffer distance around the spill location toward any directions, disregards of the orientation of wind.

DELAY COST

Accident costs are not limited to property damages, fatalities and injuries; they also include the expenses that occur as an indirect result of the accident (i.e., users of the transportation system are affected by the incident due to congestions and delays) (Inanloo et al., 2015). According to a report in 2007, congestions caused an additional 4.2 billion hours for travel in the US, resulting in consumption of 2.9 billion gallons additional fuel corresponding to a congestion cost of $78 billion (Schrank and Lomax, 2007).

Delay cost can be estimated by multiplying the delay time caused by an accident to the dollar value of travel time delay. Queuing analysis was used to estimate the incident delays as the major impacts. Based on the queuing theory, total delay time for one incident, TD, can be estimated by the following equation (Hadi et al., 2008):

$$TD=tR2(\mu-\mu R)\times(\lambda-\mu R)2\times(\mu-\lambda) \quad (5)$$

where, is the incident duration, λ is the mean arrival rate, is the mean capacity, and, is the capacity during the incident. The values and, were acquired from the Highway Capacity Manual (HCM, 2000 and Hadi et al., 2008).

In order to perform the calculations, each parameter in the Equation 5 must be defined. The proposed tool developed in this study is capable of identifying other parameters such as number of lanes, speed limit and function class of the road segments (i.e., freeway, expressway, street, etc.) to calculate the capacity of the road. To further calculate the capacity during the incident, Table 4 was taken into account, considering number of lanes before and after the accident. In this study, only lane blockage was considered, not shoulder disablements.

The delay cost for each route was estimated based on the values provided in the 2007 Urban Mobility Report (Schrank and Lomax, 2007). According to the report, the value of travel time delay is $14.60 per hour of person travel. Delay costs were estimated by multiplying the value of hourly person travel by the average passenger vehicle occupancy rate which was 1.58 occupants in Florida (FDOT, 2011). In this study the effect of ramps, as well as, intersections on the capacity of segments were not considered.

Table 4. Residual freeway capacity in incident zones (HCM, 2000).

Number of lanes before incident (One direction)	Shoulder disablement	Shoulder accident	Number of lanes blocked [a]		
			1	2	3
2	0.95	0.81	0.35	0.00	N/A
3	0.99	0.83	0.49	0.17	0.00
4	0.99	0.85	0.58	0.25	0.13
5	0.99	0.87	0.65	0.40	0.20
6	0.99	0.89	0.71	0.50	0.26
7	0.99	0.91	0.75	0.57	0.36
8	0.99	0.93	0.78	0.63	0.41

[a] Proportion of original freeway capacity.

ESTIMATION OF TRANSPORTATION COSTS

Freight transportation cost plays an important role in the economy of countries and cities. Society and transport companies try to minimize the total cost of conveyance not only to help businesses to be competitive but also to make sure goods are moved and delivered efficiently (Forkenbrock, 2001). According to a study by the American Transport Research Institute (ATRI) in 2011, the average total carrier cost in 2011 was $1.706 per mile. This value was used in this study. Transportation costs were estimated by multiplying the average total carrier cost with the travel distance for each route (Fender and Pierce, 2012). The trucking cost of each road segment was calculated by multiplying the cost per unit of length with the length of the target link.

VULNERABLE POINTS

In this study, vulnerable places such as schools, daycares, and hospitals were identified near each road segment in addition to the mentioned three criteria identified for evaluation of transportation networks for hazardous material transport. The tool developed by this study, considering the map of the public locations, searches a certain distance around the road segments for any of previously mentioned public places and keeps the records of such points, as these public places occupies vulnerable people such as children and patients who are more prone to health risks in case of being exposed to chemicals than other groups of population.

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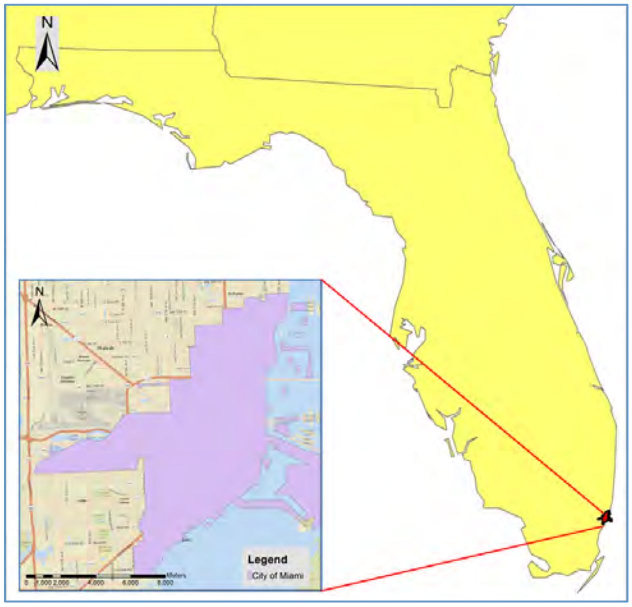
CHAPTER 3: CASE STUDY

The city of Miami in Florida, USA, was selected as the study area of this study in order to implicate the tool on a real world problem. The required data for the proposed tool were collected in the formats of maps and tables from different sources of data. However, finding data on truck shipments and their schedules were challenging, as the data were hard to obtain due to the security reasons and lack of records.

For the case study, the shipment was assumed as a full tanker truck of gasoline, with the capacity of 9,000 gallons of E-10 blend of gasoline. It was assumed that the entire tanker content is released to the atmosphere, caused by an en-route accident. In reality, releases are partial cargos releases. However, in order taken into consideration the worst case scenario, in this study the entire cargo was assumed to be released.

Gasoline consists of different compounds, with different proportions. In this study, Toluene was considered in the health risk evaluations. The quantity of Toluene was calculated based on its proportion in gasoline. Therefore, in the calculations, the suggested tool uses the predefined level of concern concentration of this substance for the impact radius identification. Figure 2 presents the location of the study area and the boundary of the area of interest, as well as the origin and destination of the cargo.



