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Risk reduction in road and rail LPG transportation by passive fire protection

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A B S T R A C T

The potential reduction of risk in LPG (Liquefied Petroleum Gas) road transport due to the adoption of passive fire protections was investigated. Experimental data available for small scale vessels fully engulfed by a fire were extended to real scale road and rail tankers through a finite elements model. The results of mathematical simulations of real scale fire engulfment scenarios that may follow accidents involving LPG tankers proved the effectiveness of the thermal protections in preventing the "fired" BLEVE (Boiling Liquid Expanding Vapour Explosion) scenario. The presence of a thermal coating greatly increases the "time to failure", providing a time lapse that in the European experience may be considered sufficient to allow the start of effective mitigation actions by fire brigades. The results obtained were used to calculate the expected reduction of individual and societal risk due to LPG transportation in real case scenarios. The analysis confirmed that the introduction of passive fire protections turns out in a significant reduction of risk, up to an order of magnitude in the case of individual risk and of about 50% if the expectation value is considered. Thus, the adoption of passive fire protections, not compulsory in European regulations, may be an effective technical measure for risk reduction, and may contribute to achieve the control of "major accidents hazards" cited by the European legislation.

1. Introduction

All over the world, and particularly in industrialized countries, the transport of hazardous materials has till years a continuously increasing trend. Together with the volumes of chemicals shipped from one site to another, also the awareness of public of the risk posed by these activities has grown [1–4]. Public concern is focused mainly on road and rail transport, since the routes used for road and rail transportation of hazardous substances necessarily come closer and sometimes also cross densely populated areas. Accidental releases of flammable and toxic material from road or rail tankers were the initiating event of accidents with multiple fatalities [5,6]. The development and assessment of preventive and protective measures for risk reduction in the transport of hazardous materials (hazmat) is thus an actual theme, also emphasized by the results of some comprehensive quantified risk analysis studies of areas where a high concentration of sites handling and storing hazardous substances is present. These studies pointed out that often hazmat transport activities give a major contribution to the overall risk, thus evidencing that a relevant risk reduction may be achieved acting on hazmat transport [7–9].

The present study focuses in detail on LPG transportation by road, which is extremely intense among Europe. It is well known that, due to the inherent properties of LPG, an accidental spill may lead to severe fire and explosion scenarios having the potential to cause injuries and fatalities also among the off-road population. Among them, one of the more severe is the BLEVE, which consists in an instantaneous catastrophic rupture of a tank containing the pressurized liquefied gas, which instantly vaporizes and expands, originating a blast that is often followed by a fireball due to LPG ignition [10–16]. Further details on BLEVEs, fireballs and their consequences are reported elsewhere [17–22].

In the present context, it is important to recall that two types of BLEVEs are usually defined: "fired" BLEVE and "unfired" or "cold" BLEVE. The first is thermally induced, and usually occurs when a tank is impinged or engulfed by an external fire, as a jet fire or a pool fire. Fire exposure causes a temperature increase of the tank wall and a consequent reduction of its mechanical resistance. At the same time, the increase of the internal pressure (due to the temperature increase of the fluid inside the tank) causes an increase of the stresses acting on the vessel shell, which may loose its integrity leading to a catastrophic rupture [16]. The "cold" BLEVE is a BLEVE not thermally induced. "Cold" BLEVEs may be caused by a violent

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Table 1
Hazmat transportation: number of "fired" and "cold" BLEVEs recorded in past accident data concerning the road and rail LPG transport.

	No. of events		
	"Fired" BLEVEs	"Cold" BLEVEs	Total
Rail transport	32	5	38
Road transport	6	1	6
Total	38 (86.4%)	6 (13.6%)	44 (100.0%)

impact on the tank during a traffic accident or by the tank sudden failure due to a material defect or to overfilling [19]. Table 1 shows the observed distribution of "fired" and "cold" BLEVEs of LPG road and rail tankers, obtained from the analysis of several transport accident reports [23–27]. As shown in the table, more than 85% of BLEVEs recorded in past accidents are thermally induced. As a consequence, the prevention of "fired" BLEVEs may lead to a relevant reduction of the risk related to LPG transportation.

