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TRENCH FIRES RESULTING FROM ACCIDENTAL RELEASES FROM TANKER TRUCKS: ASSESSING THE THERMAL EFFECT ON ROADSIDE TERRITORY

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Abstract. The risk posed by spill and subsequent fire during road transportation of flammable liquid is considered in the paper. Attention is paid to a pool fire than can occur in roadside terrain. Circumstances and road situations increasing the likelihood of a spill and fire accident are analysed. The problem under study is an assessment of thermal radiation induced by a roadside pool fire. This study applied a pool fire model known as a trench fire to a roadside situation. The trench fire is considered to be a likely type of a pool fire due to presence of roadside ditches and other oblong low areas along the road. The estimation of the thermal radiation from trench fires is carried out in the deterministic way due to actual lack of systematic uncertainty modelling related to pool fires. Deterministic models developed for estimating the radiation of pool and trench fires are presented and illustrated by a transportation case study. The case study reveals that the thermal radiation emitted by a trench fire can endanger objects positioned in the intermediate

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vicinity to the road. Further spread of fire into more distant locations is possible only through the domino effect. Incorporation of the thermal radiation models into a transportation risk assessment is discussed in brief. Findings of this study are viewed as knowledge that can be used for refining the estimation of risk posed by transportation of hazardous materials.

Keywords: hazardous material, pool fire, risk, roadside territory, traffic accident, trench fire, thermal radiation.

Introduction

Road transportation of flammable liquids is an issue of vital importance in the economy of most countries (e.g., Eurostat, 2020). Nevertheless, economic benefits of such transportation are accompanied by losses due to accidents that sporadically occur on road and involve tanker trucks (Cutter & Ji, 1997; Demir et al., 2015; Kletz & Amyotte, 2019). Such accidents are usually initiated by traffic accidents and succeeded by a series of events that can escalate into spills, fires and, in the worst case, explosions (Oggero et al., 2006; Liu et al., 2021). A maximum escalation of a traffic accident involving a tanker truck is a violent explosion of its tank known as a boiling liquid expanding vapour explosion (Birk, 2013; Gamberini et al., 2021; Planas et al., 2015; Planas-Cuchi et al., 2004).

The present study considers a scenario of a road accident that can end up in formation and ignition of an oblong pool in a low area nearby the road (see, e.g., Accident 1 described in Appendix). Burning of such a pool is known as trench or line fire (Mannan, 2012; Ding et al., 2021). Attention is paid to an assessment of the thermal damage that can be caused by a trench fire to objects located nearby the accident. A deterministic mathematical model of thermal radiation from trench fires will be used as a key element of damage assessment (Beyler, 2016). This model belongs to a family of engineering (hand calculation) methods used to assess effects of pool fires and actively applied at present (e.g., Hu, 2017; Gavelli, 2021). The engineering methods of pool fire simulation are opposed by numerical simulation methods developed in the field of the computational fluid dynamics (CFD) (Shahi, 2015). An application of the CFD simulation to pool fires is currently under rapid development and a large number of studies have been published in recent years (Dasgotra et al., 2021; Yip et al., 2020, 2021). However, applications of the CFD simulation to pool fires that are specific to spill accidents on road or rail do not seem to be available. The engineering method of trench fire simulation will be used solely as the first approach to assessing risk posed by trench fires in roadside territory. A comparison of this method to potential CFD simulations lies far outside the problematics and intricacies of road transportation of flammable liquids and is not considered in this study.

The study discusses circumstances and road situation favourable for an occurrence of a trench fire. The consideration excludes spills of liquefied combustible gasses from tanker trucks. Such spills may initiate not only pool fires but also jet fires and propagation of flames through vapour clouds known as vapour cloud explosions (Raj, 2005, 2007). Jet fires and vapour cloud fires in transportation were beyond the scope of the present study. However, a spill of liquefied combustible gas from a road tanker can result in a simple trench fire. Then an assessment of thermal radiation impinging on road and roadside territory will turn into a usual simulation of a pool fire no matter which method, engineering and numerical one, is applied to this simulation (Yi et al., 2020).

1. Methodology

1.1. Risk-based interpretation of thermal damage from pool fires in transportation

In terms of the probabilistic risk analysis (PRA), an event with the potential for puncturing a tank is a random initiating event (event E_0, say). Most probably, E_0 will be a collision and/or overturning of a tanker truck, although spills of tanker trucks occur also as non-collision accidents (Shen et al., 2014). Consequences of E_0 can involve a pool fire that will impinge on damaged truck, road traffic in the vicinity of the fire and roadside territory. The damage caused by thermal radiation from the pool fire to exposed vulnerable objects can be represented by the random event D defined as an intersection of preceding random events, namely,

$$D = E_0 \cap E_1 \cap E_2 \cap E_3 \cap E_4, \tag{1}$$

where the event E_1 represents spill from the tank and formation of a pool, E_2 is an ignition of the pool, E_3 is an impingement of thermal radiation on road elements and roadside targets and E_4 is ignition of the target or other thermal damage to the target (thermal deformations or external charring, say).

There are at least three sources of ignition (event E_2) that can inflame the pool:

- The fire can originate in the vehicle of the crashed and punctured tanker (e.g., Planas-Cuchi et al., 2004; Planas et al., 2015);

- A spreading mixture of air and flammable vapour emitted by the pool can be ignited by a running engine of a vehicle that will accidentally pass (halt at) the scene of spill accident; for instance, such an ignition is suspected in the case of BP refinery disaster in 2005 (e.g., Manca & Brambilla, 2012);
- The air and vapour cloud driven by wind can meet an ignition source in roadside terrain, for instance, a spark in open-air electrical equipment built nearby the road.

Severity of the event D will depend, among other things, on proximity of potentially exposed objects to the pool. Positions of exposed objects can be

- Fixed in case of structures, engineering works and forested areas (objects “1”, Figure 1);
- Restrained (partially fixed) in case of vehicles trapped in traffic congestion caused by a tanker accident and impaired people inside of the trapped vehicles (objects “2”, Figure 1);
- Mobile in case of vehicles unrestricted by traffic and other obstacles (object “3”, Figure 1);
- Highly mobile in case of unimpaired people (persons inside vehicles, rescuers, passers-by, gawkers) (objects “3”, Figure 1).

