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Cargo-specific accidental release impact zones for hazardous materials: risk and consequence comparison for ammonia and hydrogen fluoride

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Abstract Impacts of hazardous material releases during transport depend on the characteristics of the cargo, incident location and time, weather conditions (i.e., wind direction and speed), and land use. The objectives of this research were to characterize the dispersion characteristics of two hazardous materials (ammonia and hydrogen fluoride) in relation to meteorological parameters, land use, and cargo characteristics; and evaluate the health risks associated with the exposure after accidental releases. The magnitudes of the impact zones were compared in relation to atmospheric stability and exposure levels. Impact zones were estimated by areal locations of hazardous atmospheres software and imported to ArcGIS. For ammonia, the areas impacted by exposure levels over 1100 ppm Acute Exposure Guideline Level 3 (AEGL-3) were limited to less than 0.3 miles downwind from the incident location under unstable atmospheric conditions, which favor high vertical mixing and rapid dilution, and extended further downwind to distances between 0.5 and 0.7 miles under stable atmospheric conditions. For hydrogen fluoride, the AEGL-3 impact zone (exposure levels over 44 ppm) extended between 0.6 and 0.9 miles directly downwind from the incident location under unstable conditions, and reached approximately 2.0 miles directly downwind from the incident location under stable atmospheric conditions. The results were compared with the Emergency Response Guideline (ERG 2012) and showed agreement. The multilevel analysis of impacts after hazardous material releases during transport (i.e., type of material, geographical data, dispersion profile, meteorological information) can be used for implementing appropriate response and mitigation measures for accidental releases of hazardous cargo.

Keywords Hazardous material cargo · Geographical Information Systems (GIS) · Air dispersion · Risk analysis · Ammonia · Hydrogen fluoride

1 Introduction

The accidental releases of hazardous materials occur not only during transport, but also at fixed locations during loading and unloading activities (US DOT 2010). Each year over 15,000 hazardous material incidents are reported to the Pipeline and Hazardous Materials Safety Administration. The most common spills involve releases of hydrocarbons (i.e., diesel oil, road tar, gasoline, fuel oil, asphalt, LPG, jet fuel, hydraulic oil, and creosote). In the event of an accident, if volatile hazardous materials are released, they are dispersed in air and transported by wind, impacting the air quality in the surrounding areas. In the USA, over 1 million shipments of hazardous materials in trucks take place on a daily basis (PHMSA 2010). Due to the risks associated with accidents during hazardous material transport, consequences can be significant due to toxic nature of the chemicals (PHMSA 2010). According to US DOT, the number of large trucks carrying hazmat that

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were involved in fatal traffic crashes averaged 225 per year from 1980 through 1990. Less than 5 % of the trucks involved in the traffic crashes were carrying hazardous materials. During the period from 1991 to 2000, there were 636 hazardous materials cargo releases in fatal truck crashes, which correspond to an average of 64 release incidents per year (Craft 2004). Although the number of hazmat spills in fatal truck crashes is relatively small, the probability of a spill occurring at the time of accident is 50 % higher than that for non-hazmat cargo. Based on the historical records from 1991 to 2000, about 31 % of hazmat cargoes were spilled from the cargo compartment in an average year, as opposed to 21 % of the non-hazmat cargoes (Craft 2004).

Hazardous material shipments carried by trucks in the USA add up to approximately 1.5 million tons annually, representing about 59.4 % of the total commodity shipments in 2012 (U.S. Census Bureau 2015). The historical shipment records show an increase by 27.3 % from 2007 to 2012, and the trend is steadily increasing by 5 % annually in hazardous material volume (U.S. Census Bureau 2015).

There have been several major incidents with hazardous cargo releases near urban areas which have received national attention. For example, in 1976, in Houston, Texas, a tanker carrying about 7500 gallons of ammonia crashed causing six deaths and many people with severe injuries (NTSB 1977a). Another incident occurred in 2001, in Ramona, Oklahoma, where a flammable gas was discharged due to truck overturn and causing death, evacuation of neighboring areas, and highway blockage for 12 h (NTSB 2001). During another incident in Memphis, Tennessee, (in 1997), hydrogen fluoride was released resulting in evacuations in the surrounding area (NTSB 1977b).

Chlorine and anhydrous ammonia are two chemicals transported in large quantities and classified as Toxic Inhalation Hazards (TIH). Other chemicals transported in large quantities include sulfur dioxide, ethylene oxide, and hydrogen fluoride, and a variety of other substances used by various industries. However, since the air dispersion model used by this study was a Gaussian-based approach, ammonia and hydrogen fluoride were selected for analyses as they are lighter than air and the dispersion model would be more appropriate for predicting their behavior (Branscomb et al. 2010). Table 1 presents examples of incidents where ammonia and hydrogen fluoride releases to the atmosphere have been reported.

Air pollution increases risks of cancer, respiratory and allergy diseases, and aggravates the conditions for people suffering from such diseases (Jensen et al. 2001). Over the last three decades, many nations have been involved with research for developing operational strategies to improve transport and disposal of hazardous materials and reduce accidental release risks (Rakas et al. 2004).

In the literature, there are several studies focused on risk assessment of hazardous material transport accidents, including but not limited to a study by Saccomanno and Shortreed (1993), where they estimated the dangerous areas around accidental releases of chorine using an air dispersion model called emergency prediction information (EPI). In another study by Margai (2001), areal locations of hazardous atmospheres (ALOHA) was utilized to identify the threat zone around accidents for chlorine. Zhang et al. 2000 estimated the risk associated with hazardous material accidents by using Gaussian plume model and ArcGIS. Other similar studies such as Fabiano et al. 2002, Wu et al. 2004, Jiang et al. 2006, and Liu et al. 2012 also focused on risk quantifications of accidental hazardous material spills.

The goal of this research is to estimate the size of the areas impacted after accidental releases of hazardous materials by coupling air dispersion modeling with ArcGIS. The impact zones for two hazardous chemicals (ammonia and hydrogen fluoride) were compared in relation to atmospheric stability conditions and exposure levels (i.e., concentration), to quantify and compare the consequences after the accidental releases. Impact zones were estimated using the ALOHA software, and the output was exported into ArcGIS for aerial mapping and risk calculations. The exposure levels were defined according to the level of concern (LOC) concentrations for each chemical. The impacts zones of the two chemicals were compared with the initial and the protective action zones provided by Emergency Response Guideline (PHMSA 2012). The health risks associated with accidental releases of the materials were compared in terms of the size of impacted area and population at risk.