It is well known that "fired" BLEVE may be prevented increasing the "time to BLEVE" (that is the time interval between the beginning of fire and the catastrophic failure of the tank), thus allowing for external protection actions by emergency teams. Passive protections as pressure relief valves and thermal coatings are known to be effective measures to avoid "fired" BLEVEs [28]. In North America specific transport regulations have been adopted, requiring road and rail tankers carrying flammable liquefied gases to be equipped with pressure relief valves. In addition, rail tankers have to be also thermally insulated. In Hong Kong road tankers should be equipped with both thermal coating and pressure relief valves [29]. However, such protective measures are not compulsory in Europe, where no passive fire protection of LPG tankers is presently required by ADR and RID regulations [30,31] that define the standards required respectively for the road and rail LPG tankers. Moreover, a specific and systematic assessment of the potential effect of these passive protection systems on the reduction of the risk related to flammable liquefied gas transportation is still missing.

The aim of the present study is to investigate the effectiveness of passive protections of tankers in the reduction of the overall risk due to LPG road and rail transportation. In a first part of the study (Section 2), a detailed model of the behaviour of road and rail tankers engulfed in fire was developed and validated. The effect of the thermal protection on the "time to BLEVE" was analyzed. In the second part of the study (Section 3), the results obtained were used to investigate the extent of the risk reduction due to the reduction of the probability of the "fired" BLEVE scenario following the adoption of passive tank protections. Several case-studies derived from actual LPG road transportation scenarios in Europe were analyzed, and a Transport Risk Analysis (TRA) was performed to evidence the risk reduction due to the adoption of thermal coatings.

2. Analysis of the expected perfomances of passive fire-protection systems

2.1. Expected performances of passive fire protections

It is well known that passive fire protection of tanks, containing liquefied pressurized gas, is applied to mitigate the effect of the fire on the vessel shell, mainly aiming to avoid the tank failure and to prevent BLEVEs. BLEVE prevention may be obtained by the combination of two possible effects of passive protections [32,33]:

(1) reduction of the vessel wall temperature, usually obtained by the installation of a heat resistant coating;
(2) limitation of the vessel internal pressure by the control of the vapour pressure increase due to the raise of the liquid temperature, usually obtained by the installation of a pressure relief device.

An intense work was devoted in past years to the assessment of the performances of such devices in the protection of tanks present in fixed installations. Technical standards and data of bonfire tests are available in the technical literature concerning the use and the optimal specifications for both coating and PRVs in fixed tanks [34–39]. However, less attention was dedicated to the analysis of the performances of such devices in the specific accidental scenarios that may take place during the road and rail transportation of LPG. It is well known that in road and rail accidents severe fire engulfment or impingement may take place, while external cooling due to rescue teams or fire brigades may be widely delayed with respect to fixed installations [40]. Moreover, experimental tests addressing these specific scenarios were mostly carried out at a laboratory [32] or pilot scale [29,34,35,41–45]. Thus, in the present study, experimental data reported in the literature were