The objects just listed can be subdivided into fixed targets (the first two categories) and mobile targets (the last two categories). The event D can be decomposed into simpler events representing thermal damage to fixed and mobile targets, namely,

$$D = \left(\bigcup_{j=1}^{n_{\mathrm{fxd}}} D_{\mathrm{fxd},j} \right) \bigcup \left(\bigcup_{k=1}^{n_{\mathrm{mob}}} D_{\mathrm{mob},k} \right), \tag{2}$$

where $D_{\mathrm{fxd},j}$ and $D_{\mathrm{mob},k}$ are the events of thermal damage to the fixed target j and the mobile target k, respectively. The number of fixed targets, n_{fxd}, can be predicted with relative ease for a given location of fire accident. The corresponding number of mobile targets, n_{mob}, is much less predictable and depends on random circumstances of an accident. The events $D_{\mathrm{fxd},j}$ and $D_{\mathrm{mob},k}$ can represent different character and degree of thermal damage: burns to humans, ignition of individual objects and wildland, loss of burning objects, fire-induced structural failures, power outages due to heating of electrical lines. A special kind of $D_{\mathrm{fxd},j}$ can be damage to the superstructure of a cable-stayed bridge in case of a tanker truck fire (e.g., Rujin et al., 2019).

Probabilities of the events $D_{\mathrm{fxd},j}$ and $D_{\mathrm{mob},k}$ will depend on the thermal radiation (incident heat-flux) emitted by the pool fire and usually denoted by the symbol $\dot{q}''$ (Figure 2). In the simplest case, an occurrence of $D_{\mathrm{fxd},j}$ and $D_{\mathrm{mob},k}$ can be expressed by simple exceedance criteria. For instance, the damage to a building will occur when the thermal radiation received by this building will exceed 31.5 kW/m^2, whereas such a threshold level for people is 1.4 kW/m^2 (McGrattan et al., 2000).

In general, the probabilities of $D_{\mathrm{fxd},j}$ and $D_{\mathrm{mob},k}$ are expressed through the fragility functions $P(D_{\mathrm{fxd},j}|\dot{q}'')$ and $P(D_{\mathrm{mob},k}|\dot{q}'')$. Functions of this type are standard means of PRA in such fields as earthquake engineering and extreme wind engineering (e.g., Sundararajan, 1995). For humans exposed to thermal radiation $\dot{q}''$, values of $P(D_{\mathrm{mob},k}|\dot{q}'')$ can be estimated by applying probit models derived for burns (e.g., CPR, 2005). Fragility functions $D_{\mathrm{fxd},j}$ related to inanimate objects (structures, vehicles, roadside vegetation) are not available in the ready-to-use form. However,