2 Methodology

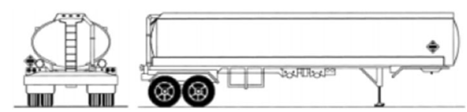
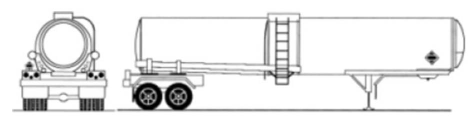
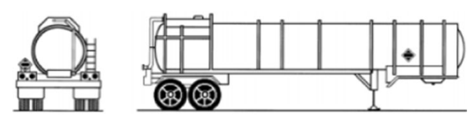
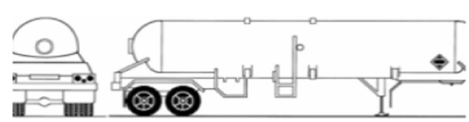
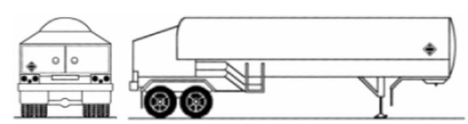
2.1 Truck types

In highway transport, cargo tanks with special safety features are used to transport hazardous materials (i.e., liquids, flammable and non-flammable liquids, and corrosive materials or compressed gases). The common classification of trucks suitable for transport hazardous materials is mandated by US Code of Regulations for transporting hazardous materials (49 CFR). In this classification, tankers are categorized in five types as non-pressure tanks, low-pressure tanks, corrosive cargo tanks, high-pressure tanks, and cryogenic liquid tanks. The appropriate truck classifications for transporting ammonia and hydrogen fluoride are provided in Table 2 (Spencer and Colonna 2003).

Table 1 Hazardous material accidents (after NTSB 2013; US EPA 1993; NTSB 1977b)

Date	Location	Chemical	Amount released (gal)
May 1976	Houston Texas	Ammonia	7500
January 1986	Gore, Oklahoma	Hydrogen fluoride	400
October 1987	Texas city, Texas	Hydrogen fluoride	3500–6300
June 1989	El Dorado, Arkansas	Hydrogen fluoride	160
April 1997	Memphis, Tennessee	Hydrogen fluoride	–
August 2003	Middletown, Ohio	Ammonia	10,600
April 2003	Calamus, Iowa	Ammonia	1300

Table 2 Truck classifications for transporting ammonia and hydrogen fluoride (after Spencer and Colonna 2003; ERG 2012)

Type	Description	Maximum capacity (gal)	Type of commodities carried	Examples	Schematic
DOT406, TC406, SCT-306 Non-pressure (MC306,TC306)	Elliptical cross section, made of aluminum	9000	Other flammable/combustible liquids	Gasoline, diesel fuel, Alcohol	
DOT407, TC407, SCT-307 Low-pressure (MC307, TC307)	Circular cross section, made of stainless steel	7000	Flammable and combustive liquids, acids, caustics, poisons	Anhydrous hydrogen fluoride	
DOT412, TC412, SCT-312 Corrosive (MC312, TC312)	Circular cross section, made of steel with reinforced ribs	7000	Heavier-than-water material, corrosive liquids	Hydrogen fluoride, aqueous ammonia (ammonium hydroxide)	
MC331, TC331, SCT-331 High-pressure	Circular cross section and rounded ends, made of single shell steel	11,500	Pressurized gases and liquids	Anhydrous ammonia	
MC338, TC338, SCT-338 Cryogenic (TC341, CGA341)	Double shell with vacuum-maintained space	14,000	Cryogenic liquids or liquefied gases	Nitrogen, Argon, Ethylene, Hydrogen, Oxygen	

2.2 Air quality estimations and exposure assessment

Different types of air dispersion models have been developed to estimate contaminant concentrations over time or affected area (Griffin 2006). Gaussian-type algorithms are the most commonly used to predict the dispersion of pollutants emitted from point sources. These models assume that dispersion of the pollutant in the atmosphere follows a normal probability distribution pattern. Gaussian models generally consider an average wind speed and constant wind direction and estimate the ground-level pollutant levels in the wind direction. In this study, the dispersion analyses were conducted using ALOHA software which was developed for accidental chemical spills by the Hazardous Materials Response and Assessment Division of National Oceanic and Atmospheric Administration

(NOAA) (US DOE 2004). The Gaussian algorithm of the model was used for the comparative analyses.

2.3 Areal locations of hazardous atmospheres (ALOHA)

The air dispersion model used is suitable for predicting the characteristics of atmospheric dispersion associated with the hazardous chemical releases. In the literature, ALOHA software has been used for the modeling of different release scenarios. For example, Dandrieux et al. (2002) used ALOHA to estimate chlorine concentration in a small-scale-release scenario; authors also compared the results from the model with the traditional Gaussian dispersion approach. Gharabagh et al. (2009) utilized the model as part of a comprehensive risk assessment study for the petrochemical feed and product pipeline network. Verma (2011) applied the model for risk management of hazardous material transported by railroad to evaluate the impacts of incidents during transport. There are also studies which use the model to analyze the historical incidents. For example, Leelossy et al. (2011) used the model as an assessment tool for prediction of the short- and long-term air quality impacts of the Fukushima Nuclear power plant accident.

The inputs to the model include properties and amount of the released chemical as well as the meteorological data (i.e., air temperature and humidity, wind direction and speed, and the atmospheric stability class). The stability class has a significant effect on the prediction of the size of the toxic threat zone under different atmospheric dispersion conditions. Atmospheric stability is related to the tendency of a parcel of air to move upward or downward after it has been displaced vertically by a small amount (Woodward 2010). ALOHA uses the Pasquill–Gifford–Turner classification system consisting of six classes based on five surface wind speed categories, three types of daytime solar insolation, and two types of nighttime cloud cover (Turner 1994). This scale, presented in Table 3, ranges from stability class A (indicating unstable atmospheres which tend to develop vertical updrafts with high turbulence intensities) to stability class F (indicating stable atmospheres which tend to suppress vertical updrafts and reduce turbulence intensity; Woodward 2010; Hanna et al. 1982).

Two chemicals, anhydrous ammonia and hydrogen fluoride, were selected to compare the dispersion characteristics and size of the impact zones after an accidental release incident. Table 4 presents the properties of these two chemicals which are highly volatile and classified as toxic compounds. Both chemicals are used in numerous industrial applications; therefore, they are transported frequently on the highways.

