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Risk to built property posed by transportation of liquefied gasses

Keywords

risk, thermal damage, hazmat transportation, road tank, railway tank car, liquefied gas, BLEVE

Abstract

An assessment of risk posed by a road transportation of liquefied gases to roadside property is considered. The attention is focused on an estimation of the probability of thermal damage to a roadside object. Such damage can be caused by a boiling-liquid expanding-vapour explosion (BLEVE) of a road tank. It is suggested to estimate this probability by a combined application of stochastic simulation and deterministic models used to predict a thermal effect of a BLEVE fireball. A development of a fragility function expressing the probability of ignition of the roadside object is discussed. The fragility function is integrated into the simulation-based procedure of an estimation of the thermal damage probability. The approach proposed in this study is illustrated by an example which considers an assessment of thermal damage to a reservoir built in the vicinity of a road used for transportation of liquefied gases.

1. Introduction

The transportation of liquefied gasses (LGs) shipped by road and rail has a non-decreasing trend in the Baltic region. Road tanks are used to ensure a small-scale distribution to end-consumers. The future construction of new gas terminals on the Baltic shore will drive up LG transportation by road tank vehicles. Accidents of such vehicles pose serious risk to people and infrastructure located in the roadside territory [12]. A traffic accident of a road tank can escalate in a severe and highly hazardous explosion known as a boiling-liquid expanding-vapour explosion (BLEVE). Such an explosion can be a stand-alone accident or, alternatively, cause secondary or “knock-on” accidents in the roadside territory. Accidents involving BLEVEs of road tankers, which carried LGs, are reported by T. Abassi and S. A. Abassi [1], Planas-Cuchi *et al.* [15], Tauseef *et al.* [18]. A large number of railway accidents which escalated into BLEVE or were near misses occurred also on rail. Accidents in Białystok (2010, Poland) and Viareggio (2009, Italy) may serve as examples of such events [10], [11].

Thermal and mechanical effects of BLEVE on roadside objects can be predicted by mathematical models, most of which are strictly deterministic. These models cover blast, fireballs, and projection of fragments (projectiles) generated by BLEVEs [4], [5], [7]; [9]. The models of BLEVE effects can be applied to predicting damage to roadside objects. A methodological framework for such predicting is available in the field of transportation risk assessment (TRA) [6]. An example of an application of TRA to an assessment of individual and societal risk due to LG transportation was reported by Paltrinieri *et al.* [13]. TRA is a widely developed methodology. However, applications of TRA are very limited where a potential damage to built roadside objects is of concern [21], [22]. An assessment of such damage will require to consider two aspects of a BLEVE accident: transportation aspect (potential position of the explosion within the road segment from which it can endanger a roadside object in question) and structural aspect (response of the roadside object to potential BLEVE effects).

2. The exposure of roadside property to effects generated by a road tank BLEVE

An accident occurring as a BLEVE of a road tank will be initiated by a traffic accident, in which the tank vehicle is involved. Then the initiator can be followed by an engulfment of a tank by a fire and

BLEVE of the tank. The fire can be fed by LG leaking from the tank or by other source, most probably, fuel of a tank truck. A fire of both LG and fuel is also possible [15].

A BLEVE can be external or internal event with respect to exposed roadside infrastructure. An external exposure to BLEVE hazard can result from a transportation of LGs over adjacent public (off-site) roads or access roads. An example of an external exposure to a BLEVE is given in *Figure 1*.

BLEVE damage to a roadside object can be caused by three effects generated this explosion: blast, projectile impact and thermal radiation from a fireball. Blasts from BLEVEs are localised and not as far reaching as fireball and projectile effects. If safe distances between the road and roadside objects can be established for fireballs then they will be safe for the blast. Such distances are also known as separation distances [7]. A separation distance equal to four times the potential fireball radius *R* is suggested as reasonable for thermal radiation effects and blast effects [3]. An illustration of the distance 4*R* is given in *Figures 1* and *2*. However, at this distance the hazard from projectiles is still very significant. At a distance of 4*R* from the side of a tank, approximately 80-90% of fragments should fall. A compensation for less than desired separation distances can be safety barriers built alongside the road [20]. If designed properly, the safety barriers will provide protection against blast and projectiles. For effective protection, the potential BLEVE epicentre should be at relatively short range from the front of the barrier [17].

