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SIMULATION-BASED PREDICTING THE POSITION OF ROAD TANK EXPLOSIONS. PART I: DATA AND MODELS

Egidijus Rytas Vaidogas¹, Lina Linkutė², Dainius Stulgys³

^{1,2}*Dept of Occupational Safety and Fire Protection, Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania*

³*Lithuanian Technology Platform on Industrial Safety, P.O. Box 2846, VACP, Gedimino pr. 7, LT-01008 Vilnius, Lithuania*

E-mails: ¹erv@vgtu.lt (corresponding author); ²lina.linkute@vgtu.lt; ³dainius.stulgys@danis.lt

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Abstract. Road tankers used for the transportation of flammable liquids and liquefied gases can be involved in accidents which escalate into fires and the so-called boiling liquid expanding vapour explosions. The damaging effects of these phenomena on roadside property depend on the position and orientation of exploding tanks in relation to vulnerable roadside objects. This study presents a simulation-based approach to the prediction of the position of road tank explosions. The position is expressed by longitudinal and transverse rest position of an exploding tank as well as departure angle of the tank. As a part of this study, data on transverse rest position and departure angle was collected and used to fit probability distributions which express uncertainties in these circumstantial characteristics of road tank accidents. It was found that data on the longitudinal rest position is difficult to obtain and modelling this accident characteristic will have to rely on a subjective specification of probability distributions. Such distributions can be chosen by applying approaches used in the field of quantitative risk assessment. Probability distributions, partly subjective and partly based on hard data, are applied to simulate values of potential explosion coordinates. The simulation results have the premise to be applied to forecasting mechanical and thermal effects of explosions on road and assessing damage from them. A case study used to evaluate the performance of the models proposed in this study is presented in the second part of the paper.

Keywords: explosion, BLEVE, fire, simulation, road accident, road tank, risk, hazardous material, Bayesian approach.

1. Introduction

Every day large amounts of hazardous materials are transported by road tanks. Accidents of these vehicles pose serious risk to road traffic and roadside territory (Planas-Cuchi *et al.* 2004; Oggero *et al.* 2006). In an extreme case a road tank accident can end up in a severe explosion known as BLEVE (boiling liquid expanding vapour explosion) (Abassi, T., Abassi, S. 2007; Taveau 2010). A BLEVE on road can be a stand-alone accident or, alternatively, cause secondary or 'knock-on' accidents in the roadside territory (Abdolhamidzadeh *et al.* 2010, 2011).

A prediction of BLEVE effects on roadside property is possible by means of mathematical modeling. The models of BLEVE effects cover blast, fireballs, and projection of fragments (projectiles) (e.g., CCPS 1994; Casal 2007). Most of these models are strictly deterministic; some models include probabilistic elements

(Hauptmanns 2001; Vaidogas 2006; Mébarki *et al.* 2009; Nguyen *et al.* 2009). The key input information of them is of geometric nature. The prediction of BLEVE effects requires knowing the distance and orientation of the tank in relation to potential targets of BLEVE (e.g., Birk 1996; Casal 2007). The identification of the position and orientation is particularly important when the potential distance between tank and target is relatively small.

As BLEVEs of road tanks are relatively rare and unexpected events influenced by many random factors, the prediction of the tank position and orientation at the instant of BLEVE will have to deal with considerable uncertainties. Methods of quantitative risk assessment (QRA) are naturally suited to quantify and propagate such uncertainties. Quantitative measures of uncertainties in position and orientation of exploding tank can serve as input into a QRA problem which will relate BLEVE to its risk profile.

There is a history of applications of QRA to transportation of hazardous materials or transportation risk assessment (TRA) (CCPS 1995; CPD 1999; Fabiano *et al.* 2002; Bubbico *et al.* 2004a, 2004b; Gheorghe *et al.* 2005). The common features of these applications are as follows:

1. Large traffic fragments are considered and divided into smaller route segments, for which risk is estimated. The method of route disaggregation varies in different applications.
2. Methods used for the estimation of risk related to individual route segments are in most cases suitable for fixed installations.
3. Most applications deal with individual and societal risk to exposed population. Risk to built roadside property (buildings, objects of traffic infrastructure, industrial installations) is mentioned but not considered in detail.
4. The accident scenario prevailing in the applications of TRA is a release of toxic materials and subsequent intoxication of population. Fires and explosions are not considered in detail, especially in the context of risk to fixed roadside objects.
5. When it comes to a fire and/or explosion accident on road and rail, authors often simply refer to models proposed in the literature for the prediction of effects of these phenomena, for instance, to the ‘coloured’ books issued by the Dutch organisation TNO (CPD 1992, 2005). Attempts to relate in detail characteristics of traffic accidents to fires and explosions on road and rail are not known to us.
6. Methodological aspects of QRA applications to TRA look ‘suspiciously flat’. Applications of TRA have few if any considerations on the uncertainty of risk assessments, quality and relevance of data, formal separation of experts’ opinions and hard historical data.

In summary, one can say that TRA is a widely developed extension of QRA; however, applications of TRA lack ‘attention to detail’, where fires and explosions on road and rail are of concern. A BLEVE-related example of this state of investigations is the assessment of individual and societal risk due to LPG transportation done by Paltrinieri *et al.* (2009).

The idea that explosions and fires on road and rail may require an in-depth consideration of the risk to a specific object built in the vicinity of the route with the hazard of fire and explosion accidents is not new. Gheorghe *et al.* (2005) and Vaidogas (2007a) considered specific situation of exposure of roadside objects to fires and explosions on road and rail. The present study can be viewed as a refining of these approaches.

We think that the assessment of risk to specific roadside property posed by road tank explosions requires a detailed simulation of the road accident preceding the BLEVE event. Results of such simulation will yield input information for the simulation-based prediction of BLEVE effects and eventually potential damage

to roadside objects. The simulation results can be useful for a risk-based design of barriers which could provide protection against BLEVEs. The present study focuses on a stochastic (Monte Carlo) simulation of position and orientation of road tanks before they undergo an explosion.