Table 5 presents the accidental release scenarios considered in this study. For a specific location in Miami-Dade County, Florida, these scenarios were compared for the dispersion of either anhydrous ammonia or hydrogen fluoride as a function of varying only the Pasquill–Gifford stability classes. This was performed by applying the Gaussian algorithm of the model to predict the dispersion of the hazardous chemicals under specific conditions of air temperature, humidity, and wind speed and direction.

Based on the information presented in Table 3, a wind speed of 5 mph is amenable to the selected criteria for comparison since five of the six stability classes are possible at this wind speed, either during the day or night (however, the sixth class was also considered). The remaining inputs for weather conditions were selected to be representative of the winter conditions in the selected location (Miami, Florida).

2.4 Risk estimation

Risk can be quantified from the number of similar events occurring per year and the corresponding consequences. The consequence can be expressed from different perspectives (i.e., impacted population, fatalities, size of the impacted areas, cost of traffic congestion due to delay, environmental impacts) and the frequency of events can be estimated from the number of similar events occurring per year. In this study, the health risk due to exposure to a hazardous chemical released to the atmosphere was estimated by the following equation (US DOT 2015):

$$\text{Risk} = \text{Likelihood} \times \text{Consequences} \tag{1}$$

In order to estimate the consequences in Eq. 1, the health impact zones estimated by ALOHA were utilized based on the air quality and by incorporating the possible health impacts due to exposure to hazardous materials which are released to the atmosphere. The likelihood of an accident occurrence is broken into two related quantities: the rate that an accident takes place (threat), and the likelihood that the accident leads to a chemical release (vulnerability). In order to calculate the accident rate, 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 travelled was calculated by Eq. 2. Crash rate was acquired by the Eq. 3 (HCM 2000).

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

$$\text{Crash rate} = \frac{\text{Total crash count}}{\text{EXPO}} \tag{3}$$

Table 3 Atmospheric stability categories (Turner 1994)

Surface wind speed[a] (at 10 m) (m/s)	Day[b]			Night	
	Incoming solar radiation			Cloudy	Clear
	Strong[c]	Moderate[d]	Slight[e]		
<5	A	A–B	B	E	F
5–7	A–B	B	C	E	F
7–11	B	B–C	C	D	E
11–13	C	C–D	D	D	D
>13	C	D	D	D	D

[a] Surface wind speed measure at 10 m above ground

[b] A, very unstable; B, moderately unstable; C, slightly unstable; D, neutral; E, slightly stable; F, stable

[c] Clear summer day with sun higher than 60° above the horizon

[d] Summer day with a few broken clouds, or a clear day with sun 35–60° above the horizon

[e] Fall afternoon, or a cloudy summer day, or clear summer day with sun 15–35°

where EXPO is exposure and AADT is annual average daily traffic. The truck AADT was considered in the equation to represent the frequency of truck accidents, as the main focus of this research and the primary cause of chemical releases. The total crash count was calculated by identifying accidents involving trucks within a search radius around the target segment of the road which the accident assumed to happen. In order to take into account the probability of releases caused by accidents involving trucks, as they may not lead to spills always, statistics of hazardous material accidents were considered as the percentage of the accidents which led to releases to the number of total hazardous material accidents according to PHMSA, which was equal to 27.3 % (Battelle 2001). In the accident rate calculation, 8 years of crash data in the area were taken into account. The accidents involving trucks were selected and then enumerated; further, the crash rate was computed using AADT data of trucks using Eq. 3. All the calculations related to estimation of the impacted areas, population at risk, truck crashes identification, crash rate calculation, and visualization of the impact zones were executed employing ArcGIS.

3 Results

One of the display outputs of the model is the toxic threat zone plots which provide visualization and mapping of concentration contours (or threshold concentrations for specific effects due to exposure). The size of the impact zones estimated by the model depends on the level of concern (LOC) defined by the user. A toxic LOC refers to exposure limits at which exposure for a defined length of time poses a specified health risk. For this study, the LOC was set to be equal to the Acute Exposure Guideline Levels (AEGLs). AEGLs concentrations, expressed in ppm, are available for individual chemicals and are categorized in three levels according to the type of risk that a given exposure duration may cause to the general public, including sensitive individuals. The first level, AEGL-1, refers to the threshold concentration for mild effects (i.e., discomfort, irritation, or any other temporary and reversible symptoms) on the exposed individuals. The second level, AEGL-2, refers to the irreversible or long-lasting adverse health effects which may impair the individual's ability to escape the zone of exposure. The third level, AEGL-3, refers to life-threatening health effects or death. All three levels are established for five exposure periods: 10, 30, 60 min, 4, and 8 h. Only the 60-min AEGLs are provided in the model which is the maximum time limit for the model prediction. However, other types of possible consequences could have been taken into account, such as flammable zones and overpressure areas identification around accidents (Inanloo and Tansel 2015), which were beyond the scope of this study.

Figure 1 presents the threat zone output plots for the dispersion of ammonia and hydrogen fluoride under atmospheric stability C for the conditions specified in Table 5. The model generates the puff isopleth plots, the isoconcentration contours corresponding to each of the three AEGLs. These contour lines represent the longitudinal and lateral boundaries of the area where the ground-level concentration is predicted to reach or exceed the specific LOC (i.e., AEGL) during the advection of the puff. The confidence lines enclosed the area where the gas cloud is expected to be found with 95 % of confidence if probable changes in the wind direction occur. Confidence lines are depicted around the longest travel distance.