Unfortunately, barriers can provide no protection against fireball radiation because dimensions of fireballs from BLEVEs of road tanks exceed any reasonable dimensions of barriers. An illustration of these dimensions is given in *Figure 2*. The geometry of the fireball shown in *Figure 2* was calculated for a typical tank semi-trailer carrying 24.7 tons of propane by applying the so-called TNO fireball model [8].

A protection of roadside objects against thermal radiation from BLEVE fireballs should be based on either providing adequate separation distances or compensating less than desired safety distances by adequate resistance of target objects to thermal radiation. The latter option can be achieved by shielding the target objects from thermal radiation or making them inherently more resistant to such radiation. Both options require to predict intensity of thermal radiation from a road tank BLEVE and to assess the risk of thermal damage to exposed roadside object. An assessment of this risk will require to deal with transportation and structural aspect of the problem.

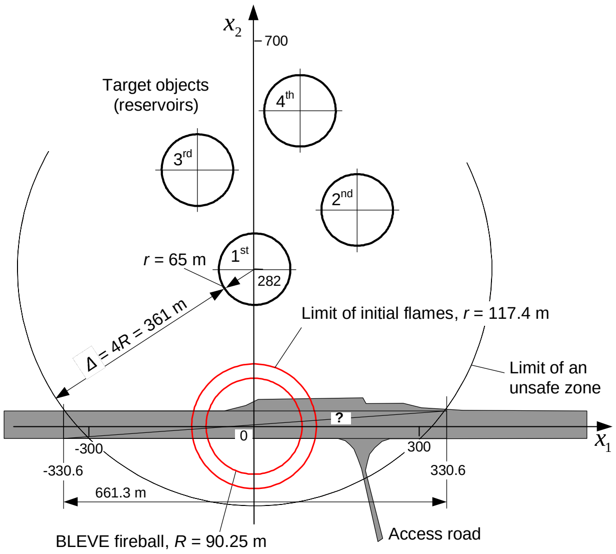
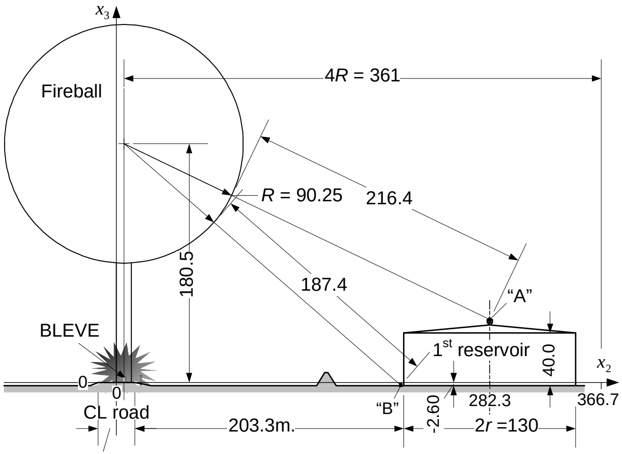


Figure 1. An example of exposure of four reservoirs with flammable materials to a BLEVE on road



Four-lane road with 3.75 m lanes; width of all road elements is 28.0 m

Figure 2. Exposure of a roadside reservoir to a fireball generated by a BLEVE of a road tank carrying 27.4 tons of propane

2. Risk posed by a road (railroad) tank BLEVE

Blast and projectiles generated by a road tank BLEVE can cause mechanical damage, whereas the thermal radiation can ignite combustible parts of the exposed object and so the damage will be caused by a subsequent, secondary fire. Many combustible materials ignite at ten-second exposure to 50 kW/m^2 radiation [16]. The duration of a fireball generated by a BLEVE of a typical road tank is up to 20 seconds. Blast and projectiles will reach the target object within first two or three seconds after the explosion and act a very short time. Thermal radiation from a fireball will act on the object a longer time and will increase from zero to a maximum value during the first third of fireball duration [4]. If the events of mechanical and thermal damage are modelled by the respective random events D_M and D_T, the event D_M will occur first and D_T will follow D_M.