This study is comprised of two parts. The first part contains a description of a data on the rest position of road tanks involved in traffic accidents. Probabilistic models fitted to this data are presented as well. Finally, the first part presents considerations on the stochastic simulation of the accident position. The second part describes a case study used to illustrate the simulation procedure (see next issue of the Journal).

2. Risk Related to Road Tank Explosions

In terms of QRA, a BLEVE accident of a road tank is a low-probability initiating event. It can be internal or external event with respect to exposed installation (e.g., Kumamoto 2011; Garrick 2008). QRA can be focused on a specific random damage event D , for instance, loss of containment of a tank or rupture of a pipeline due to mechanical and thermal actions of BLEVE. In this case the frequency of D can be expressed as a product of transportation frequency (mission frequency) $F(M)$ and three conditional probabilities which relate M to D :

$$F(D) = F(M) P(A|M) P(B|A) P(D|B), \quad (1)$$

where: A is the random event of a road accident, in which the road tank will be involved, and B is the random event of BLEVE.

The estimation of the conditional damage probability $P(D|B)$ requires to assess mechanical and thermal effects of BLEVE. If these effects are grouped into a vector \mathbf{y} , the damage probability can be expressed as follows (Vaidogas, Juocevičius 2009):

$$P(D|B) = \int_{\text{all } \mathbf{y}} P(D|\mathbf{y}) f(\mathbf{y}) d\mathbf{y} = \int_{\text{all } \mathbf{x}} P(D|\boldsymbol{\psi}(\mathbf{x})) f(\mathbf{x}) d\mathbf{x}, \quad (2)$$

where: $P(D|\mathbf{y})$ is the fragility function relating the probability of D to \mathbf{y} ; \mathbf{x} is the vector of characteristics of BLEVE accident; $\boldsymbol{\psi}(\mathbf{x})$ is the vector-function which relates \mathbf{x} to \mathbf{y} (i.e., $\mathbf{y} = \boldsymbol{\psi}(\mathbf{x})$); and $f(\mathbf{x})$ and $f(\mathbf{y})$ are the joint probability density functions of \mathbf{x} and \mathbf{y} , respectively.

The development of the fragility function $P(D|\mathbf{y})$ is a highly case-specific task of reliability-based structural analysis. It must be solved for individual components of installation subjected to the hazard of BLEVE (e.g., Vaidogas 2003, 2007a, 2007b). The development of $P(D|\mathbf{y})$ will not be considered here. We can only say that a BLEVE accident may require to develop $P(D|\mathbf{y})$ for a combined action of three effects (components of \mathbf{y}): blast wave, thermal radiation and missile impact. Any attempts to do this are not known to us. The closest result was obtained by Lee, Rosowski (2006) who developed a fragility function for a combined action of earthquake and snow.

Fitting the density $f(\mathbf{y})$ to the direct data on BLEVE effects is impracticable. BLEVE accidents on road are unique, short-lasting and unexpected events and the post mortem data on them is too sparse for fitting $f(\mathbf{y})$. However, the density $f(\mathbf{y})$ and so the probability $P(D|B)$ can be estimated by propagating uncertainties expressed by the lower-level density $f(\mathbf{x})$ through the model $\psi(\mathbf{x})$ (Vaidogas 2007a, 2007b, 2009; Vaidogas, Juocevičius 2008a, 2008b, 2009; Juocevičius, Vaidogas 2010). The function $\psi(\mathbf{x})$ can be composed of a relatively large number of models available currently for the prediction of individual effects of BLEVE. Most of these models are deterministic; some are in competition in modelling individual effects. Table 1 contains a selection of literature on modelling the effects of BLEVE.

The density $f(\mathbf{x})$ expresses uncertainties in those characteristics of BLEVE accident which serve as input in the model $\psi(\mathbf{x})$. This density can be specified by means of two basic approaches to QRA known as classical Bayesian approach and predictive Bayesian approach (e.g., Aven 2003). We think that the latter approach is better suited to the assessment of risk posed by BLEVEs on road. However, an extensive discussion on the choice among the classical and predictive approaches will not be presented here. Such a discussion can be found in publications dedicated to methodological issues of QRA (e.g., Aven 2009; Aven, Zio 2011). All probabilistic models presented in the subsequent text will be interpreted in line with the predictive Bayesian approach.

The vector \mathbf{x} must contain physical characteristics of the tank undergoing BLEVE. The effects of BLEVE will also depend on the position and orientation of the tank in relation to the target. A scattering of projectiles from a cylindrical vessel BLEVE is significantly directional; some studies indicate that the blast from BLEVEs can also be directional (Birk 1996; Casal 2007). The position and orientation are key input information for the models described in the references cited in Table 1. In what follows, the position and orientation of the tank will be expressed by the first three components of \mathbf{x} :

1. The coordinates of explosion (tank) centre, x_1 and x_2 , specified in a coordinate system which includes the target and the section of the road in which the explosion can happen (Fig. 1).
2. The angle of the tank axis in relation to the road axis, x_3 (Fig. 1).

The further consideration is about the prediction of x_1 , x_2 , and x_3 for a specific situation of exposure to BLEVE hazard, and thus the prediction of the distance

from the explosion to a target under analysis. This distance will be denoted by Δ (Fig. 1). Despite the fact that the dimensions x_1 , x_2 and x_3 are not among physical characteristics of exploding tank, the proper choice of range and probability distribution of x_1 , x_2 and x_3 can substantially influence results of further risk assessment.