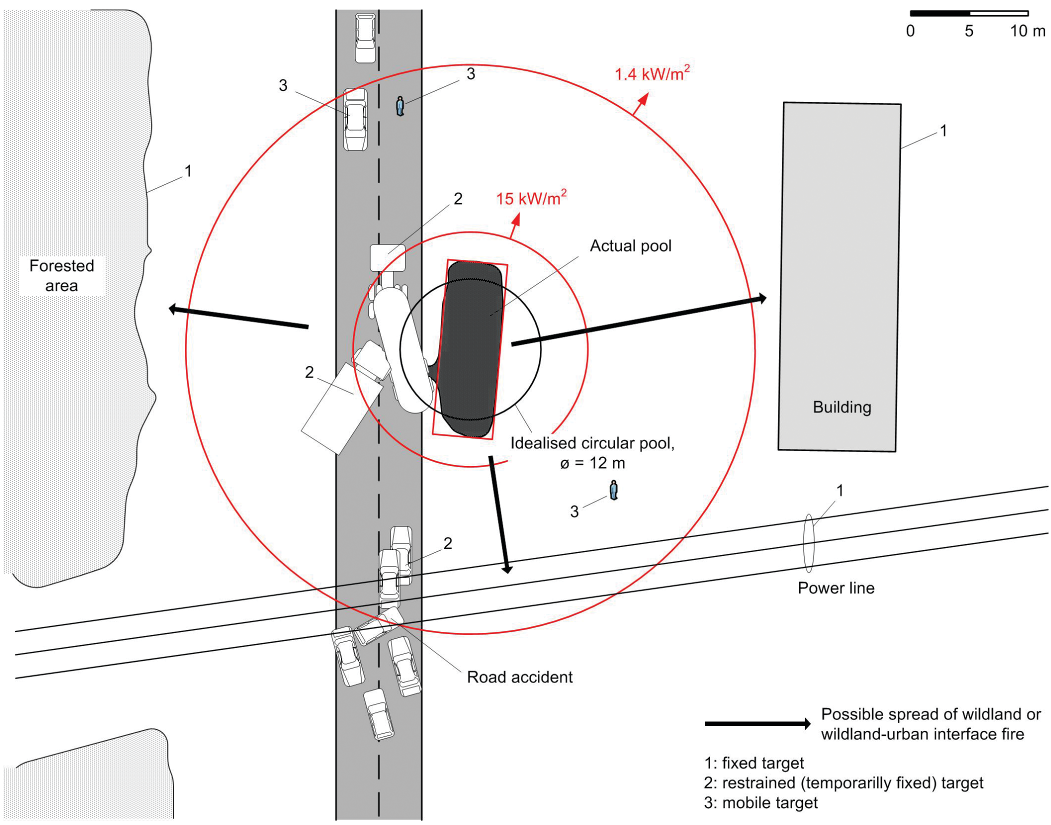


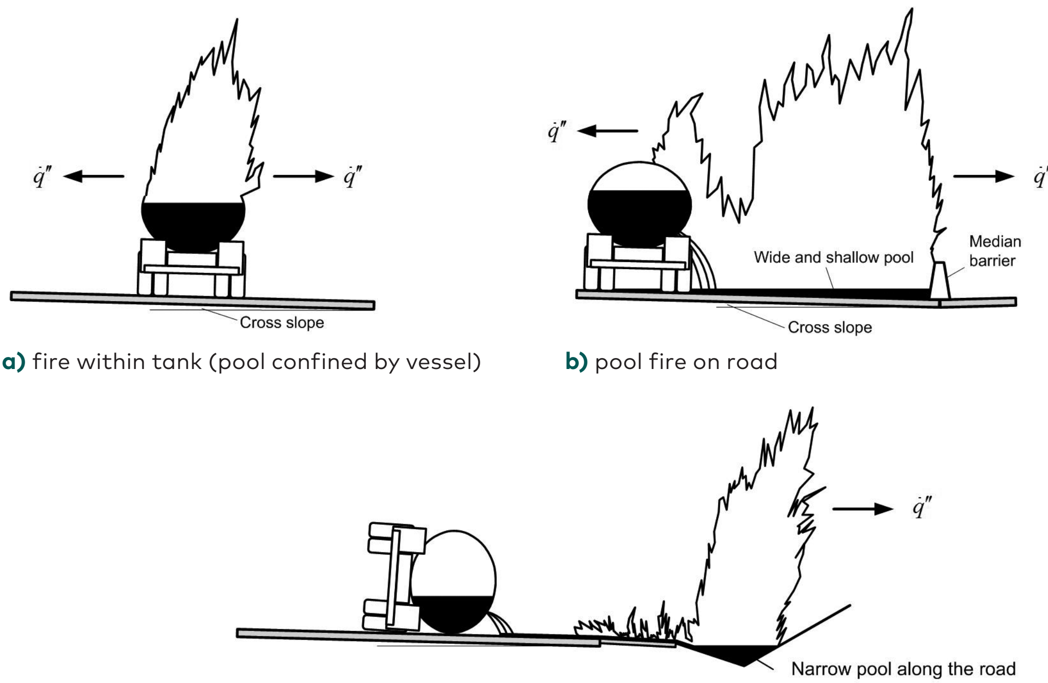
Figure 1. An illustration of an accident caused by release and ignition of flammable liquid shipped by a tanker truck (the thermal radiations of 1.4 kW/m^2 and 15 kW/m^2 are approximate values obtained for a gasoline pool by means of a point source model (Beyler, 2016))

development of such functions is basically a technical task rather than a problem of theoretical development.

A prediction of the events $D_{\mathrm{fxd},j}$ and $D_{\mathrm{mob},k}$ will be governed by an assessment of the radiation $\dot{q}''$, regardless of how an occurrence of $D_{\mathrm{fxd},j}$ and $D_{\mathrm{mob},k}$ is defined mathematically. The radiation $\dot{q}''$ depends, among other things, on geometry of pool fire. In the case of release and fire on road, the pool geometry will depend on the relief of roadside terrain surrounding the accident site (e.g., Figure 2b, c). The following section will address the problem of pool formation in roadside terrain.

1.2. The situation of a trench fire accident in roadside terrain

Pool fires have been investigated over several decades by considering releases of flammable liquids and gases on land and water. It is argued that pool fires are the most frequent accidents in stationary industrial equipment (Vasanth et al., 2017). Thermal radiation induced by pool fires and usually denoted by the symbol $\dot{q}''$ depends mainly on



a) fire within tank (pool confined by vessel) **b)** pool fire on road

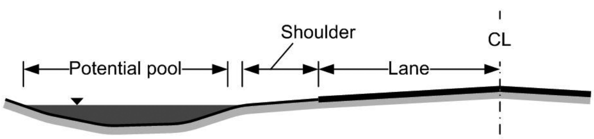
c) trench fire in the roadside ditch

Figure 2. Three types of pool fires caused by ignition of flammable liquid cargo

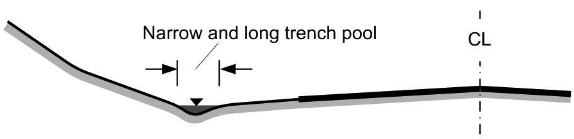
composition of fuel, size and shape of pool and its vicinity to a potential target. From the transportation standpoint, these factors can be viewed as follows:

- The type and composition of fuel that can be involved in a pool fire accident depends on the type of liquid cargo;
- The amount of released liquid will be limited by the tank capacity;
- The shape of pool will depend on a transverse cross-section of road and configuration of roadside terrain (Figure 2b, c and Figure 3a, b);
- The formation of a pool can be influenced also by a vertical alignment in the longitudinal direction (Figure 3c, d).

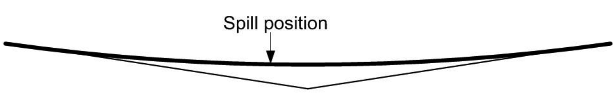
The territory affected by a pool fire radiation will be relatively small. Therefore, the hazard of a pool fire should be assessed only in certain



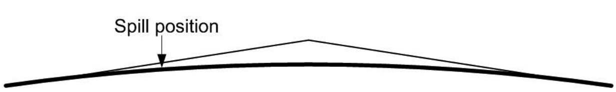
a) unfavourable configuration of cross section potentioally leading to a large-sized pool



b) favourable configuration of cross section causing formation of a shallow trench pool



c) unfavourable sag curve in the longitudinal section



d) favourable crest curve or slope in the longitudinal section

Figure 3. Transverse and vertical alignments of road causing escalation or de-escalation of spill accidents

locations of road network. Three specific features of these locations should coincide:

- Road section (junction) under analysis is a road location with a record of increased number of traffic accidents, especially, crashes involving heavy vehicles (see, Figure 4a);
- Targets vulnerable to thermal radiation $\dot{q}''$ are present in the proximity of this road section (junction). The vulnerability can be approximately evaluated by a plotting a safe separation distance for the target as is shown in Fig. 4a. In the simplest case, this distance could be expressed through a thermal radiation that is still tolerable for the target. A more sophisticated, probabilistic problem statement can be applied for specifying the tolerable distance (e.g., Juocevicius & Vaidogas, 2010; Gavelli, 2021; Vaidogas & Linkute, 2012);
- The configuration of the roadside territory at the road section (junction) under analysis is liable to form a flammable pool. Several alternative pools that are different in terms of location, size and shape could be considered (Figure 4a).

The pair of the first two features can be identified with relative ease from traffic accident data, geographic information and fire safety assessments. The third feature, namely, the proneness of roadside terrain to a pool formation can be assessed by creating a terrain model and applying several methods used for predicting terrestrial dispersion of liquids:

- Direct tests with water release at the site of potential pool (e.g., Ingason & Li, 2017);
- Methods used for modelling oil spills (Fingas, 2017);
- Methods developed for high-resolution flood modelling (e.g., Hartnett & Nash, 2017).