An occurrence of the mechanical damage event D_M can lead to two conditions of the target object with respect to the vulnerability of this object to thermal radiation:

1. An occurrence of D_M does not change the vulnerability to fire damage (e.g., a local damage to a masonry wall of an industrial building hit by a projectile from a tank vessel fragmentation will not affect the vulnerability of its roof to thermal radiation, *Figure 3a*). The events D_M and D_T can be considered independent and so the probability $P(D_T \mid B)$ estimated independently from $P(D_M \mid B)$, where B denotes the random event of BLEVE.
2. An occurrence of D_M increases abruptly the vulnerability to fire damage (e.g., loss of containment by a reservoir used to store flammable liquid due to a projectile impact and so spill and exposure of this liquid to the direct action of thermal radiation will increase the chance of fire, *Figure 3b*). The events D_M and D_T can not be considered to be independent and so $P(D_T \mid D_M \cap B) > P(D_T \mid B)$.

The probabilities $P(D_T \mid B)$ and $P(D_T \mid D_M \cap B)$ represent two different accident scenarios. They can be related to the frequency of thermal damage, $Fr(D_T)$, by a simple expression

$$Fr(D_T) = Fr(T) \times P(A \mid T) \times P(B \mid A)$$
$$\times P(D_T \mid B) \tag{1a}$$

or

$$Fr(D_T)=Fr(T)\times P(A \mid T)\times P(B \mid A)$$
$$\times P(D_T \mid D_M \cap B)) \tag{1b}$$

where $Fr(T)$ is the usually annual frequency of LG transportation through the road segment under analysis (event T); $P(A \mid T)$ is the conditional probability of a traffic accident (event A) given T and $P(B \mid A)$ is the probability of a BLEVE given A.

If D_T is a stand-alone event, a vector of consequence severities, $\boldsymbol{S}$, can be assigned to $Fr(D_T)$ and the pair $\{Fr(D_T), \boldsymbol{S}\}$ considered a simple expression of risk. In the case of an escalation of D_T into a larger, domino accident, the estimation of the frequency $Fr(D_T)$ can be treated as an estimation of frequency of an initiating event which triggers out a domino sequence. In both cases, the estimation of $Fr(D_T)$ will involve an estimation of the thermal damage probabilities $P(D_T \mid B)$ and $P(D_T \mid D_M \cap B)$.

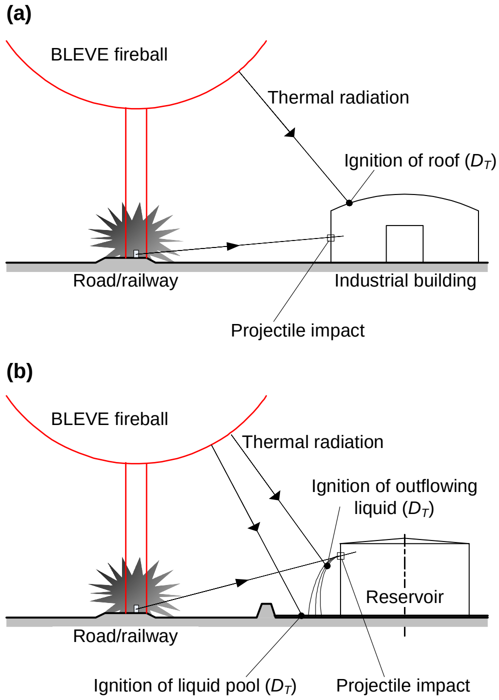


Figure 3. Two cases of the thermal damage event D_T: (a) an independent occurrence of D_T with respect to the mechanical damage by a projectile; (b) the case where D_T is dependent on an occurrence of mechanical damage