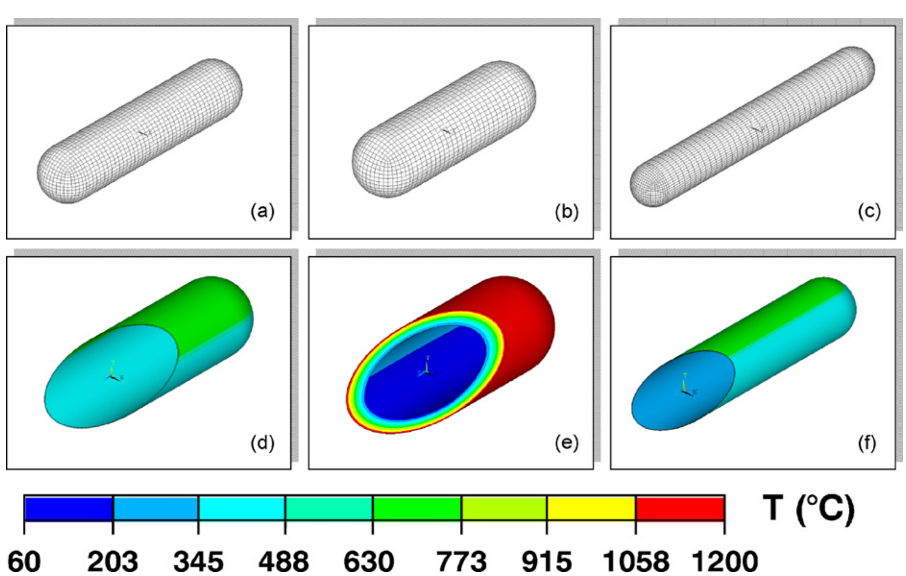

Fig. 1. Details on the geometry and mesh used for the validation of FEM with experimental results for tests: (a) BF1—4 m^3 tank; (b) BF2—4.85 m^3 tank; (c) BF3—120 m^3 tank. Temperature maps (T, in °C) calculated at the end of simulation runs are also reported: (d) test BF1; (e) test BF2; (f) test BF3.

combined to the results obtained from a full scale detailed model, based on finite elements simulations, to assess the effectiveness of passive protection in "fired" BLEVE prevention for severe accidental scenarios specific of the road transportation of LPG.

2.2. Modeling approach

A finite element model (FEM) was implemented on the ANSYS software, using the ANSYS/Multiphysics module. Further details on the fundamentals of finite element modeling and on the ANSYS software are reported elsewhere [46,47]. The FEM was used to perform detailed simulations of the radiation mode, of the wall temperature and of the stress over the vessel shell under pool-fire full engulfment conditions.

The first step in FEM development was the creation of the mesh necessary to represent the tank geometries. The tanks were modelled as cylindrical bodies with spherical heads. A uniform brick mesh was used for the calculations. Where necessary, an insulating coating having constant properties and constant thickness was considered in the model. Fig. 1 reports some examples of geometries implemented in the validation runs.

The further step was the development of a thermal module for the calculation of the transient temperature distribution. The module calculates the temperature map on the basis of the mesh and of the fire conditions: radiation intensity on the shell surface and surface emissivity. External routines were implemented in order to consider the behaviour of the LPG inside the tank and were used to provide the necessary input for the FEM analysis. In particular, these routines allowed taking into consideration: (1) temperature evolution of both gas and liquid phases, (2) discharge rate from the PRV, and (3) internal pressure rising curve.

Table 2 reports the input parameters used for some validation runs, while Fig. 1 shows some examples of temperature maps obtained by the module. As it can be noticed, the more critical zone is located on the top of the tank, among the wall in contact with the vapour phase. This is in agreement with experimental findings and is due to the lower heat transfer coefficient of the vapour if compared to that of the liquid [33,48].

The final step was the development of a mechanical module, aimed to determine the local stress distribution on the vessel shell. The module calculates the stress intensity (σ_{eq}) using the Von Mises criterion for each time step of the simulations, taking into account the loads deriving from gravity, from internal pressure (evaluated in the previous step) and from the effects of thermal dilatation. The input values for the mechanical simulations used in some validation

Table 2
Features of the tank used for the test reported in [34,44,45], parameters implemented in the FEM simulations and summary of results.

