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Risk Analysis of Stationary Rail Cars Containing Hazardous Materials; A Case Study

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A B S T R A C T

The purpose of this study is to analyze the risks associated with stationary rail cars carrying hazardous materials (Hazmat) in railway stations. This study considers risk analysis of the Liquefied Petroleum Gas (LPG) storage cars queued in Sarakhs Railway Station in Iran. The congestion of LPG cars at station may lead to some incidents which can endanger people and cause damages to the properties and the environment, etc. This paper analyzes the consequence of any accident involving LPG at a railway station using Quantitative Risk Analysis (QRA) model. Part of the aim of this study is to estimate population exposed in cease of accident using ALOHA, MARPLOT and GIS. Main required information of this survey includes LPG transportation data, GIS, population statistics. The result of this study shows that more than 3500 people could be affected in the worst case scenario. Therefore, the recommendation is to reduce the stopping time of LPG cars in Sarakhs railway station.

1. Introduction

Accidental release and explosion of dangerous chemicals pose serious risks to people and environment. Such as the crescent accident in Illinois, U.S. which led to the death of a dozen of people and harm to properties [1]. Also catastrophic disaster in Mexico City, Mexico that killed over 500 people [2]. The intensity of such hazard depends on the chemical features of the materials, release mode, population density and geological factors. Liquefied petroleum gas (LPG) is one of these hazardous materials which may quickly evaporate and form a large cloud of gas which can remain in planetary boundary layer (PBL). The LPG, appearing in various hazardous substances lists can pose a significant vapor hazard which may cause spontaneous combustion and explosion. LPG is commonly made of propane and butane. Although incidents are unpredictable, risk assessment is necessary for reducing human and property losses. This study focused on analyzing the risks and vulnerability of population around LPG cars in Sarakhs railway station.

Vulnerability analysis has been examined with several methods such as the quantity of people who may be killed, harm or exposed by explosion [3], [4]. Li et al developed a conceptual model of human vulnerability to chemical accidents and proposed a GIS for estimating the number of exposed human in area. [5]. Also, Cutter et al, used population density to reflect relative human vulnerability in an urban area [3]. The mixture of estimated pattern surrounding the hazardous storage plotted on GIS of the area required for emergency management, rapidly identifying the area at risk, modeling different scenarios consequences and is also very helpful for making effective response and decisions for managers [6]. Some studies have been using ALOHA and GIS to analyze risk [7] and [8].

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2. Methodology

Areal Locations of Hazardous Atmospheres (ALOHA) is a dispersion modeling program able to estimate threat zones associated with hazardous chemical releases, including toxic vapor clouds, flash fires, and explosions. The model is able to expect the outcome of a sudden release of a chemical in the air and visualization of the impacted area on maps in order to have a better understanding of the situation and the extent of the impacted area. The model can keep the track of a chemical from release to vapor cloud in the air, through flammable cloud and finally fire and explosion. The model considers a number of parameters like the chemical characteristics; the cloud volume at the time of explosion; ignition type and time; and congestion level. The ignition type, which has a significant influence on the severity of the explosion practically, is the source of ignition. Deflagration and detonation explosions are two types of ignition defined in ALOHA. The former explosions are most often triggered by usual ignition like sparks, flames, heat, and electricity or even if a chemical is above its auto ignition temperature it will spontaneously catch on fire without an external ignition source. The later ignition type covers those ignitions, which are initiated by detonation. Generally, detonation explosion is more destructive than deflagration [9].

Depended on the characteristics of the materials, in case of existence of a flammable vapor, the probability of contacting the toxic gas with an ignition source should be taken into account. Occurrence of an explosion, not only menace people's life and properties, but since the explosion happens in a very few glance of time, makes the control and the prevention of expansion of the fire significantly difficult. The ignition destructive power is a function of the amount of released chemical, chemical type and presence of ignition sources in the surrounding area. The higher the amount of release, the larger the area covered by flammable cloud and the higher the probability of the vapor reaching an ignition source and causing an explosion. The type of materials is also crucial. Some hazardous chemicals are not flammable and some are extremely volatile and flammable [10].

