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Accidents occurring during transportation of hazardous substances and modeling of their consequences

by

Tasneem Abbasi[*1], R. Ramyapriya[1], S. M. Tauseef[2], and **S. A. Abbasi[1]**

[1]Centre for Pollution Control & Environmental Engineering
Pondicherry University, Chinakalapet
Puducherry 605 014, India
[2]Environmental Research Institute
University of Petroleum and Energy Studies
Dehradun 248 007, India

Abstract

A large number of process industries deal with reactants and products that are highly flammable and/or toxic. Such substances have to be transported to and from the industries in large quantities on a regular basis. If the automobile, train, or ship carrying such a substance meets with an accident, it may lead to the spilling of the substance and an escalation of the transportation accident into a chemical-related disaster as a consequence. It may also happen that a flammable substance gets leaked out, catches fire, and causes the carriage to suffer an accident which otherwise would not have occurred. In either situation great harm may be caused to the area where a transportation accident of this type takes place. This paper tracks the case histories of some of the major accidents involving transportation of hazardous substances and examines the models available to forecast the severity and the consequences of such accidents.

Keywords: Flammable substances, toxic chemicals, accidents, transportation, consequence modeling

1. Introduction

Petrol, diesel, compressed natural gas (CNG), liquid petroleum gas (LPG) and kerosene are among the liquid/gaseous fossil fuels which are highly hazardous due to their flammability. But these substances have to be transported in very huge quantities from oil/gas wells to refineries to users round the clock throughout the world. Then there are industrial gases like chlorine and ammonia and liquids like oleum, nitric acid, and hydrochloric acid, which are highly toxic and corrosive. These also have to be transported in huge quantities either to the industries which use these chemicals or from the industries which manufacture these chemicals. Whereas storing and handling of such hazardous substances in any industry generates risk of accidents ─ explosions/fire/toxic release ─ the risk is heightened when such substances are to be transported (Birk, *et al.*, 1990). Unlike the situation within an industry, where several systems of alarms, cushions, and buffers are installed to forewarn people of an accident and to contain the accident, no such layers of protection exist outside the industry on the routes along which hazardous substances are transported. A transportation accident involving a chemical takes the people of the area, where the accident occurs, completely by surprise (www.tunnelfire.com). Nor, unlike within industries, are experts available to handle the consequences of a transportation accident. Moreover, a transportation accident can cause other accident, or 'domino effect' For these reasons many chemical transportation accidents take a very heavy toll of lives.

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2. Illustrative case histories of past accidents

Tables 1 and 2 present catalogues of several major accidents that have occurred during the transformation of hazardous substances by rail-road (Table 1) and road (Table 2) The lists are only representative, and are by no means exhaustive.

The manner in which some of these accidents unfolded is illustrated below.

Table 1: An illustrative list of some of the major rail road accidents Abbasi and Abbasi, 2007; Khan and Abbasi, 1999; Haastrup and Brockhoff,1990; Abbasi and Abbasi, 2007; Khan and Abbasi 1997; Khan and Abbasi, 1997; Khan and Abbasi, 1999; www.rssb.co.uk)

Date	*Location*	*Cause*	*Material*	*Event*	*Deaths (d), Injured (i)*
Jul.7,13,1928	Asbokan, NY	Rail tank car accidents	Chlorine	Toxic Exposure	-
Feb. 28,1934	Niagara Falls, NY	Rail tank car accidents	Chlorine	Toxic Exposure	-
Mar.13, 1935	Griffith, IN	Rail tank car accidents	Chlorine	Toxic Exposure	-
Jan. 26, 1940	Mjodalen, Norway	Rail tank car accidents	Chlorine	Toxic Exposure	3d
Jul. 29,1943	Ludwigshafen, Germany	Rail tank car accidents	Butadiene	Vapor Cloud Explosion	57d, 439i
Feb.4, 1947	Chicago, IL	Rail tank car accidents	Chlorine	Toxic Exposure	-
July 23,1948	Ludwigshafen, FRG	Rail tank car accidents	Dimethyl ether	Vapor Cloud Explosion	207d, 3818 i
Oct. 1949	Winthrop, MO	Rail tank car accidents	LPG	Fire	1d
Jul. 20,1950	Billingham, UK	Rail tank car accidents	Chlorine	Toxic Exposure	-
Jun. 4,1954	Institute, WV	Rail tank car accidents	Acrolein	Internal Explosion	-
Oct. 18,1954	Portland, OR	Rail tank car accidents	LPG	Vapor Cloud Explosion	-
Jul. 19,1955	Ludwigshafen, FRG	Railroad accident	LPG	BLEVE	2i
Jan.3,1958	Celle, FRG	Rail tank car accidents		Explosion	-
Jan. 22 1958	Niagara Falls, NY	Rail tank car accidents	Nitromethane	Fire	200i
Jun. 28 1958	Meldrim, GA	Rail tank car accidents	LPG	BLEVE	23d
Jun. 2 1959	Deer Lake, PA	Rail tank car accidents	LPG	BLEVE	11d, 10i
Jan. 31 1961	La Barre, LA	Rail tank car accidents	Chlorine	Toxic Exposure	1d, 114i
Nov. 30 1962	Cornwall, Ont.	Rail tank car accidents	Chlorine	Toxic Exposure	89i
Apr. 28 1963	Brandtsville, PA	Rail tank car accidents	Chlorine	Toxic Exposure	-
Aug. 9 1963	Philadelphia, PA	Rail tank car accidents	Chlorine	Toxic Exposure	430+ i
Jun. 14 1966	La Spezia, Italy	Rail tank car accidents	Chlorine	Toxic Exposure	-
Nov. 8 1967	Newton, AL	Rail tank car accidents	Chlorine	Toxic Exposure	-
Jan. 1 1968	Dunreith, IN	Rail tank car accidents	VCM , Ethylene oxide	BLEVE	5i
Jan. 25 1969	Laurel, MS	Rail tank car accidents	LPG	BLEVE	2d, 23+ i

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Feb. 18 1969	Crete, NE	Rail tank car accidents	Ammonia	Toxic Exposure	9d, 53i
1969	Cumming, IA, USA	Derailment	Ammonia	BLEVE	-
Sep. 11 1969	Glendora, MS	Rail tank car accidents	VCM	Toxic Exposure, Vapor Cloud Explosion	1i
Jan. 21 1970	Belle, WV	Rail tank car accidents	Ammonia	Toxic Exposure	1i
June 21 1970	Crescent City, IL, USA	Derailment	Propane (5)	BLEVE	66i
Jan. 19 1971	Baton Rouge, LA	Rail tank car accidents	Ethylene	Vapor Cloud Explosion	21i
Oct. 19 1971	Houston, TX	Rail tank car accidents	VCM	BLEVE	1d, 5i
Feb. 9 1972	Tewksbury, MA, USA	Collision	Propane	BLEVE	-
Sep. 21 1972	NJ Turnpike, NJ,USA	Collision	Propylene	BLEVE	2d
Oct. 22 1972	East St Louis, IL	Rail tank car accidents	Propylene	Vapor Cloud Explosion	1d, 230i
Mar. 5,1973	Loos, BC	Rail tank car accidents	Chlorine	Toxic Exposure	-
May 24 1973	Benson, AR	Rail cars accidents	Munitions	Explosion	-
Jul. 5 1973	Kingman, AZ	Rail tank car accidents	Propane	BLEVE	13d, 95i
Nov. 6 1973	Ventura County, CA	Rail tank car accidents	LPG	Explosion	2d, 4i
Feb 12 1974	Oneonta, NY	Derailment	Propane	BLEVE	25i
Jun. 26 1974	Climax, TX	Rail tank car accidents	VCM	Vapor Cloud Explosion	7d
Jul. 19,1974	Decatur, IL	Rail tank car accidents	Iso-butane	Vapor Cloud Explosion	7d, 152i
Aug. 6 1974	Wenatchee, WA	Rail tank car accidents	Monomethylamine Nitrate	Fire	2d, 113i
Sep. 21 1974	Houston, TX	Rail tank car accidents	Butadiene	Vapor Cloud Explosion	1d, 235i
April 29 1975	Eagle Pass, TX, USA	Collision	Propane	BLEVE	16d
Sep. 1 1975	Des Moines, IA	Rail tank car accidents	LPG	BLEVE	3i
1975	Des Moines, IA, USA	Rail Tank Car accidents	LPG	BLEVE	3i
May 11 1976	Houston, TX, USA	Collision	Ammonia	BLEVE	6d
Nov. 26 1976	Belt, MT	Rail tank car accidents	LPG	BLEVE	22i
1976	Belt, MN, USA	Rail tank car accidents	LPG	BLEVE	22i
1977	Dallas, USA	Rail tank car accidents	Isobutene	BLEVE	1i
Date	Location	Cause	Material	Event	
1977	Goldona, VA	Rail tank car accidents	LPG	BLEVE	2d, 9i
Feb. 20 1977	Dallas, TX	Rail tank car accidents	Isobutene	Vapor Cloud Explosion	1i
Nov. 9 1977	Pensacola, FL	Rail tank car accidents	Ammonia	Toxic Exposure	-
Dec. 28 1977	Goldonna, LA	Rail tank car accidents	LPG	Fire Ball	2d, 9i
Feb. 24 1978	Waverly, TN	Rail tank car accidents	Propane	BLEVE	16d, 43i
Feb. 26 1978	Youngstown, FL	Rail tank car accidents	Chlorine	Toxic Exposure	8d, 114i
May 29 1978	Lewisville, AR	Rail tank car accidents	VCM	Fire Ball	2i
Sep. 27 1978	Oviedo Province, Spain	Rail tank car accidents	Gasoline	Explosion, Fire	7d
Apr. 8 1979	Crestview, FL	Rail tank car accidents	HMs	Toxic Exposure	14i
Jul. 18 1979	Bayonne, NJ	Rail tank car	Chlorine	Toxic Exposure	-
Sep. 8 1979	Paxton, TX	Rail tank car accidents	Chemicals	BLEVE	8i