	Test ID BF1 Data source: [34]	BF2 Data source: [44]	BF3 Data source: [45]
Tank specifications			
Geometry	Horizontal cylinder	Horizontal cylinder	Horizontal cylinder
External diameter (m)	1.2	1.25	3
Total length (m)	4	4.3	18.3
Minimum wall thickness (mm)	7.1	6.4	16
Filling level (%)	60	20	90.7
Pressure relief device nominal diameter (mm)	32	32	70
Opening gauge pressure (MPa)	1.72	1.46	1.93
Steel properties			
Thermal conductivity (W/mK)	50	50	50
Heat capacity (J/kg K)	460	460	460
Surface emissivity	0.4	0.4	0.4
Density (kg/m^3)	7850	7850	7850
Thermal dilatation coefficient (ppm/K)	11.5	11.5	11.5
Poisson's ratio	0.3	0.3	0.3
Elastic modulus (GPa)	201.5	201.5	201.5
Insulating coating properties			
Coating type	–	Rock wool	–
Applied thickness (mm)	–	2×100[a]	–
Thermal Conductivity (W/mK)	–	0.38	–
Heat capacity (J/kg K)	–	920	–
Surface emissivity	–	0.9	–
Density (kg/m^3)	–	100	–
Thermal dilatation coefficient (ppm/K)	–	11.5	–
Poisson's ratio	–	0.3	–
Elastic modulus (GPa)	–	1	–
Data on stored material			
Type	Propane	Propane	Propane
Average liquid temperature (°C) implemented in FEM	65	55	65
Vapour temperature (°C) implemented in FEM	180	150	130
Density (kg/m^3)	585	585	585
Liquid heat transfer coefficient (W/m^2 K)	400	400	400
Vapour heat transfer coefficient (W/m^2 K)	6	6	6
External heat source			
Ambient temperature (°C)	20	25	21
Type of fire	Jet fire engulfment	Surrounding fire	Pool Fire
Thermal load in simulations (kW/m^2)	140	60	110
Results of FEM simulations			
Time to failure, experimental (min)	3.6	–	24.5
Time to failure, calculated (min)	3.2	–	22.0

[a] Coating was encapsulated in a watertight steel sheet coating 1 mm thick; 30 mm air gap was left between the sheet and the coating.

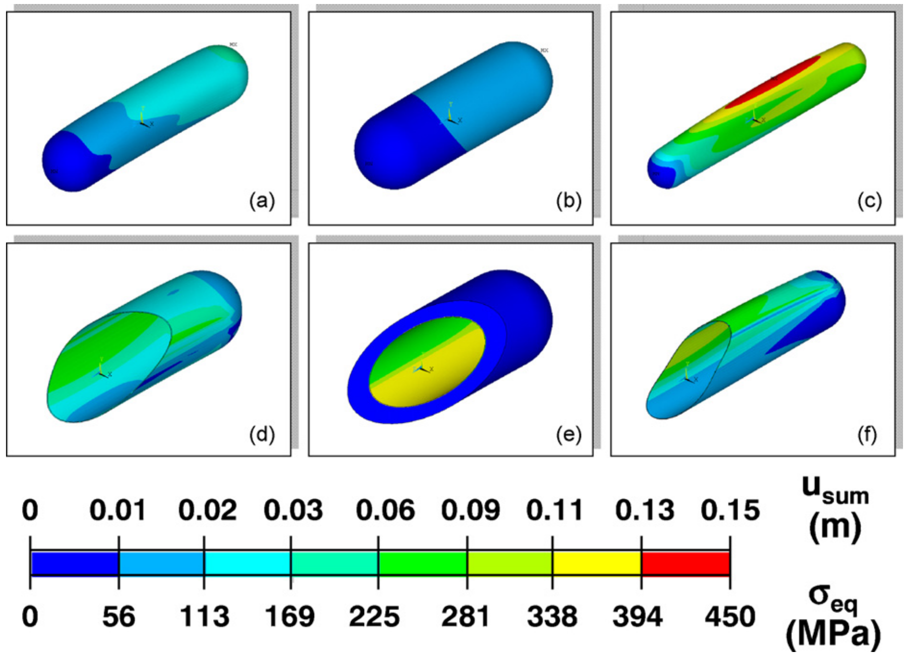

Fig. 2. Deformation maps (u_{sum}, in m) and stress intensity distributions (σ_{eq}, in MPa) for tests BF1 (a and d), BF2 (b and e) and BF3 (c and f), calculated on the basis of thermal simulations reported in Fig. 1.

runs are also reported in Table 2. The local values of the σ_{eq} may be thus compared to the local values of the maximum allowable stress, σ_{adm}, that was calculated as a function of temperature according to ASME codes [49]. A simplified failure criterion [49] was adopted to calculate vessel time to failure. The detailed results of the mechanical simulations are reported in Fig. 2. As shown in the figure, the more critical zone under the mechanical point of view is the interface between liquid and vapour. As evidenced by the deformed shapes, the tank appears to be divided in two parts, due to the different wall temperatures. The upper part, in contact with the vapour phase, experiences higher thermal dilatation than the lower, in contact with the liquid. This results in higher stresses at the interface between the two phases. Also the upper part of the tank is characterized by high stresses, due to the thermal dilatation loads.