3. Geometric Information on Road Tank Accidents

The position and orientation of the tank after a road accident which escalates into BLEVE is growing in importance when the distance between tank and target decreases. Two coordinate systems can be used for the prediction of tank position and orientation (Franck H., Franck, D. 2010). The assessment of the risk to a fixed target requires to consider the position and orientation in the earth-fixed coordinate system $\{0; x_1, x_2, x_3\}$ (Fig. 1). However, the data on road tank accidents can be collected and processed using a coordinate system based on both vehicle and travel lane, $\{0; y_1, y_2, y_3\}$ (Fig. 2). The data recorded in the latter system can be transformed into data related to the former one with relative ease.

3.1. Transverse Rest Position and Departure Angle

The prediction of the tank position and orientation after it comes to a complete stop and can explode consists in the choice of either joint probability density function $f(y_1, y_2)$ or marginal densities $f(y_1)$ and $f(y_2)$ for the transverse rest position of the tank centre, y_1 , and the angle of rest departure of the tank relative to the travel lane centreline, y_2 (Fig. 2). For brevity, we will call y_1 and y_2 the transverse rest position and departure angle, respectively. In line with the aforementioned approaches to QRA, the densities $f(y_1, y_2)$ or $f(y_1)$ and $f(y_2)$ can be chosen using data on past accidents or expert opinion or both. The data can provide answer to the question of a stochastic dependence of y_1 and y_2 .

We think that the statistical variability of transverse rest position y_1 and departure angle y_2 can be assessed from data on road tank accidents. The potential data on y_1 and y_2 are of three sorts:

1. Data on road tank accidents which escalated into BLEVEs (A-data, for brevity).
2. Data on accidents which did not escalate into BLEVEs but were capable to do so in consequence of spill of flammable liquid or fire impinging the tank ('near misses' in terms of QRA) (B-data).

Table 1. A selection of literature on models used to predict BLEVE effects (components of the vector-function $\psi(\mathbf{x})$)

BLEVE effect	References
Blast	Prugh (1991); CCPS (1994); Planas-Chuci <i>et al.</i> (2004); CPD (2005); Abbasi, T., Abbasi, S. (2007); Casal, Salla (2006); Casal (2007); Genova <i>et al.</i> (2008)
Fireball	CCPS (1994); Prugh (1994); Robets <i>et al.</i> (2000); CPD (2005); Abbasi, T., Abbasi, S. (2007); Casal (2007)
Projectiles	Hauptmanns (2001); Gubinelli <i>et al.</i> (2004); CPD (2005); Vaidogas (2006); Abbasi, T., Abbasi, S. (2007); Casal (2007); Genova <i>et al.</i> (2008); Gubinelli, Cozzani (2009); Mébarki <i>et al.</i> (2009); Nguyen <i>et al.</i> (2009)

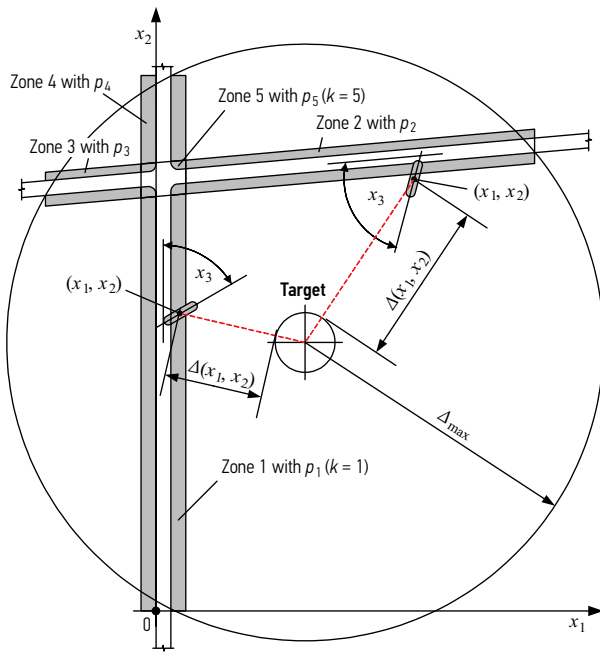


Fig. 1. Exposure of a roadside object (target) to the BLEVE hazard in the earth-fixed coordinate system $\{0; x_1, x_2, x_3\}$

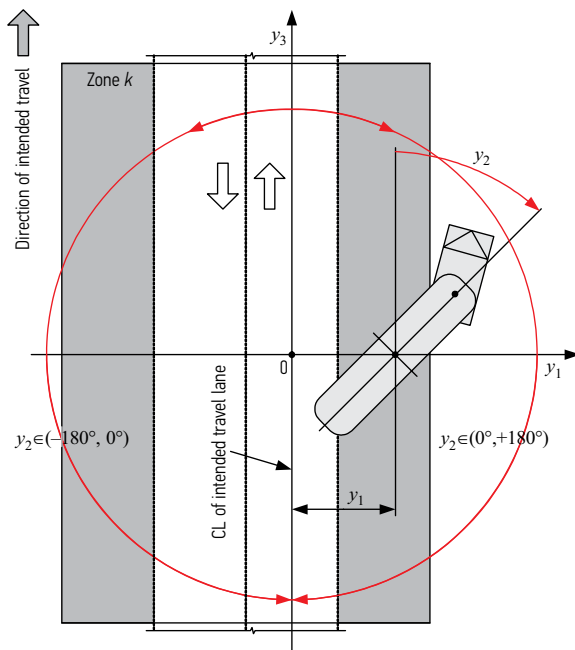


Fig. 2. Vehicle-based coordinate system $\{0; y_1, y_2, y_3\}$ used for collecting and processing data on road tank accidents

3. Data on accidents of road tanks which transported liquids, but not necessarily liquefied gases, and had dynamic characteristics similar to road tanks capable to cause BLEVE (C-data).

The A- and B-data are likely to be more relevant to future BLEVE accidents on road than C-data. However, the amount of C-data exceeds considerably the amount of A- and B-data because the number of road accidents which developed into BLEVEs or occurred as

“near misses” is relatively small (see, e.g., Oggero *et al.* 2006). In addition, information on y_1 and y_2 available in the reports on BLEVE accidents can be vague because tanks are displaced and destroyed during these explosions (see, e.g., Planas-Cuchi *et al.* 2004).