The estimation of the conditional thermal damage probability $P(D_T \mid B)$ is similar to that of $P(D_T \mid D_M \cap B)$, with the difference that the first probability must be estimated for a mechanically undamaged target object and the second one for an object in a damaged state and so more vulnerable to a thermal impact. Due to this similarity and for the sake of brevity, the symbol $P(D_T \mid B)$ will represent both probabilities. The thermal damage probability $P(D_T \mid B)$ can be expressed as follows:

$$P(D_T \mid B) = \int_{\text{all}\, \boldsymbol{y}} P(D_T \mid \boldsymbol{y})\, f(\boldsymbol{y})\mathrm{d}\boldsymbol{y}$$
$$= \int_{\text{all}\, \boldsymbol{x}} P(D_T \mid \boldsymbol{\psi}(\boldsymbol{x}))\, f(\boldsymbol{x})\mathrm{d}\boldsymbol{x} \tag{2}$$

where $\boldsymbol{y} = (y_1, y_2)$ is a two-component vector, the first component of which, y_1, expresses a thermal radiation intensity (heat flux) and the second, y_2, the duration of exposure to this radiation (fireball duration); $P(D_T \mid \boldsymbol{y})$ is the fragility function relating the probability of D_T to $\boldsymbol{y}$; $\boldsymbol{x}$ is the vector of characteristics of BLEVE accident resulting in the impact expressed by $\boldsymbol{y}$; $\boldsymbol{\psi}(\boldsymbol{x})$ is the vector-function which relates $\boldsymbol{x}$ to $\boldsymbol{y}$ (i.e., $\boldsymbol{y} = \boldsymbol{\psi}(\boldsymbol{x})$); and $f(\boldsymbol{x})$ and $f(\boldsymbol{y})$ are the joint probability density functions (p.d.f.s) of $\boldsymbol{x}$ and $\boldsymbol{y}$, respectively.

Table 1. Input vector $\boldsymbol{x}$ of the model $\psi(\boldsymbol{x})$ developed in by the Dutch organisation TNO [8]

Component of $\boldsymbol{x}$	Description	Units	Value
x_1	Position of the BLEVE centre along the axis {0; x_1 }* (Fig. 1)	m	0
x_2	Position of the BLEVE centre along the axis {0; x_2} (Figs. 1 and 2)	m	5.65
x_3	Position of the BLEVE centre along the axis {0; x_3} (Fig. 2)	m	0
x_4	Capacity of the tank	m^3	56.14
x_5	Pressure in the vessel just before the explosion*	N/m^2	20×10^5
x_6	Degree of tank filling	%	85
x_7	Density of LG (propane)	kg/m^3	585
x_8	Combustion heat of LG at its boiling point	J/kg	46.0×10^6
x_9	Vaporisation heat of LG at its boiling point	J/kg	0.426×10^6
x_{10}	Specific heat capacity at constant pressure	J/(kg°K)	0.002582
x_{11}	Temperature of the fireball flame	°K	2000
x_{12}	Partial vapour pressure of carbon dioxide in the atmosphere	N/m^2	30.39
x_{13}	Ambient temperature	°C	10
x_{14}	Relative humidity	%	70

* Relief pressure of the safety valve can be assumed as the pressure at the instant of explosion [4]

The development of the fragility function $P(D_T \mid \boldsymbol{y})$ is a highly case-specific task of probabilistic structural analysis. Fragility functions are widely applied to seismic risk assessment and extreme-wind risk assessment. However, any attempts to develop a fragility function for thermal actions of external fires are not known to us. What is more, recipes allowing to relate the thermal radiation y_1 and duration y_2 to a specific thermal damage are very sparse and deterministic in nature. It is stated in the books CCPS [5], [7] that the radiation of 37.5 kW/m^2 is sufficient to cause damage to process equipment and 12.5 kW/m^2 is the minimum energy required for ignition of wood and melting of plastic tubing. Most sources interpret the thermal damage simply as an ignition of materials exposed to thermal radiation and distinguish between ignition and non-ignition by specifying a pair of fixed threshold values ($y_{1,min}$, $y_{2,min}$) [2], [4], [16], [19]. Unfortunately, such values are insufficient to easily develop a fragility function $P(D_T \mid y_1, y_2)$, especially for short-term exposures (values of y_2 ranging roughly between 5 and 20 seconds). It is highly probable that at present the analyst will have to rely on a simplified fragility function expressed as

$$P(D_T \mid y_1, y_2) = \begin{cases} 1 & \text{if } y_1 \geq y_{1,min} \;\&\; y_2 \geq y_{2,min} \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

Fitting a well-known bivariate density $f(\boldsymbol{y})$ to the direct data on BLEVE effects can be problematic. BLEVE accidents on road are unique, short-lasting and unexpected events. The post mortem data on them is too sparse for fitting $f(\boldsymbol{y})$. However, the density $f(\boldsymbol{y})$ and so the probability $P(D_T \mid B)$ can be estimated by propagating uncertainties expressed by the lower-level density $f(\boldsymbol{x})$ through the model $\psi(\boldsymbol{x})$. The function $\psi(\boldsymbol{x})$ can be composed of a relatively large number of models available currently for the prediction of individual effects of BLEVE. These models are strictly deterministic, some are in competition for modelling individual characteristics of BLEVE fireballs [1].