The model determines the final shape of the confidence line via the implicit standard deviation of wind direction, a parameter termed sigma-theta (Turner 1994). The value of this parameter in the algorithm reflects the amount of

Table 4 Characteristics of ammonia and hydrogen fluoride (EPA 2013)

Property	Ammonia	Hydrogen fluoride
Chemical formula	NH_3	HF
Industrial uses	Fertilizers, synthetic nitrogen compounds, general-purpose cleaner, antimicrobial agent for food products, semiconductor manufacturing, refrigerant	Oil refineries, semiconductor manufacturing, production of chemicals (refrigerants, hydrofluorocarbons and fluoropolymers)
General description	Flammable gas	Colorless gas, produces fumes on contact with air, completely miscible with water
General health effects	Toxic if inhaled, causes severe skin burns and eye damage, very toxic to aquatic life.	Toxic if breathed in, ingested or via skin contact. Can cause severe burns to skin and eyes.
Molecular weight (g/mol)	17.03	20.01
Boiling point (K)	240	293
Density (kg/m^3)	0.73	1.15
GHS pictograms		
NFPA 704		
Flash point	Flammable gas	NA
Explosive limits	15–28 %	NA
Permissible exposure limit (PEL)	50 ppm (25 ppm ACGIH-TLV; 35 ppm STEL)	3 ppm
LD_{50}	0.015 mL/kg (human, oral)	
LC_{50}		1276 ppm (rat, 1 h, inhalation)
AEGL-1 (ppm)	30	1
AEGL-2 (ppm)	160	24
AEGL-3 (ppm)	1100	44
ERPG-1 (ppm)	25	2
ERPG-2 (ppm)	150	20
ERPG-3 (ppm)	750	50

Table 5 User-specified settings used for dispersion analysis after accidental cargo spills

Parameters	Settings
Hazardous materials	Ammonia, hydrogen fluoride
Amount released (tons)	2
Atmospheric stability class	A, B, C, D, E, F
Wind speed (mph)	5
Wind direction	SW
Temperature (°F)	55
Air humidity (%)	80
Time (min)	60

variation in wind direction. Since the probable amount of variation is different for each stability condition, the shape and size of the confidence outline changes according to the stability class. Figure 1 shows the differences in the mobility of the two chemicals for an identical release scenario (i.e., amount released, wind conditions). In the case of ammonia, the threat zone outer limit extends for 1.1 miles while that of the hydrogen fluoride extends for 3.0 miles. This difference can be explained based on the time it takes for the puff to be diluted and reach the specific concentration (i.e., AEGL selected). For example, the AEGL-1 concentration for hydrogen fluoride is 1 ppm; 30 times lower than that of ammonia at 30 ppm.

The atmospheric dispersion resulting from the accidental release of hydrogen fluoride and ammonia was studied using several different sets of atmospheric inputs for summer and winter conditions, and the model predictions were found to be very similar. Furthermore, wind speeds in the range from 5 to 11 mph were tested, and only minor differences in the final downwind transport distance was

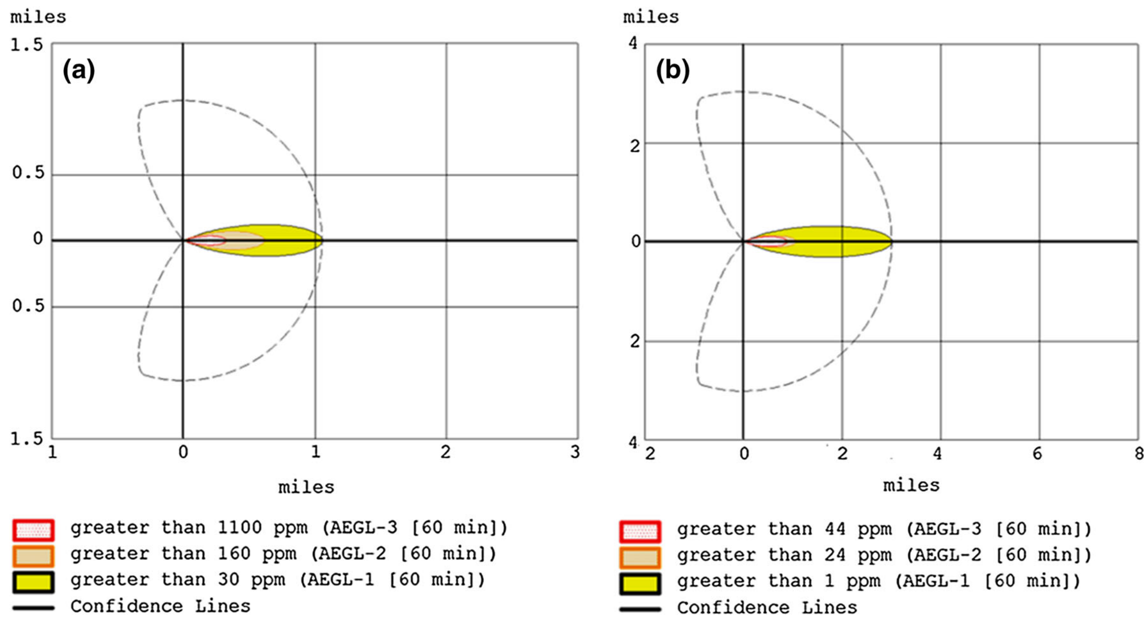


Fig. 1 Comparison of ALOHA's threat zone plots for the case scenario of an accidental release of ammonia and hydrogen fluoride based on their acute exposure guideline levels (AEGLs). Calculations performed using input data given in Table 5 for a class C atmospheric stability. **a** Ammonia and **b** hydrogen fluoride

found between the puff scenarios of the two chemicals. In these cases, the main difference was that the confidence lines area became wider as the wind speed became lower. This is a result of the greater uncertainty (standard deviation) in the wind direction at lower wind speeds.

The results from the winter scenario modeling, which was conducted at a wind speed of 5 mph (other inputs reported in Table 5) for the possible atmospheric stability conditions, were similar to the results of the other scenario. Therefore, only results of summer modeling are shown in Fig. 2. Figure 2 presents the predicted toxic threat zone plots for ammonia for the six atmospheric stability classes superimposed to the GIS maps. This representation provides an easy visualization tool for the geographical areas that would be impacted by the toxic release. Results show that the downwind distance travelled by the puff is predicted to be progressively larger with atmospheric stabilities, from 0.7 miles for class A (turbulent) to 2.7 miles for class F (very stable). Considering the same wind speed, the higher turbulence of a vertically unstable atmosphere will facilitate rapid dilution of the initial cloud of buoyant gas (both gases are less dense than air) via upward movement and consequently, the threat zone (as defined by AEGL) will extend to a shorter downwind distance.

The model also allows displaying the output for the downwind concentration as a function of time at a specific point or location (user-defined) by entering a downwind and crosswind distance relative to the release point. This concentration profile plot follows a symmetrical bell-shaped curve. For example, for the scenario depicted in Fig. 2, for the atmospheric stability class C, plots of the concentration profiles show that the cloud of ammonia would arrive at the 0.3 miles threshold for the AEGL-3 in about 7 min, at the 0.6 miles threshold for the AEGL-2 in about 17 min, and at the 1.1 miles threshold for the AEGL-1 in about 20 min. Figure 2 presents the dispersion predictions for ammonia to reach the 60-min time limitation at atmospheric stability E (Fig. 2e).