A special problem related to the prediction of pool formation can be the influence of dense vegetation on the ground of expected pool. Impact of vegetation on contaminant transport has attracted considerable attention in both theoretical modelling and experimentation (Murphy et al., 2007; Lu & Dai, 2017). However, studies revealing the influence of roadside plants on dispersion of liquid cargos are not known to us. The problem is also complicated by the fact that dense vegetation nearby road shoulders can be a result of poor road maintenance. The lack of sufficient maintenance is difficult to predict. Currently, one can only hypothetically assume that dense vegetation will increase the proneness of roadside terrain to formation of pools and, of course, aggravate rain water drainage.

A comment also must be made on a detailed determination of geometry of roadside terrain by means of geographic information systems. Altitudes of individual surface points in low areas near the road retrieved from these systems can be imprecise. Information on these altitudes should be verified by in-the-field measurements. We faced this problem during the case study presented in Section 2. Our actual measurements of the terrain shown in Figure 8 did not coincide precisely with the altitudes retrieved from the Lithuanian geographic information system Maps.lt.

Thermal damage to some targets can be particularly dangerous due to potential loss of these targets or initiation of domino sequences. Examples of such targets are bridge, pipeline or power line situated above a road (Figure 4b). In this case, the risk posed by a pool fire can be assessed conservatively, that is, by assuming that the fire will occur

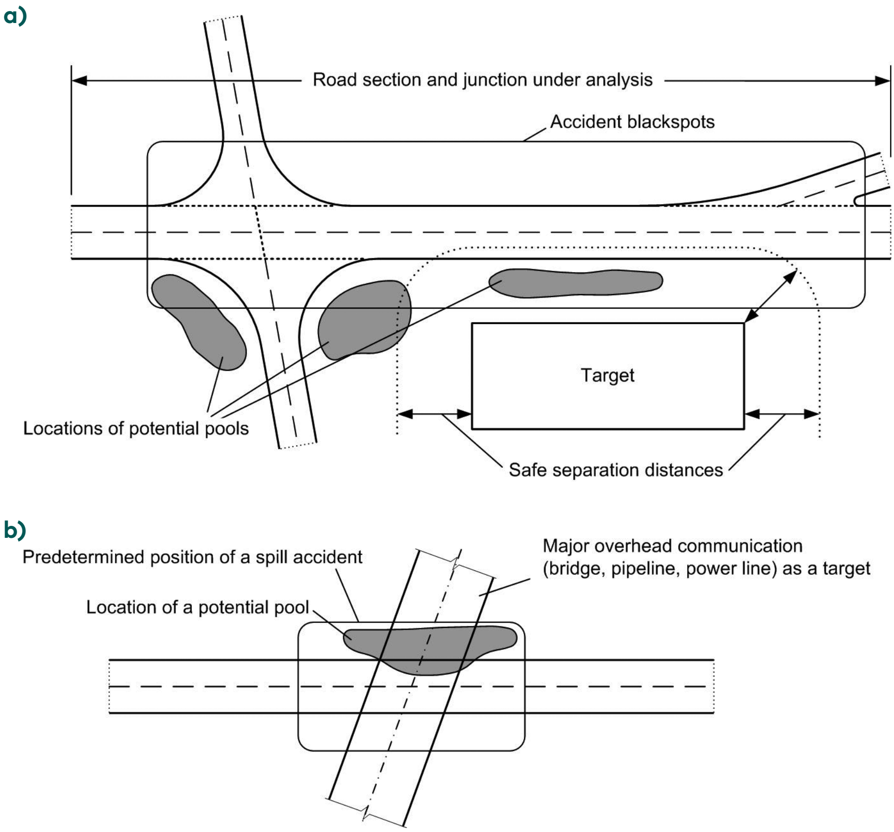
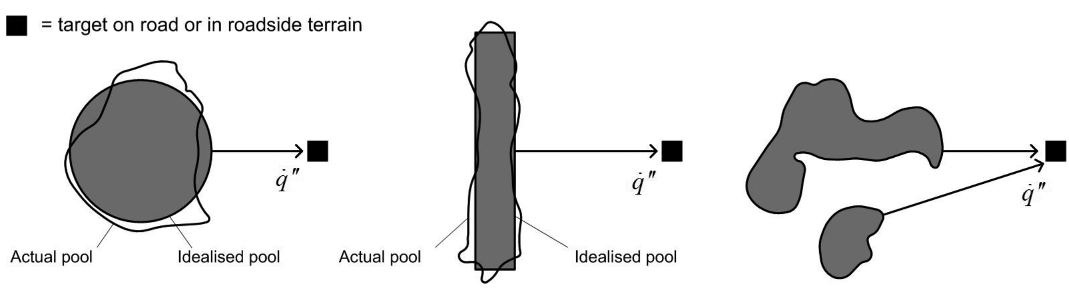


Figure 4. Two locations of the road network where pool fire accidents should be considered: a) road section and junction with increased concentration of traffic accidents, b) predetermined position of a hazardous spill accident

under these structures (Alos-Moya et al., 2014; Giuliani et al., 2012; Quiel et al., 2015; Timilsina et al., 2021). The location of an accident will be predetermined and not assessed from traffic accident data. It is obvious that the probability of a pool fire occurring under, say, a bridge is small. However, reports of such accidents can be found on the web and in some journal articles (see Kodur & Naser, 2019; Song et al., 2021; and Accidents 2 to 4 described in Appendix).

1.3. Thermal effects of a trench fire

In case where the shape of pool is regular enough, it can be idealised by a circle or a rectangle (Figure 5a, b). Engineering (hand calculation) methods are available to assess the radiation $\dot{q}''$ for circular and rectangular pools (Ma et al., 2018). In a general case, the spill from a tanker can result in a pool with highly irregular shape or even several irregular pools (Figure 5c). Then the radiation $\dot{q}''$ can be estimated by means of a numerical simulation of the pool fire based on methods (e.g., Vasanth et al., 2017; Yi et al., 2019). CFD methods applied to pool fire modelling, like many numerical methods, overperform the hand calculation methods by at least the possibility for modelling burning pools of any shape. However, a comparison of CFD simulation results to results of physical experiments on medium and large-scale circular and rectangular pool fires reveals that CFD simulation is relatively inaccurate (Rengel et al., 2018; Stewart et al., 2021).



a) circular pool fire model **b)** trench (line) fire model **c)** numerical CFD fire model

Figure 5. Three models used to predict the fire radiation $\dot{q}''$ impinging a target on road or roadside terrain (CFD = computational fluid dynamics)

The most frequently used hand calculation method for the estimation of $\dot{q}''$ is expressed as follows:

$$\dot{q}'' = E\,F_{F \to T}\,\tau, \tag{3}$$

where E is the average emissive power of flame surface expressed usually in kW/m^2, $F_{F \to T}$ is the view or configuration factor (ratio between radiation emitted by fire "F" and received by target "T", $0 < F_{F \to T} < 1$), τ is the atmospheric transmissivity (a coefficient accounting for absorption of thermal radiation by air).