a. Location of the case study area

b. Origin and destination of the cargo

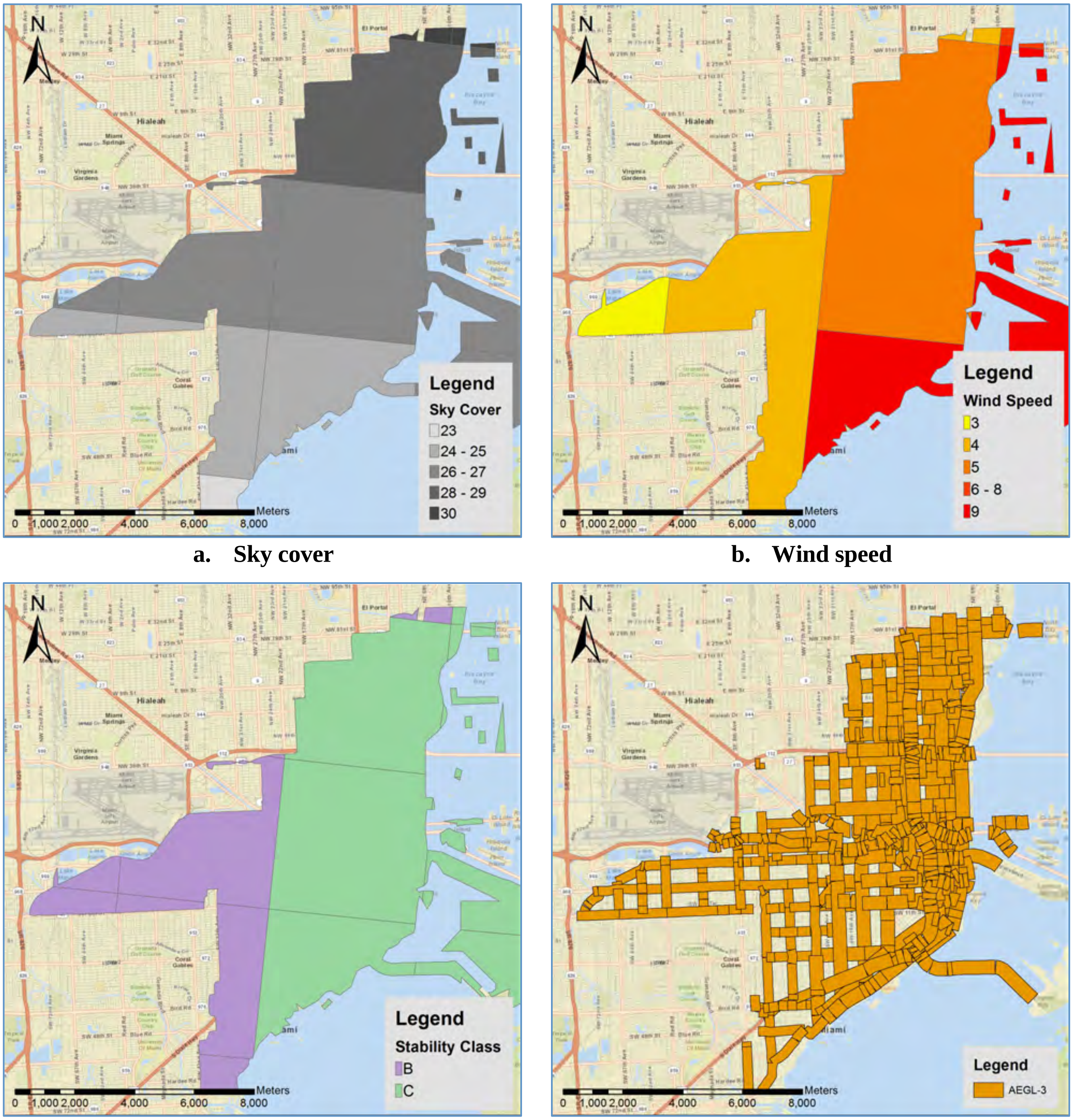
Figure 2. Case study area, and origin and destination of the cargo

CHAPTER 4: RESULTS

The output results include several maps, as well as, tables showing calculated and evaluated properties of transportation networks, ready to be interpreted. According to the methodology of this study, equipped with required data, calculations were performed employing Python, and were visualized using ArcGIS afterwards, ultimately the suggested routes were generated using ArcGIS Network Analysis tool.

Figure 3 presents the data maps and the output result of health impact buffer zone. As it is shown in Figure 3a the sky cover data map was available for the area of study which is used in Table 3; in case the cloud cover is more than 9/10 during day; or night; or cases of solar elevation angle of less than 15 degrees. The solar elevation angle was calculated for the entire area of interest once and considered constant.

The map of wind speed also was available, making the identification of stability classes based on Table 3 possible, as it is shown in Figures 3b and 3c. After identifying the stability classes of atmosphere around the road segments, the buffer distances for transportation branches were taken into consideration and delineated around the segments. As presented in Figure 3d, the buffer distances are different according to the stability of atmosphere, as it plays a significant role in the dilution of chemicals in the air. According to Figure 3c two stability classes were expected in the area of interest (B and C) at the time, date and location of the study. Stability class B is more unstable than the stability class C; since a chemical which enters the more stable atmospheres tends to stay in the air longer than unstable conditions, the health impact radius is also bigger under stable atmosphere, as it can be seen in Figure 3d. The buffer zones which were delineated based on the data (i.e., solar elevation angle, wind speed, cloudiness, etc.) are presented in Figure 3d.



a. **Sky cover**

b. **Wind speed**

c. **Stability class**

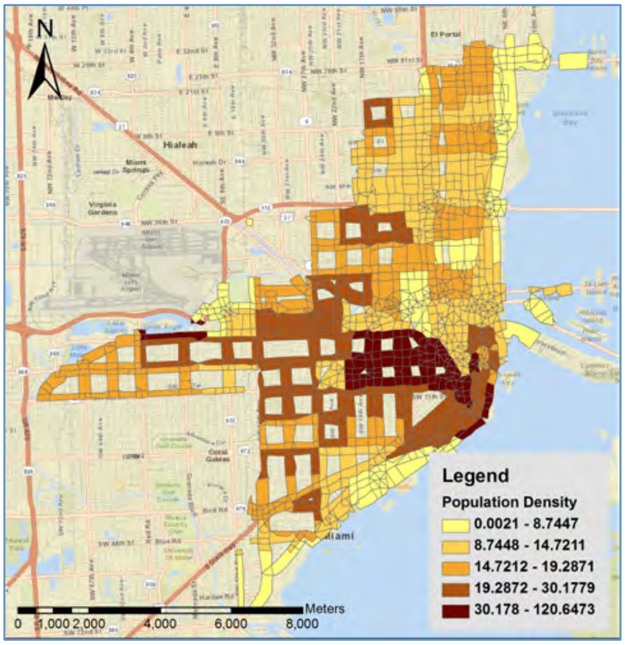
d. **AEGL-3 buffer zones**

Figure 3. Health risk data and output of inhalation hazard buffer zones.

Based on the health risk zones around segments presented in Figure 3d, populations at risk were calculated using population density map in Figure 4a, as presented in Figure 4b, and then were assigned to the road segments. In this study, the population estimates were based on the population density data of 2010. Having approximated the population at risk for each segment, also equipped with the eight year crash history in the area (2003-2010) (Figure 4c), as well as, truck traffic volume (Figure 4d), and crash rates (Figure 5a), health risks were calculated for road segments; as they are shown in Figure 5b. The risk calculated in this study is the multiplication of the number of people and the truck involved crash rates (crashes per 100 million vehicles), to the probability of the en route accident which lead to material releases (percentage of total truck crashes).

The vulnerable places that were prone to health risk were identified based upon their proximity to the health risk buffer zones, as whether they were located within the risky areas of the segments. Number of the vulnerable points which fall into the health risk zones of each segment were assigned to the link of the transportation network (Figures 5c and 5d).

Figure 6 was allocated to the declaration of the calculations and results of delay cost. Based on the assumptions of this study, closure of three lanes of the segment due to a truck involved accident for one hour was presumed, and calculations were done based on this scenario. Hazardous material accidents are large and serious events, as the accidents which lead to release only, usually cause road closure with the average duration of cleanups of 5 hours (Battelle, 2001). As shown in Figure 6a, the road capacities were identified based on the number of lanes, function of the road and speed limit. Capacities of the segments after accident were also calculated as presented in Figure 6c. After estimating the road capacity before and after the accident for each segment as well as traffic volume (Figure 6b), delay time was calculated for each of the network branches. Unlike to the health risk calculations, traffic volume for delay time computations were considered as the vehicle traffic volume, while for the crash rate assessment only truck traffic volume was considered.



a. 2010 Population density

b. Population at risk

c. Crashes during 2003-2010

d. Truck Annual Average Daily Traffic

Figure 4. Data and output of health risk.