The potential sources of A-, B- and C-data are:

1. Hazmat transportation accident databases.
2. Accident databases of general nature.
3. Road accident databases collected and maintained usually by the police.
4. Databases of occupational accidents including road transportation events in which workers were injured and killed on duty.

These databases are maintained and updated by various official and professional bodies and organisations in many countries. However, several researchers have noticed the lack of statistical reliability of such databases due to the systematic underreporting of the circumstances of road accidents (see Trépanier *et al.* 2009 and the references cited therein). We think that a special study is necessary to determine whether these data sources contain such circumstantial data as a rest position y_1 and departure angle y_2 of the tank. To our knowledge, none of Lithuanian organisations maintains a database which includes circumstantial information on y_1 and y_2 . We also did not find any freely accessible database maintained outside Lithuania which would contain data on y_1 and y_2 .

Information on y_1 and y_2 can be elicited from the reports on road tank accidents presented by the mass-media and in the internet. These reports should not be neglected because they often contain pictures of the accident site and description accident circumstances. Consequently, such reports can serve as a source of C-data. We found a series of the reports and collected a small road tank accident database containing 151 events mainly for 2007–2011 period. Our database includes records of 65 accidents of the tank trucks and 86 accidents of tank semi-trucks. In 120 cases the accidents took place in the area with flat or almost flat roadside territory and zero vertical grade (gradient). In 17 and 5 cases accidents occurred on downhill and uphill road segments, respectively. The vertical grade was difficult to assess in 9 cases. Most accidents occurred in the US and were reported by US media. An extraction from the database is presented in Table 2.

The values of the transverse rest position, y_{1i} , were determined visually for 129 events and the departure angle y_{2i} was obtained also visually for 122 events. The data allowed to form 119 observation pairs (y_{1i}, y_{2i}) for the assessment of the stochastic dependence of y_1 and y_2 . Table 3 contains descriptive measures of the samples $\{y_{1i}, i = 1, 2, \dots, 129\}$ and $\{y_{2i}, i = 1, 2, \dots, 122\}$. Fig. 3 shows the histograms of these two samples. The scatter diagram of the pairs (y_{1i}, y_{2i}) is given in Fig. 4. The correlation coefficient computed for the pairs (y_{1i}, y_{2i}) was equal to 0.29. The p -value in Fig. 4 indicates a statistically significant relationship between y_1 and y_2 .

It was possible to fit two well-known probability distributions, normal and logistic, to the values y_{1i} .

Table 2. An extraction from a database containing information on 151 road tank accident

Date	Location	Material	Quantity, m ³	y_1 , m	y_2 , degs
06/12/2007	Everett	Gasoline	35.58	0.0	0
25/07/2009	Oak Park, Michigan	Diesel	49.21	2.0	0
22/10/2009	Indiapolis	Propane	20	8.5	85
23/10/2009	Fayetteville	Fuel	not reported	2.0	0
30/11/2009	Kansas City	Hydrochlorid acid	20.41	2.0	340
23/01/2010	Melville, New York	Fuel	45.42	6.5	340
25/01/2010	Monperlier, France	Fuel	not reported	-6.5	270
01/04/2010	Chikago, Illinois	Fuel	not reported	2.0	0
02/04/2010	Burverde, Texas	Fuel	not reported	-3.0	260
07/04/2010	Wamsutter, Wyoming	Crude oil	not reported	0.0	0
14/04/2010	Roy, Utah	Diesel	28.39	9.0	270
16/05/2010	Miami Gardens, Florida	Fuel oil	not reported	2.0	0
28/05/2010	Carona, Los Angeles	Gasoline	33.31	3	0
29/05/2010	Tynsborough, Massach.	Aerosol paint	not reported	3	0
22/06/2010	Foxboro, Mass.	Jet fuel	41.64	5.0	45
20/08/2010	Coloma, Michigan	Fuel	not reported	8	340
20/08/2010	Arnold, Maryland	Fuel	not reported	0	-5
21/08/2010	Arizona	Diesel	18.9	15.0	50
28/08/2010	Utah	Diesel	28.39	8.5	90
29/08/2010	Hamshire, Texas	Isobutane	32.76	10.0	90
03/09/2010	Dearborn County, Indiana	Phthalic anhydride molten	15.14	13.0	40
23/10/2010	Fayetteville	Fuel	not reported	2	0
29/10/2010	Albuquerque, New Mexico	Fuel	not reported	-5.0	280
09/11/2010	California	Tar	not reported	5.0	15
20/12/2010	Utah	Crude oil	40.33	-5.0	310

Table 3. Descriptive measures of the samples consisting of observations of transverse rest position y_{1i} and departure angle y_{2i}

Measure	Positions y_{1i}	Angles y_{2i}
Sample size	129	122
Mean	2.02 m	2.83°
Std. deviation	5.62 m	56.8°
Minimum	-12.25 m	-170°
Maximum	18 m	180°
Skewness	0.0551	0.119
Kurtosis	-0.1059	1.679
Std. skewness	0.256	0.536
Std. kurtosis	-0.246	3.79

Table 4. Goodness-of-fit tests for the sample of y_{1i} values

Measure	Normal	Logistic
Kolmogorov-Smirnov D_n	0.05755	0.05320
Kolmogorov-Smirnov p	0.7863	0.8586
Shapiro-Wilk W	0.9851	-
Shapiro-Wilk p	0.7542	-

Although neither of the distributions was rejected by standard goodness-of-fit tests, the logistic distribution Logistic (2.02 m, 3.10 m) fits the data better than the normal distribution $N(2.02 \text{ m}, 31.6 \text{ m}^2)$ (see Table 4 and Fig. 3a). Thus the logistic distribution will be used for the purposes of the simulation described in Sec. 4.