Nov. 10 1979	Mississauga, Ont.	Rail tank car accidents	Chlorine	Toxic Exposure	-
Jul. 26 1980	Muldraugh, KY	Rail tank car accidents	VCM	Fire	4i
Aug. 1 1981	Montana, Mexico	Rail tank car accidents	Chlorine	Toxic Exposure	17d, 280i
Sep. 28 1982	Livingston, LA	Rail tank car accidents	Flammables, Toxic Exposure	Fire, BLEVE	-
Apr. 3 1983	Denver, CO	Rail tank car accidents	Nitric acid	Toxic Exposure	-
Jul. 30 1983	Baton Rouge, LA	Rail tank car accidents	VCM	Fire	-
Nov. 2 1983	Dhurabar, India	Rail tank car accidents	Kerosene	Explosion	47d
Feb. 23 1985	Jackson, SC	Rail tank car accidents		Fire	-
Jun. 9 1985	Pine Bluff, AR	Rail tank car accidents	HMs	Fire	-
Aug. 23 1987	Lanzhou, China	Rail tank car accidents	Gasoline	Fire	5d
June 4 1988	Arzamas, USSR	Rail station accidents	Explosives	Explosion	73d, 230i
Jul. 30 1988	Altoona, IA	Rail tank car accidents	HMs	Explosion	-
Jul. 22 1989	Freeland, MI	Freight train accidents	HMs	Explosion	-
March 4 1996	Weyauwega, WI, USA	Derailment	Propane, LPG	BLEVE	-
Feb 14, 1998	Yaounde, Cameroon	Collision and derail	Crude oil	Explosion and Fire	200d,150i
Sep 23 1999	Toronto, Canada	Derailment	LPG	BLEVE	-
Dec 30 1999	Quebec, Canada	Derailment, Collision	Hydrocarbons	BLEVE	2i, 350 evac
May 27 2000	Eunice, LA, USA	Derailment	Flammable PLGs	BLEVE	2000 evac.
Feb 20 2002	Cairo, Egypt	Fire caused in a passenger train by a butane tank	Butane	BLEVE	373d, 7500i
February 18,2004	Nishapur, Iran	Derailment	petrol	Fire and Explosion	300d,460i
Jan 6, 2005	Graniteville, US	Collision	chlorine	Explosion	9d,250i
Oct 15 , 2005	Texaekana, US	Derailment	propylene	Explosion	-
Jan 16, 2007	Kentucky, US	Derailment		Fireball and Fire	-
July 16, 2007	Lviv, Ukraine	Derailment	phosphorus	Toxic Exposure vapor and fire	-
Oct 10, 2007	Painesville, US	Derailment	Ethanol and butane	Explosion and Fire	-
Oct 22, 2007	Vermont, US	Derailment	gasoline	Explosion and Fire	-
Dec 23 2008	Ventspill, Latvia	Collision	Diesel	Fireball and Fire	2d
June 29 2009	Viareggio, Italy	Collision	LPG	Vapor Cloud Explosion	31d ,30i
28 Aug 2009	Yaounde, Cameroon	Derailment	Diesel and petrol	Explosion and Fire	1d
Oct 31 2011	Kota Kinbalu, Malaysia	Grade crossing	gasoline	Explosion and Fire	12i
Jan 6 2012	Porter country	Collision	diesel	Pool Fire	2i
July 11 2012	Columbus, US	Derailment	ethanol	Explosion (Fire Ball)	2i
Oct 29 2012	Kentucky, US	Derailment	butadiene	Explosion and Pool Fire	5i
Nov 9 2012	Kantbalu, Burma	Collision	Petrol and diesel	Explosion and Pool Fire	27d,80i
May 3 2013	Schellebelle, Belgium	Derailment	acrylonitrate	Explosion and Toxic Exposure	1d,33i
July 6 2013	Lac megantic, Canada	Derailment	Crude oil	BLEVE	-
Oct 1 2013	Edmonton, Canada	Derailment	LPG	Explosion and Pool Fire	-

Nov 8 2013	North Dakota, US	Derailment	Crude oil	Explosion	-
Dec 30 2013	Casselton US	collision	Crude oil	BLEVE	-
Jan 7 2014	New Brunswick, Canada	Derailment	Crude oil	Pool Fire	-
Jan. 20 2014	Philadelphia, US	Derailment	Crude oil	Pool Fire	-
Apr 30 2014	Lynchburg, US	Derailment	Crude oil	Pool Fire	-
May 10 2014	Colorado, US	Derailment	Crude oil	Pool Fire	-
Oct. 7 2014	Clair, Canada	Derailment	Petroleum distillate	Pool Fire	-

Table 2: An illustrative list of some of the major road accidents Abbasi and Abbasi, 2007; Khan and Abbasi, 1999; Haastrup and Brockhoff,1990)

Date	*Location*	*Cause*	*Material*	*Event*	*Deaths (d), Injured (i)*
Jan. 18, 1943	Los Angeles, CA	Road tanker accident	Butane	Vapor Cloud Fire	5d
Oct.13, 1948	Sacramento, CA	Road tanker accident	Butane	Fire	2d
Aug., 1950	Wray, CO	Road tanker accident	Propane	Vapor Cloud Fire	2d
Aug. 7, 1956	Cali, Columbia	Road vehicle accident	Dynamite, munitions	Explosion	1200d
Feb.27, 1959	Portland, OR	Road tanker accident	LPG	Fire	-
Jul. 25, 1962	Berlin, NY	Road tanker accident	LPG	Vapor Cloud Explosion	10d, 17i
Apr. 3, 1963	Norwich, CT	Transport tank	Organic peroxides	Explosion	4d, 4i
Aug. 21,1968	Lievin, France	Road tanker accident	Ammonia	Toxic Release	5d, 20i
May 30 1970	Brooklyn, NY	Road tanker accident	Oxygen	Fire	2d, 30i
Nov.12 1970	Hudson, OH	Road tanker accident	LPG	Fire	6d
Jun. 4 1971	Waco, GA	Road vehicle accident	Explosives	Explosion	5d, 33i
Aug 8, 1971.	Gretna, FL	Road tanker accident	Methyl bromide	Toxic Release	4d
Mar. 9 1972	Lynchburg, VA	Road tanker accident	Propane	Fire Ball	2d, 5i
Sep. 21 1972	NJ Turnpike, NJ	Road tanker accident	Propane	Fire	2d, 28i
Feb. 1, 1973	St-Amand-les-Eaux	Road tanker accident	Propane	VCE	9d, 37i
Jan. 4, 1974	Holly Hill, FL	Road tanker accident	Propane	Vapor Cloud Explosion	-
Jan. 17, 1974	Aberdeen, UK	Road tanker accident		Fire Ball	-
Apr.30,1975	Eagle Pass, TX	Road tanker accident	LPG	Fire Ball	17d, 34i
Dec.14,1975	Niagara Falls, NY	Road tanker accident	Chlorine	Toxic Release	4d, 80i
May 11,1976	Houston, TX	Road tanker accident	Ammonia	Toxic Release	6d, 178i
Sep.11,1976	Westoning, UK	Road tanker accident	Petrol	Explosion	3i
Jan. 27,1977	Baytown, TX	Road Tanker accident	Gasoline	Vapor Cloud Explosion	3d
Sep.24,1977	Beattyville, KY	Road tanker accident	Gasoline	Fire	7d, 6i
May 29,1978	Mexico City, Mexico	Road tanker accident	Propylene	Fire	12d
Jul. 11,1978	San Carlos, Spain	Road tanker accident	Propylene	Vapor Cloud Fire	216d, 200i

Jul. 15,1978	Xilatopic, Mexico	Road tanker accident	Butane	Vapor Cloud Fire	100d, 220i
Jul.16, 1978	Tula, Mexico	Road tanker accident	Butane	Explosion	12d
Mar. 3,1980	Los Angeles, CA	Road tanker accident	Gasoline	BLEVE	2d, 2i
Nov 25,1980	Kenner, LA	Road tanker accident	Gasoline	Fire	7d, 6i
May 3 1982	Caldecott Tunnel, Oakland, CA	Road tanker accident	Gasoline	Fire	7d
Dec.29,1982	Florence, Italy	Road tanker accident	Propane	Explosion	5d, 30i
Mar. 22,1989	Peterborough, UK	Road vehicle accident	Explosives	Explosion	1d, 107i
Sep. 24,1990	Bangkok, Thailand	Road tanker accident	LPG	Vapor Cloud Fire	68d, >100i
18 Mar,1996	Palermo, Italy	Collision in a highway tunnel	Propane	BLEVE	5d, 25i
Apr, 30 1999	Between Athens and Lamia, Greece	Traffic accident	LPG	BLEVE	4d, 13i
Jan. 7 2001	Kanpur, India	Highway accident	LPG	BLEVE	12d, 6i
June 22 2002	Tivissa, Spain	Tanker overturned	LNG	BLEVE	1d, 2i
Jan 13 2004	Baltimore, Washington Highway, USA	Traffic accident	Propane	BLEVE	10d
Feb 2 2007	Tigbao, Philippines	Tanker overturned	Liquefied Carbon-di-oxide	Explosion	50d, 65i
Mar 28 2007	Kagarko, Kaduna, Nigeria	Road Tanker	Gasoline	Fire and Explosion	80d, 100+ i
May 14 2007	Ahmedabad, India	Road oil tanker and bus collision	Petrol	Explosion	30d
Sep 22 2007	Udupi, India	Road Tanker accident	LPG	Fire	2d
Sep 9 2007	Monclova, Mexico	Tractor overturned	Ammonium Nitrate	Fire	30d, 150+ i
Feb 18 2008	Beijing–Zhuhai expressway, China	Bus and Truck collision		Fire and Explosion	15d, 25i
July 26 2008	Lagos, Nigeria	Road tanker accident	Gasoline	Explosion	10d
Oct 6 2009	Islamabad, Pakistan	Collision		Explosion	9d, 7i
July 2 2010	Sange, in South Kivu province, Congo	Tanker Overturned	Petrol	Explosion	230d, 196i
Jan 23 2011	Sindh province, Pakistan	Collision		Explosion	32d
Feb 1 2011	Molo city, Kenya	Road tanker accident	Petrol	Explosion	110d
Feb 4 2011	Tundla UP, India	Road-tanker accident	LPG	Explosion	3i
April 2 2011	Close to Narabi. Nigeria	Road tanker overturned	Gasoline	Fire	50d
Dec 29 2011	Caracas-Los Teques Route, Venezuela	Road tanker overturned	Gasoline	Explosion	14d, 16i
April 26 2011	Emirates Road, Ajman, United Arab Emirates	Petrol tanker overturned	Petrol	Collision	2d, 2i
June 9 2012	Lagos-Ibadan Expressway, Nigeria	Road tanker accident	Petrol	Fire and Explosion	-
June 26 2012	Parañaque city, Philippines	Road tanker overturned	Petrol	Fire and Explosion	1i
July 12 2012	Okobie, Nigeria	Road tanker overturned	Petrol	Explosion	200d, 75i