Figure 7 presents the results for delay and trucking costs. Delay cost is estimated by multiplication of the results of Figure 6a with the cost per hour of delay in the area and the occupancy rate. Figure 7b presents travel costs for each segment of the network.

a. Crash rates of road segments

b. Health risk

c. Public places whithin the study area

d. Number of vulnerable points

Figure 5. Outputs of health risk and vulnerable areas.

a. **Road capacity**

b. **Annual Average Daily Traffic**

c. **Capacity after accident**

d. **Delay time (hr)**

Figure 6. Results of the delay calculations.

The colors on the maps (Figures 3-7) are based on division of the value ranges to equal intervals. However, the user can choose different thresholds for each criterion to be shown on the maps.

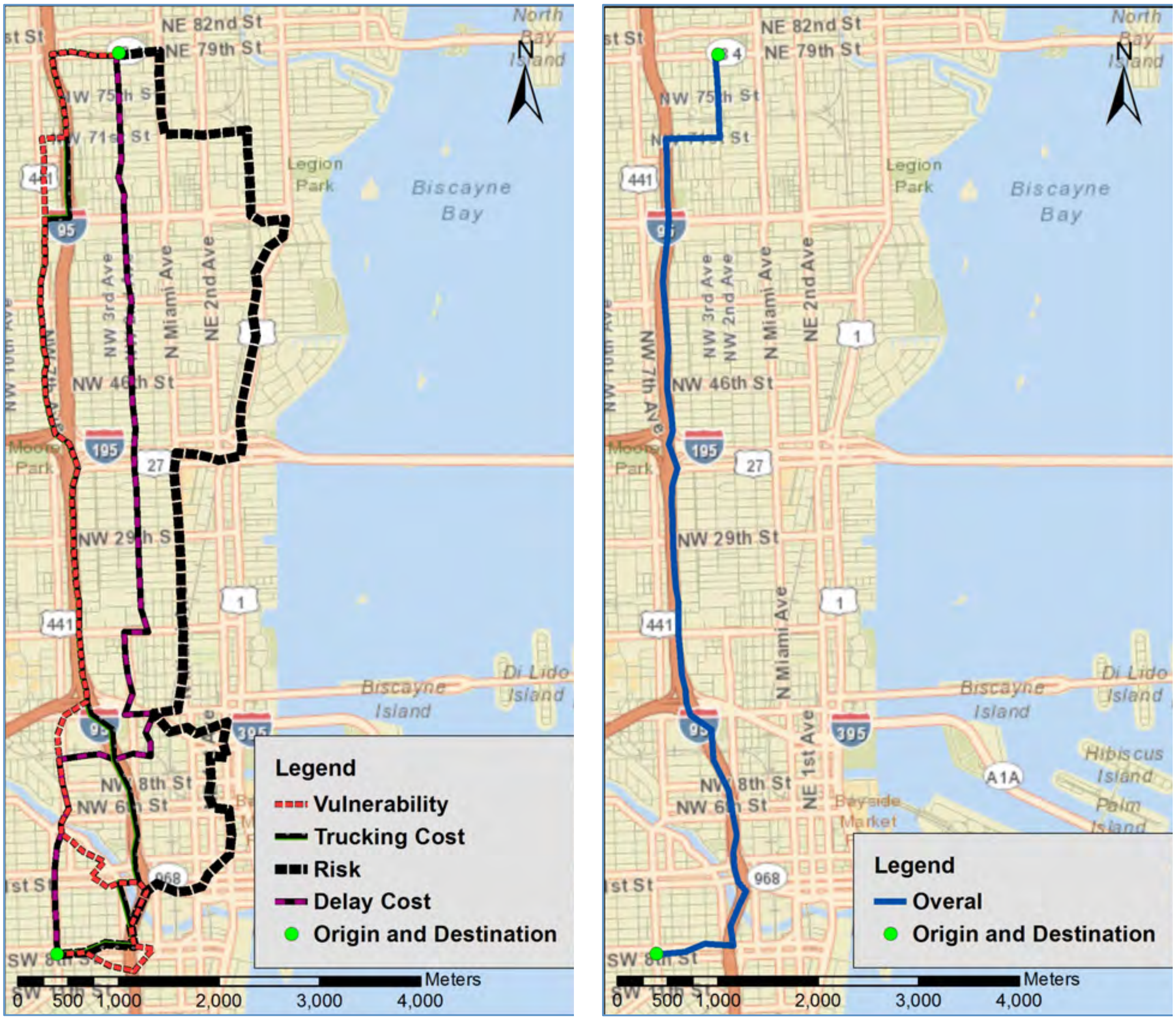
a. Cost of delay ($)

b. Travel Cost ($)

Figure 7. Results of the delay and travel costs calculations.

Acquiring the networks of the criteria, the next step was to find the best route for carrying the cargo from the origin to the destination of this study (Figure 2). For clarification purposes, in this section the best routes based on each criterion are presented in Figure 8 (a). As there were four assessment criteria, there would be the same number of routing options, as of each for one criterion; and one best route considering all the criteria overall. Thus, Figure 8 (a) presents the four different route options representing “Vulnerability” as the best option based on only proximity of the route to the vulnerable places; “Trucking Cost” shows the shortest path, which leads to the lowest cost path; “Risk” shows the safest route as a matter of health threat to human health; and “Delay Cost” shows the path with the least delay cost.

As presented in Figure 8 (a), the routes that offered best options in view of health risk, number of vulnerable points and delay cost were longer in comparison to the path determined by the by trucking cost.



a. Routing options of each criterion   b. Best routing option based on the criteria

Figure 8. Delay and travel costs networks.

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CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

The main purpose of this study was to develop a flexible and user friendly decision making tool to routing hazardous materials, which is capable of (1) filling the gap between environmental health and transportation, and (2) evaluating the cost of transporting hazardous materials. The tool developed is flexible, as it can model any area of interest, by provided the required data (i.e., location, chemical characteristics). The decision making tool is user friendly, as it can be used by entering a few simple parameters by the user.

The proposed approach of this research considers not only health risks of possible chemical releases, but the delay that the accident may pose on transportation networks and accordingly people. The economy of hazardous material transport also is considered as the economy and benefits of carriers are a great drive in choosing routes for carrying cargos. Using GIS maps provides users a perspective view of situations which leads to smarter and faster decision making abilities.

The results of this study can provide the decision makers insight into the suitability of the transportation networks from the four aspects that were considered in the development of the tool (i.e., health risk, delay cost, travel expenses, and vulnerable places). The tool proposed by this study is not recommended for long distance routing, as the available data are related to a specific location and also the moment that the program is run. It should be pointed out that considerations for the age of the affected population, and whether the time of calculations corresponded to weekdays or weekends (i.e., different schedules) were not considered in this study. However, these adjustments can be incorporated. The time of the accidents, as well as, traffic volume in different time of day/night and weekdays/weekends can be taken into account for scheduling the cargos through generating different corresponding network assessments. The results of this study can be useful for routing and scheduling of hazardous cargo for selecting the most suitable routes between any origin and destination; or even through suggesting networks depending of the specific characteristics of the hazardous material being transported.