The values y_{2i} do not seem to obey any standard probability distribution. An empirical distribution function of the sample of y_{2i} can be used as a tentative model for the purposes of simulation (e.g., Evans *et al.* 2000). This function is represented by the histogram of the cumulative frequencies shown in Fig. 3b.

The reports of the 151 accident underlying our database provide at least minimum statistical information on the probability distribution of the transverse rest position y_1 and the departure angle y_2 . However, these reports tell little about the influence of accident situation and configuration of accident site on the rest position of the tank along its intended route. We will call this position the longitudinal rest position and denote it by y_3 (Fig. 2). Unfortunately, the data from the 151 accident do not allow drawing any specific conclusions about a stochastic relation between position y_3 and other two circumstantial characteristics y_1 and y_2 .

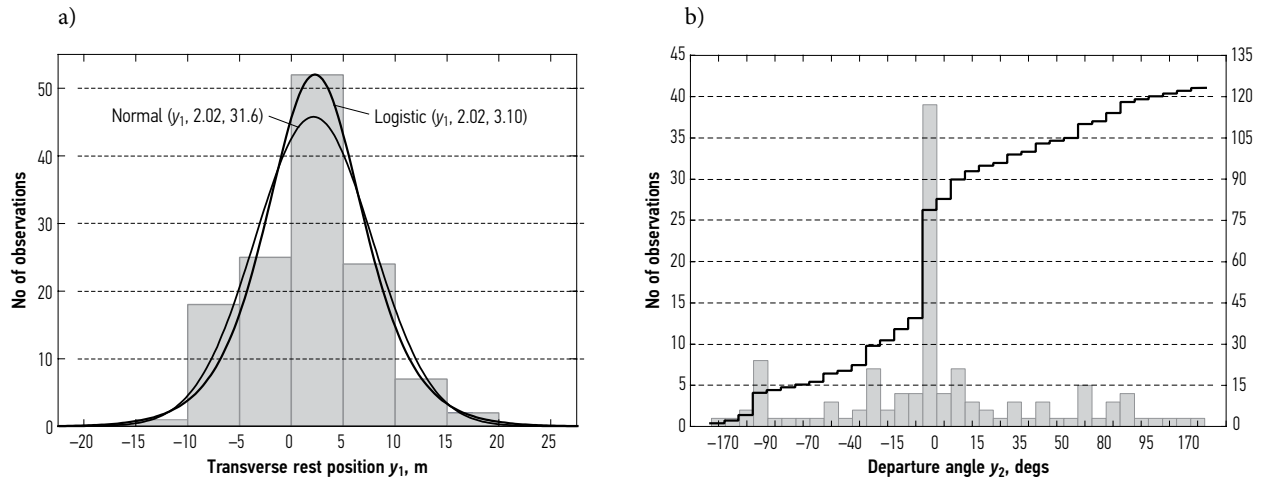


Fig. 3. Visualisation of data on road tank accidents: a – histogram of the transverse rest position values y_{1i} with superimposed normal and logistic densities; b – standard and cumulative histograms the of the rest departure angle values y_{2i}

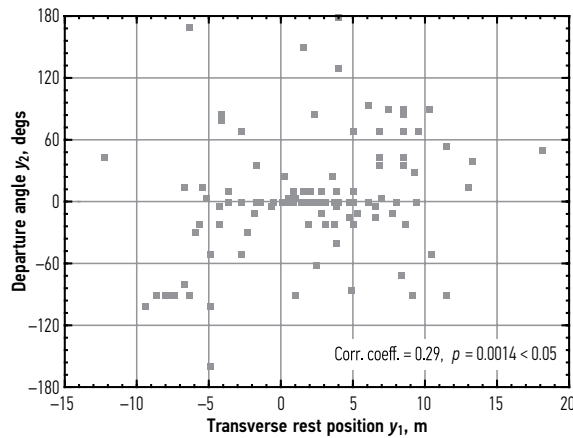


Fig. 4. Scatter diagram of the 119 observation pairs (y_{1i}, y_{2i})

3.2. Longitudinal Rest Position

A road tank BLEVE will affect a relatively small territory within the transportation network. The road network fragment in this territory can be determined by introducing an unsafe distance around a vulnerable roadside object, for instance, the radius Δ_{\max} around the ‘target’ shown in Fig. 1. The most general and consistent criterion for the unsafe distance Δ_{\max} can be a non-exceedance of a tolerable value P_{\max} of the damage probability $P(D | B)$ expressed as a function of the explosion stand-off Δ :

$$\Delta_{\max} = \underset{\Delta}{\operatorname{argmax}} \{P(D | B, \Delta) | P(D | B, \Delta) \leq P_{\max}\}. \quad (3)$$

A solution of the above maximisation problem requires to predict uncertain BLEVE effects and to utilise methods of structural reliability analysis for a repeated estimation of the damage probability $P(D | B, \Delta)$ for different values of Δ (see, e.g., Vaidogas, Juocevicius 2007). The determination of Δ_{\max} is beyond the scope of the present paper.

As the road network fragment defined by Δ_{\max} will be relatively small, any history of road tank accidents

in this area will almost certainly not be available. Consequently, a prediction of the longitudinal rest position y_3 will have to rely on either the knowledge about road tank accidents in comparable situations or an educated guess. We think that the best way to deal with such a data situation is the predictive Bayesian approach to QRA (e.g., Aven 2003, 2009). Quantitative measures of uncertainty related to y_3 expressed in line with this approach can be integrated into a simulation-based prediction of accident locations.

4. Monte Carlo Simulation of Accident Positions

4.1. Disaggregation of Road Segment

The prediction of the longitudinal rest position y_3 can be simplified by dividing the road network fragment within Δ_{\max} into simpler shapes for which the density $f(y_3)$ can be assigned subjectively or on the basis of some prior knowledge. The roadway can be disaggregated into zones consisting of fixed length segments or homogenous segments in terms of roadway geometry, roadside features, traffic characteristics, etc. These zones should begin and end when their characteristics change. A disaggregation of road and rail network is basic to many applications of TRA, although the road network fragments considered in these applications are much larger than the area determined by the BLEVE-specific distance Δ_{\max} (e.g., CCPS 1995; Gheorghie *et al.* 2005; Samuel *et al.* 2009). The disaggregation of roadways is also used for an assessment of road accident likelihoods (e.g., Chang 2005).