Fire and explosion are common consequences of accidents that include chemicals. Fire can damage by radiation or by direct impingement. Explosion is the result of chemical reactions or catastrophic break of pressurized gas rail car. Explosion models involving measurement of TNT equivalents are used to calculate the effects of such accidents. For liquids, the TNT equivalent could obtain good results when calculated based on the amount of vapor present. It is calculated as following equation (2-1) [11].

$$W_v = \frac{\left(2W_l \times C_{pl} \times (T_l - T_{bp})\right)}{L} \quad (1)$$

where,

W_l weight of vapor, kg

C_{pl} specific heat of the liquid in the plant I (kJ/kg)

T_l temperature of the liquid in the plant I (Celsius)

T_{bp} boiling point of the liquid at atmospheric pressure (Celsius)

L latent heat of vaporization at T_{bp} (kJ/kg)

3. Case Study for Explosion of Stationary LPG Car

Sarakhs station which is located in North-South of Iran, is the most important international railway station in the country. This station is located near Sarakhs international Airport, Sarakhs-Mashhad road and two villages. It contains 75Km of rail tracks which include wide rails for East Asia rail transporting. A major proportion of Iran international rail transportation is being moved by Sarakhs station [12]. This station has the transportation capacity of 7 million tons of goods per year. Some main hazardous materials which has been transported are as follows: LPG, Sulfur, petroleum and fertilizer. Since this considerable volume of hazardous materials may stock for a long time, the probability of incidents happening increase [13].

Sarakhs, Iran has moderate climate with 18.6 annual average temperature, contains of open

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country grounds and bumps. The wind blows with 13.6 meter per seconds and SE direction [14]. Based on observation capacity of one LPG rail car determined 312 cubic meters. That occupied 150 tons [8]. In the worth case the length of the LPG tank queue reaches to 10 rail cars [12].

A case study was developed for hazardous material release from stationary cars that stopping in siding in Sarakhs station, Khorasan Razavi, Iran. As a result, explosion of a cloud containing hazardous chemical (Propane, Table 1) released from the source point. In this case study two series of stationary cars of quantity 150 and 1500 tons were used to evaluate the impacts after release from the accident location causing a cloud of Propane affecting the surrounding area. In this study, first flammable cloud was identified, then, the overpressure waves followed by an explosion were modeled. The treat zones were visualized using ArcGIS.

To analyze the probable treat zone of such a casual release. Two scenarios of spill as a matter of quantity of the chemical were considered (150 and 1500 tons). The amount of releases was selected based on a report from Iran's railway company [12]. Thus 1500 tons of propane releases were considered as partial and entire releases of the stationary cars to be investigated. In approximation of the impact of the overpressure waves, the worth-case scenario by the ignition by detonation was used. Different atmospheric conditions were defined to forecast the consequence of the incident for visualizing the probable consequences and treat zones (Table 2).

As stated by [15], stability class is defined as the propensity of an element of air to swing upward and downward after release through the atmosphere. Stability class "A" incline to create vertical upward movements which increases the turbulence intensity. Therefore, dispersion of chemicals in the air happens rapidly. Conversely, stability class "F" inclines to conquer turbulence and updraft movements which leads to impeded dispersion of chemicals comparing to unstable atmospheres (Table 3). The measurement of stability is difficult to calculate, [16]. A scheme for estimating the stability classes by taking into consideration the solar radiation, cloudiness, and wind speed is recommended [17]. In this study, wind speed was considered to be constant from the moment that accident occurs through complete reduction of the chemical, therefore solar radiation or cloudiness was the only parameter that could change the stability class. With regarding to different stability classes under predefined wind speed, three classes would be happened (out of six classes) (Table 2). The features of scenarios used illustrate how the conditions of accident can be integrated to reflect the site-specific information for analysis of possible impacts.

Table 1. Characteristics of Propane [18]

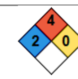
Chemical	Chemical formula	General description	Density (related to air)	Boiling point(°C)	NFPA 704
Propane	$CH_3CH_2CH_3$	Colorless, odorless gas, highly flammable, can rapidly evaporate	1.55	-42	

Table 2. Parameters used for impact analysis after accidental stationary car source

Parameters	Setting
Hazardous material	Propane
Release amount (Tons)	150, 1500
Stability Class	D, E, F
Wind speed (m/s)	13.6
Wind direction	SE
Temperature (˚c)	18.7

Table 3. The Sarakhs, Khorasan Razavi, Iran stability classes [13]