The assessment of the quantities E and $F_{F \to T}$ for circular pools has been developed by many authors over several past decades and resulted in commonly recognised models (Mannan, 2012). However, if we look at the problem of pool fires from the standpoint of transportation, the assessment of E and $F_{F \to T}$ for trench pools may be of greater interest. Roadside ditches and low areas alongside the road are natural terrains for the formation of trench pools (Figure 3a, b). The geometry of a trench (line) fire is idealised by a regular vertical or tilted parallelepipedic shape (Figure 6). The flame tilt θ correlates with Froude number (dimensionless wind velocity) defined as $0.5u_{\mathrm{w}}(gw)^{-1/2}$, where u_{w} is the wind speed (m/s), g is the acceleration of gravity (m/s^2) and w is the trench width (m). However, this correlation was mathematically expressed only for liquefied natural gas (LNG) fires.

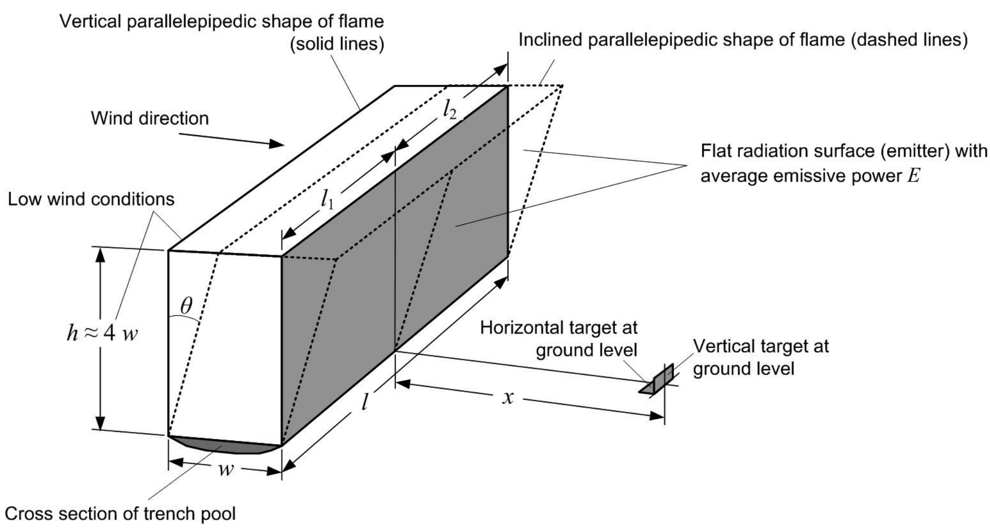


Figure 6. The solid flame model for a trench fire with papallelepipedic shape

The view factor $F_{F \to T}$ is a purely geometrical quantity that depends on the shapes of radiation emitter and target. In the case of the parallelepipedic flame model, the view factor $F_{F \to T}$ will be a function of the dimensions shown in Figure 6 (see, e.g., Appendix A in CCPS (2010) for details). The factor $F_{F \to T}$ can be viewed as the means of modelling the geometrical situation of the spill and fire accident in roadside terrain.

The estimation of the emissive power E is a challenging problem. At least two models were proposed for estimating E in case of circular pools (McGrattan et al., 2000). These models relate E to a diameter of a circular pool. In case of longitudinal trench pools, information on models for assessing E is very sparse. Measurements of thermal radiation from trench fires suggest that values of E may range between 75 kW/m^2 and 170 kW/m^2. The emissive power of 100–120 kW/m^2 is a conservative representation of experimental data.

A special scenario of a pool fire can be a continuously released liquid fuel spill fire. It is an opposite of the still liquid fire considered previously. The spill fire may develop when the burning cargo is ignited immediately after release and spreads into the roadside terrain. In such a case, the thermal radiation $\dot{q}''$ should be modelled as a time-function $\dot{q}''(t)$. At present, spill fires are investigated in small-scale experiments and models for assessing $\dot{q}''(t)$ were proposed by Li et al. (2018). However, a special study is necessary to understand whether these models are applicable to real-world situations in transportation.

Finally, a comment must be made on accident scenarios involving liquefied combustible gasses like LNG or LPG. Liquefied gas released from a tanker truck may form a pool that will erupt into fire. However, the escaping gas may evaporate so rapidly that combustion will occur as a fireball or a turbulent jet fire (Raj, 2005). In principle, the release of gas may also result in formation and ignition of a vapour cloud that will be succeeded by a flash fire or even a vapour cloud explosion (e.g., Landucci et al., 2011).

2. Application of the proposed method

A potential spill and fire accident on the European route E28 is analysed (Figure 7). The road section under study includes an oblique intersection with an increased concentration of traffic accidents. It is assumed that a single-chamber 3-axle tank semitrailer carrying 28 tons (38.9 m^3) of gasoline will be punctured and gasoline will be released and ignited in consequence of a traffic accident. The aim of this case study is to assess the thermal radiation $\dot{q}''$ that will be emitted by a gasoline pool fire and impinge on the site of a used car store shown in Figs. 7 and

8. Inflammable targets are automobiles parked directly beyond a store fence.

2.1. The road-side situation under study

The site of the potential spill and fire accident is a land strip between road and target. The gasoline will be released (spilled) in the point "S" shown in Figure 7. In the course of an accident, ambient temperature and relative humidity will be 16 °C and 79 %, respectively. These values are necessary for calculating the atmospheric transmissivity τ. The wind velocity will be low and so the flame tilt θ will be close to 0 (Figure 6).

The following worst-case scenario will be considered in this case study:

- the tanker truck will be fully loaded at the instant of the accident;
- the entire cargo of the volume V_{rlsd} = 38.9 m^3 will be released and form a pool in roadside terrain;
- the average emissive power of flame surface, E, will be the aforementioned conservative value of 120 kW/m^2.