Fig. 1 shows a simple example of a disaggregation of the road segments within Δ_{\max} into five zones with simple shapes. The width of these zones exceeds the road width to indicate that the transverse rest position of the tank can leave the road surface. In the absence of any historic data on road accidents in such zones, a uniform probability distribution of y_3 along the zone axes can be assumed for the purpose of simulation. Then the uniform density $f_k(y_3)$ will express maximum uncertainty related to the values of y_3 in the zone k .

The zones can be specified with relative ease for straight road segments and long horizontal curves.

However, the specification can be conjectural and arbitrary to a degree in the road portions that have more complicated layout and/or indicate a higher proneness to road accidents. Such road portions are intersections and crossings, sharp curves, changes in the road width, wide variations in traffic volume. Roadside features (e.g., numerous roadside objects) can also have influence on zones specification.

The simulation requires to introduce a discrete probability distribution with the weights p_k ($k = 1, 2, \dots, n_k$) assigned to individual zones, where n_k is the number of zones within A_{\max} (e.g., $n_k = 5$ in Fig. 1). The weight p_k expresses the proneness of the zone k to a road accident involving tank vehicle. In line with the predictive Bayesian approach to QRA, the weights p_k quantify the analyst's degree of belief and can be a result of an educated guess or, alternatively, judgement based on some prior knowledge. In our opinion, there are at least four sources of such knowledge:

1. Statistical data obtaining the distribution of relative frequencies of vehicle accidents by location (intersections, non-intersections, circles, etc.) (e.g., Al-Ghamdi 2003).
2. Mathematical models used to estimate the probabilities of vehicle accidents in specific locations (Spek *et al.* 2006; Ye *et al.* 2009; Haleem *et al.* 2010).
3. Models relating vehicle accidents to geometric design of roadway, roadside features, traffic characteristics and environmental conditions (Abdel-Aty, Radwan 2000; Lee, Mannering 2002; Chang 2005; Elvik *et al.* 2009).
4. Methods developed for an identification of crash hotspots (e.g., Cheng, Washington 2005; Huang, Abdel-Aty 2010; Montella 2010).

The data and models just listed have potential to be used for the specification of the weights p_k . However, we think that this body of knowledge is too loose and a special study is necessary to develop more or less formal procedures which utilise the knowledge for the choice of p_k . Practical procedures for ranking and weighting the zones can be borrowed in the field of multiple criteria decision making (MCDM). For instance, the weights p_k can be specified by organising an expert panel and utilising expert opinions by means of a well-known MCDM method called AHP (e.g., Luria, Aspinall 2003; Turskis, Zavadskas 2010; Vaidogas, Šakėnaitė 2010, 2011).

4.2. Modelling the Transverse Rest Position

A further discrete probability distribution is necessary to choose a travel lane of the road tank. For brevity, we will consider a two-lane road only. Consequently, the distribution will have only two weights, say, π_1 and π_2 . In the case where travelling frequencies of road tanks in both directions are equal, one can assume that $\pi_1 = \pi_2 = 0.5$. If the tank vehicles travel only in one direction, $\pi_1 = 0$ or $\pi_2 = 0$. With the weights π_1 and π_2 and the probability distribution of the transverse rest position y_1 obtained in Sec. 3.1, the rest position of the tank centre with respect to the road centreline, y_4 , can be modelled by the mixed density:

$$\varphi(y_4 | \pi_1, \pi_2) = \pi_1 f(y_4 | \theta_1) + \pi_2 f(y_4 | \theta_2), \quad (4)$$

where: $f(\cdot)$ is the logistic density of the transverse rest position y_1 with the parameter vectors θ_1 and θ_2 adjusted to the cross-sectional dimensions of the road. If, for instance, the lane width is equal to 3 m and $y_1 \sim \text{Logistic}(2.02 \text{ m}, 3.10 \text{ m})$, the densities $f(y_4 | \theta_1)$ and $f(y_4 | \theta_2)$ will be logistic ones with the parameter vectors:

$$\theta_1 = (-3.52 \text{ m}, 3.10 \text{ m}) \text{ and } \theta_2 = (3.52 \text{ m}, 3.10 \text{ m}). \quad (5)$$

The logistic densities $f(y_4 | \theta_1)$ and $f(y_4 | \theta_2)$ with the above parameters are shown in Fig. 5a. This figure illustrates also the density $\varphi(y_4 | \pi_1, \pi_2)$ with $\pi_1 = 0.7$ and $\pi_2 = 0.3$.

The densities $f(y_4 | \theta_l)$ ($l = 1$ or 2) and $\varphi(y_4 | \pi_1, \pi_2)$ in Eq. (4) are suited to the modelling of the transverse rest position y_4 in the case where y_4 is unbounded on both sides. However, the roadway and roadside territory can include natural and man-made obstacles which restrict the motion of vehicles after they leave the road surface or cross into opposite lanes of traffic. Examples of such obstacles are roadside barriers, medium barriers, back slopes, roadside structures.

A collision of a tank vehicle with a roadside obstacle (medium barrier) and its post-collision travel until a complete stop is a fairly uncertain process. A prediction of the transverse rest position y_4 resulting from this process is far from being trivial. However, one can say with fair degree of certainty that the obstacles, which are able to withstand an impact of a tank vehicle, determine the outermost values of y_4 . Let these values be y_{4L} and y_{4R} . Then for the purposes of simulation one can assume that $y_4 \in [y_{4L}, y_{4R}]$ when obstacles are on both sides of the travel lane and $y_4 \in [y_{4L}, \infty [$ or $y_4 \in]-\infty, y_{4R}]$ when the obstacles are on the left or the right side, respectively. An illustration of y_{4L} and y_{4R} for a two lane road is shown in Fig. 5b, where $y_{4L} = 9 \text{ m}$ and $y_{4R} = -12 \text{ m}$ for the lane 1 and $y_{4L} = -12 \text{ m}$ and $y_{4R} = 9 \text{ m}$ for the lane 2.