Stability class	Setting
D	Neutral
E	Slightly stable
F	Moderately stable

4. Results

The flammable area is located between two boundary values defined by the lower explosive limit (LEL) and upper explosive limit (UEL). The range between LEL and UEL denote the focus of chemical vapor in the air for explosivity. Explosive chemical vapor may contact with an ignition source and start explosion only if the focus of the materials in the air is between the two boundaries. Beyond these boundaries, the ignition will not happen; since below the LEL the focus of the chemical is too small to start and maintain burning and explosion and above the upper limit the amount of oxygen required to help the ignition is not enough to begin fire. ALOHA uses 60% and 10% of LEL as the limits of flammable area identification. Once the chemical vapor cloud approaches to an ignition source, part of the cloud which has a mix of air-chemical between the LEL and UEL cloud burn. In some cases, (like this case) the chemical will burn fast enough to cause an explosion force. The severity of explosion is a function of the chemical, cloud size, type of ignition, and exposure population level inside the vapor cloud.

The destructive explosion force of the vapor cloud in parts depends on the speed of explosion spread. The explosion forms a pressure wave which is destructive to people and properties in its way dispersing over surrounding areas. The quicker spread the more intense the pressure wave and destructive force and harm to hindrances along the wave path. Table 4 presents the levels of harm that can be expected at specific overpressure values.

There are no specific standards or guidelines to appraise the effects of explosion danger [19]. Therefore, in this study overpressure values (values in pounds per square inch, psi) were used in ALOHA model that are based on a review of broadly accepted sources on overpressure and explosions. The overpressure wave zones were defined as follows: 8.0 psi (destruction of buildings), 3.5 psi (serious injury likely), and 1.0 psi (shattered glass).

The flammable impact zone of propane presented in Figure 1.a demonstrates the areas which are located in between the two threshold values (2,100 ppm and 12,600 ppm), thus have the potential to experience an explosion if the chemical reaches an ignition source. Figure 1.b presents the blast wave zone (overpressure wave) based upon the location where the inhabitants can experience shattered windows, injuries or destruction of buildings.

This study employed ArcGIS and MARPLOT both to visualize the impacted areas and for further analysis of the threat zones where the hazardous consignment accidents may pose on people living or working around the incident location. The size and the characteristics of the impact areas as well as the number of people who would be affected by the accident were estimated by overlaying maps using ArcGIS.

Figure 2 shows flammable impact zones under each scenario. The flammable impact zones of both quantities of propane (150 and 1500 tons) showed affected areas, became greater from stability class of D to F. In Figure 2, from (a) to (c) the flammable zones of 150-tons release are shown, and (d) to (f) represent the impact zones from a 1500-tons release condition. Figure 3 shows the estimated impact zones for overpressure waves at different stability classes on the map using MARPLOT under each scenario. The study of the impact zones showed that the waves expand in semicircular shapes which is the nature of the explosion. According to assuming that surrounding zones did not have tall building which may block the explosion wave and therefore change the shape of the overpressure waves significantly. Thus, the areas of the impacted zones were significantly larger in comparison to those for the flammable impact zones. However, the amount of release increased significantly from 150 to 1500 tons. The expansion of the impacted areas by overpressure waves increased greater than the impacted areas of flammable impacted zones by same factor. The comparison of the overpressure waves under stability conditions D with those under classes E and F showed the inability of the atmosphere in decrease of the chemical, which led to more existence of the chemical in the air (larger impact zones) and consequently movement of the material elements with the power of wind along the wind direction. Under stability of E and F impacted areas of detonation waves were in oval shape because of the movement of air and the chemical by wind.

The life threating impact areas (blast waves over 8.0 psi) expansion along the wind direction under two extreme atmospheric conditions of D and F for the case of 150-tons release showed around 419 and 470 meters respectively, and for 1500-tons release values change to 2.4 and 2.7 kilometers long for the atmospheric conditions of D and F, respectively. This fact shows the enlarging of the impact areas by changing the shipment size, however not in a linear relationship with the amount of chemical. This study shows that if 150 tons release happens and leads to explosion more than 500 people may harm, on the other hands, for 1500 tons release case, more than 1600 people can be killed after these cases occur.

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The impact zones of all scenarios are calculated with ALOHA and import this area to ArcGIS for calculating exposure people. The results are presented in Table 5.