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July 27 2012	Surajpur, Dadri area, India	Gas tanker accident	LPG	Explosion	2d, 20i
August 27 2012	National highway in the Chala area, India	Tanker overturned	LPG	Fire	2d, 41i
August 26 2012	Northern China, China	Bus and tanker collision	Methanol	Explosion	36d
Sep 6 2012	Mumbai-Pune Expressway, India	Collision	Isobutene	Explosion	-
Sep 11 2012	Teheran, Iran	Road tanker Road tanker	Petrol	Explosion	70d
Sep 14 2012	Kabul-Kandahar highway, Afghanistan	Bus and tanker collision		Collision	51d

Crescent city derailment, Illinois, USA, 1970 (Figure 1)

On June 21, 1970, fifteen cars of a 108-car freight train derailed in crescent city, Illinois. Ten of the derailed cars carried propane. Several of those propoane-filled tanks which had suffered cracks underwent boiling liquid expanding vapour explosion (BLEVE), generating fireballs. During the firefighting operations a hitherto intact tank also underwent a BLEVE. One part of the tank was thrown 183 m away. Two other explosions followed, leading to a fireball of 150-200 m diameter. It took 3 days for all the released propane to burn out.

Decatur tank car accident, Illinois, USA, 1974

On July 19, 1974, a freight rail containing isobutene collided with a box car causing puncture in the tank car, releasing about 118700 litres of isobutene. A vapour cloud was formed from the released gas which got ignited 10 minutes later, leading to an explosion. The accident led to the death of 7 persons and injury to 349. Structural damage was noticed up to 4.8 kilometres from the accident site.

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Figure 1: The havoc caused by Crescent city derailment, USA, in 1970 (left) (www.daily-journal.com) and the Los Alfaques disaster at Spain 1978 (right) (gettyimages.in/photos/alfaques)

Los Alfaques disaster, Spain, 1978 (Figure 1)

On 11 July 1978, a tanker containing 23,000 kg of propylene suffered failure while moving across the campsite near Los Alfaques. The tank leaked and a cloud of gaseous propylene was formed, which got ignited and exploded, rupturing the weakened tank and igniting full load of propylene, resulting in a fireball. As many as 217 people died and 200 were injured.

Yaounde train explosion, Cameroon, 1998

On February 14, 1998, a train carrying petrol collided with the another freight train and derailed, spilling its content. A large number of people rushed to collect the fuel, where accidently one of the persons dropped a lit cigarette which generated flash fire. The fire travelled into the tankers leading to explosion a massive fireball which engulfed the surrounding area. There were 200 people dead.

LPG tank trucker explosion, Kanpur, India, 2001 (Figure 2)

On 7 January 2001, a tanker carrying LPG from Jamnagar to Varanasi met with a head-on collision due to poor visibility with another truck carrying plywood. There was a profuse leakage of LPG which formed a pool fire below the bullet carrying the LPG, thereby heating the bullet. It suffered a massive BLEVE. It caused the bullet to burst into 5 pieces which flew in different directions. The accompanying fire ball went 15 m high. The two dish ends were thrown 150 m away.

Twelve persons, including the driver died and 6 others suffered burn injuries.

Figure 2: Explosion and fire due to LPG tank trucker explosion at Kanpur in 2001, (left), (thehindu.com/news/national/Three-killed-as-LPG-tanker-explodes/article1856354.ece) and the Sange catastrophe Congo of 2010 (right), (lesignalducontinent.over-blog.com)

Viareggio Train Derailment, Italy, 2009

On June 29, 2009, a freight train carrying LPG was derailed near Viareggio station. The first tank crashed into a signaling stake and LPG was released from the vessel. The LPG flashed partially and the remaining liquid fraction spread over and formed liquid pools. On evaporation they formed a vapour cloud which drifted to the nearby areas. There it got ignited and exploded.

Thirtyone people died and another 30 were injured.

Catastrophe of Sange, Congo, 2010 (Figure 2)

On 2, July 2010, a road tanker carrying gasoline overturned in the village of Sange, while trying to overtake a bus. There was huge leak of petrol from the tanker and people gathered to collect the gasoline. Suddenly the tanker got ignited due to a cigarette spark and exploded, leading to a fireball which destroyed the entire village. About 230 people died and another 196 were injured.

LPG tanker explosion, Kannur, India, 2012 (Figure 3)

On August 27, 2012 a tanker lorry carrying 16 tons of LPG from Kannur to Thalasseri rammed a divider while trying to overtake another vehicle. The LPG gas leaked forming a pool fire, which was followed by a BLEVE. Witnesses say that there were 3 explosions at intervals of 3 minutes each. Due to the third explosion, one third of the container was thrown 500 m away. The accident killed 20 people and injured another 21.

Figure 3: Scenes of LPG tanker explosions at Bangkok, 1990 (left), (ndtv.com/topic/tanker-explosion), and Kannur, 2013 (right), (richardbarrow.com/2012/09/24-september-1990-bangkok-gas-explosion-kills-about-90/)

Lac Megantic Derailment, Canada, 2013

On July 6, 2013 a freight train carrying crude oil was derailed in the city of Lac Megantic, because of break system failure. Sixty three of the derailedtank cars leaked about 6 million

litres of crude oil which was spontaneously ignited leading to a series of BLEVEs. According witnesses, there were 6 explosions, each generating a massive fireball.
As oil flowed all over the ground, the fire entered into storm sewers and huge firesemerged in all sewer drains and manholes in that area. The heat from the fires was felt as far as 2 kilometres away from the accident area. The accident killed 42 people and destroyed 20 buildings.
Bangkok road tanker explosion, Bangkok, 1990 (Figure 3)

On September 24, 1990 a road tanker carrying 20,000 litres of LPG was speeding up to avoid the traffic signals but eventually tipped at an intersection. Two of the storage tanks which contained LPG went rolling across the road. One of the cylinders got cracked; spilling its contents which were ignited due to sparks from the crash. The fire spread and ignited the second cylinder which exploded. Fiftynine people were killed and 45 cars which happened to be around, were destroyed.

3. Causes and consequences of accidents occurring during transportation

Past accident analysis (PAA), which involves a detailed post-mortem of post-accidents, provides valuable clues to the reasons why that accident took place and the way it evolved. This exercise tells us a lot about how to prevent the recurrence of such an accident. The 'wisdom of hindsight' thus obtained forms a very major input in accident forecasting and prevention. All industrial accidents follow a three-step sequence: initiation, propagation and termination (Crowl and Louvar,2011).The initiating events forms the most basic part of risk analysis, and it is believed that accidents can be best controlled by eliminating the initiating events (Khan and Abbasi,1999; Crowl and Louvar,2011). Though achieving such an elimination is practically impossible, detailed knowledge on the cause-consequence relationships gives valuable pointers for designing strategies for the prevention, control, and of accidents (Planas Cuchi *et al.*,1996).

3.1 Events (causes) that initiate transportation accidents involving a hazardous substances

The initiating events for transportation of flammable liquids can be'accident initiating events' and 'non- accident initiating events' (CCPS. 2008; Lees*et al.*,2005).

3.1.1 The accident initiating events

These are caused by factors (Shen *et al.*, 2013; Linkute, 2011; CCPS, 2008; Oggero *et al.*, 2006; Lees *et al.*, 2005) which can lead to a transportation accident:

- Vehicle defects
- Human factors
- Road/rail defects

3.1.2 The non- accident initiating events

These events are associated with weakness that occursindependent of whether a chemical is under transport or not: They do not include the external impact during transportation, and are caused by internal failures and defects. The possible causes are (Shen *et al.*, 2013; Linkute, 2011; CCPS, 2008; Oggero *et al.*, 2006; Lees *et al.*, 2005):

- Improper securement
- Corrosion and other factors weakening the containers of the chemicals
- Overfilling or under filling
- Contamination
- Temperature changes leading to loss of refrigeration and consequent overheating)

3.2 Consequences of accidents

According to CCPS (Centre for Chemical Process Safety), the consequence of a process industry accident is defined as the "direct, undesirable result of an incident outcome, specifically the impacts resulting from the release of hazardous material. Consequence is generally a function" of the material released, the extent of the release, and the nature of the area to which the consequences propagate (CCPS, 2008; EPA, 1994).

As per CCPS (Centre for Chemical Process Safety), the extent of the impacted area of a transportation accident depends on:

- "The physical properties of the released material
- Its quantity being transported
- Shipping conditions (pressure and temperature)
- Container design and features
- Conditions of the accident
- Atmospheric conditions (ambient temperature, humidity, wind speed, wind direction, etc)".

The possible outcomes of the release of hazardous materials during transportation are:

- Fire
- Explosion
- Toxic release
- Deaths, injuries, property damage
- Contamination of land, water, and air

The event tree with various likely sequences is shown in Figure 4.

4. Models and codes for forecasting transportation accidents and their likely consequences

Risk assessment involves the forecasting of both the frequency and the consequences of accidents. For accidents involving flammable substances, fire and explosion models enable forecast of thermal radiation, overpressure, and missiles. For toxic releases the models forecast the pattern of the build-up and the dispersion of the toxicity. The effect models assess the effects of the accident vecotrs on people (injury or death) and structures.