Fitting a probability distribution of y_4 over the two-sided or one-sided intervals introduced above can be problematic. A relatively large amount of data required by standard fitting procedures will hardly be available for the reasons mentioned in Sec. 3.1. In addition, accident situations involving roadside obstacles are unique and this raises the question, whether the data collected in one roadside situation is representative to another situations. However, the fact that values of y_4 are bounded by the values y_{4L} and y_{4R} suggests that the probability distribution of y_4 can be obtained by truncating the densities $f(y_4 | \theta_l)$. The truncated density $f'(y_4 | \theta_l)$ is obtained from $f(y_4 | \theta_l)$ by means of the standard relations:

$$f'(y_4) = \begin{cases} \frac{f(y_4)}{F(y_{4R}) - F(y_{4L})} & \text{if } y_4 \in]y_{4L}, y_{4R}[, \\ \frac{f(y_4)}{1 - F(y_{4L})} & \text{if } y_4 \in]y_{4L}, \infty[, \\ \frac{f(y_4)}{F(y_{4R})} & \text{if } y_4 \in]-\infty, y_{4R}[. \end{cases} \quad (6)$$

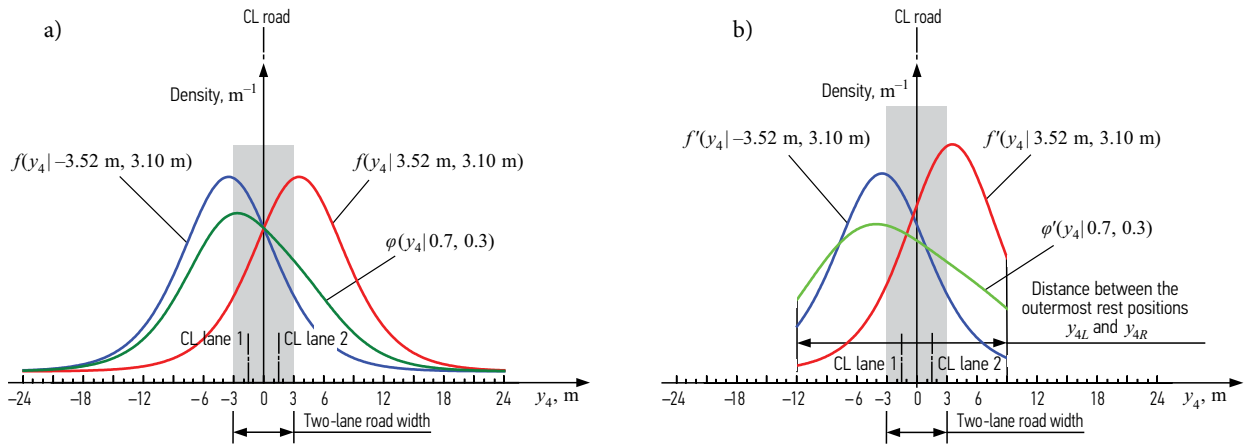


Fig. 5. An illustration of the densities expressing uncertainties in the transverse rest position y_4 with respect to the centreline of a two-lane road: a – standard densities; b – truncated densities

In the above relations, $F(y_4)$ is the cumulative distribution function of y_4 and the parameter vector θ_i is skipped for brevity. With the truncated densities related to opposite lanes, the truncated density related to the whole width of a two-lane road is obtained by:

$$\varphi'(y_4 | \pi_1, \pi_2) = \pi_1 f'(y_4 | \theta_1) + \pi_2 f'(y_4 | \theta_2). \quad (7)$$

The density $\varphi'(y_4 | \pi_1, \pi_2)$ is defined on the same interval as the constituent densities $f'(y_4 | \theta_i)$ (see Eq. (6)).

Fig. 5b presents an illustration of the densities $f'(y_4 | \theta_1)$ and $f'(y_4 | \theta_2)$ obtained by a truncation of a standard logistic density. The densities $f'(y_4 | \theta_1)$ and $f'(y_4 | \theta_2)$ are defined on the intervals $(y_{4L}, y_{4R}) = (9 \text{ m}, -12 \text{ m})$ and $(y_{4L}, y_{4R}) = (-12 \text{ m}, 9 \text{ m})$, respectively. Fig. 5b shows also the density $\varphi'(y_4 | 0.7, 0.3)$ calculated by means of Eq.(7).

The outermost rest positions y_{4L} and y_{4R} may not necessarily be fixed values. Such obstacles as trees and bushes planted in the roadside territory with moderate density may stop the motion of a tank vehicle after its departure from the road. Obstacles of this type may have randomly distributed distances from the road edge. In addition, the depth of a vehicle encroachment into the area of such obstacles may be highly random. Consequently, the outermost rest positions y_{4L} and y_{4R} may be uncertain quantities. They can be modelled as random variables with respective densities $f(y_{4L})$ and $f(y_{4R})$. Fig. 6 shows an illustration of the density $f(y_{4R})$ and the truncation point y_{4Rj} sampled from a probability distribution represented by $f(y_{4R})$.