4.1. TNT equation

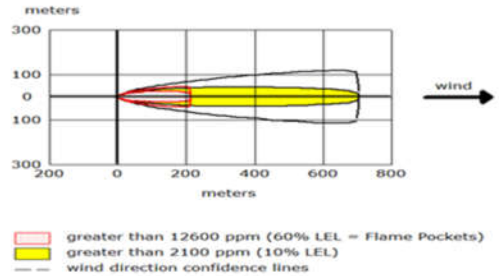
In this study the TNT equivalent of the LPG cars is calculated. The LPG cars exploded (actually, propane is considered for calculations of this equation) with two amounts. If a 150 tons LPG car exploded, the power of the explosion would have been equal to 94 tons of TNT. Also 10 cars of LPG which contains 1500kg, has the power of explosion equal to 946 tons of TNT.

4.2. FTA analysis

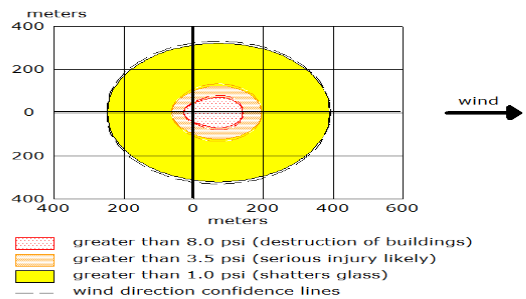
Completing the assessment of incident scenarios by the mechanism of fault tree analysis (FTA) is necessary for risk analysis. This technical term is defined as follows: “Fault tree analysis begins with fault event and the process trace back to its original causes. Using the tree the exercise is reversed, beginning at the external basic events and proceeding forward to the final consequence” [20]. Using the FTA analysis helps identifying major causes and prevent them to happen again. The FTA is presented in Figure 4. It has been drawn by Visio software.

Table 4. Levels of damage expected at specific overpressure values [1]

Expected damage	Overpressure (psi)
Loud noise; sonic boom glass shattering.	0.04
Typical pressure for glass failure.	0.15
Limited minor structural damage.	0.4
Windows usually shattered; some window frame damage.	0.5-1
Minor damage to house structures.	0.7
Partial demolition of houses; made uninhabitable.	1
Range for slight to serious laceration injuries from flying glass and other missiles.	1.0-8.0
Partial collapse of walls and roofs of houses.	2
Non-reinforced concrete or cinder block walls shattered.	2.0-3.0
Range for 1-90% eardrum rupture among exposed populations.	2.4-12.2
50% destruction of brickwork of houses.	2.5
Steel frame buildings distorted and pulled away from foundation.	3
Nearly complete destruction of houses.	5.0-7.0
Probable total destruction of buildings.	10
Range for 1-99% fatalities among exposed populations due to direct blast effects.	14.5-29.0



(a)

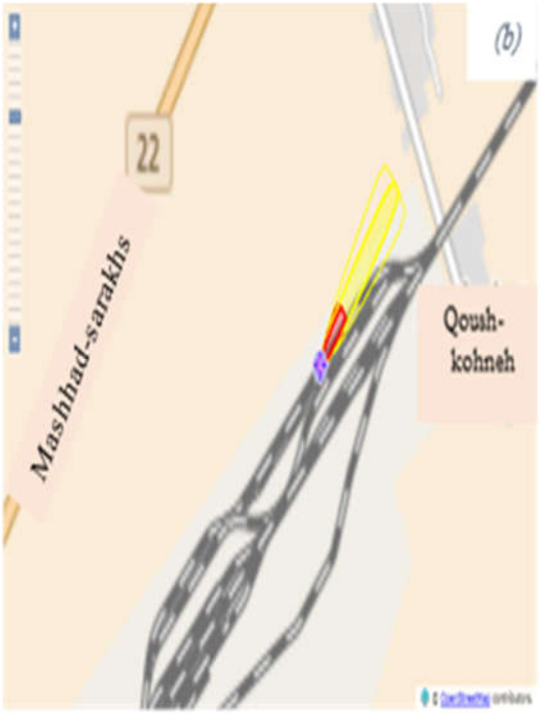


(b)

Figure 1. Definition of impact zones of propane, a: flammable zone, b: overpressure wave zone

Figure 2(a)

Figure 2(a)