4.1 Heat load generated by a propane Fireballs (Hardee and Lee, 1973)

Let us assume that a truck containing propane is involved in an accident. A cloud of fuel and air is formed. When it ignites, a fireball is formed and thermal energy is emitted from the fireball. For such scenarios, the model of Hardee and Lee (1973) discusses heat load on an object at the center of the fireball and at various distances from the fireball (Hardee, 1973).

The assumptions made are (www.dtic.mil):

1. Rate of propane addition to fireball is constant
2. Stoichiometric mixture exists at ignition
3. All available fuel participates in the fire ball
4. Fire ball is a spherical, isothermal and homogenous body
5. Fireball is assumed to radiate as a black body

Reaction time: The lift off time is computed as

$$\tau_b = 0.6W_b^{1/6}$$

Where, $W_b$is the weight of fuel plus air in the mixture prior to ignition (Hardee, 1973).

Fireball growth rate: The rate at which fuel is added to the reaction is assumed to be approximately constant. With this assumption of a constant fuel addition rate, *R*,

$$R = \frac{W}{\tau} = \frac{W_b}{\tau_b} = 5/3\, W_b^{5/6}$$

The radius of the fireball is then:

$$r = (3R\tau/4\pi\rho)^{1/3}$$
$$= \left(5W_b^{5/6}/4\pi\rho\right)^{1/3}\tau^{1/3}$$

Fireball heat flux: As per Hardee (1973), the energy balance of the fireball considers enthalpy of entering mass, heat loss by radiation, expansion work of the control volume, and energy accumulation within the fireball.

The total incident heat on a body outside the fireball is Hardee (1973)

$$\mathcal{Q} = \tau_b \int_o^1 \frac{q_o}{2} \{1 - [1 - (r/d)^2]^{1/2}\}\, dt$$

The final fireball radius is computed as

$$r_b = 0.1837T^{1/3}W_b^{1/3}$$

Inputs Required
The inputs required are weight of fuel.
Strength and Weakness

The assumption that all available fuel participates in fireball reaction yields conservative results.

4.2 LPG I Model (Aerde et al., 1988)

This model deals with effects of LPG release from the tanks due to transportation accidents. Accident scenarios have been formulated and the release of liquid and gas is modeled. Models for pool formation and cloud dispersion are also considered.

The model constitutes modules for spill, fireball formation, vapour cloud explosions and pool fire.

Spill sub model: The purpose is to determine the fractions of substance contributing to a fireball or a vapour cloud explosion or a pool fire, following an accident (Van Aerde, *et al.*, 1988). The consequence depends on the size of the material transported, the prevailing environmental conditions and other factors which may affect the expected time to ignition.

According to Van Aerde (1988), spill mass is considered as spill fraction, depending upon the "type of accident. The amount of vapour contributing to either a fireball or a vapour cloud explosion is derived from the mass spilled, the multiplied by the flash fraction and the additional amount of liquid entrainment".

Amount of liquid spilled is computed as (Van Aerde, *et al.*, 1988):

$$Q_T = SF * WT$$

Where,
Q_T = tonnes spilled
SF = fraction of container spilled

Fireball formation: The damage caused from a fireball is calculated on the basis of the size and the duration of the fireball, and the heat radiation thresholds for various types of damage.

$$R = C_R * (Q_T)^{1/3}$$
$$A_S = 2 * 3.1416 * R^2$$
$$t_{fb} = C_t * (Q_T)^{1/3}$$

Where (Van Aerde, *et al.*, 1988):
R = fireball radius
C_R = coefficient for fireball radius equation
Q_T = quantity spilled
As = surface area of fireball
t_{fb} = duration of fireball
C_t = coefficient for fireball duration equation

Vapour cloud shock: The damage effects from a vapour cloud explosion are calculated using a TNT equivalent weight for the vapour cloud and a unique coefficient which considers for partial combustion for each damage level (Van Aerde, *et al.*, 1988).

The distance to damage is given by

$L = C * W^{1/3}$
Where
L = distance to damage
C = coefficient for specific damage level

Pool fire: The most severe consequence of a pool fire, according to Van Aerde (1988),"is the heat radiation which ignites secondary fires or other containers to cause a BLEVE. The damage contours around a pool fire are established based on the surface area of the pool and the heat radiation thresholds for various types of damage".

The dimensions of pool is given by

$V = (W * 1000)/D_L$
$A = V/(d * 0.01)$
Where
V = volume
DL = liquid density
A = area
d = pool depth
Inputs Required

The inputs are weight of LPG in a container, volume of the container, fireball flame temperature.

Strength and weakness

Both interactive and batch versions are made, so as to implement as separate model or as modules for lager risk assessment.

It is very conservative in estimating the damage produced by the vapour cloud.

4.3 FASIT (Fire growth and smoke movement in tunnel) (Charters et al., 1994; David, 1994))

The model predicts mass flows, velocities and smoke concentrations and heat transfer due to fire inside tunnels.
A tunnel is defined as series of zones at ambient temperature and flow conditions. The movement of smoke and heat is predicted using three layer model at various times intervals. The layers are described as hot or cool mixing layers having their associate wall layers.
The three layer approach is suitable for tunnel fires because of stronger mixing due to horizontal ventilation. The velocity of gases is predicted using correlation buoyancy driven flow and/or expansion driven plug flow.
The assumptions are:

1. Mass and energy are conserved
2. Pressure differences are small
3. The mixing layer velocity is half the sum of the hot and cool layer velocities
4. The tunnel section is constant and smooth

5. Plume properties are assumed to be Gaussian from the center line

The model is categorized into sub models plume flow, layer flow, mixing, heat transfer, life and property hazards.

Plume flow: As noted by Charters (1994), the mass flow rate depends on ventilation and plume conditions. The flow conditions are assumed to be turbulent or laminar. For laminar flow, the equations are:

$$b = 0.12\left(\frac{T_{hp}}{T_a}\right)^{1/2}(h_p - h_o)$$

$$T_{hp} = T + \left[9.1\left(\frac{T_a}{g c_p \rho_a}\right)^{1/3} q_c^{2/3}(h_p - h_o)^{-1/3}\right]$$

$$u_{hp} = 3.4\left[\left(\frac{g}{c_p \rho_a T_a}\right)^{1/3} q_c^{1/3}(h_p - h_o)^{1/3}\right]$$

"Where, b is plume radius, T_{hp} and U_{hp} are plume centerline temperature and velocity, $h_p$is height of plume above fire, h_0 is the height of the virtual origin above fire and $q_c$is convective heat release.
For turbulent flow, Gaussian temperature and velocity distributions are based on mean temperature and velocity of fire induced flow across the tunnel". The ventilation is also assumed as natural or longitudinal.
Layer flow: The layer flows depend on the plume flow and on each other layers. The hot layer velocity is determined by previous mass and heat flows (David 1994) while mixing layer and cool layer velocities are calculated using previous mass and energy flows.

Hot layer velocity is

$$U_h = K\left[\frac{q_c T_h}{T_a\ w}\right]^{1/3}$$

Where, K is an empirical coefficient that varies depending on ventilation condition, q_c is convected heat flow rate, T_h and T_a are hot layer and ambient temperatures respectively and w is the tunnel width (David 1994). Similarly cool layer and mixing layer velocities are also determined.
For mixing of layers, the Richardson number criterion is applied:

$$R_i = \frac{g(h_h + 0.5_m).(T_h - T_c)}{T_h.(U_h - U_c)^2}$$

If R_i is greater than 1, the flow is assumed to be stratified and no mixing takes place and if R_i is less than 1 the flow is assumed to be completely mixed.
Heat transfer: Heat layer is calculated forRadiation from flames and layers for conduction from wall surfaces and layers are taken into account for convection heat layer calculation.

The risks to life and property include radiant heat flux, toxic smoke concentration, loss of visibility, wall surface temperature, flame height, flame length down the tunnel, smoke front length down the tunnel, smoke back flow length up the tunnel (David 1994).

Inputs Required

The inputs are fire heat depth, mass flow, zone positions and zone length.

Strength and weakness

It has three-layer approaches, which proves to be more suitable for tunnel fires than the two layer approaches. Incorporation of the model is very easy**.**

The model over predicts temperature. The model does not account for the production of particulates in the smoke.

4.4 SOLVENT (Parsons Brinckerhoff Quade & Douglas, Inc., 1999; www.firemodelsurvey.com; www.tunnelfire.com)
This is a computational fluid dynamics (CFD) model for the simulation of fluid flow, heat transfer and smoke transport in tunnels. It particularly deals with the longitudinal and transverse ventilation system. The tunnel ventilation model employs the buoyancy-augmented k-εmodel to represent the turbulent transport and includes component models for jet fans, ventilation ducts, fire, radiation heat transfer, and smoke (www.firemodelsurvey.com).

The model solves, using a numerical method, the three-dimensional, time-dependent equations (field equations) describing the laws of conservation for mass, momentum, energy, turbulence parameters, and species ,pertaining to the boundary conditions. The component models for the fire, radiation, jet fans, and the ventilation ducts introduce additional source terms in these equations (www.tunnelfire.com).

General equation: The governing equation for transport of mass, momentum, energy, turbulence is described as

$$\frac{\partial}{\partial t}(\rho\phi) + \frac{\partial}{\partial x_i}(\rho u_i \phi) = \frac{\partial}{\partial x_i}\left(\Gamma \frac{\partial \phi}{\partial x_i}\right) + S$$

Where, ϕ is the general dependent variable, ρ is the air density, Γ is the generalized diffusion coefficient, and S is the source term.

*Turbulence model(www.tunnelfire.com):*The tunnel model is based on the buoyancy-augmented k-εmodel. In the k-εmodel turbulence is represented by the turbulence kinetic energy, k, and its rate of dissipation.