The toxic threat zone plots for hydrogen fluoride are shown in Fig. 3. Similar to ammonia, the downwind distance travelled by the puff also becomes progressively larger from atmospheric stability class A to F. However, the distances are much larger than those for ammonia, ranging from 1.8 miles for class A (turbulent) to 4.6 miles for class D (neutral). The model could not provide useful concentration information for stability classes E and F, as the threat zone is greater than 6 miles. The plots of the concentration profiles for the advection of the hydrogen fluoride puff scenario under atmospheric stability C, corresponding to the threat zone shown in Fig. 3b, indicate that the cloud of hydrogen fluoride would arrive at the 0.9 mile threshold for the AEGL-3 in about 18 min, at the 1.1 mile threshold for the AEGL-2 in about 22 min, and at the 3 mile threshold for the AEGL-1 in about 60 min. Hence, the dispersion predictions for hydrogen fluoride only provide useful information for stability classes A, B and C (Fig. 3).

Figure 4 compares the magnitude of the impact zones in relation to exposure levels for ammonia and hydrogen fluoride under different stability conditions. For a similar

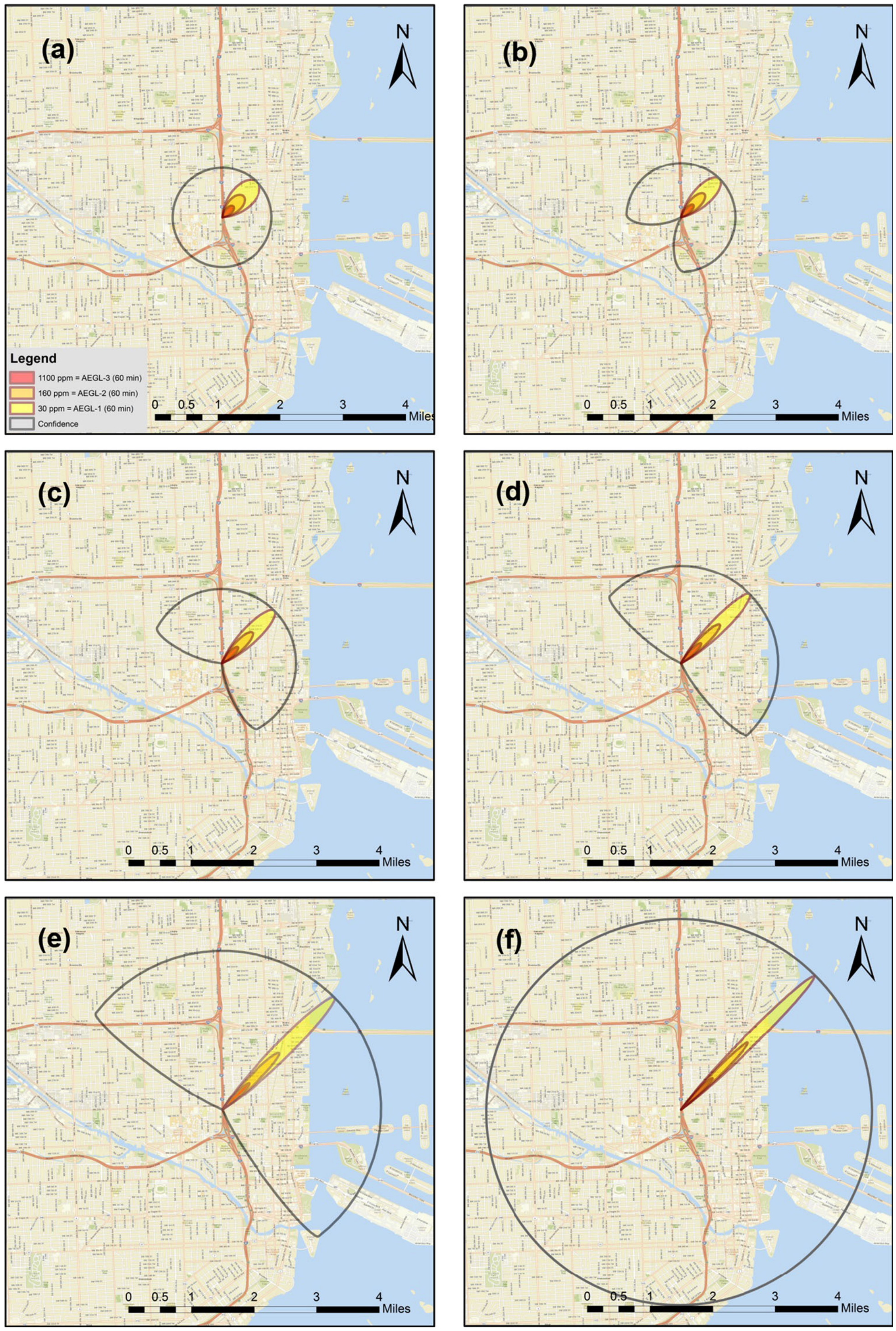


Fig. 2 Geographical areas impacted by the dispersion of toxic release of ammonia under different atmospheric stability classes: **a** A, **b** B, **c** C, **d** D, **e** E, **f** F

release quantity, the impact zone for hydrogen fluoride covers a significantly larger area in comparison with that for ammonia.

In order to validate the results from the models, ERG 2012 manual was used and the predicted impact zones by the two approaches were compared. Pipeline and Hazardous Materials Safety Administration's (PHMSA) ERG describes the procedures for the first emergency responders (i.e., police, firefighters or other emergency service providers) who deal with hazardous material accidents during the first 30 min after the incident. The initial isolation zone distances is defined as the area surrounding an accident, within which people may be exposed to hazardous (upwind) and life threatening (downwind) concentration of