The model was validated using several experimental data sets available in the literature. These were obtained for both coated and uncoated tanks. Further details on the model setup, validation procedure and results are reported elsewhere [43,50]. Some significant examples of validation results are summarized in Table 2. As shown in the table, the model is able to predict the time to failure with a small relative error (about 10%). In the case of BF2 [34], no rupture occurred after 90 min exposure, as confirmed by experimental data. The small difference between the experimental and the predicted results is on the safe side and is related to the simplified assumptions introduced in the model. In particular, the mechanical behaviour of the structure is supposed elastic, without considering the residual strength in the plastic region.

Fig. 3 reports a comparison between model predictions and available experimental data for the maximum tank wall temperature in several fire tests. The model shows good confidence with the experimental results. A slight over-prediction of wall temperature is only present at temperatures lower than 100 °C. In the case of coated tanks, the model yields a limited under-prediction of wall temperatures at temperatures higher than 300 °C due to coating degradation, not accounted in the simulations [29,43]. However, the model never predicted the failure of coated tanks, in agreement with the experimental results.

2.3. Simulation of fire engulfment scenarios

The FEM was extended to real scale tanks, in order to investigate the effects of the coating and the PRV on tank resistance in severe fire engulfment scenarios that may follow road or rail accidents involving LPG tankers. Table 3 reports the vessel geometries assumed for real scale calculations. These correspond to a 60 m^3 road tanker complying to ADR regulations [30] and to a 95 m^3 rail tank wagon complying to RID regulations [31], the standards ruling the respectively road and rail transportation of hazardous substances in Europe. Table 3 also reports the input data assumed for the fire scenarios considered and other necessary parameters for the FEM setup.

Model simulations were carried out both for unprotected and protected tanks. Thermal protection by a widely used commercial intumescing organic material was considered. An effective average thickness of 25 mm was considered for the protection layer,

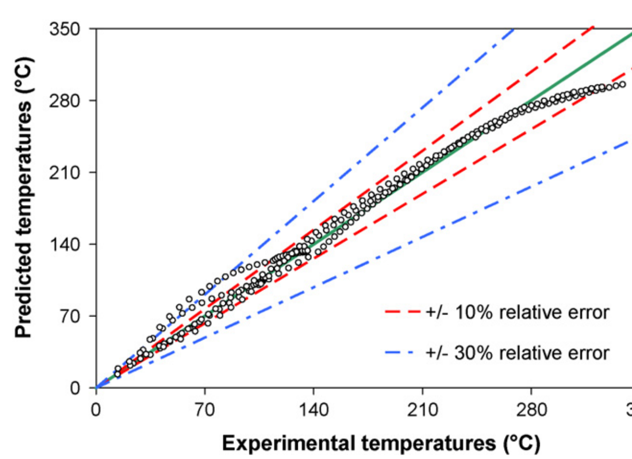

Fig. 3. Parity plot reporting the comparison between the maximum wall temperatures predicted by the model and those reported in several previous experimental studies [34,35,43].

Table 3
Input parameters implemented in the real scale simulations of road tankers and tank wagons engulfed by the fire.

	Road tanker	Tank wagon
Tank specifications		
Nominal Volume (m^3)	60	95
Geometry	Horizontal cylinder	Horizontal cylinder
External diameter (m)	2.4	3.1
Total length (m)	13.5	15
Minimum wall thickness (mm)	12.2	16
Filling level (%)	20	80
Type of material	High yield carbon steel (P460NH)	High yield carbon steel (P460NH)
Pressure relief device discharge area (m^2)	0.004	0.008
Opening gauge pressure (MPa)	1.82	2.5
Insulating coating properties		
Coating type	Organic intumescing	
Average effective thickness (mm)	25	
Thermal Conductivity (W/mK)	0.066	
Heat capacity (J/kgK)	1172	
Surface emissivity	0.9	
Density (kg/m^3)	1000	
Thermal dilatation coefficient (ppm/K)	11.5	
Poisson's ratio	0.3	
Elastic modulus (GPa)	1	
Data on stored material		
Type	Propane	Propane
Average liquid temperature ($0 \leq {}^\circ C$) implemented in FEM	65	70
Vapour temperature ($0 \leq {}^\circ C$) implemented in FEM	140	170
Density (kg/m^3)	585	585
Liquid heat transfer coefficient (W/m^2 K)	400	400
Vapour heat transfer coefficient (W/m^2 K)	6–140[a]	6–140[a]
External heat source		
Exterior temperature (°C)	10	10
Type of fire	Diesel pool fire	LPG pool fire
Thermal load in simulations (kW/m^2)	130	180