The source terms of kinetic energy and dissipation are given by,

$$S_k = P + G_B - \rho\varepsilon$$
$$S_\varepsilon = c_1(P + G_B)\frac{\varepsilon}{k} - c_2\rho\frac{\varepsilon^2}{k}$$

Where, P is the turbulence generated due to shear and G_B is the production due to buoyancy. The turbulent viscosity is given by

$$\mu_t = c_\mu \rho \frac{k^2}{\varepsilon}$$

Conjugate heat transfer: Conjugate heat transfer involves both conduction in the solid and convection in the fluid. The problem is solved as a convection-diffusion problem throughout the entire domain, but since the velocities in the solid regions are zero, a pure conduction calculation is performed for these regions (www.tunnelfire.com).

Two types of boundary conditions are specified,

1. Tunnel portals
2. Tunnel walls

Tunnel portals are mentioned as inflow or outflow boundaries with known values of pressure.

Tunnel walls are considered as hydraulically smooth or rough surfaces. The wall functions are suitably modified accounting the effect of wall roughness on momentum and heat transfer.
Representation of Fire: The model considers fire as a source of heat and mass. The model does not simulate combustion. Instead it computes the heat release rate as volumetric heat source in the region. The heat release rate is calculated as (www.tunnelfire.com),

$$Q = m_{fu} H_{fu} \eta$$

Where, rate of fuel consumption is m_{fu}, the heating value of the fuel is H_{fu}, and combustion efficiency is η.

Radiation heat transfer: The model treats radiation heat transfer by two approches

1. Radiative fraction
2. Detailed radiation treatment

Radiation fraction approach (nparc.cisti-icist.nrc-cnrc.gc.ca): In the radiative fraction approach, thermal radiation in the participating medium is ignored and a fixed fraction of the total heat released in the fire is assumed to be lost to the surroundings without affecting the temperature distribution within the tunnel and the remaining energy is transported away by the fluid.

The energy convected by the fluid is given by (www.tunnelfire.com)

$$Q_c = m_{fu} H_{fu} \eta (1 - \chi_R)$$

Where, χ_R is the radiative fraction.
Detailed radiation treatment approach: In it the fux model is used. The entire heat release in the fire region is described as source where the radiation model determines the energy lost to the tunnel walls.

The radiation contribution to the enthalpy source term for each control volume is calculated as

$$S_{h,rad} = -\sum_{i=1}^{3} S_i = a\sum_{i=1}^{3}(I_i^+ + I_i^-) - 6aE_b$$

Where, $E_b$is the black body emissive power, a and s are local absorption and scattering coefficients, I^+_i , I^-_i are radiation field.

Treatment of wall boundaries: The radiation heat flux lost from the fluid in the walls depends up on the wall temperature, wall emissivity, and reflectivity. The radiation intensity leaving the wall has contributions from the wall emission and reflection (www.tunnelfire.com).

The amount of radiation absorbed by the walls is specified as

$$q_x = -\frac{\varepsilon_w}{2-\varepsilon_w}(2\sigma.T_w^4 - R_x)$$

Where, ε_w and ρ_w are wall emissivity and reflectivity and T_w is temperature of wall.

Representation of smoke(www.tunnelfire.com): A separate conservation equation dealing with source term in the fire region is solved for smoke. It is assumed that complete combustion takes place and the total rate of smoke production is calculated from the rate of fuel consumption and the stoichiometric ratio for the fuel.

Total rate of smoke is given by

$$m_{smoke} = m_{fu}(1+s)f_{smoke}$$

Where, s is the stoichiometric ratio (kg of air / kg of fuel) for the fuel. f_{smoke} depends on interpretation of smoke.

The volumetric source term in the smoke equation is given by

$$S_{m,smoke} = \frac{m_{smoke}}{V_{fire}}$$

The model for smoke movement does not account for soot formation.
Representation of jet fan: A jet fan is represented as a constant volumetric flow rate device. The flow induced by the jet fan is not constant inside the tunnel. The model is also used for representation of ventilation ducts.
The sources for k and ε are calculated,

$$k = I.u_{jet}^2$$

$$\varepsilon = \frac{k^{1.5}}{D}$$

Where, $u_{jet}$is the discharge velocity, I is related to the turbulence intensity and D is the jet fan diameter.

Inputs Required

The inputs are surface roughness, geometrical parameters, rate of fuel consumption, and temperature of walls.

Strength and Weakness

Temperature predictions are accurate.

The model does not account for soot formation.

4.5 UPMTUNNEL (Migoya et al., 2009; rss.sciencedirect.com)

This is a steady simplified model for accidental fires in tunnels with longitudinal ventilation. The model combines the characteristics of both field and zone mode. The tunnel is divided in two zones the plume zone and the ventilation zone. The zones are assumed to be in steady state condition.

The fire is assumed to be located in the centre of the tunnel. The first zone, plume zone includes region of upstream from the point, where smoke hits the ceiling and is treated by one dimensional model. The diffusion zone which is the second zone spreads downstream from the plume.

Plume: The plume model assumes that the chemical reaction occurs only in the plume region. The sub models are combustion model and mechanical model for plume.

Combustion model: The model is based on a single and irreversible chemical reaction.

Plume description: It is considered that the fire is not affected by the tunnel walls in the region. The bending effect of the ceiling is taken into account by introducing a source term in the momentum conservation equation. It is assumed that the ambient flow created by the ventilation system is constant and parallel to the longitudinal direction of the tunnel

The plume trajectory, contained in a symmetry xz plane, is obtained from

$$\sin\theta = \frac{dz}{ds} = \frac{\langle \tilde{u}_z \rangle}{\langle \tilde{u} \rangle}$$

Where, θ is the inclination of the plume.

Diffusion zone: It is assumed that the flow is one-directional and steady, with a velocity U parallel to the tunnel axis. Temperature variations in this region are small compared to the absolute value of temperature

The plume zone ends and the diffusion region begins when

$$h_T = z + b\cos\theta$$

Where, *z*is the height of the plume center-line and *bcosθ*is the vertical projection of the equivalent plume radius.

Inputs Required

The inputs required are mixture fraction, enthalpy, and ventilation velocity.

Strength and Weakness

It is a mixed approach, combining both zone an field models

It requires less computational resources than 3D models and incorporates phenomena of radiation and heat transfer easily compared to 3D models

There is a need for minimum air ventilation speed so as to prevent back layering at low air speeds.

There is a discrepancy in calculation of temperature, tending to give higher values.

4.6 Nimble model (Cattaneo et al., 2014)

The model focuses the effects of accident involving spill of fuel causing fire in a road tunnel. This evaluates three major aspects (www.aidic.it):

- Walls temperature increase due to the fire, which could lead to structural damages and subsequent collapse;
- Air temperature inside the tunnel; and
- The effect of irradiation on a specific target (e.g. human body).

1. The following assumptions have been made: The heat source is assumed to be circular pool fire present in the middle of the tunnel.
2. The pool is located at a distance *Y* (m) from the tunnel entrance.
3. The flame can be considered as a tilted cylinder of radius *R (t)*.
4. A simple point source model is considered for heat generated by flame which affects temperature of wall.
5. A solid flame model is considered for radiant heat affecting generic target the tunnel has been hypothesized as empty and tunnel ventilation velocity prevents back-layering of the smoke upstream of the fire source.
6. Temperature gradient is considered solely only in longitudinal direction(y).

Gasoline pool: The spill of fuel from a hole in the tank truck generates a gasoline pool whose radius *R (t)*

$$R(t) \approx \left(\frac{4{,}32gQ}{3\pi}\right)^{\frac{1}{4}} . t^{\frac{3}{4}}$$

Where (www.aidic.it),

g is gravitational acceleration,

Q is volumetric flow rate exiting from the hole in the truck structure and *t* is the time.

Heat radiated by the flame, W_{rad}*(W),*

$$W_{rad} = m.A_{pool}.\Delta h_{comb}.\eta$$

Where,

A_{pool} is the free pool surface

Δh_{comb} is the combustion enthalpy and

η is the fraction of heat effectively radiated by the flame.

Temperature of walls: The temperature of walls is determined using the following equation

$$I_{neat,i}(y) = I_i(y) + \sigma.\sum_{j=1}^{n} F_{j\to i}(y).[T_j^4(y) - T_a^4(y)] - \sigma.\sum_{j=1}^{n} F_{i\to j}(y).[T_i^4(y) - T_a^4(y)]$$

Where,
σ is the Stephan-Boltzmann constant *Fj*,
i is the view factor of element *j* with respect to the element *i*,
Ti/j is the temperature of the surface element *i/j*,
Ta is the air temperature and the summations (index *j*) are extended to all the elements of all the walls.
*Air temperature:*The temperature of the air along the tunnel length is not constant and it varies as a function of *y* which is calculated using an energy balance equation on each single elemental volume.

$$B.H.dy.\frac{d}{dt}\left[\rho_a \left|T_a(y).c_{p,a}\right|_{T_a(y)}.T_a(y)\right] = H_{a,IN}(y) - H_{a,OUT}(y) + H_{smoke}(y)$$

Where (www.aidic.it),

Bis the tunnel width,
H is the tunnel height,
dy is the infinitesimal length along *y* direction,
$c_{p,a}$is the specific heat of the air calculated at the temperature *Ta(y)* in the element and
Ha,IN/a, OUT/smoke is the enthalpic fluxes of air and smoke.
*Target radiation:*The flame has been considered as a solid cylinder tilted in the airflow direction to evaluate the effects on generic target.
The emissive power of flame is calculated as

$$I(s) = \alpha.\tau.F_{flame}.\left(T_{flame}^4 - T_a^4(y)\right)$$

Where,

α is the absorbance of the target,
$T_{flame}$is temperature of the flame and
F_{flame} is the view factor of the flame with respect to the target.
Inputs Required
The inputs required are volumetric flow rate, air velocity inside tunnel, tunnel dimensions and temperature of the flame

Strength and Weakness

It is relatively simple model employing short computational time
Evaluation of risk is done in a short span of time
No back-layering of cold air from the fire source is considered**.**

4.7 TCTCM (tank car thermal computer model) (Birk, 1988; Birk 1990)

The model simulates the effects of fire impingement on a rail tank-car and its lading (Birk, 1988). This model has been completely useful in safety and protection of rail tank cars. When a tanker is exposed to external fire impingement, heat is transferred from the fire to the tank outer surface by convection and thermal radiation. Radiation will be dominant if the fire is large, and if the fire impingement involves a high velocity jet (such as a burning relief valve flare from a neighbouring tank) then both convection and radiation are important. The tank is assumed to a two-dimensional representation of a circular cylindrical tank (Birk, 1988).