The land strip between road and target includes a trench (a U-shaped low area approximately 17–19 m wide) (Figure 8). This terrain is naturally prone to the formation of a pool. The trench is covered by dense vegetation that may slow down the spread of the pool in the longitudinal direction.

Figure 7. The view on the land strip between the route E28 and the target (the site of a used car store) (obtained with Google Earth program)

A cross-section of the trench at the point "S" (Section 1–1) is shown in Figure 9. The highest level the potential pool may spread between points "A" and "B". It is assumed that the level of the pool will not overtop the horizontal line "A"–"B" because the spilled liquid will not have obstacles to spread in the longitudinal direction. The cross-sectional area between the line "A"–"B" and the bed of the trench is 9.69 m^2 (see the shaded area in Figure 9). Correspondingly, the geometrically possible minimal length of the pool will be l_{min} = 38.9 m^3 / 9.69 m^2 = 4.02 m. The depth of the trench decreases or increases monotonically. Consequently, the formation of several local pools is unlikely.

A longitudinal section of the trench (Section 2–2 in Figure 7) is depicted in Figure 10. The length of the section is 120 m. The position of the spill point "S" is at 37.5 m. Altitudes of points within 120 m section vary in the range of 0.7 m. In addition, the inclination of the straight line fitted to the altitudes measured along 120 m line is only 1:1250 (Figure 10). Therefore, the bed of the trench will be considered horizontal in the longitudinal direction and local differences in altitudes will be ignored.

It is assumed that the target in question is positioned in the middle of the radiation surface corresponding to the point "S", that is, l_1 = l_2 (Figure 6). The distance from the radiation surface to the target, x, is

Figure 8. The view on the land strip between the route E28 and the target (the site of a used car store) (the authors' photo)

calculated as the sum x_{act} + 3 m, where the distance of 3 m accounts for a possible shielding of the target territory by the fence and x_{act} is the distance between the pool edge and the fence (Figure 9). However, this shielding might be only temporary and partial. The thermal flux emitted by the pool fire will overtop the fence and spread behind it. In addition,

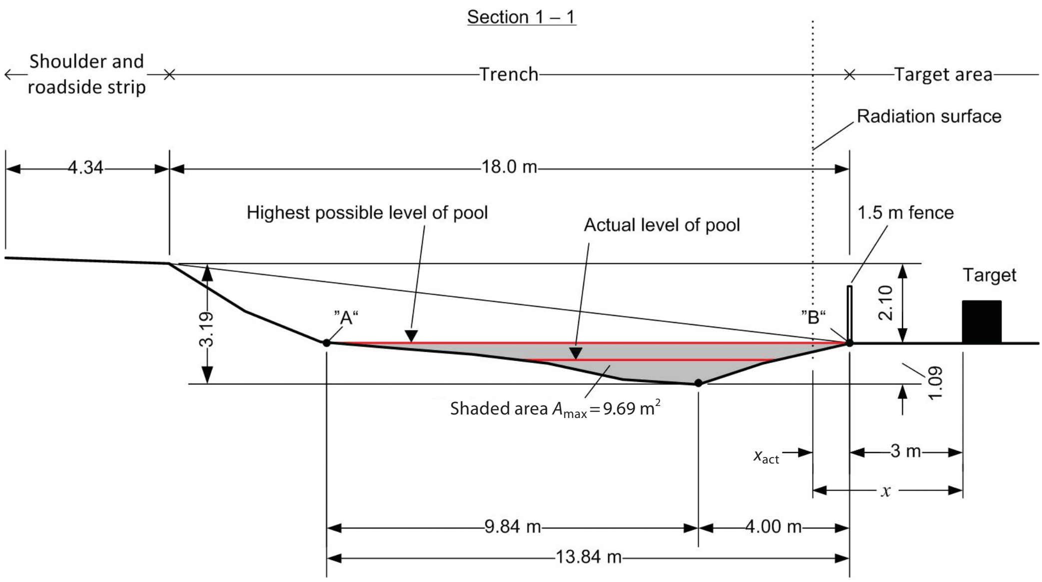


Figure 9. Cross-sectional dimensions of the trench at the assumed location of spill (see Section 1–1 in Figure 7)

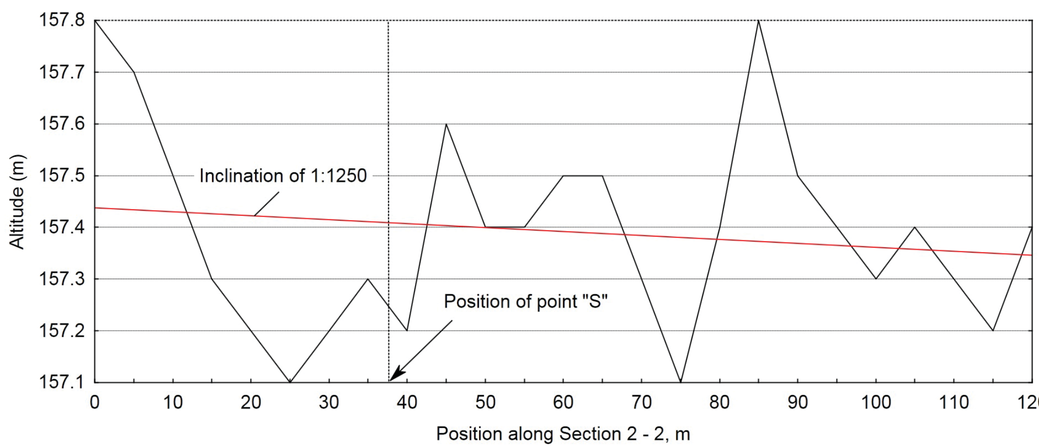


Figure 10. Longitudinal section of the trench (see Section 2–2 in Figure 7) (the altitudes were obtained by using the Maps.lt program)

the fence is built of long and flexible profiled steel sheets with flammable paint coating. In all likelihood, the coating will be ignited and the fence will lose its integrity in a short time due to thermal deformations.

2.2. The estimation of thermal radiation

As the pool length l is not known in advance, the thermal radiation $\dot{q}''$ was estimated by means of the model (3) for values of l ranging between 10 m and 40 m (Table 1). The corresponding width of the pool, w, declined from 8.77 m to 4.39 m (Table 1, Line 2). The respective aspect ratio l/w varied between 1.14 and 9.12 (Table 1, Line 3).