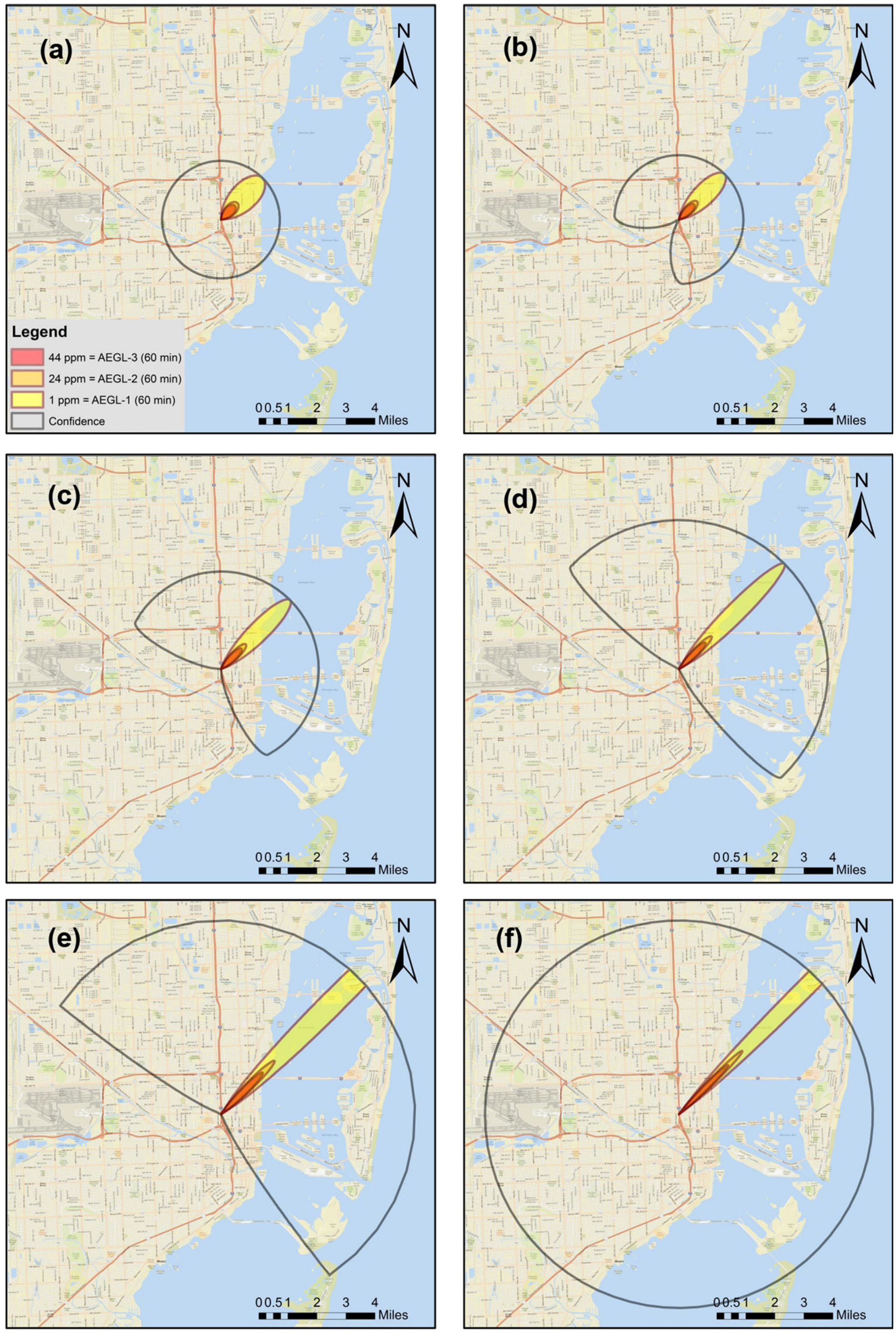


Fig. 3 Geographical areas impacted by the dispersion of a toxic release of hydrogen fluoride under different atmospheric stability classes: **a** A, **b** B, **c** C, **d** D, **e** E, **f** F

chemical, and protective action zone is the area downwind from the incident in which people may suffer irreversible health impacts (Fig. 5). These zones are derived from the historic data on similar incidents and by the statistical models. The initial isolation and protective action distances vary according to the chemical, time of release (day or night), and amount of release (small or large). According to ERG, the protective action zone considers AEGL-2 or ERPG-2 (Emergency Response Planning Guideline 2) values for exposure concentration limits.

ERG defines the isolation and the protective zones in accordance with the released chemical, time of release (day or night), and amount of release (small or large). According to the ERG 2012 table, for highway truck or trailer carrying

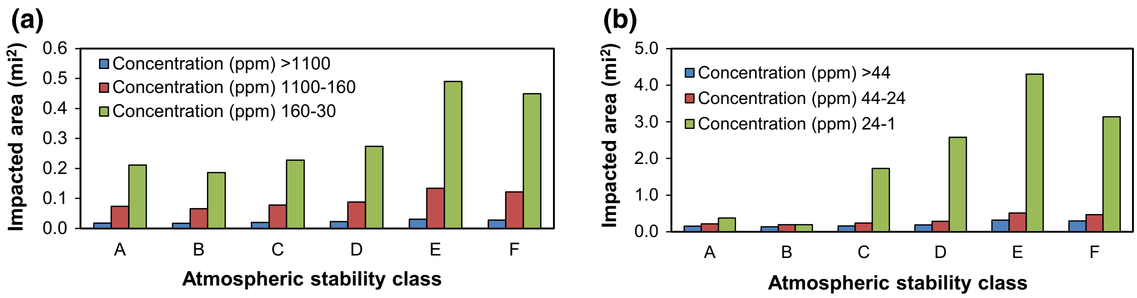


Fig. 4 Comparison of the magnitude of the areas impacted (square miles) at specific exposure levels under different atmospheric stability conditions: **a** ammonia and **b** hydrogen fluoride

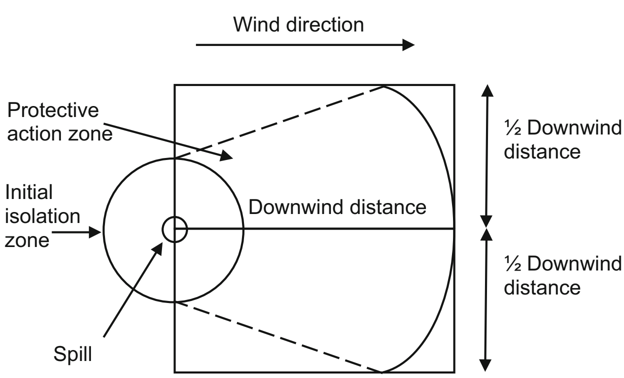


Fig. 5 Initial isolation and protective action zones

ammonia and hydrogen fluoride, extension of initial isolation and protective action distances are shown in Table 6.