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APPENDIX A: DETAILED INCIDENT HISTORY IN THE US

Gasoline incident history in the U.S. (PHMSA, 2014)

Incident City	Incident State	Date of Incident	Quantity Released (Gal)	Release	Evacuations	Fatality	Injury
Detroit	MI	9/16/2003	13400	Yes	No	No	Yes
Hazel Park	MI	7/15/2009	13400	Yes	No	No	No
Lewistown	MT	9/10/2008	12500	Yes	No	No	No
Melville	NY	1/23/2010	12000	Yes	No	Yes	No
Rochester	NY	4/29/2003	12000	Yes	No	Yes	No
Wappingers Falls	NY	6/10/2004	12000	Yes	No	No	No
Needham	MA	7/12/2008	11500	Yes	No	No	No
Detroit	MI	5/27/2000	11400	Yes	No	Yes	No
Geneva	NY	8/24/2004	11400	Yes	No	No	No
Salt Lake City	UT	3/24/1997	11400	Yes	No	No	No
Saco	ME	8/12/2001	11300	Yes	No	Yes	No
Fall River	MA	1/27/2014	11235	Yes	No	No	No
Quincy	MA	8/21/2003	11000	Yes	No	No	No
Brothers	OR	5/12/2010	10400	Yes	No	No	No
Saugus	MA	7/23/2011	10001	Yes	Yes	Yes	No
Juana Diaz	PR	12/23/2010	10000	Yes	No	Yes	No
Santa Isabel	PR	7/25/2008	10000	Yes	No	No	Yes
Caguas	PR	7/29/2012	10000	Yes	No	No	No
Moca Puerto Rico		5/18/2002	10000	Yes	No	No	No
Caguas	PR	8/15/2005	10000	Yes	No	No	No
Warm Springs	OR	11/26/1991	10000	Yes	No	No	No
Birmingham	AL	1/5/2002	9900	Yes	No	Yes	No
Portland	OR	1/25/1995	9900	Yes	No	No	No
Grand Prairie	TX	7/31/2004	9650	Yes	Yes	No	No
Chicopee	MA	3/28/2008	9500	Yes	No	Yes	No
Vestal	NY	9/10/2002	9500	Yes	No	No	No
Overland Park	KS	6/14/2003	9500	Yes	No	No	No
Rye	CO	10/19/1992	9500	Yes	No	No	No
Port Allen	LA	12/14/2006	9497	Yes	No	No	Yes
Everett	MA	12/5/2007	9400	Yes	Yes	No	No
Davie	FL	1/25/1999	9200	Yes	No	No	No
Benton	AR	11/9/1996	9200	Yes	No	Yes	No
Boger City	NC	8/30/2006	9197	Yes	No	No	Yes
Baton Rouge	LA	10/17/2005	9195	Yes	No	Yes	No
Orlando	FL	8/27/2005	9140	Yes	No	Yes	No
Chatsworth	CA	12/13/1995	9110	Yes	No	Yes	No
Raleigh	NC	12/18/1998	9100	Yes	No	Yes	No

Incident City	Incident State	Date of Incident	Quantity Released (Gal)	Release	Evacuations	Fatality	Injury
Lakewood	NJ	1/20/2000	9056	Yes	No	No	No
Port allen	LA	7/27/1997	9045	Yes	No	Yes	No
Lancaster	SC	1/13/2009	9010	Yes	No	No	No
Decatur	GA	11/11/2006	9004	Yes	No	Yes	No
Cane Creek	NC	9/6/2004	9003	Yes	No	No	No
Dallas	TX	12/10/2005	9003	Yes	Yes	No	No
Middletown	CT	1/5/1990	9001	Yes	No	No	Yes
Miami	FL	11/6/2006	9001	Yes	Yes	Yes	No
Vernon	NJ	7/16/1992	9000	Yes	Yes	Yes	No
Federal Way	WA	11/4/2012	9000	Yes	No	No	No
Grandy	NC	5/22/2003	9000	Yes	No	No	No
Duluth	GA	5/13/2000	9000	Yes	No	No	No
Wale Township	NJ	5/10/2007	9000	Yes	No	No	No
Henderson	LA	1/12/1993	9000	Yes	No	No	Yes
Granite City	IL	5/19/2001	9000	Yes	No	No	No
Jim pond	ME	8/17/1996	9000	Yes	No	No	Yes
El Paso	TX	5/7/2003	9000	Yes	No	No	No
Clemmons	NC	7/29/1997	9000	Yes	No	No	No
Irving	TX	8/30/2003	9000	Yes	No	No	No
New Baltimore	MI	4/21/2000	9000	Yes	No	No	No
Denver	CO	11/3/1990	9000	Yes	No	Yes	No
Kingman	AZ	7/5/2008	9000	Yes	No	No	No
Greensboro	NC	9/30/1999	9000	Yes	No	No	Yes
Anaheim	CA	1/13/1997	9000	Yes	No	No	No
Austin	TX	3/29/1995	9000	Yes	Yes	Yes	No
Naples	FL	10/2/2000	9000	Yes	No	No	No
Indianapolis	IN	10/31/1999	8999	Yes	No	No	No
Marshall	IL	2/21/1997	8985	Yes	No	No	No
Fort Smith	AR	2/1/1991	8975	Yes	Yes	No	No
Sierra Vista	AZ	7/13/2000	8925	Yes	No	Yes	No
Chester	PA	5/23/1998	8900	Yes	No	Yes	No
Why	AZ	7/17/2004	8900	Yes	No	No	No
Huntsville	AL	10/17/1998	8900	Yes	Yes	Yes	No
Byrd	SC	8/6/2002	8900	Yes	No	No	No
Hereford	TX	6/29/1994	8900	Yes	No	Yes	No
Mcfarland	WI	1/22/1997	8900	Yes	No	No	No
Camden	AL	2/19/1991	8895	Yes	No	No	No
Rogersville	TN	10/25/1996	8893	Yes	No	No	No
Glen Burnie	MD	7/31/1991	8850	Yes	No	No	No
Guyton	GA	11/21/2013	8809	Yes	Yes	Yes	No
Annapolis	MD	3/6/1999	8807	Yes	No	No	No