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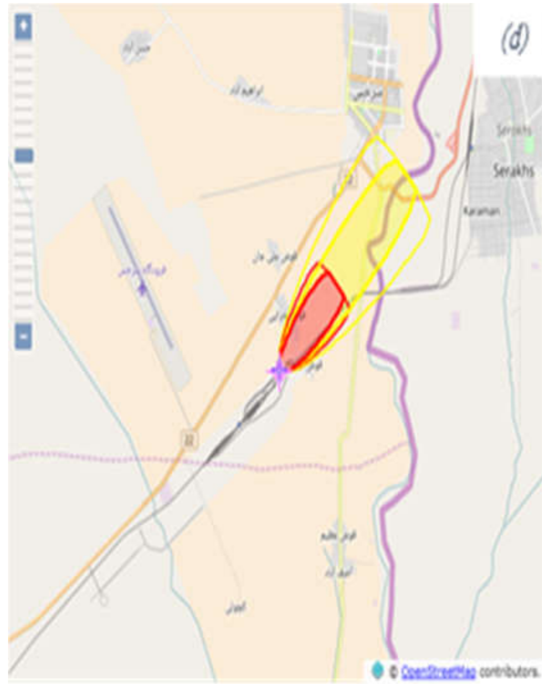

Figure 2(d)

Figure 2(c)

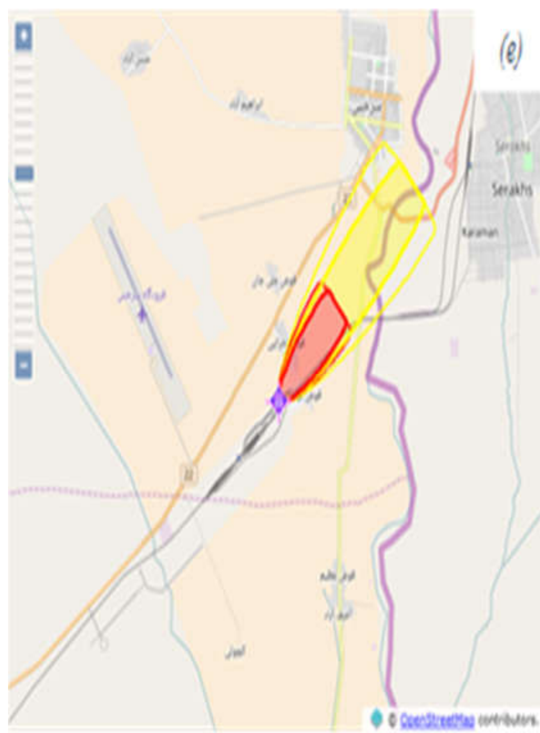

Figure 2(e)

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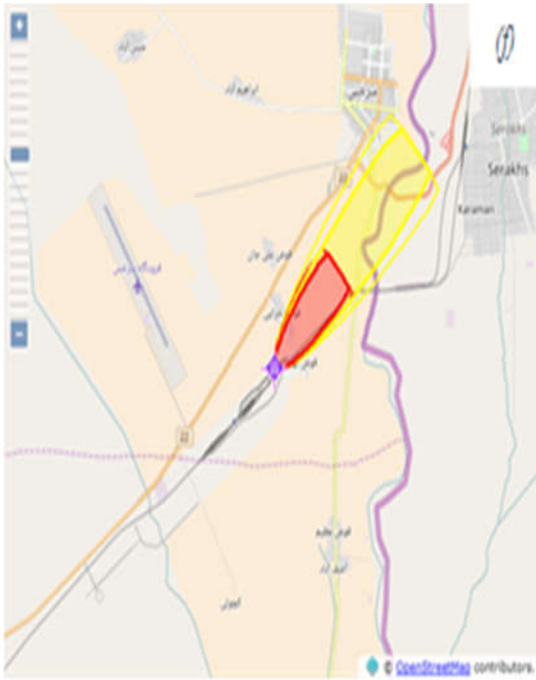


Figure 2(f)

Figure 2. Flammable impact zones for different quantities of Propane release. (1) 150-tons release: (a) stability class D, (b) stability class E, (c) stability class F; (2) 1500-tons release: (d) stability class D, (e) stability class E, (f) stability class F