4. Transportation aspect of damage assessment

The thermal effect from a BLEVE fireball depends on a number of transportation-specific characteristics which can be taken as components of the input vector $\boldsymbol{x}$ in the model $\psi(\boldsymbol{x})$. A list of these characteristics depends on the type of the model used to predict the thermal radiation y_1 and the fireball duration y_2. For instance, the TNO model allows to classify transportation-specific components of $\boldsymbol{x}$ listed in *Table 1* as follows:

1. The position of exploding tank in respect to a target object.
2. The segment of road from which a road tank BLEVE can endanger the target object (unsafe road segment).
3. Characteristics of the tank vessel used to ship LG: capacity, degree of filling, relief pressure of the safety valve built into the vessel and, more generally, mechanical characteristics of the vessel metal heated by an external fire preceding BLEVE.

Table 2. Characteristics of two vulnerable points in the reservoir system that can be ignited by a BLEVE fireball

Point	Position in the coordinate system $\{0; x_1, x_2, x_3\}$	Condition of thermal damage		Estimate of damage probability, $P_e(D_T\|B)$* (see (4))
		$y_{1,min}$ (kW/m^2)	$y_{2,min}$ (s)	
A	(0 m, 282.3 m, 47.5 m), Fig. 2	25	10	1.021×10^{-3}
B	(0 m, 215 m, –2.17 m) , Fig. 2	30	10	0.1814

* Computed with $N = 1\times10^5$

Table 3. Probability distributions of the random components of the vector ***X*** used to describe a road tank BLEVE accident

Random variable	Mean	Coefficient of variation (standard deviation)	Probability distribution
X_1	335.1* m	0.577 (193.4 m)	Uniform over the length of **ω**
X_2	2.174 m	5.20 (11.31 m)	Mixed distribution
X_6	0.85	0.05 (0.0425)	Normal
X_{11}	2000 °K	0.11 (220 °K)	Lognormal
X_{13}	15 °C	0.20 (3 °C)	Normal
X_{14}	70%	0.1 (7%)	Normal

* In the accident simulation the mean value of X_1 was shifted to the zero value of the axis $\{0; x_1\}$

4. Characteristics of LG being shipped in the vessel: type and density of LG, combustion and vaporization heat, specific heat. Temperature of the fireball flame can also be attributed to the characteristics of LG.

The tank position can be defined by applying a coordinate system fixed to both road and target object. An example of such a coordinate system denoted by $\{0; x_1, x_2\}$ is shown in *Figure 1*. If the altitudes of BLEVE centre and target object differ much and/or the road has a non-negligible gradient, a three-dimensional coordinate system $\{0; x_1, x_2, x_3\}$ must be used (e.g., *Figure 2*). Unlike scattering of projectiles from a cylindrical vessel BLEVE and blast generated by such an explosion, the propagation of the thermal radiation is not directional [3]. Therefore there is no need to model the orientation of the exploding tank (the angle of tank axis in relation to the road axis) in the coordinate system $\{0; x_1, x_2\}$ [21], [22].

The unsafe road segment denoted by, say, **ω** can be determined by plotting a safety distance around the target object. If this object has a relatively simple geometry in plan, the safety distance can be determined a single variable, say, Δ. *Figures 1* and *2* illustrate such a distance for the cylindrical tank “1”. It was assumed that Δ is equal to four fireball radii R estimated for a BLEVE of a road tank carrying 27.4 tons of propane. The safety distance Δ plotted around the target object formed a road segment **ω** with the length of 661.3 m (*Figure 1*). The geometry and of a target object and road network in the vicinity of the object can be irregular. However, the unsafe road segment **ω** can be identified also in such a case [22].