In the idealised papallelepipedic fire, the flame height h is taken to be equal to the height of actual fire. However, on average 20% of the surface area of the idealised fire may consist of the visible flames and 80% will be smoke (McGrattan et al., 2000). In other words, the fire will consist of a luminous zone at the fire base and a part of flames obscured by smoke (Figure 11). As the target in question is a near-field target, the emissive power E will be regarded as the emissive power of the luminous zone, rather than an emissive power averaged over the flame height h, that is, $E = E_{\text{lum}}$ = 120 kW/m^2 (Figure 11). This value is approximately the midpoint of the aforementioned interval (75 kW/m^2, 170 kW/m^2).

Well elaborated models allowing one to estimate the height of the luminous zone, h_{lum}, as well as the emissive power E_{obscured} for a trench (papallelepipedic) fire do not seem to be available. Therefore, the assessment of thermal radiation $\dot{q}''$ will be based on the following three assumptions:

- the height of the solid papallelepipedic flame, h, is equal to $4w$ (Eq. (66.7) given by Beyler (2016));
- the height of the luminous zone, h_{lum}, will reach 20% of h;
- the effect of the obscured flames on near-field targets is negligible.

The calculated luminous zone heights h_{lum} are presented in Line 4 of Table 1 with an illustration of the luminous zone with the height h_{lum} is given in Figure 11. With the values of h_{lum}, the factor $F_{F\to T}$ was calculated as the maximum configuration factor given by a vectorial sum of horizontal and vertical view factors (e.g., CCPS, 2010):

$$F_{F\to T} = (F^2{}_{F\to T,H} + F^2{}_{F\to T,V})^{1/2}. \quad (4)$$

Values of $F_{F\to T}$ are presented in Line 5 of Table 1.

Values of the thermal radiation $\dot{q}''$ calculated for the aforementioned pool lengths are presented in Line 6 of Table 1. These values range between 24.3 kW/m^2 and 35.3 kW/m^2. Such radiation will be sufficient to ignite plastic and rubber parts of the automobiles parked in the target area. The critical radiation intensity for these synthetic materials is

15 kW/m² (CPR, 2005). The automobiles are positioned very close to each other (Figure 7). This may cause a spread of fire over a large part of the target area.

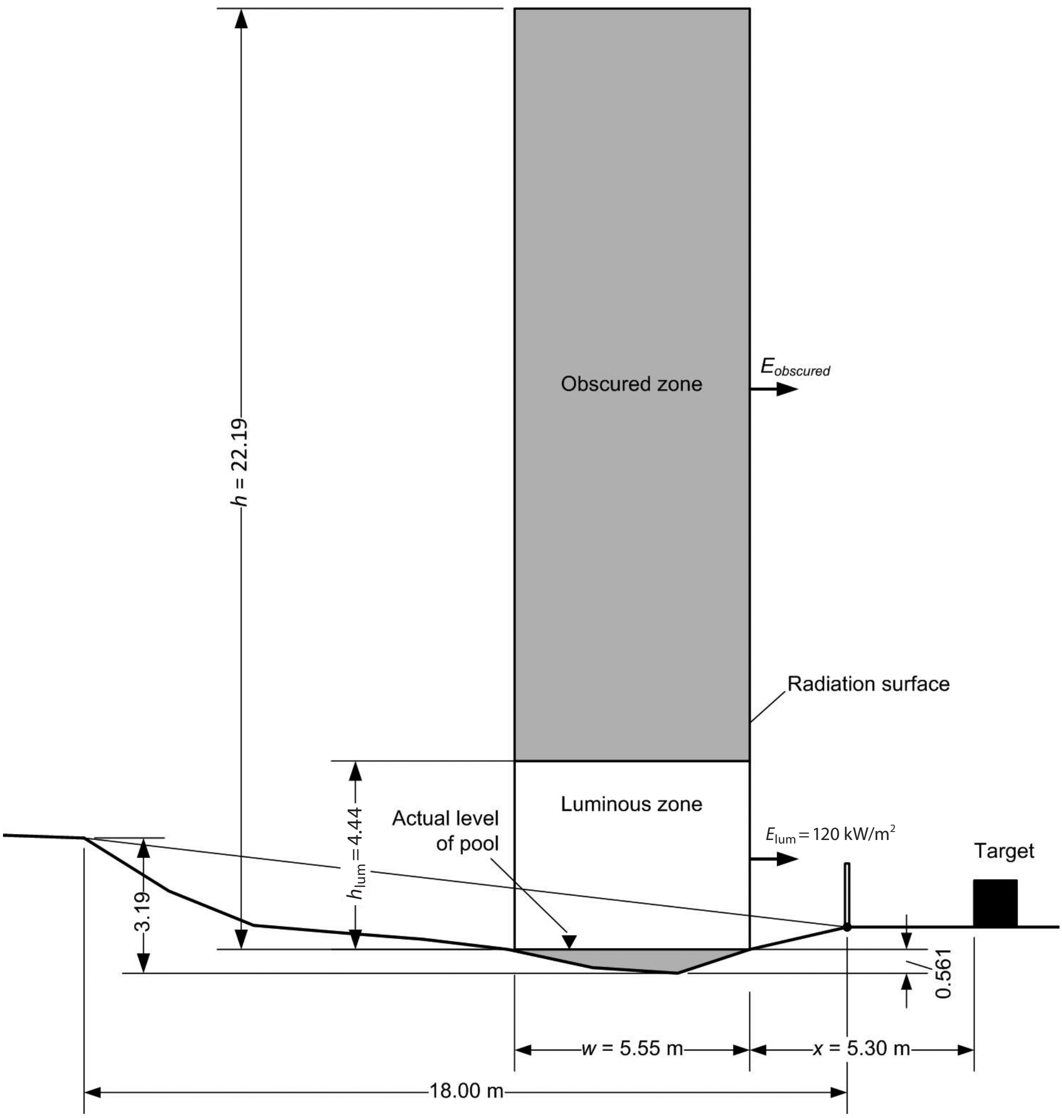


Figure 11. The configuration of the solid flame with luminous and obscured zones depicted for the pool length l = 25 m and width w = 5.55 m (see also Table 1)

Table 1. Results of the Estimation of the Thermal Radiation $\dot{q}''$ at Different Values of the Pool Length