Incident City	Incident State	Date of Incident	Quantity Released (Gal)	Release	Evacuations	Fatality	Injury
Rosebud	MO	11/9/1990	8804	Yes	No	No	No
North Little Rock	AR	12/4/2008	8804	Yes	No	No	No
Elk Ridge	MD	1/13/2004	8803	Yes	No	Yes	No
Barnesville	MN	1/29/2001	8803	Yes	No	Yes	No
Milwaukee	WI	11/27/1992	8802	Yes	No	Yes	No
Cubero	NM	11/3/2012	8801	Yes	No	No	No
Carmichael	CA	2/13/1991	8800	Yes	Yes	No	No
Detroit	MI	10/6/2003	8800	Yes	No	Yes	No
Jennings	LA	7/5/1996	8800	Yes	Yes	No	Yes
Woburn	MA	7/16/2012	8800	Yes	No	No	No
Marietta	GA	7/28/2002	8800	Yes	No	No	No
Elmore	AL	11/13/2004	8800	Yes	Yes	No	No
New haven	CT	1/1/2002	8800	Yes	Yes	No	No
Springtown	TX	6/27/2005	8800	Yes	No	Yes	No
Westlake Village	CA	12/19/1998	8800	Yes	No	No	No
Houston	TX	9/12/2010	8800	Yes	No	No	No
Naples	FL	4/15/1993	8800	Yes	No	No	No
Ocala	FL	5/29/2010	8800	Yes	No	No	No
Carteret	NJ	6/23/1991	8800	Yes	No	No	No
Plano	TX	6/7/2007	8800	Yes	No	No	Yes
Beckley	WV	9/12/2001	8800	Yes	No	No	No
Arlington	TX	9/29/2008	8800	Yes	No	No	No
Houston	TX	11/2/2012	8800	Yes	No	No	No
Brownsburg	IN	9/5/1997	8800	Yes	No	No	No
Reisterstown	MD	5/31/1993	8800	Yes	Yes	No	Yes
Trinidad	TX	4/14/2005	8800	Yes	No	No	No
Gila bend	AZ	9/22/1998	8800	Yes	No	Yes	No
Corona	CA	5/28/2010	8800	Yes	No	No	No
Dunn	NC	2/13/1993	8800	Yes	No	Yes	Yes
San Antonio	TX	3/29/1991	8800	Yes	No	No	No
Junction	TX	8/11/2007	8800	Yes	No	No	No
Ridgefield	CT	7/12/2005	8800	Yes	No	Yes	No
Port Tampa City	FL	8/3/1996	8800	Yes	No	No	No
Pattison	TX	10/5/1998	8800	Yes	No	No	No
Denver	CO	10/10/1992	8800	Yes	No	Yes	No
Thedford	NE	4/2/1990	8800	Yes	No	No	No
Humble	TX	12/26/2012	8800	Yes	No	Yes	No
Mount Pleasant	NY	9/25/1999	8800	Yes	No	Yes	No
Hesperia	CA	9/15/2012	8799	Yes	No	No	No
Los Angeles	CA	6/23/1995	8799	Yes	No	No	No
Ventura	CA	12/2/1995	8798	Yes	No	Yes	No

Incident City	Incident State	Date of Incident	Quantity Released (Gal)	Release	Evacuations	Fatality	Injury
Nashville	TN	8/22/2007	8748	Yes	No	Yes	No
Stockton	CA	6/24/1997	8728	Yes	No	No	No
Palm Coast	FL	12/24/2013	8722	Yes	No	Yes	No
Shelbyville	IN	10/11/2012	8710	Yes	No	Yes	No
Merritt Island	FL	1/21/2011	8702	Yes	No	Yes	No
Lemont	IL	4/2/2008	8702	Yes	Yes	No	Yes
Phoenix	AZ	10/19/2003	8701	Yes	No	No	Yes
Santa Barbara	CA	5/20/1991	8700	Yes	Yes	No	No
Jacksonville	FL	8/12/2000	8700	Yes	No	Yes	No
Lafayette	LA	3/3/1993	8700	Yes	No	No	Yes
Bear Creek Springs	AR	11/27/1995	8700	Yes	No	No	No
Harmony	MN	5/20/1995	8700	Yes	No	No	No
Port Deposit	MD	8/24/2012	8700	Yes	No	Yes	No
Spartanburg	SC	4/4/1994	8700	Yes	No	No	No
Colt's Neck	NJ	1/22/2010	8700	Yes	No	No	No
Mount Hope	IL	4/3/2001	8698	Yes	Yes	No	No
Millcreek	OH	10/25/2000	8698	Yes	Yes	Yes	Yes
Venango	PA	6/12/2008	8659	Yes	No	No	No
Payson	AZ	5/6/2003	8657	Yes	No	Yes	Yes
Columbia	TN	12/11/2010	8634	Yes	No	No	No
Bridge City	LA	4/22/2004	8610	Yes	No	No	No
Meriden	CT	9/24/2000	8606	Yes	No	No	No
Twig	MN	8/8/2002	8603	Yes	No	No	No
Brightwood	VA	11/18/2002	8600	Yes	Yes	No	No
Carpenter	MS	8/8/2003	8600	Yes	Yes	No	No
Oakland	CA	10/22/2008	8600	Yes	No	No	No
Zumbrota	MN	1/21/1995	8600	Yes	No	No	No
Waco	TX	2/27/1999	8600	Yes	No	No	No
Oakland	CA	4/29/2007	8600	Yes	No	No	Yes
Amite	LA	10/11/1998	8600	Yes	Yes	Yes	No
San Antonio	TX	4/20/2011	8600	Yes	No	No	Yes
Sacramento	CA	9/12/1995	8600	Yes	No	No	No
Austin	TX	3/15/1993	8600	Yes	No	No	No
Montebello	CA	12/14/2011	8600	Yes	No	No	No
Baltimore	MD	6/12/2001	8600	Yes	No	No	No
Lumpkin	GA	3/17/1999	8600	Yes	No	No	No
Minerva	NY	9/12/2007	8600	Yes	No	No	No
Roanoke	VA	7/12/2008	8599	Yes	No	No	No
Big Spring	TX	2/19/1990	8589	Yes	No	Yes	No
Brooksville	FL	12/12/1992	8577	Yes	No	No	No
Little Rock	AR	7/10/1997	8572	Yes	No	Yes	No

Incident City	Incident State	Date of Incident	Quantity Released (Gal)	Release	Evacuations	Fatality	Injury
Big Spring	TX	2/6/2009	8551	Yes	No	No	Yes
Big Spring	TX	3/6/2009	8551	Yes	No	No	No
Westfield	IN	6/27/2005	8546	Yes	No	No	No
Boca Raton	FL	3/16/2004	8519	Yes	No	No	No
Pine bluff	AR	10/30/2004	8518	Yes	No	No	No
Florence	SC	8/17/1998	8516	Yes	No	No	No
Tazewell	TN	6/30/1997	8516	Yes	No	No	No
Wilder	KY	12/11/1993	8510	Yes	No	No	No
Hayesville	OH	10/4/2010	8510	Yes	No	No	No
Carryville	TN	7/29/2007	8508	Yes	No	Yes	No
Nestorville	WV	12/17/1993	8505	Yes	Yes	No	No
Port Clinton	OH	3/12/2010	8504	Yes	Yes	No	No
Weston	VT	2/18/1995	8503	Yes	No	No	No
Bardstown	KY	3/4/1992	8503	Yes	No	No	No
Harrisburg	OH	1/18/1993	8503	Yes	No	No	No
Loveland	CO	9/11/2011	8502	Yes	No	Yes	No
Newington	VA	8/29/2012	8501	Yes	No	Yes	No
Fairhaven	MA	12/2/2001	8500	Yes	No	No	No
Lima	OH	11/14/2006	8500	Yes	Yes	No	No
Jacks Creek	TN	9/5/2001	8500	Yes	No	No	No
Jefferson City	MO	11/27/2008	8500	Yes	Yes	Yes	No
Starkville	MS	12/8/2003	8500	Yes	No	No	Yes
Richmond Hill	GA	4/7/2011	8500	Yes	No	Yes	No
San Antonio	TX	3/25/2002	8500	Yes	No	Yes	No
Comfort	NC	10/22/2004	8500	Yes	Yes	No	No
Cumberland	MD	6/1/1991	8500	Yes	No	No	No
Warriors Mark	PA	11/19/2007	8500	Yes	No	No	Yes
West Hamlin	WV	5/11/1993	8500	Yes	No	Yes	No
Dodge City	KS	9/22/2001	8500	Yes	No	No	No
Euless	TX	6/26/2002	8500	Yes	No	No	No
Union City	PA	8/26/1994	8500	Yes	Yes	Yes	No
Leary	GA	2/13/2007	8500	Yes	No	Yes	No
Fort Lauderdale	FL	3/17/1993	8500	Yes	No	Yes	Yes
Tampa	FL	11/23/2007	8500	Yes	No	No	No
Hearne	TX	4/19/2007	8500	Yes	No	No	No
Wytheville	VA	10/2/2013	8500	Yes	No	Yes	No
Arlington	VA	12/22/2004	8500	Yes	Yes	Yes	No
West Deptford	NJ	1/12/2003	8500	Yes	No	No	No
Dupont	IN	7/3/2005	8500	Yes	No	No	No
Princeton	NC	3/8/1998	8500	Yes	No	No	No
Hoosick	NY	2/13/2013	8500	Yes	No	No	Yes