Since ERG uses AEGL-2 thresholds for predicting the protective action zone, in this study the areas predicted by ALOHA under AEGL-2 and EPRG-2 levels were considered for the comparison with the protective zones defined by ERG 2012. The comparisons were conducted between two stability classes of C and F for both chemicals. The reason for selection of these two stability classes (Table 3) is because the most expanded impact zone during day (considering wind speed of 5 mph) happens under atmospheric class of C. Therefore, this scenario was selected for comparison with the protective zone defined by ERG during day time and under low wind category of protective action zone. In addition, class of F was used to compare the most extended impact zone with the protective zone defined by ERG during night (also under low wind category of protective action zone).

According to the model, the vapor cloud of ammonia would arrive at the 0.6 miles threshold for the AEGL-2 in about 17 min under stability class C (the most unstable conditions) during day time) with the assumed wind speed (5 mph). For hydrogen fluoride under the same conditions, the expansion of toxic cloud would be around 1.1 miles in 22 min, while, according to ERG 2012, the protective zone of ammonia and hydrogen fluoride during day expand to 0.6 and 1.2 miles downwind, respectively. Comparison between results of ALOHA and ERG 2012 manual shows that the result of this study is very close to those provided by ERG but more accurate in terms of retention time (Table 7). On the other hand, for the chemicals under stable atmospheric class of F (at night), ammonia would travel 1.4 miles in 38 min. However, ALOHA does not report the expansion of AEGL-2 for hydrogen fluoride, since its retention time exceeds 1 h, which is the limitation of ALOHA. Under the stability class of E hydrogen fluoride would arrive at 2.35 miles from the release point in 55 min. The results of ALOHA in comparison with that of ERG are comparable as presented in Tables 6 and 7. The similar comparison was performed, comparing Emergency Response Planning Guidelines 2 (ERPG-2) threshold, and the results of both approaches were close (Table 7).

For the size of the impacted zones estimated by ALOHA and ERG, however, the areas assigned by ERG

Table 6 Initial Isolation and protective action zones for highway truck or trailer

Chemical	Isolation zone (feet)	Protective action zone (miles)					
		Day (mph)			Night (mph)		
		Low wind <6	Moderate wind 6–12	High wind >12	Low wind <6	Moderate wind 6–12	High wind >12
Ammonia	400	0.6	0.3	0.2	1.6	0.5	0.3
Hydrogen fluoride	700	1.2	0.6	0.5	2.4	1.0	0.6

Table 7 ARPG-2 and AEGL-2 impact zone information

Level of concern[a]	Stability class	Ammonia		Hydrogen Fluoride	
		Distance (mile)	Time (min)	Distance (mile)	Time (min)
ERPG-2	C	0.63	15	1.15	23
	E	1.20	28	2.55	57
	F	1.40	38	–	–
AEGL-2	C	0.60	17	1.10	22
	E	1.15	28	2.35	55
	F	1.40	38	–	–

[a] ERG 2012 Manual: ERPG is emergency response planning guideline level, and AEGL is acute exposure guideline level

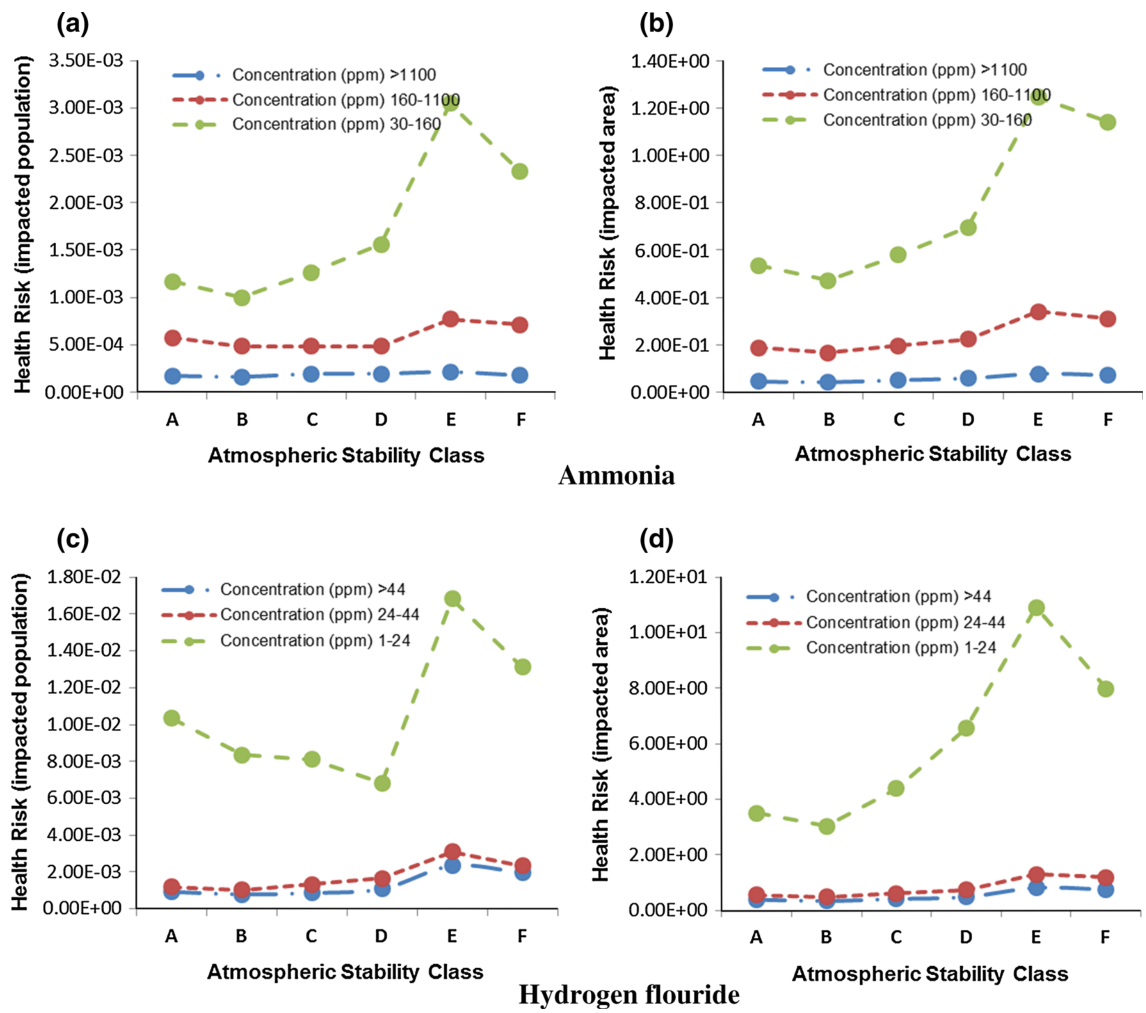


Fig. 6 Health risks based on impacted area and population for ammonia: **a** health risk based on impacted population, **b** health risk based on impacted area, and for hydrogen fluoride: **c** health risk based on impacted population, **d** health risk based on impacted area

are significantly larger than the areas by ALOHA under different stability of atmosphere. However, ALOHA does not consider any impact area upwind, while ERG defines a circular area (initial isolation) surrounding the incident in all directions to be evacuated. Since ALOHA is based on Gaussian dispersion in which the concentration only disperses downwind, the model does not provide any chemical concentration upwind, and assumes the chemical to be carried by wind in downwind only.