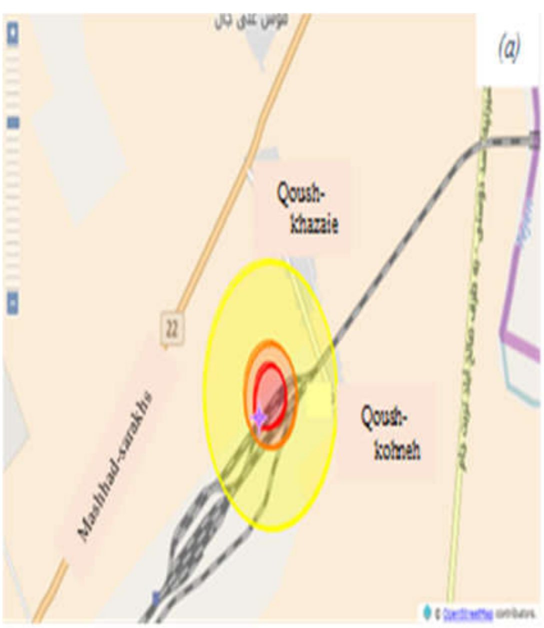
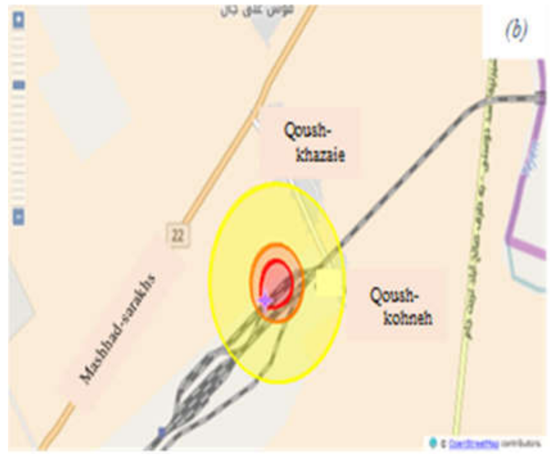


Figure 3(a)



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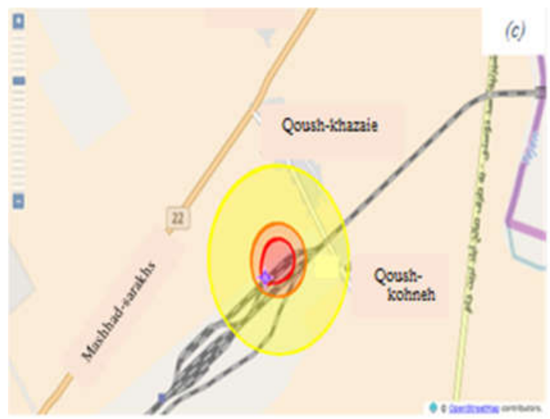

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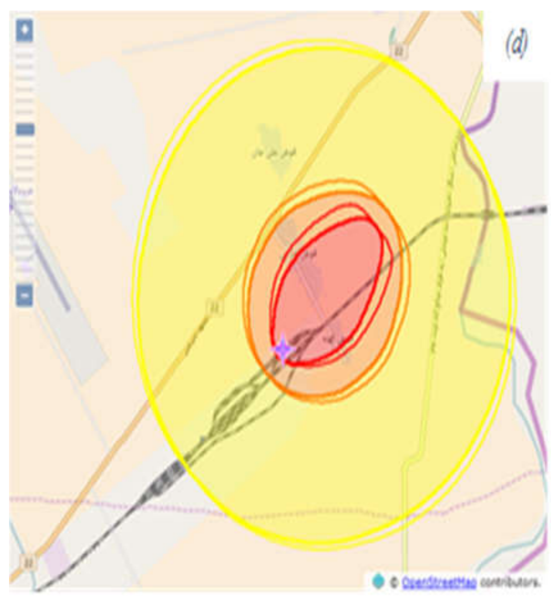

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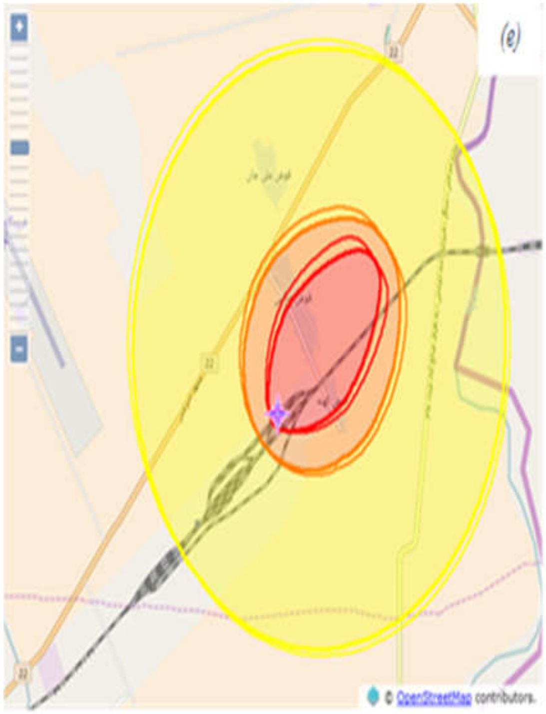