Line	Value	Length of pool, *l*, m						
		10	15	20	25	30	35	40
1	Width of pool, *w*, m	8.77	7.16	6.20	5.55	5.06	4.69	4.39
2	Aspect ratio, *l*/*w*	1.14	2.10	3.23	4.51	5.92	7.47	9.12
3	Distance to the target, *x*, m	4.37	4.83	5.11	5.30	5.44	5.55	5.63
4	Height of luminous zone, h_{lum}, m	7.02	5.73	4.96	4.44	4.05	3.75	3.51
5	Maximum view factor $F_{F\to T}$ (–)	0.386	0.378	0.355	0.330	0.308	0.289	0.272
6	Atmospheric transmissivity τ (–)	0.905	0.900	0.897	0.895	0.894	0.893	0.892
7	Thermal radiation to the target, $\dot{q}''$, kW/m^2	35.0	34.0	31.8	29.6	27.5	25.8	24.3

3. Discussion

An assessment of damage caused by pool fires, which can occur on/nearby the road, is undoubtedly a problem of a PRA in transportation (e.g., CCPS, 2008; Yin et al., 2019). However, the PRA applied to the case of pool fires on road will be encumbered by the key element of the analysis, namely, the prediction of the thermal radiation $\dot{q}''$. Models available for this prediction are purely deterministic. Any attempts to systemically quantify inaccuracies of these models and uncertainties related to the calculated values of $\dot{q}''$ are not known to us.

The available models treat pool fires and emission of the radiation from them as a "static" process. This is justified in part by the fact

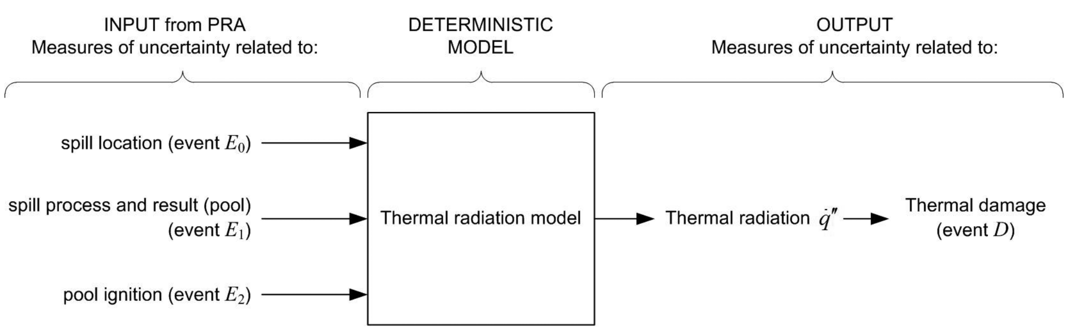


Figure 12. The position of the deterministic thermal radiation prediction model in the framework of a transportation PRA

that the heat release rate of flammable liquids and liquefied gasses is constant over the course of fire. However, strictly speaking the pool fire must be treated as a stochastic process or, at least, the time-dependence due variation of wind speed and direction as well as spread of pool must be regarded in the risk analysis. At present, the only exception to the "static" approach seems to be the attempt to model the time-dependence in the case of small-scale spill fires (e.g., Li et al., 2018).

The currently available deterministic models used for the prediction of the thermal radiation $\dot{q}''$ make the PRA related to transportation of hazardous materials technically possible and potentially useful. However, these models can be seen only as a means of uncertainty propagation (Figure 12). Random input information for these models can be provided by standard tools of PRA. Stochastic simulation can be applied to transform this information into random output related to values of $\dot{q}''$ and then to thermal damage represented by the event D.

Conclusion

The hazard posed by road transportation of flammable liquids has been considered in the paper. Attention has been paid to the traffic accidents that result in a spill of flammable cargo from tanker trucks. The prime objective of this study has been to assess the hazard of the accidents that end up in formation and ignition of flammable pools on/nearby the road. The main finding of the study is that a trench fire model is naturally suitable for assessing the thermal radiation from fires of such pools. Calculations presented in the study have revealed that the thermal radiation emitted by a trench fire can endanger objects positioned in the intermediate vicinity to the road. A direct spread of radiation to further distances from the road is not probable. However, the trench fire can have a domino effect when ignition of the closest flammable object can cause a domino effect and ignite objects positioned at greater distance from the road. It has been found that mathematical models developed for assessing thermal radiation of trench fire are purely deterministic. Thus, the incorporation of these models into probabilistic transportation risk analysis will require supplementing them with modelling uncertainties related to the thermal radiation and factors influencing intensity of this radiation.

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Appendix

This appendix contains a short description of road tanker fire accidents that illustrate the problem considered in this study.

Accident 1

- Location and date: Heibei province (China), Beijing – Harbin expressway, February 2018.
- Description: Reportedly, LNG tanker overturned, gas was released into roadside ditch and ignited. A massive and long trench fire occurred.
- URL: https://www.youtube.com/watch?v=1lOEK24UbQM (Retrieved on October 25, 2021)
- URL: https://www.youtube.com/watch?v=u76lYhr3y2E (Retrieved on October 25, 2021)

Accident 2

- Location and date: California (USA), December 2011.
- Description: A gasoline tanker fire underneath an overpass (Paramount Boulevard bridge) melted and demolished a part of the bridge. Further details of the accident are described by Guliani et al. (2012).
- URL: https://www.firehouse.com/home/news/10535588/california-tanker-fire-forces-freeway-demolition (Retrieved on October 25, 2021)

Accident 3

- Location and date: Harrisburg, Pennsylvania (USA), May 2013.
- Description: A tanker truck fully loaded with diesel fuel overturned and erupted into flames and exploded repeatedly. Overpass was badly damaged.
- URL: https://www.nbcphiladelphia.com/traffic/transit/Tanker-Fire-81-206732591.html (Retrieved on October 25, 2021).

Accident 4

- Location and date: Birmingham, Alabama (USA), January 2002.
- Description: a tanker truck traveling on the I-65 overpass and carrying 37.5 m3 of gasoline, swerved and crashed into the piers supporting the central span. Bridge girders were badly damaged (Alos-Moya et al., 2014).
- URL: https://www.nbcphiladelphia.com/traffic/transit/Tanker-Fire-81-206732591.html (Retrieved on October 25, 2021).