[a] Low value for thermal protected tank simulations; high value for non-protected tank simulations.

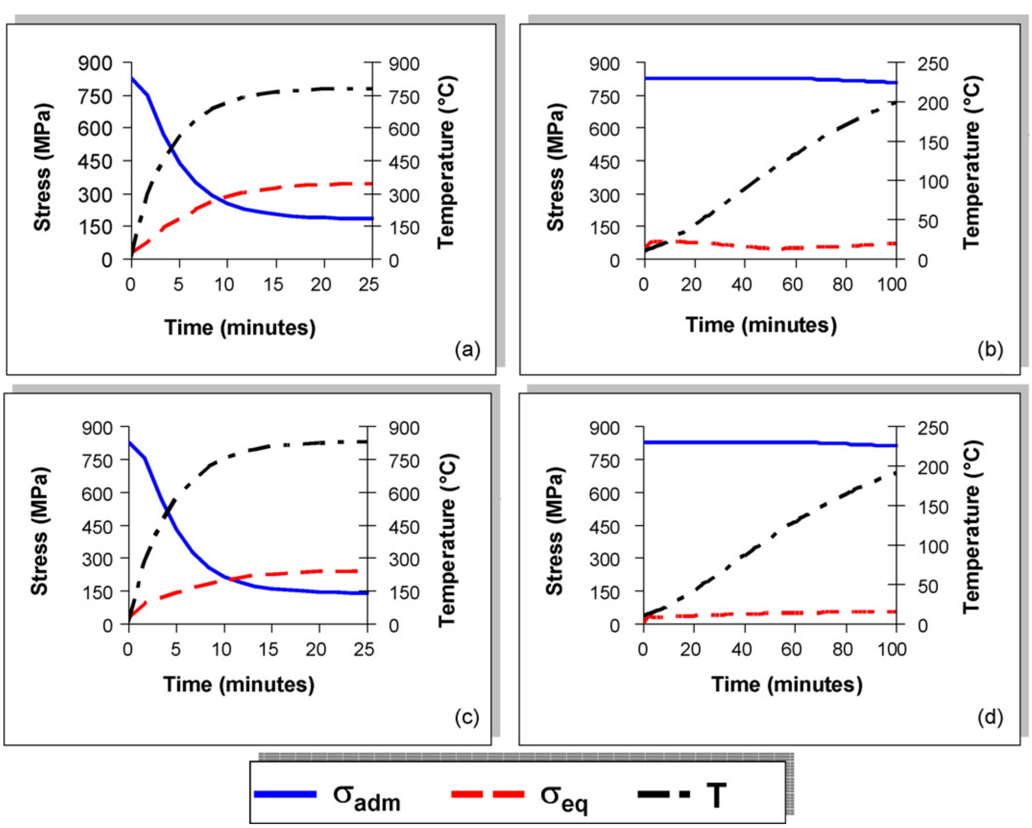

Fig. 4. Real scale simulations: dynamic behaviour of maximum allowable stress (σ_{adm}), stress intensity (σ_{eq}) and temperature (T) in the more critical points. Results are referred to (a) unprotected and (b) protected road tanker; (c) unprotected and (d) protected tank wagon. Stress in MPa, Temperature in °C.

Table 4
Initial assumptions used for the consequence and risk analysis of accidents involving LPG tankers. FO: final outcome.