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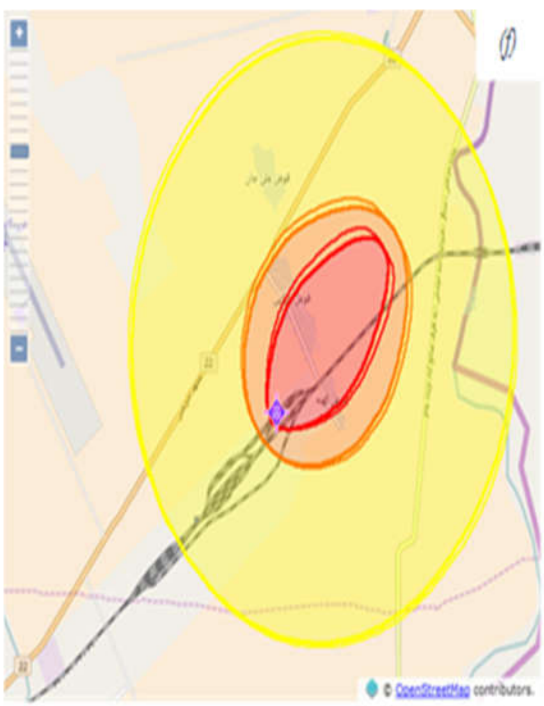

Figure 3(f)

Figure 3. Overpressure wave impact zones for different quantities of Propane release. (a), (c) 150-tons release and (b), (d) 1500-tons release, (e) & (f)

Table 5. Scenarios and consequences

Volume	Event	Weather Condition	No. of exposure
150 tons	Flammability	D	0
		E	0
		F	0
	Explosion	D	550
		E	550
		F	550
1500 tons	Flammability	D	1470
		E	1470
		F	1470
	Explosion	D	2064
		E	3534
		F	3534

5. Conclusions

In this paper population exposure in the case of LPG explosion at Sarakhs railway station has been analyzed with ALOHA and ArcGIS software. ALOHA predict the number of people whom exposed by incident in area due to the six scenarios include two different LPG volume and three weather conditions. Comparing these scenarios proves 1500 tons of propane (10 stationary cars of LPG) is the worst situation. Using ArcGIS and MARPLOT help in analyzing the exposable population in the area that more than 1600 people exposed by this danger in the worst scenario. The explosion area contains three villages, a communication road, parts of international boundary and an airport. According to this result, it is necessary to plan some functions before, during and after incident that need to be studied in future. Some enforcements must be planned to minimize the LPG train stop time at railway station or using some tools and materials to mitigate the risk. To minimize the train stop time in Sarakhs station, it is necessary to make some changes such as increasing the number of locomotives while the number of LPG cars decreases, mark the LPG cars as high priority cars to speed up their departure period. Using some preventions may reduce the explosion rate or eliminate it.

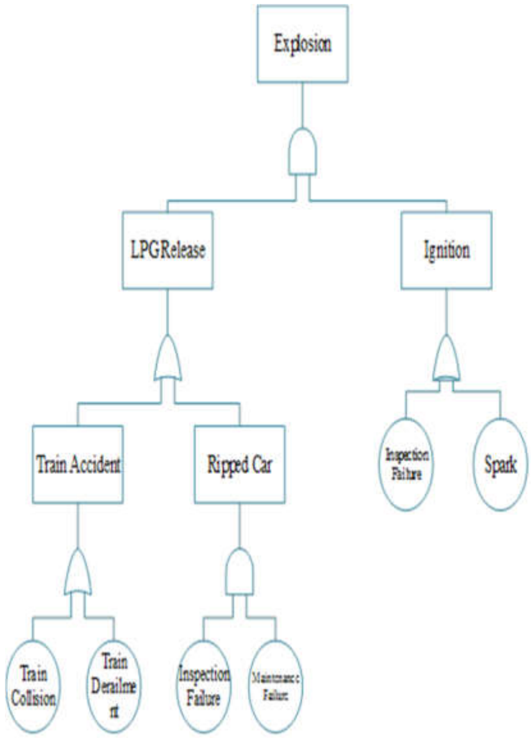

Figure 4. Fault Tree Analysis

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