The health risks were calculated for the two chemicals and under different atmosphere stability scenarios. Two approaches were taken into account in order to estimate the risk, which are based on the size of the impact area and the population under risk. The size of the area impacted after a chemical release depends on the characteristics of the chemical along with the meteorological and atmospheric conditions. However, the magnitude of the population exposed depends on the population density in the surrounding area. In this regard, a similar an accidental release in two different locations would affect similar square miles but different number of people depending of the populations density (i.e., rural, urban). In this study, health risks were calculated according to the three concentration levels of the chemicals as defined by AEGLs which correspond to life threatening, significant or short-term health impacts.

Figure 6 compares the risks based on the impacted area and exposed population for each chemical at different AEGLs. In comparison with impacted areas under different stability classes from stability class of B to E, the risk increased by increase in instability of atmosphere for both chemicals. However, comparing population at risk for the two substances reveals different patterns of change. As for ammonia, similar to the pattern of impacted area, the population increased from stability B to E, for hydrogen fluoride, the trend was different so that the population decreased from stability class of B to D. This is due to the fact that considering the population affected by the chemical, the impacted zones of hydrogen fluoride became narrower and extended further along and above the water bodies close to the accident location by moving from unstable atmospheres to stable ones (Fig. 3). Therefore, the number of people who live or work in the surrounding area decreases because most parts of the impacted areas are located above the water bodies covering the regions with no population density (Fig. 3). The results presented in Fig. 6c indicate that stability condition D had the smallest risk based on the population exposed; however, stability condition B had the smallest risk based on the size of the impacted area (Fig. 6d). The analyses show that the impacts of the release and the consequences would be different if the release location was near densely populated areas.

4 Conclusions

Impact zones after a hazardous material release of either ammonia or hydrogen fluoride were compared for 2 tons of the chemicals subject to atmospheric dispersion at wind speed of 5 mph for different Pasquill–Gifford atmospheric stability classes. The study area was in Miami, FL, and USA, considering the crash data, traffic volume, and meteorological data in the region. The results of the simulations showed that for ammonia releases that occur at atmospheric conditions conducive to vertical mixing (therefore rapid dilution), at stability classes A (turbulent) to C (unstable), the downwind concentrations that are deemed to be immediate danger (over AEGL-3 threshold of 1100 ppm) extend up to 0.3 miles from the release location. Under less favorable vertical mixing conditions (e.g., typical of the nighttime), at stability classes E (stable) and F (very stable), the downwind distance over the threshold levels extends up to 0.5–0.7 miles. Zones with concentrations over the exposure threshold levels for mild/reversible symptoms (AEGL-1 threshold of 30 ppm) extend approximately 0.7–1.1 miles downwind under unstable atmospheric classes (A, B, and C) and 2–3 miles under stable conditions classes (E and F).

The impact zones estimated for hydrogen fluoride release scenario were significantly larger than those estimated for ammonia. Dilution of the chemical to the AEGL-3 threshold of 44 ppm extended approximately 0.6–0.9 miles downwind under unstable atmospheric conditions (classes A, B, C), and approximately 2 miles downwind under stable atmospheric conditions (classes E and F). Concentration within the exposure threshold for mild/reversible symptoms (AEGL-1 threshold of 1 ppm) extended approximately 1.8–3.0 miles downwind under unstable atmospheric conditions and are predicted to be larger than 4.6 miles under neutral atmospheric conditions (class D); at which point the 60-min cutoff of the model was reached.

The analyses showed that the impact zones can be significantly different for different types of hazardous cargo. The aerial magnitudes of the impact zones are highly dependent on the atmospheric stability. Releases during the day time would have relative smaller impact areas in comparison with those that occur at night. The overlay of the toxic threat zone plots over the GIS map of the accident location provided an effective tool to visualize the geographical domain affected by the release (number of people exposed, age distribution of the exposed population, potential secondary exposure routes such as water and soil). Comparison between the results of ALOHA with ERG manual for the impacted areas showed acceptable accuracy for the estimates by ALOHA. The health risks estimated based on the area and population at risk showed the significance of the consequences of the accidental releases. The analyses showed that the risk which is quantified for a specific consequence can be different from the risk quantified based upon another type of consequence (e.g., impacted area vs. population). For example, for the case of hydrogen fluoride release scenario, the lowest quantity of health risk corresponded to the stability condition D when the magnitude of impacted area was taken into account for consequence calculation. However, when the size of the exposed population was considered, stability class B was the favorable scenario (with less number of exposed people). Therefore, a great consideration should be focused on the selecting of the consequences of accidents. The results vary depending on the released chemical, atmospheric condition, location, traffic volume, and crash rate data. However, the US emergency response guideline and any other similar guidelines provide reactive approach for responding to accidents, as in recommendation of evacuation or protective distances after the accident happen. Nonetheless, this research provides a proactive action strategy, based on quantitative risk assessment and prediction of the threat zones. Considering uncertainties and lack of data, risk assessments similar to the proposed approach can help to decrease the accidental release risks of hazardous chemicals during transport by avoiding densely populated areas or segments with high crash rates, as well as selecting specific paths or road segments based on their level of accident risks. The multilevel analysis of impacts after hazardous material releases during transport (i.e., type of material, geographical data, dispersion profile, meteorological information, population density, and traffic data) can be used for planning and implementing appropriate response and mitigation measures for hazardous cargo releases to atmosphere. The insights provided by this research can aid decision makers for routing and scheduling of hazardous material cargos and developing strategies which avoid high-risk and vulnerable regions for transporting hazardous materials.

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