Generally, all component of the input vector $\boldsymbol{x}$ should be considered random and modelled by random variables. However, the variability of some components can be expected to be small one and so these components can be represented by fixed values. The position of the BLEVE centre in the road segment **ω** in undoubtedly uncertain and must be modelled by two random variables X_1 and X_2. For the model $\boldsymbol{\psi}(\boldsymbol{x})$, they will be the first two random input variables. The altitude of the explosion centre with respect to the target, x_3, can be expressed as a linear function of X_1 if the road within **ω** has a longitudinal gradient. Consequently, X_3 will have the same probability distribution as X_1. The capacity of the tank, x_4, and the relief pressure of the safety valve, x_5, can be assumed to be fixed values if it is known what type of the tank vessel will undergo a BLEVE. However, the degree of tank filling, x_6, can vary more than x_4 and x_5 and so this degree should be modelled by a random variable X_6.

The characteristics of LG expressed by the components x_7 to x_{10} will depend on the type of LG and chemical composition of LG. The variability of x_7 to x_{10} must be determined by tests of LGs shipped by road tanks. If a specific material shipped by a road tank, which may undergo a BLEVE, is known in advance, the LG characteristics x_7 to x_{10} can be assumed to be fixed. However, the temperature of fireball flame, x_{11}, should be modelled as a random variable X_{11}. This temperature is influenced by several random factors and, in addition, is difficult to measure it in experiments [2].

The ambient conditions in the TNO model are expressed by the input variables x_{12} to x_{14} (*Table 1*). Partial vapour pressure of carbon dioxide in the atmosphere, x_{12}, do not vary much and can be considered non-random and equal to a fixed value 30.39 N/m^2 [8]. The ambient temperature at the instant of BLEVE, x_{13}, and the corresponding relative humidity x_{14} are clearly uncertain values and they must be modelled by the respective random variables X_{13} and X_{14}. These variables are not inherent characteristics of the LG transportation process. They can be attributed to the target object because depend on the location of a potential BLEVE accident. However, certain combinations of values of X_{13} and X_{14}.

The uncertainties related to the components of the input vector $\boldsymbol{x}$ call for replacing this vector by a vector with some random components, namely, $\boldsymbol{X} = (X_1, X_2, X_3, x_4, x_5, X_6, x_7, x_8, x_9, x_{10}, X_{11}, x_{12}, X_{13}, X_{14})$. With the random input vector $\boldsymbol{X}$, the output of the model $\boldsymbol{\psi}(\boldsymbol{X})$ will be random and can be modelled by two random variables: random thermal radiation $Y_1 = \psi_1(\boldsymbol{X})$ and random fireball duration $Y_2 = \psi_2(\boldsymbol{X})$. The probability distributions of Y_1 and Y_2 can be estimated by applying a simulation-based propagation of uncertainties through the model $\boldsymbol{\psi}(\cdot)$. Values of the random input vector, $\boldsymbol{x}_j$, can be sampled from probability distributions of the random components of $\boldsymbol{X}$ and the corresponding output values y_{1j} and y_{2j} calculated by means of $\boldsymbol{\psi}(\cdot)$. A repetition of this process a large number of times, say, N will yield an estimate of the damage probability $P(D_T\,|\,B)$, namely,

$$P_e(D_T\,|\,B) = N^{-1}\sum\nolimits_{j=1}^{N} P(D_T\,|\,y_{1j}, y_{2j}) \tag{4}$$

where $P(D_T\,|\,y_{1j}, y_{2\ j})$ is a value of the fragility function $P(D_T\,|\,\boldsymbol{y})$ computed for the pair (y_{1j}, y_{2j}).

5. Example

The potential thermal damage from a road tank BLEVE fireball to the 1st of the four reservoirs shown in *Figure 1* will be analysed. The thermal radiation will be estimated at the centre of reservoir roof, where system components sensitive to thermal radiation are installed (point "A"), and at the bottom of the diked area around the reservoirs, were piping and other system components are attached to the reservoir (point "B") (*Figure 2*). Characteristics of the points "A" and "B" are given in *Table 2*. A BLEVE of a road tank semi-truck carrying 24.7 tons of propane will be considered. The BLEVE can occur on an unsafe road segment $\boldsymbol{\omega}$ with the length of 661.3 m (*Figure 1*). The area between the road and the reservoirs is flat; the road segment $\boldsymbol{\omega}$ has no gradient. The road has four lanes, each 3.75 m wide and a 5,5 m wide median which separates opposing lanes of traffic (*Figure 4*). The LG is transported along the four lanes of the road segment $\boldsymbol{\omega}$ with relative frequencies $\pi_1 = 0.35$, $\pi_2 = 0.04$, $\pi_3 = 0.07$ and $\pi_4 = 0.54$. These frequencies were obtained from an observation of traffic in the road segment $\boldsymbol{\omega}$.