The model is made up of a series of sub-models simulating the following processes (Birk, 1988):

1. Flame to tank heat transfer.
2. Heat transfer through the tank wall and associated coverings.
3. Interior-surface to lading heat transfer.
4. Thermodynamic process within the tank.
5. Thermodynamic properties of the lading.
6. Pressure relief device operating characteristics.
7. Wall stresses and material property degradation.
8. Tank failure.

Flame to tank heat transfer sub model accounts for either pool fire or two dimensional torch fire considering radiation and convection.

Heat transfer through the tank wall and associated coverings, is represented by finite difference techniques. The finite difference solution accounts for pure conduction through the tank wall and insulating layers, and pure conduction, convection, and radiation between wall and radiation shielding (Birk, 1988).

The interior surface heat transfer sub-models account for convection and radiation in the vapour space, and convection and boiling in the liquid region (Birk, 1990). The radiation calculation is assumed that the wall communicates only with the lading.

The thermodynamic process sub-model treats the lading as three distinct regions - the vapour space, the liquid boundary, and the liquid core. It is assumed that the vapour and liquid boundary are in thermodynamic equilibrium and saturated; the core is assumed to be sub cooled initially, but after some period of venting it is assumed to be in equilibrium with the liquid boundary and vapour space.

The pressure relief valve sub-model accounts for both the mechanical action of a relief valve and the fluid mechanics. The valve mechanics are established using a steady state model (service.rintd.ur).

The tank failure analysis is based on the maximum normal stress theory of failure. The wall stresses are calculated at the point on the wall circumference experiencing the highest temperature and includes pressure induced (hoop) stress and stresses due to radial temperature gradients in the tank wall (Birk, 1990).

Inputs Required

The inputs required are flame temperature, dimensions of tank, liquid boundary thickness.

Strength and Weakness

The model lowers cost and time in evaluation of risk for tanks.

The model is capable of analysing pitched and rolled tanks

The model under predicts of liquid release rate needed for emptying the tank.

Wall temperature values do not conform to the actual values**.**

The model has been updated as AFFTAC, which is described below.

4.8 AFFTAC (Analysis of fire effects on tank cars) (Birk et al., 2000; Ird,yahooapis.com)

The AFFTAC computer code is used to simulate the effects of fire impingement on tank-cars equipped with thermal protection systems(Ird,yahooapis.com).

Important factors in fire exposure simulation include the following(Ird,yahooapis.com):

i. Fire heat flux.
ii. Tank exposure (fraction of tank involved in fire and fire location relative to vapour space).
iii. Tank lading thermodynamic response.
iv. PRV operating characteristics.
v. Vapour space heat transfer and wall temperature prediction.
vi. Tank material properties and failure criteria

*Fire heat flux:*It models both pool fire and torch fire. Pool fire is considered as black body which radiates at 816 C. Convection is not considered in modeling pool fire and jet fire.

*Tank exposure:*Afftac assumes that the tank engulfs completely inside the fire, in pool fire simulation while in torch fire simulation assumes that the torch covers only 1 percent of the tank then the tank will pressurize slowly.

*External heat transfer:*The external heat transfer is driven by the fire model and the tank external surface radiating properties. In AFFTAC it is assumed that the tank outer and inner surface has an emissivity of 0.8.

*Internal heat transfer:*The internal heat transfer involves convection and boiling in the liquid wetted regions and convection and thermal radiation in the vapour region. The liquid wetted wall temperatures are equal to liquid temperature due to cooling effect of liquid, whereas vapour temperature is hot because of poor cooling effect of vapour.

Liquid space:The liquid space has high convective heat transfer coefficient

Vapour space: In AFFTAC it is assumed that the vapour space wall has a uniform temperature and this temperature is calculated from an energy balance that accounts for the fire heat transfer on the outside of the tank and for convection and radiation on the inside of the tank.

*Vapour space radiation:*The following assumptions are used to model the vapour space radiation in AFFTAC:

i. Vapour space consists of two radiating zones, the wall and the liquid surface.
ii. Liquid surface has an emissivity of 0.9.
iii. Absorption of radiation by the vapour is ignored.
iv. Vapour space has uniform pressure

*Tank thermodynamic response:*In AFFTAC it is assumed that the tank pressure is dictated by the liquid thermal properties (i.e. the liquid saturation pressure) and the liquid is assumed to be isothermal.

*Failure criteria:*In AFFTAC the tank is assumed to fail immediately when the tank pressure equals 100 percent of the tank burst pressure. The burst pressure is calculated from the following expression:

$$P_b = \frac{2\sigma t}{D}$$

Where
t = wall thickness
D = tank diameter
σ□= wall material ultimate strength at temperature.

Inputs Required

The inputs required are temperature of container, surface area of tank, tank shell thickness, tank diameter.

Strength and Weakness

The failure model is very simple to use
Erroneous values have been predicted for vapour space temperature.
Factor of safety is not included in failure model.

4.9 PLGS-I (Aydemir et al., 1988; Aydemir et al., 1988)

This is a two dimensional mathematical model which accounts for LPG tanks engulfed in fire. The cause of fire is assumed to be collision of a transport vessel resulting in a leakage followed by spilling and ignition of the LPG. The model assumes both liquid and vapour as thermally stratified. The external fire is assumed to be uniform.

*Heat Transfer:*The heat transfer from the fire to the tank takes place in two modes:

1. Radiation
2. Convection

For radiation, the tank and fire are considered to be grey bodies.

$$q_R = \sigma\left(T_f^4 - T_S^4\right)/\left[1/\varepsilon_f + 1/\varepsilon_S - 1\right]$$

σ – Stefan-Boltzman constant
T_f - Temperature of the body
T_s - Temperature of the surroundings
ε_f – Emissivity of the surface at temperature T_f
ε_S – Emissivity of the surface at temperature T_s
For convection, the heat transfer is

$$q_C = h_C\left(T_f - T_s\right)$$

$$h_c = a_1*(a_2/D)^{a3}$$

a_1, a_2, a_3 – Correlating coefficients
The total heat transfer from the flames to the vessel is therefore

$$q = q_R + q_c$$

*Tank insulation and shell:*The layers of insulation and shell are divided into 24 circumferential sections containing eight radial elements.

*Vapour space:*The two essential modes of heat transfer in the vapour space are convection and radiation. The convection component is based on Newton's cooling law.

$$q = h_V(T_W - T_V)$$

Where,
h_v - heat transfer coefficient
T_w – Temperature of the body
T_v – Temperature of the surrounding.
The radiation heat transfer is computed with the assumption that the properties of the gas and the liquid interface are uniform.
Liquid space: The liquid space is subdivided into four different zones as

1. Stratified liquid
2. Boundary layer region
3. Bulk liquid and
4. Bottom regions of the tank.

The two major modes of heat transfer in the liquid space are natural convection and nucleate boiling.

i. *Natural Convection:* Depending on whether the surface can be considered vertical or horizontal, the equations are formed.

For vertical plate,
Laminar flow,

$$Nu = 0.59(Ra)^{0.25}$$

Turbulent flow,

$$Nu = 0.10(Ra)^{0.33}$$

$$Nu = h_{nc}L_c/k,$$

$$Ra = gL_c^3\rho\beta\,(Tw-Tl)/(\mu\alpha)$$

L_c- ratio of area to perimeter
and h_{nc} - natural convective heat transfer coefficient.

ii. *Nucleate boiling:* The onset of nucleation is determined by monitoring the criterion:

$$T_r - T_{sat} = 2V_{gsat}T_{sat}\sigma_1/(h_{fg}r)$$

Where r is the radius of an active nucleation site.

iii. *Transition to Film boiling:* Transition to film boiling is done when the local heat flux reaches the value of critical heat flux.

iv.

The critical heat flux is expressed as:

$$q_{CHF} = (3.14/24)h_{fg}(\rho_1\rho_V)^{1/2}[\sigma_1 g(\rho_1 - \rho_V)/(\rho_1 + \rho_V)]^{1/4}$$

The heat transfer coefficient is computed as,

$$h_{tr} = [q_{CHF}(\Delta T_{LP} - \Delta T) + q_{LP}(\Delta T - \Delta T_{CHF})]/[\Delta T(\Delta T_{LP} - \Delta T_{CHF})]$$

v. *Film Boiling:* When the temperature differential exceeds ΔT_{Lp}, film boiling begins.

$$h_{fb} = 0.714\{[k_V^3 g \rho_V \rho_1 (h_V - h_1)]/[L_C \mu_V (T_W - T_{sat})]\}^{1/4}$$

Fluid Flow:

i. *Boundary layer flows:*The boundary layer flows inside the vessel are computed. The rate of flow is determined as

Laminar flow

$$B_{st} = 0.558\phi_2^{8/7}(\sin\phi_2)^{2/7}\mu_1(Pr_1/Gr_R^*)^{-2/7}$$

Turbulent flow

$$B_{st} = 3.22\phi_2^{4/5}(\sin\phi_2)^{1/5}\mu_1[(1/Pr_1^2 + 1.25/Pr_1)/Gr_R^*]^{-1/5}/Pr_1$$

ii. *Boiling boundary layers:* Vapour generated at the walls in the boundary layer is mixed with the sub-cooled liquid due to collapsing/condensing of the bubbles at the outer edge of the boundary layer.

*Relief Valve:*Relief valve opens whenpressure inside the vessel reaches the set pressure, and discharge commences.
The discharge rate is,

$$G = C_D(\rho AV)_{throat}$$

Inputs Required

The inputs required are area of container, flame temperature, radius of nucleation site, mass of liquid.
Strength and Weakness

It considers the thermal stratified behavior for both of liquid and vapour**.**
Importance of discharge coefficient for high fill levels is stressed.