Incident City	Incident State	Date of Incident	Quantity Released (Gal)	Release	Evacuations	Fatality	Injury
State College	PA	2/17/2012	8500	Yes	No	No	No
New Germany	MN	8/29/1996	8500	Yes	No	No	Yes
Jefferson City	MO	11/27/2007	8500	Yes	Yes	Yes	No
Doraville	GA	6/15/1999	8500	Yes	Yes	No	No
Pleasant View	TN	9/20/1999	8500	Yes	No	Yes	No
Charlotte	NC	4/22/2006	8500	Yes	No	No	No
Eunice	NM	4/5/2011	8500	Yes	No	No	No
Coatesville	PA	3/15/1992	8500	Yes	No	Yes	No
Gregory	TX	5/17/2001	8500	Yes	No	Yes	No
New Haven	IL	12/18/2004	8500	Yes	No	No	No
Parkersburg	WV	11/3/1991	8500	Yes	No	No	No
Tulsa	OK	5/24/1998	8500	Yes	No	No	No
Colorado Springs	CO	5/20/1991	8500	Yes	No	No	No
Detroit	MI	4/5/1995	8500	Yes	Yes	Yes	No
Sulphur Springs	TX	6/7/2008	8500	Yes	No	No	No
Bertrand	MO	7/14/1999	8500	Yes	No	No	Yes
Pound	VA	11/18/2011	8500	Yes	No	No	No
Marathon	FL	10/3/2005	8500	Yes	No	Yes	No
Sioux Falls	SD	8/25/2006	8500	Yes	Yes	No	No
Monroeville	PA	1/29/1993	8500	Yes	Yes	No	No
Maricopa	AZ	1/19/1993	8500	Yes	No	No	No
Murfreesboro	AR	12/12/1996	8500	Yes	No	No	No
Kearny	NJ	1/12/2012	8500	Yes	No	No	No
Opolis	KS	12/19/1995	8500	Yes	No	No	No
Old bridge	NJ	1/15/1997	8500	Yes	No	No	No
Tucson	AZ	10/17/1999	8500	Yes	No	No	No
Millersville	MD	1/4/1996	8500	Yes	No	No	No
Pojoague	NM	10/2/2009	8500	Yes	No	No	No
East Rutherford	NJ	11/20/2008	8497	Yes	No	No	Yes
Hendersonville	TN	6/13/2007	8496	Yes	No	No	No
Woodbridge	NJ	7/11/2008	8494	Yes	No	No	No
Las Vegas	NV	8/2/2000	8484	Yes	No	No	No
Luling	LA	5/20/1997	8480	Yes	Yes	Yes	No
Buellton	CA	3/10/2012	8476	Yes	No	Yes	No
Elkton	KY	10/18/1999	8467	Yes	No	Yes	No
Tofte	MN	3/21/1993	8412	Yes	No	No	No
Ft. Mill	SC	8/16/2010	8405	Yes	No	Yes	No
Chalmette	LA	6/25/2004	8401	Yes	Yes	No	No
Revere	MA	4/9/2000	8400	Yes	No	No	No
Denver	CO	9/8/2001	8400	Yes	No	No	No
Mount House	CA	3/24/2006	8400	Yes	No	No	No

Incident City	Incident State	Date of Incident	Quantity Released (Gal)	Release	Evacuations	Fatality	Injury
Neville Island	PA	5/26/2000	8400	Yes	No	No	No
Carnesville	GA	6/6/2000	8354	Yes	Yes	No	Yes
Malvern	AR	9/13/1996	8338	Yes	No	No	No
Glenwood Springs	CO	12/7/2001	8312	Yes	No	Yes	No
Parker	AZ	6/14/2001	8307	Yes	No	No	No
Stockton	CA	9/6/1995	8300	Yes	No	No	No
Albany	GA	4/21/2000	8300	Yes	No	No	No
Newbury	OH	6/19/2010	8300	Yes	Yes	No	No
Golden	CO	10/4/2001	8300	Yes	No	No	No
Big Bear Lake	CA	9/20/2011	8300	Yes	No	No	No
Brentwood	MO	11/6/1996	8300	Yes	Yes	No	No
Crum	WV	2/4/1992	8250	Yes	No	No	No
Lafayette	LA	8/21/1993	8229	Yes	No	No	No
Parker	AZ	3/6/2011	8202	Yes	No	No	No
Dumont	CO	11/9/2001	8201	Yes	No	No	No
Newtown	CT	9/27/2003	8200	Yes	Yes	No	No
Fort worth	TX	3/20/1995	8200	Yes	No	No	No
Oklahoma City	OK	9/27/1996	8200	Yes	No	No	No
Atalissa	IA	7/21/1999	8200	Yes	No	Yes	Yes
Berthoud Falls	CO	6/22/1996	8200	Yes	No	No	No
Booneville	AR	3/16/2002	8200	Yes	No	Yes	No
Accokeek	MD	1/15/2003	8101	Yes	No	No	No
Norlina	NC	5/16/2004	8100	Yes	No	No	Yes
Campo	CO	2/27/2001	8100	Yes	No	No	No
Forum	AR	1/10/1995	8100	Yes	Yes	No	No
Campbellsville	KY	6/20/1992	8075	Yes	No	No	No
Americus	GA	9/4/1990	8029	Yes	No	No	No
Benbrook	TX	12/16/1996	8024	Yes	No	No	No
Alvwood	MN	6/8/2000	8017	Yes	No	No	No
Orlando	FL	5/30/2005	8011	Yes	No	Yes	No
Carlos	TX	9/13/2004	8005	Yes	No	No	No
Sumterville	FL	10/3/1991	8004	Yes	No	No	No
New Lebanon	NY	9/26/1996	8003	Yes	Yes	No	Yes
St. Petersburg	FL	3/28/2007	8000	Yes	No	Yes	No
Irving	TX	10/23/1999	8000	Yes	No	No	No
Lake Harbor	FL	9/11/2011	8000	Yes	No	No	No
Harrisonburg	VA	10/27/1991	8000	Yes	No	Yes	No
Tinton Falls	NJ	10/31/2003	8000	Yes	No	No	No
Warm Springs	OR	6/28/2011	8000	Yes	No	Yes	No
Conshohocken	PA	3/14/1994	8000	Yes	No	Yes	No
Benton	AR	2/25/2011	8000	Yes	No	No	No