4.3. Algorithm of the Simulation

With the models described in this section, the stochastic simulation of the tank rest position will consist in sampling values of the tank rest position and departure angle from underlying probability distributions. Each loop of the stochastic simulation of accident position, say, loop j should start from sampling of the zone number k from the discrete probability distribution defined by the weights p_k (Fig. 7). Then the values of the longi-

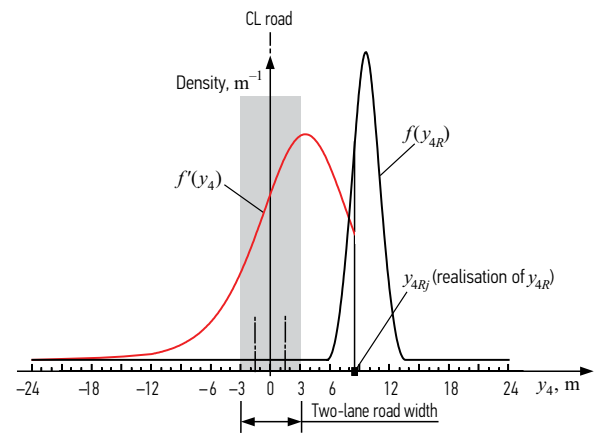


Fig. 6. The case of the density of the transverse rest position y_4 truncated at a random point

tudinal and transverse position, y_{3j} and y_{4j} , must be sampled from corresponding probability distributions. This operation will be straightforward in case where y_3 and y_4 are considered to be independent. Finally the value of the departure angle y_{2j} can be sampled.

An application of the proposed simulation procedure with the flowchart shown in Fig. 7 is presented in the second part of this study (see next issue of the Journal). The case study described in the second part applies the procedure to an existing site of the potential BLEVE accident located in the coastal region of Lithuania.

5. Conclusions

A prediction of the road tank accidents capable to escalate into explosions on road has been considered. The attention was focussed on boiling liquid expanding vapour explosions (BLEVEs). The potential damage caused by BLEVEs to roadside objects depends on distance and orientation of an exploding tank in relation to an exposed object. Consequently, an assessment of the damage will require predicting the position of the tank within a road segment going in the vicinity of a vulnerable roadside object.

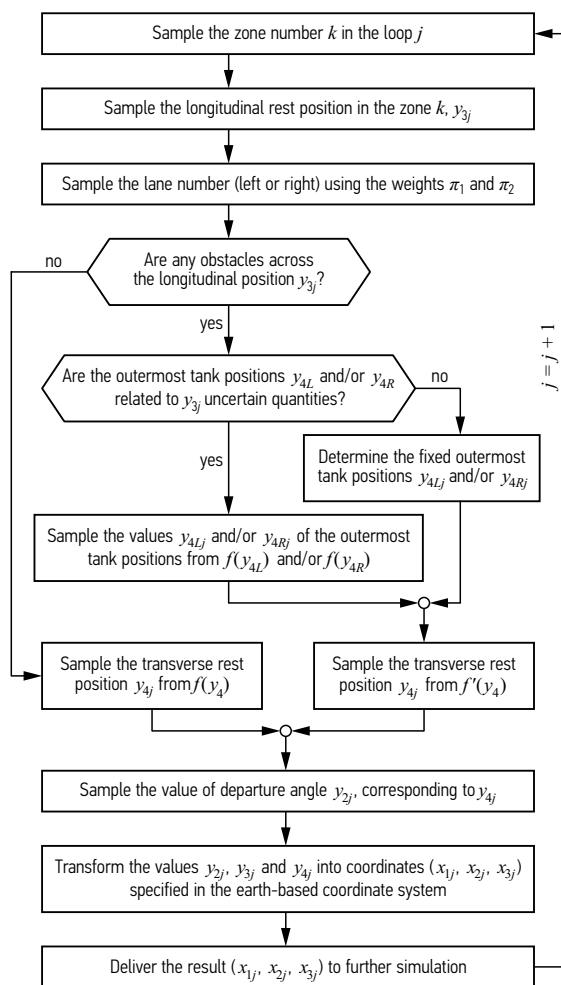


Fig. 7. A flowchart of the simulation step j

The prediction of the position of road tank explosions can be subdivided into the prediction of three circumstantial characteristics: longitudinal and transverse rest positions of the tank with respect to road centreline or other longitudinal reference line as well as departure angle of the tank. These three characteristics are uncertain quantities and uncertainty related to them must be modelled by means probability distributions. Some of these distributions can be fitted to statistical data; others will have to be specified subjectively in line with the principles of a quantitative risk assessment (QRA).

Any systematic set of data on the position of road tanks which underwent BLEVEs is not available or, at least, accessible. BLEVEs on road are rare, unexpected and short-lasting events, in the course of which tanks are destroyed. However, data on transverse rest position and departure angle can be gained from accidents which were precursors of BLEVEs or accidents of non-explosive tanks which were similar to tanks capable of causing BLEVEs. It was possible to extract such data from reports on past road tank accidents presented in the mass-media and on the internet. Data on 151 road tank accidents collected from these sources allowed us to fit a logistic probability distribution for the transverse rest position and to establish empirical probability distribu-

tion for the departure angle. The stochastic dependence between these two circumstantial characteristics is weak, albeit statistically significant.

A probabilistic modelling of the tank rest position along a road segment, from which BLEVE can affect a vulnerable roadside object, is problematic in terms of data. Such a road segment will be relatively small and data on tank accidents in this or similar segments will hardly be available. Consequently, the probability distribution of the longitudinal rest position will have to be chosen subjectively. Methods of the specification of subjective probabilities and probability distributions developed and widely applied in the field of QRA can be used for the modelling of the longitudinal rest position.

An assessment of damage caused by BLEVEs on road and rail is in essence a QRA problem. An estimation of risk posed by these events will require to choose among two basic approaches to QRA, namely, classical Bayesian approach and predictive Bayesian approach. All probabilistic models presented in this study were interpreted in the context of the predictive Bayesian approach. We think that this approach allows to deal effectively with sparseness of data on past road tank BLEVEs and the need to apply extensively judgement to the prediction of such accidents. However, an extensive discussion on why the predictive Bayesian approach was preferred to the classical Bayesian approach was not presented here. Such a discussion can be found in numerous publications dedicated to methodological issues of QRA.

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