Only cylindrical shaped tanks are considered.
The extent of mixing of vapour in boundary layer between walls and sub-cooled liquid remains unidentified.

4.10 DERACS (A.M. Birk et al.,1990)

This program is a computer simulation of consequences of a derailment accident. This accounts various sub models such as train derailment mechanics, flammable liquid spills, fire effects on remote targets, fire impingement on tank cars carrying dangerous commodities, explosion blast over-pressure and thermal radiation, and heavy plume and puff dispersion. The program handles up to forty cars in a train, in which eight can be tank cars carrying propane, chlorine or hexane. These substances were chosen due to their flammable and toxic characteristics.

The assumptions are:

1. Rupture of the tank may lead to
   i. Catastrophic failure of the vessel with resulting explosive release of the contents and subsequent ignition to form a fire ball.
   ii. Instantaneous release in the form of a toxic heavy gas puff with subsequent dispersion and possible ignition at some time.
   iii. Continuous release of the gas with possible ignition at some time.

2. The sub-models of DERACS consider the following processes (Birk,1990):

   i. Derailment mechanics
   ii. Derailment impact induced rupture of tank cars
   iii. Liquid and vapour release
   iv. Flammable liquid spill growth
   v. Plume and puff dispersion of heavy gases
   vi. Liquid pool fires and effects on surroundings
   vii. Fire impingement on tanks and thermal ruptures
   viii. Blast and thermal effects of explosions/BLEVE

*Derailment mechanics:*The derailment mechanics sub-model involves the solution of the governing equations for rigid body motion of the vehicles with four degrees of freedom. The forces which act on the vehicles are assumed to be inter-car forces applied by the couplers and the ground forces.

The ground forces are considered as coulomb's friction force which acts between the centres of two trucks.

*Derailment impact induced rupture of tank cars:*According to Birk (1990), it "is assumed that puncture will only occur when a free coupler comes in contact with a tank shell and the relative velocity between the coupler and the impacted tank is greater than 20 m/s".

*Liquid and vapour release:*The rate of release and the phase of release substance determine the formation of liquid pool or toxic cloud or flammable cloud. Pool fire is formed in case of liquid pool and vapour explosion is formed if vapour is released.

Birk (1990) further observes that the"rates of release of liquids and vapours are calculated using a modified version of the computer program LEAKR by Belore and Buist. The LEAKR program can handle different chemicals, tank shapes, and puncture sizes and geometries. Release rates can be predicted for both subsonic and sonic gaseous releases, single phase liquid releases and two phase subsonic releases".

LEAKR predicts time required for emptying the vessel by performing time integration of the release of material from a tank. This accounts for heat transfer effects between the tank lading and the ambient surroundings.

*Flammable liquid spill growth:*A simple pool model is developed based purely on mass conservation effects. The ground is assumed to be of concave shape in the region of the spill, where radius of curvature is used to describe the shape of the surface. The size of the spill is calculated as a function of the mass of liquid currently in the pool (Birk, 1990).

Volume of the spill is given by

$$V = M/\rho$$

$$V = \pi(Rh^2 - h^3/3)$$

Where, M is the mass of liquid in the spill, R is the local radius curvature of the ground, h is the spill depth.

*Thermal effects of pool fire:*Brik (1990) describes these as, "direct fire impingement of tank cars is only accounted in DERACS. It is assumed that the fire acts as a vertical right circular cylinder. The radiation from the pool fire to the target can be calculated from the following expression for radiant exchange between surfaces separated by an absorbing intervening gas".

The radiation from the pool fire is calculated as

$$Q = F\ r\ E$$

Where, Q is heat transferred by thermal radiation, *r is* atmospheric transmissivity, E is pool fire emissive power and F is surface to surface exchange factor.

*Plume and puff dispersion of heavy gases:*Deracs model accounts for heavy gases such as chlorine and propane. If the release is instantaneous, puff dispersion model is used, and if the release is continuous, plume model is used. Both plume and puff releases are modeled in DERACS using the Box Puff Model of Meroney.

*Fire impingement on tanks and thermal ruptures:*TANKCAR model accounts for Fire impingement on tank cars. According to Birk (1990) the "tank car thermal model can simulate a long cylindrical tank filled partially with liquid and partially with vapour exposed to either an engulfing type fire, such as caused by a burning pool, or a torch type fire, such as that caused by a relief valve flare from a neighbouring tank".

According to Birk (1988), the computer model "is capable of predicting the tank internal pressure, mean lading temperatures, wall temperature distribution, relief valve flow rates, liquid level, tank wall stresses and tank failure, all as functions of time from initiation of the fire impingement".

Thermal effects of explosions/BLEVES: DERACS assumes a fire ball type explosion during rupture of tank where the resulting fire ball will have both blast and thermal effects of the surroundings.

$$D_{max} = 5.33m^{0.327}$$

Where, D_{max} is maximum diameter of fireball and m is mass of fuel (kg)

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Emissive power of fireball is calculated as

$$E = E_{max}(1 - e^{-bD_s})$$

Where
E_{max} = 469 kW/m'
b = 18 m^{-1}
D_s = fire ball diameter
The flux reaching the remote target
$Q = ErF$
Where,
r = atmospheric transmissivity
F = radiant exchange view factor.

Blast Effects of Explosions/BLEVES (Birk, 1990):

When an explosion or BLEVE occurs, a pressure disturbance will propagate outwards from the blast centre. The blast hazard and the distance from the centre of the explosion are estimated in DERACS. The initial mass of the explosive is assumed to equal the total mass of lading in the tank.

$$\frac{P_o}{P_a} = \frac{808[1 + (Z/4.5)^2]}{\sqrt{1 + (Z/.048)^2}\sqrt{1 + (Z/.32)^2}\sqrt{1 + (Z/1.35)^2}}$$

Where
P_0 = fire field overpressure
P_a = ambient pressure
Z = scaled distance
d = actual distance
W = TNT equivalent mass
T_o and P_0 = reference atmospheric temperature
Inputs Required
The inputs are tank radius, rolled distance, pool depth, and local radius of curvature, surface regression rate, pool fire emissive power and mass of fuel.
Strength and Weakness
This program evaluates derailment incident completely. (Starting from the mechanism till the consequences.
The program is suitable only up to 40 rail tank cars.
The commodities used for simulation is very limited.

4.11 CFAST (Jones and Forney., 1990; www.firemodelsurcey.com; reserachspace.auckland.ac.nz))
This is a version of FAST. CFAST "Consolidated model of Fire growth And Smoke Transport is one of the zone models which predicts fire environment in a multi compartment structure on fire. The model considers tunnel as two layers, hot and cool. The equations of conservation of mass, momentum, energy are solved along with plume models, vent flow equations, radiation and combustion models. The parameters solved are pressure above reference value, temperature in upper and lower layer, volume of upper layer.
Inputs Required

The inputs are thermo physical properties, geometrical data, and rate of mass loss and generation rates of products of combustion.

Strength and Weakness

It gives accurate values of pressure terms.
It is capable of multiple fire simulation
Only limited length is considered.
The model does not predict air flow pattern, temperature and smoke contours.

4.12 PHOENICS-3D (Cham Ltd., 1981)

PHOENICS 3D is a general code, where combustion was modeled using the k–εmethod. It is used to model fire in tunnels for roads and rails. The physical phenomena which are taken into account are turbulence modeling, buoyancy phenomena generated by the fire in momentum and turbulence, Heat and smoke release. The calculation is done for turbulence effects, heat transfer, chemical reaction, multiphase behavior of fluids and complex geometries.

In the discretization of the conservation equations, central-differences and hybrid schemes (upwind or central-differences) were used for the diffusion and convective terms, respectively. The simplest algorithm was used to solve the coupling between mass and momentum conservation equations.

FLAIR is a reduced version of PHOENICS for use in analysing air flows in air conditioning and ventilation systems and fire or smoke spread.

Inputs Required

The inputs required are geometrical data and thermo-physical parameters.

Strength and Weakness

It provides estimate of radiation due to hot smoke layer
It is better suitable for long tunnels
Density stratification is not included.

4.13 FLUENT: 3-D model (Creare. X.,1983)

FLUENT is a general-purpose computational fluid dynamics (CFD) code that solves the Navier–Stokes equations using a finite volume method. The standard conservation equations of the k–εmodel implemented in the code were used, except for the conservation equation of the mixture fraction variance. Instead of using this equation, the species conservation equations were employed, and combustion was modeled using the 'eddy break-up' method. This method relates the reaction rate with turbulence characteristics and the eddy dissipation rate. The following discretization scheme was used: upwind differences for first order derivatives and centered differences for second order derivatives. The iterative method SIMPLE to solve the coupling between mass and momentum equations was employed.

Inputs Required

The inputs required are geometry data and thermo physical properties.

Strength and Weakness

Thermal stratification is included in this model
It could model even for complex geometry tunnels

4.14 JASMINE (Cox and Kumar et al., 1987)

JASMINE uses PHOENICS, a CFD code for computation of fluid motion, and three dimensional solutions for heat and mass transfer.it solves full partial differential equations equation describing conservation of mass, momentum, energy and species using two equation models for turbulence together with simple radiation.

Inputs Required

The inputs are description of source, thermal properties of structure, structure geometry and ventilation.

Strength and Weakness

It is very simplistic model
Gas temperatures are predicted accurately
Radiative heat transfer between gas phase control volumes is not included.
Frictional losses in ducts are not included.

4.15 FDS (fire dynamic simulator) (Mcgrattan et al., 2000; service.rintd.ru; Chirs, 2002; Krieger, 2008)

FDS is a computational fluid dynamics (CFD) code of fire-driven fluid flow. The model numerically solves Navier-Stokes equations appropriate for low-speed, thermally-driven flow emphasizing on smoke and heat transport from fires. The partial derivatives of the conservation equations of mass, momentum and energy are approximated as finite differences. Thermal radiation is computed using a finite volume technique. Lagrangian particles are used to simulate smoke movement, sprinkler discharge, and fuel sprays. Smokeview is a companion program to FDS that produces images and animations of the results.