Incident City	Incident State	Date of Incident	Quantity Released (Gal)	Release	Evacuations	Fatality	Injury
Gowers Corner	FL	7/19/2006	8000	Yes	No	No	No
Houston	TX	5/28/1998	8000	Yes	No	No	No
Wills Point	TX	8/23/2012	8000	Yes	No	No	No
Benton	MO	6/11/2000	8000	Yes	No	No	No
Bridgeport	WA	6/10/1998	8000	Yes	No	No	No
Phoenix	AZ	4/3/1998	8000	Yes	No	No	No
Philadelphia	PA	6/22/2005	8000	Yes	No	No	No
Gibsonton	FL	11/15/2006	8000	Yes	No	No	No
Spanish Fork	UT	4/24/2006	8000	Yes	No	Yes	No
Paducah	KY	6/21/2006	8000	Yes	Yes	No	Yes
Stratford	CT	6/14/1998	8000	Yes	No	No	No
New Wells	MO	12/27/1993	8000	Yes	Yes	No	No
Bloomington	MN	8/4/2001	8000	Yes	No	No	No
Jamestown	CA	3/26/2000	8000	Yes	No	No	No
Bristow	VA	7/11/2013	8000	Yes	No	No	Yes
Tulsa	OK	3/7/1998	8000	Yes	No	No	Yes
Madill	OK	10/15/2006	8000	Yes	No	No	No
Yabucoa Puerto Rico		7/25/1999	8000	Yes	No	No	No
New Castle	KY	5/26/2000	8000	Yes	No	No	No
Waco	TX	3/20/2004	8000	Yes	No	No	No
Mount Jewett	PA	11/18/2005	8000	Yes	No	Yes	No
Colleyville	TX	6/23/1991	8000	Yes	No	No	No
Moss Hill	TX	5/11/2010	8000	Yes	No	No	No
Embudo	NM	9/16/1997	8000	Yes	No	No	No
Knoxville	TN	3/26/2007	7920	Yes	No	No	Yes
Pensaukee	WI	1/3/1991	7900	Yes	No	No	No
Santa Fe	NM	8/17/2005	7867	Yes	No	Yes	No
Dallas	TX	1/7/2011	7845	Yes	No	No	No
Summerville	SC	4/27/2013	7800	Yes	No	No	No
Athens	AL	4/28/1998	7800	Yes	No	No	No
Dallas	TX	10/12/2008	7800	Yes	No	No	No
Green Bay	WI	4/2/2001	7800	Yes	No	Yes	No
Fort Worth	TX	3/28/2011	7780	Yes	No	Yes	No
Belleville	IL	11/20/2000	7751	Yes	No	No	No
Boynton Beach	FL	8/23/1995	7750	Yes	No	No	No
Colorado city	AZ	7/22/1993	7727	Yes	No	No	No
Freer	TX	3/14/2010	7700	Yes	No	No	Yes
Suffolk	VA	1/27/2002	7700	Yes	No	No	No
Martin	GA	11/17/2004	7700	Yes	No	Yes	No
Seneca	SC	3/27/2000	7650	Yes	No	Yes	No
Brooksville	AL	9/13/2001	7601	Yes	No	No	No

Incident City	Incident State	Date of Incident	Quantity Released (Gal)	Release	Evacuations	Fatality	Injury
Blue Water	NM	9/26/2005	7600	Yes	No	No	No
Annandale	VA	3/16/1995	7600	Yes	No	No	No
Durant	MS	12/29/1991	7596	Yes	No	No	No
Morning Star	AR	7/24/1998	7589	Yes	No	No	No
Utica	MS	6/2/1992	7556	Yes	No	No	No
Pikeville	NC	2/21/2000	7545	Yes	Yes	No	No
North Charleston	SC	11/4/2008	7503	Yes	No	No	No
Inver Grove Heights	MN	10/5/1992	7502	Yes	No	No	No
Cloudland	GA	12/22/2008	7501	Yes	No	No	No
Mount Gilead	NC	2/28/2010	7500	Yes	Yes	No	No
Austin	TX	3/28/2012	7500	Yes	No	Yes	No
Dacula	GA	4/9/2012	7500	Yes	No	No	No
Oswego	IL	11/3/2000	7500	Yes	No	No	Yes
Lubbock	TX	3/15/2004	7500	Yes	No	No	No
Lawton	OK	8/12/2006	7500	Yes	No	No	No
Carnesville	GA	6/15/1996	7436	Yes	No	No	No
Poplar Bluff	MO	7/11/1996	7435	Yes	No	No	No
Hanover	NY	5/1/2000	7430	Yes	No	No	No
Wauchula	FL	5/19/2007	7404	Yes	No	No	No
Mentor	OH	3/12/2003	7400	Yes	Yes	No	No
Columbia	SC	9/16/1999	7400	Yes	Yes	No	No
Hillister	TX	11/30/2012	7383	Yes	Yes	Yes	No
Eufaula	OK	12/17/2001	7319	Yes	No	No	No
Stony Point	NY	12/18/2010	7300	Yes	No	No	No
Miami	FL	8/3/1996	7300	Yes	No	No	No
Rialto	CA	6/29/2012	7269	Yes	No	No	No
Lanesboro	MN	10/11/1990	7200	Yes	No	No	No
Houston	TX	5/15/1997	7200	Yes	No	Yes	No
Memphis	TN	9/23/2013	7199	Yes	Yes	No	No
Queens	NY	5/15/1994	7197	Yes	No	Yes	Yes
Beechwood	OH	4/24/1995	7100	Yes	No	No	No
Unknown	AL	8/2/2007	7072	Yes	No	No	No
Spring Hill	FL	1/8/2001	7001	Yes	No	No	No
Chama	NM	5/2/2013	7001	Yes	No	No	No
Centerville	UT	11/4/2000	7000	Yes	No	No	No
Kremmling	CO	4/13/2002	7000	Yes	No	No	No
Newport	TN	5/30/1991	7000	Yes	No	No	No
Milan	OH	3/20/2003	7000	Yes	No	Yes	No
Bussey	IA	1/17/1992	7000	Yes	No	No	No
Eunice	NM	7/6/2002	7000	Yes	No	No	No
Davie	FL	10/30/2007	7000	Yes	No	No	No

Incident City	Incident State	Date of Incident	Quantity Released (Gal)	Release	Evacuations	Fatality	Injury
Ganado	AZ	11/9/2001	7000	Yes	No	No	No
Miller	SD	6/23/2000	7000	Yes	No	No	No
Fort Lauderdale	FL	2/17/2002	7000	Yes	No	No	No
Franklin Springs	GA	12/3/1996	7000	Yes	No	No	No
Marshall	AR	11/13/2002	7000	Yes	No	No	No
Las Vegas	NV	2/21/2004	7000	Yes	No	No	No
Middlebourne	WV	9/3/2006	7000	Yes	No	Yes	No
Crawford	CO	5/22/2013	7000	Yes	No	No	No
Sea cliff	CA	4/9/2000	6900	Yes	No	No	No
Kenly	NC	3/5/2008	6885	Yes	No	No	No
Plainfield	CT	4/3/2009	6850	Yes	No	No	No
Assumption	LA	3/25/2004	6846	Yes	Yes	No	No
Coleville	CA	8/10/2005	6800	Yes	No	No	Yes
Gray	LA	4/21/2002	6800	Yes	No	No	No
Sierra Vista	AZ	6/11/2006	6800	Yes	No	No	No
Warren	WI	2/27/2012	6700	Yes	No	Yes	No
Fort worth	TX	1/3/2002	6700	Yes	No	No	No
Cincinnati	OH	6/4/1992	6700	Yes	No	No	No
Salida	CO	1/28/2011	6503	Yes	No	Yes	No
Palisades	ID	10/28/2011	6500	Yes	No	No	No
Hillsboro	TX	7/10/2003	6500	Yes	No	No	No
Oklahoma City	OK	3/25/2011	6500	Yes	No	No	No
Minneapolis	MN	1/9/2008	6500	Yes	No	No	No
Patrick	VA	2/17/2005	6428	Yes	Yes	No	No
Palson	MT	4/2/2008	6403	Yes	Yes	No	No
Yadkinville	NC	10/30/2001	6400	Yes	No	No	No
Dumont	CO	9/21/2009	6350	Yes	No	No	No
Spartanburg	SC	5/24/2002	6347	Yes	Yes	No	No
Duncannon	PA	7/27/2010	6300	Yes	Yes	No	No
Wildorado	TX	9/16/2004	6299	Yes	No	No	No
Greenville	NC	4/17/2004	6283	Yes	No	No	No
Lake Worth	FL	3/8/1998	6282	Yes	No	No	No
Lancaster	SC	12/23/2008	6244	Yes	No	No	No
Lynnwood	WA	7/12/2003	6200	Yes	No	No	No
Scottsburg	OR	9/8/2003	6200	Yes	No	No	No
Corry	PA	9/3/2003	6200	Yes	No	No	No
Amity	OR	7/3/2004	6200	Yes	Yes	No	No
Loveland Pass	CO	11/8/1994	6200	Yes	Yes	Yes	No
Franklin	NJ	8/7/1998	6101	Yes	Yes	No	No
Austin	TX	10/30/2010	6100	Yes	No	Yes	No
Gravesville	AR	5/23/1996	6100	Yes	No	No	No