The BLEVE accident is described by the vector $\boldsymbol{X}$ defined above. The probability distribution of the longitudinal rest position of the road tank and so the position of a potential BLEVE centre, X_1, was assumed to be uniformly distributed over the length of $\boldsymbol{\omega}$ (*Figure 2*). This distribution expresses maximum uncertainty related to a potential BLEVE centre along the axis $\{0; x_1\}$. The road segment did not experienced tank car accidents in previous years. The probability distribution of the transverse tank position after it comes to a complete stop and can explode, X_2, depends on the lane of intended travel. Our previous analysis of tank car accident data led to the result that the transverse rest position of the tank centre with respect to the centreline of intended travel lane can be modelled by a logistic distribution Logistic(2.02 m, 3.10 m) [21]. The positive location parameter of this distribution, 2.02 m, means that the transverse rest position lies in average 2.02 m outwards the travel lane centreline. The distribution Logistic(2.02 m, 3.10 m) can be associated with each of the four lanes of the road under consideration by adding (subtracting) its location parameter to (from) the coordinate of the lane centreline along the axis $\{0; x_2\}$ (*Figure 4a*). This will allow to construct a mixed p.d.f. of X_2, in which the frequencies π_1 to π_4 will play the role of probabilistic weights:

$$\varphi(x_2) = \pi_1 f_1(x_2\,|\,-10.4, 3.10) + \pi_2 f_2(x_2\,|\,-6.65, 3.10) + \pi_3 f_3(x_2\,|\,6.65, 3.10) + \pi_4 f_4(x_2\,|\,10.4, 3.10) \tag{5}$$

where $\varphi(x_2)$ denotes the mixed p.d.f. of X_2 and $f_l(x_2\,|\,\cdot,\cdot)$ ($l = 1, 2, 3, 4$) are the logistic p.d.f.s related to the respective travel lanes. Parameters of the densities $f_l(x_2\,|\,\cdot,\cdot)$ in (5) are in meters. The graph of the bimodal density $\varphi(x_2)$ is shown in *Figure 4a.*

The probability distributions of the remaining random variables considered in the present example, X_6, X_{11}, X_{13} and X_{14}, were assumed by following the recommendations given by Papazoglou and Aneziris [14] who considered the quantification of uncertainties related to the BLEVE thermal radiation. The values $\boldsymbol{x}_j$ of the random input vector $\boldsymbol{X}$ were sampled by means of a stochastic simulation from the probability distributions given in *Table 3*. Then the simulated values $\boldsymbol{x}_j$ and the model $\boldsymbol{\psi}(\cdot)$ described in tno book [8] were used to compute values of the thermal radiation and fireball duration, y_{1j} and y_{2j}. The simulation was repeated 1×10^5 times (N = 10 000). *Figures 5* and *6* show the scatter diagram of the simulated pairs (x_{1j}, x_{2j}) and (y_{1j}, y_{2j}).