The major components of FDS are hydrodynamic model, combustion model, radiation transport, geometry, boundary conditions, sprinklers, and detectors.

Inputs Required

The inputs required are material properties, geometric parameters, thermal properties and boundary conditions.

Strength and Weakness

The simple rectilinear numerical grid makes the code swift to use.
The fast direct solver for pressure fields also makes computations easy.
The model accurately predicts flow velocities and temperatures if heat release rate is known.
The use of FDS is limited only to low speed flow.
It leads to a non-uniform distribution of the radiant energy for targets away from the source.

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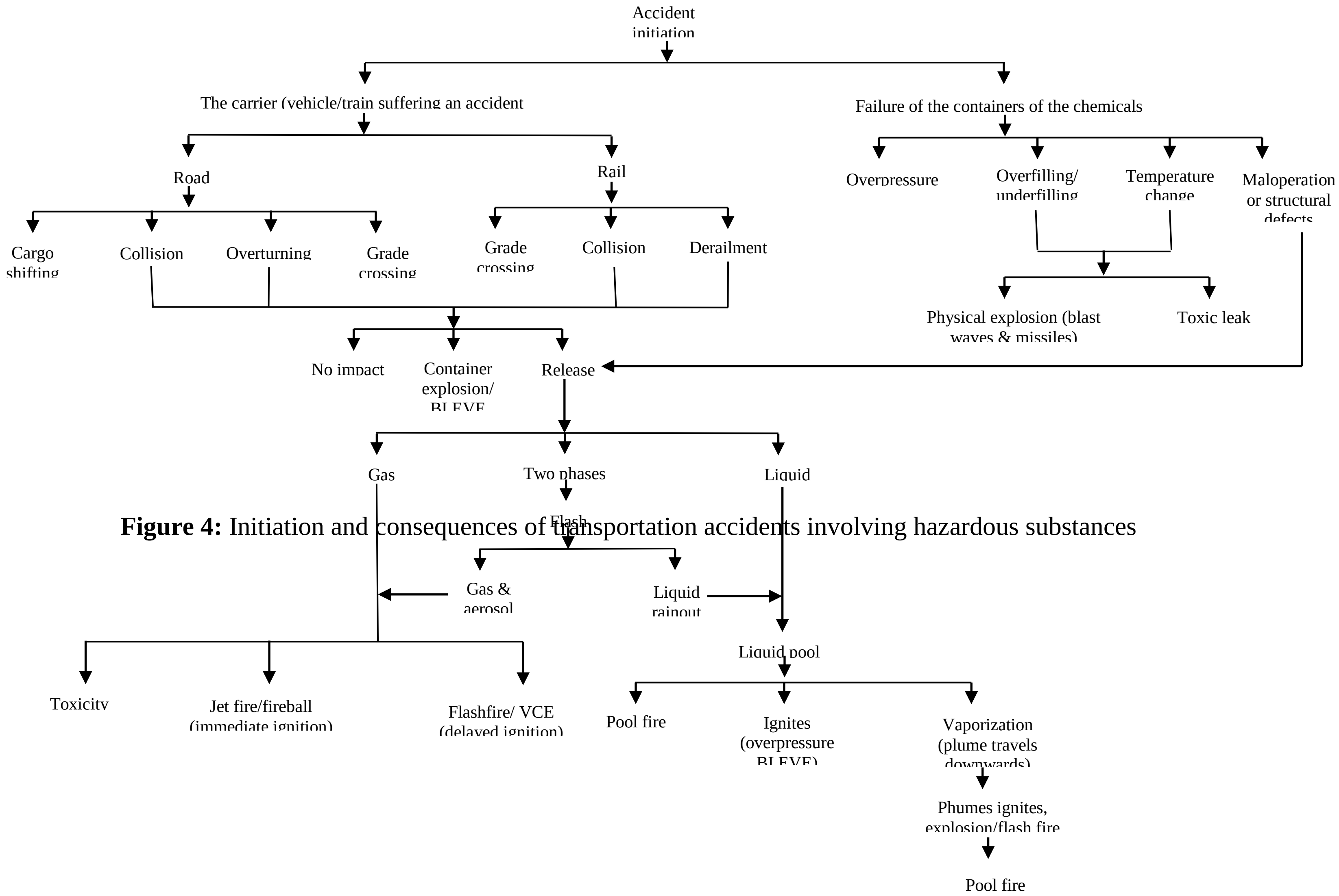

Figure 4: Initiation and consequences of transportation accidents involving hazardous substances

References:

1. Abbasi, T., and Abbasi, S. A., (2007). The boiling liquid expanding vapour explosion (BLEVE): mechanism, consequence assessment, control, *Journal of Hazardous Materials, 141,* 489-519.

2. Acord, S., Cooney, K., Dash, S., Lingo, L., Rocker, L., and Trierweiler, S. (1978). The Crescent City disaster: a small town rebuilds.

3. Aydemir, N. U., Magapu, V. K., Sousa, A. C. M., and Venart, J. E. S. (1988). Thermal response analysis of LPG tanks exposed to fire. *Journal of Hazardous Materials*, *20*, 239-262.

4. Barbato, L., Cascetta, F., Musto, M. and Rotondo, G., (2014). Fire safety investigation for road tunnel ventilation systems–an overview. *Tunnelling and Underground Space Technology*, *43*, pp.253-265.

5. Birk, A. M. (2000). Review of AFFTAC (Analysis of Fire Effects on Tank-Cars) Thermal Model.

6. Birk, A. M., Anderson, R. J., and Coppens, A. J. (1990). A computer simulation of a derailment accident: Part I-Model Basis. *Journal of Hazardous Materials*, *25*(1-2), 121-147.

7. Birk, A.M., (1988). Modelling the response of tankers exposed to external fire impingement. *Journal of Hazardous Materials*, *20*, pp.197-225.

8. Centre for Chemical Process Safety (CCPS), (2010). *Risk Assessment Fundamentals*, Guidelines for Chemical Transportation Safety Security and Risk Management, CCPS/Guidelines of 2010.

9. Charters, D. A., Gray, W. A., and McIntosh, A. C. (1994). A computer model to assess fire hazards in tunnels (FASIT). *Fire Technology*, *30*(1), 134-154.

10. Cox, G., and Kumar, S. (1987). Field modelling of fire in forced ventilated enclosures. *Combustion Science and Technology*, *52*(1-3), 7-23.

11. Crowl, D. A., and Louvar, J. F. (2011). Chemical Process Safety-Fundamentals with Applications, (2011). *Process Safety Progress*, *30*(4), 408-409.

12. Haastrup, P., and Brockhoff, L. (1990). Severity of accidents with hazardous materials: a comparison between transportation and fixed installations. *Journal of Loss Prevention in the Process Industries*, *3*(4), 395-405.

13. Hardee, H. C., and Lee, D. O. (1973). Thermal hazard from propane fireballs. *Transportation Planning and Technology*, *2*(2), 121-128.

14. Jones, W. W., and Forney, G. P. (1990). *A Programmer's Reference Manual for CFAST, the Unified Model of Fire Growth and Smoke Transport*. US Department of Commerce, National Institute of Standards and Technology.

15. Khan, F. I., and Abbasi, S. A., (1997). Risk Analysis of a chloralkali industry situated in a populated area using the software package MAXCRED -II, *Process Safety Progress (AIChE, USA)16*, 172-184.

16. Khan, F. I., and Abbasi, S. A., (1997). Accident simulation as a tool for assessing and controlling environmental risk In chemical process industries: A case study, *Korean Journal of Chemical Engineering*, 124-135.

17. Khan, F. I., and Abbasi, S. A., (1999). Major accidents in process industries and an analysis of causes and consequences, *Journal of Loss Prevention in the Process Industries, (Elsevier), 12*, 361-378.

18. Khan, F. I., and Abbasi, S. A., (2001). Risk analysis of a typical chemical industry using optimal risk assessment, *Journal of Loss Prevention In Process Industries, 14*, 43–59.

19. Khan, F.I. and Abbasi, S. A., (1999). Major accidents in process industries and an analysis of causes and consequences, *Journal of Loss Prevention in Process Industries*, 12(4): 361–378.

20. Krieger, J., Steinauer, B. and Mayer, G., (2008), January. Simulation of fire tests in road tunnels. In *IABSE Symposium Report* (Vol. 94, No. 5, pp. 1-8). International Association for Bridge and Structural Engineering.

21. Lee, J. S., Chon, H. T., and Kim, K. W. (2005). Human risk assessment of As, Cd, Cu and Zn in the abandoned metal mine site. *Environmental geochemistry and health*, *27*(2), 185-191.

22. Linkutė, L. (2011). Data on traffic accidents involving fires and explosions.

23. McGrattan, K. B., and Forney, G. P. (2000). *Fire Dynamics Simulator: User's Manual*. US Department of Commerce, Technology Administration, National Institute of Standards and Technology.

24. Migoya, E., Crespo, A., Garcı, J., and Hernandez, J. (2009). A simplified model of fires in road tunnels. Comparison with three-dimensional models and full-scale measurements. *Tunnelling and Underground Space Technology*, *24*(1), 37-52.

25. Oggero, A., Darbra, R. M., Munoz, M., Planas, E., and Casal, J., 2006. A survey of accidents occurring during the transport of hazardous substances by road and rail. *Journal of hazardous materials,* 133(1), 1-7.

26. Parsons, B. (1999). Quade and Douglas Inc., 1996. *Transit and urban form*, *1*.

27. Planas-Cuchi, E., Casal, J., Lancia, A., and Bordignon, L. (1996). Protection of equipment engulfed in a pool fire. *Journal of loss prevention in the process industries*, *9*(3), 231-240.

28. Sala Cattaneo, C., Tavelli, S., Derudi, M., Rota, R., Raboni, M., Torretta, V., and Copelli, S. (2014). Study of a nimble model to evaluate the effects of a gasoline fire in a road tunnel. *Chemical engineering transactions*.

29. Van Aerde, M., Stewart, A., and Saccomanno, F. (1988). Estimating the impacts of LPG spills during transportation accidents. *Journal of Hazardous Materials*, *20*, 375-392.