Incident City	Incident State	Date of Incident	Quantity Released (Gal)	Release	Evacuations	Fatality	Injury
Rosston	AR	8/7/2005	6080	Yes	No	No	No
Dover	NC	1/8/2007	6049	Yes	No	No	No
Spartanburg	SC	12/15/2009	6032	Yes	No	No	No
Merchantville	NJ	5/28/2006	6000	Yes	No	No	No
Tampa	FL	5/23/2006	6000	Yes	No	No	No
Newark	OH	5/23/2007	6000	Yes	No	No	No
Gateway	CO	1/25/2013	6000	Yes	No	No	No
Venre	IL	8/16/2012	6000	Yes	No	No	No
Boger City	NC	7/17/2001	6000	Yes	No	No	No
Noti	OR	7/24/2006	6000	Yes	Yes	No	No
Bethel	VT	10/3/2000	6000	Yes	No	No	No
Saint Pauls	NC	3/16/2007	6000	Yes	No	No	No
Saint Paul	NC	3/16/2007	6000	Yes	No	No	No
Phoenix	AZ	1/19/2003	6000	Yes	No	No	No
Austin	TX	12/9/1994	6000	Yes	No	No	Yes
Zolfo Springs	FL	2/8/1996	6000	Yes	No	No	No
Carpinteria	CA	11/25/1990	6000	Yes	No	No	No
Saint Louis	MO	11/8/2007	6000	Yes	No	No	No
Tucson	AZ	2/8/2003	6000	Yes	No	Yes	No
Little Rock	AR	12/6/2010	6000	Yes	No	No	No
Texico	NM	9/20/2006	6000	Yes	Yes	No	No
Hornbeck	LA	8/7/1990	6000	Yes	No	No	No
Gramercy	LA	6/26/1998	6000	Yes	No	No	No
Bolton	CT	7/1/1991	6000	Yes	No	No	No
Aneth	UT	4/26/2004	5952	Yes	No	No	No
Bronx	NY	4/7/2012	5900	Yes	No	No	No
Brentwood	AR	3/16/1998	5900	Yes	Yes	No	No
Oromocto Nb Canada		8/31/1992	5856	Yes	No	No	No
Phoenix	AZ	9/8/2001	5800	Yes	No	No	No
Forest City	NC	5/22/2009	5723	Yes	Yes	No	No
Canton	GA	7/26/2005	5700	Yes	No	No	No
Elgin	TX	1/6/2002	5700	Yes	No	No	No
Myrtle Beach	SC	11/2/2003	5700	Yes	No	No	No
Bath	NY	8/16/2002	5700	Yes	No	Yes	No
Bath	NY	8/16/2002	5700	Yes	No	Yes	No
Tuscaloosa	AL	4/9/2010	5603	Yes	No	Yes	No
Hamilton	NJ	9/11/2001	5539	Yes	No	No	No
Hernando	FL	10/18/2005	5506	Yes	No	Yes	No
Albertville	MN	7/12/2009	5500	Yes	No	No	No
Greensboro	NC	8/28/2002	5500	Yes	No	No	No
Tulsa	OK	6/9/2002	5500	Yes	No	No	No

Incident City	Incident State	Date of Incident	Quantity Released (Gal)	Release	Evacuations	Fatality	Injury
Gurnee	IL	7/18/2005	5500	Yes	No	No	No
Orlando	FL	8/11/2002	5500	Yes	No	No	No
Bakersfield	CA	1/17/2006	5500	Yes	No	No	No
Potomac	MD	10/19/1992	5500	Yes	No	Yes	Yes
Belfry	MT	7/26/2009	5402	Yes	No	Yes	No
Pleasant Hill	IA	6/14/2002	5400	Yes	No	No	No
Londonderry	NH	1/31/1992	5400	Yes	No	No	No
Thomaston	CT	9/12/2011	5393	Yes	No	No	No
Warm Springs	OR	3/4/1999	5389	Yes	No	No	No
Durango	CO	1/7/2004	5350	Yes	No	No	No
Champaign	IL	12/26/2007	5300	Yes	No	No	No
Newark	NJ	7/19/2001	5300	Yes	No	No	No
North Port	FL	2/2/2004	5300	Yes	No	Yes	No
Berryman	MO	1/25/2002	5279	Yes	No	No	No
Palo Verde	CA	11/8/2013	5250	Yes	No	No	No
Newark	OH	3/5/2001	5222	Yes	No	No	No
Arnold	MO	8/15/2002	5200	Yes	Yes	No	No
Vail	CO	9/16/2007	5188	Yes	No	No	No
Jackson Heights	NY	1/16/2006	5150	Yes	No	No	No
Lynnwood	WA	7/12/2003	5100	Yes	No	No	No
Warm Springs	OR	9/24/2013	5049	Yes	No	No	No
Birmingham	AL	10/21/2004	5000	Yes	No	No	No
Hot Sulphur Springs	CO	6/11/2008	5000	Yes	No	No	No
Ontario	CA	3/11/2005	5000	Yes	No	No	No
Everett	MA	1/26/1991	5000	Yes	No	No	No
Magnolia	TX	6/4/2005	5000	Yes	Yes	No	No
Lares Puerto Rico		7/12/2001	5000	Yes	No	No	No
Glendale	CA	4/7/2012	5000	Yes	No	No	No
Niles	IL	8/3/2009	5000	Yes	Yes	No	No
Irving	TX	5/28/2005	5000	Yes	No	Yes	No
Porter	ME	8/17/1990	5000	Yes	No	Yes	No
Benns Church	VA	1/29/1996	5000	Yes	No	No	No
Wallagrass	ME	5/31/2011	5000	Yes	No	No	No
Veedersburg	IN	6/21/1997	5000	Yes	No	No	No
Spangle	WA	3/23/2009	5000	Yes	No	No	No
Whitewater	CO	3/22/1990	5000	Yes	No	No	No
Louisville	KY	1/2/1990	5000	Yes	Yes	No	No