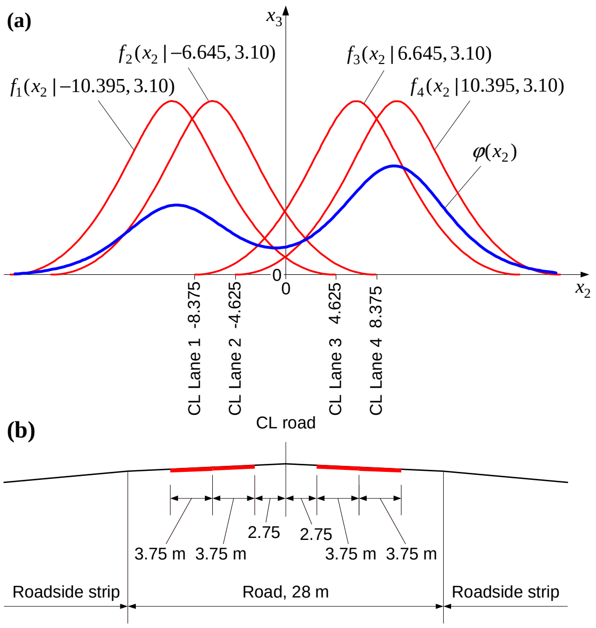


Figure 4. Probabilistic model of the transverse rest position of the tank: (a) densities of the transverse departure from the centrelines of individual lanes and a mixture of these densities, $\varphi(x_2)$; (b) road profile and adjacent roadside territory

With the pairs (y_{1j}, y_{2j}), estimates of the probability of thermal damage, $P_e(D_T|B)$, were computed for points "A" and "B" (*Table 2*). These estimates indicate that the point "B" is much more vulnerable to thermal radiation than "A" and so thermal insulation (shielding) should be provided in order to protect this part of the reservoir system against BLEVE.

6. Conclusions

An assessment of the risk to roadside property from a boiling-liquid expanding-vapour explosion (BLEVE) of a road tank carrying liquefied gas (LG) has been considered. The attention was focussed on the thermal damage from a radiation generated by a BLEVE fireball. Such damage is usually understood as an ignition of a roadside object. The risk assessment requires to estimate the conditional probability of thermal damage to the roadside object under analysis given a BLEVE. The estimate of this probability can be used for assessing the annual frequency of thermal damage. This frequency is a key element in the expression of risk posed to a specific roadside object by LG transportation through an adjacent public (off-site) or on-site road.

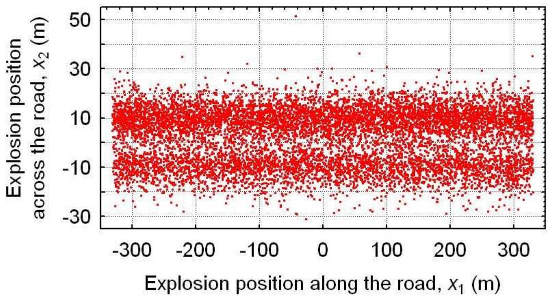


Figure 5. Simulated positions of BLEVE explosion centre, (x_{1j}, x_{2j})

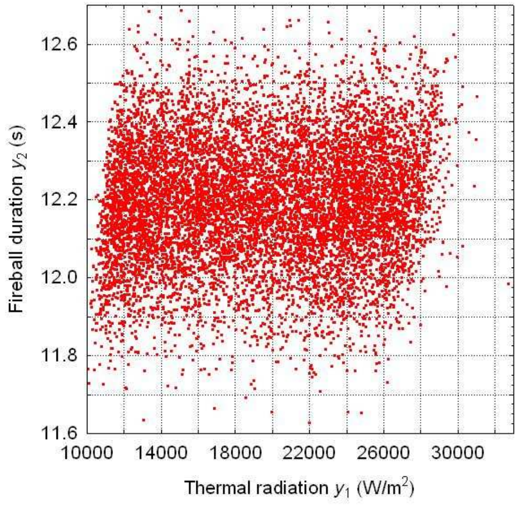


Figure 6. Simulated pairs of the thermal radiation and fireball duration, (y_{1j}, y_{2j})

The thermal impact of BLEVE on the roadside object will depend on a generally random position of the vehicle at the instant of explosion. Characteristics of vehicle and properties of LG shipped by it will also influence the thermal impact. In the risk assessment, some of these vehicle and cargo characteristics must be treated as random quantities. Uncertainty related to them can be transformed into uncertainty in characteristics of thermal impact: thermal radiation (heat flux) impinging the roadside object and duration of this radiation.

The structural aspect of the assessment of risk posed by a road tank BLEVE will consist in developing a fragility function for a potential target. The demand variables in this function must be intensity and duration of thermal radiation. Results obtained in this study can be applied to a general transportation risk assessment. However, these results can be also useful for specifying separation distances between road and roadside objects and design of shielding for these objects as a compensation for less than desired separation distances.

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