Loss Of Containment (LOCs) events of LPG tankers		LOCs occurrence probability	Final Outcomes (FOs)	FOs occurrence probability	FOs impact distance *m*
LOC1	Continuous release from a 50 mm equivalent diameter	1.95×10^{-1}	Jet-fire Flash-fire	0.80 0.20	155 164
LOC2	Instantaneous release of the entire inventory	1.05×10^{-1}	Fireball Flash-fire	0.80 0.20	270 132

also taking into account the coating expansion following heat exposure [43,51]. The physical average properties of the protection layer (Table 3) were provided by the supplier of the material.

Fig. 4 reports a comparison of the performances of the protected and unprotected tanks, showing the temperature and stress profiles for the most critical point of the structure. As evident from the figure, both the unprotected road tanker and tank wagon result in a rupture in less than 20 min. This is in good agreement with the time to failure experienced for both tank wagons and road tankers involved in several accidental fire events where fire engulfment or impingement took place [52]. Wall temperatures rise up to 600–700 °C, as demonstrated also by the experimental tests, and rupture is predicted due to the extreme weakening of the material.

The behaviour of the protected vessels is dramatically different. Failure conditions were not verified by the model up to a maximum simulation time of 100 min, mostly due to the lower wall temperatures. As shown in Fig. 4b and d, the maximum wall temperature after 15–20 min (that correspond to the ttf of the unprotected tanks) is of about 50 °C, 10 times lower than the correspondent temperature evaluated for the unprotected tank. Also the stress intensity results drastically reduced, since the internal pressure rise is limited by the lower vapour temperature. At the end of the simulation, after 100 min, the wall temperature was always lower than 250 °C.

Therefore, the results of the FEM simulations demonstrated that if a proper coating is applied, tank failure may be prevented for long lapse of time (up to 100 min). The time lapses calculated may be considered sufficient to start mitigation measures by external emergency teams even in the case of road or rail accidents. Although the time lapse necessary to start the fire mitigation actions and to provide a sufficient amount of water for an effective cooling of tank walls after the accident is strongly dependent on the location and on the context of the accident, previous studies and operational experience indicate that in a European context 75 min may be considered as a sufficient time to start effective mitigation actions [28]. Thus, the results of the simulations carried out, indicating that even in severe fire conditions the time to failure of protected tanks is higher than 100 min, confirm that thermal coatings may be an effective protective measure for the prevention of "fired" BLEVEs during liquefied flammable gas transportation.

3. Risk reduction due to passive fire protection

3.1. Modeling

The FEM results presented above confirm that the coating of road and rail tanks is an effective measure to avoid, or at least strongly delay, the tank rupture in the case of fire engulfment or impingement. It should be recalled that these results were obtained for tanks and accidental scenarios that are representative of the European context with respect to tank sizes, tank design and accidental scenarios. The above results confirm that the adoption of a thermal coating may be an effective measure to prevent BLEVE also in a European scenario. Thus, a specific quantitative Transport Risk Analysis was performed to investigate the potential risk reduction that would derive from the introduction of fire protections for LPG tankers. The individual and societal risk values calculated for three representative case-studies referred to the current situation (i.e. to LPG tankers without thermal protection) were compared to those obtained considering fire-protected tankers.

The risk due to accidents involving a LPG tanker may be calculated by the contribution of all Final Outcomes (FOs) which may arise from a spill scenario [53]. The Dutch guidelines reported in the "Purple Book" [54] suggest to consider two Loss Of Containment (LOCs) events, as reported in Table 4. The first (LOC1) is a major leak with a continuous release, from which a jet-fire or a flash-fire may result as a consequence of immediate or delayed ignition. The second (LOC2) is an instantaneous release of the entire tank content, that may trigger a fireball or a flash-fire, depending on the presence and on the delay of ignition. In the case of LOC2, the fire may be preceded by a BLEVE producing a blast wave. Even if a limited increase in liquid temperature inside the vessel is experienced during fire exposure of coated vessels, the liquid temperatures are in the range of the superheat temperature, at least in the case of propane [18,43]. However, following the approach suggested by the "Purple Book" [54], the overpressure effects of the BLEVE were neglected in risk calculations, since the area impacted by the thermal effect of the fireball is much greater than the area that may be damaged by the blast. The occurrence probability values of the LOCs and of the FOs suggested by [54] are reported in Table 4. The table also shows the maximum impact distances of each scenario. The maximum impact distances were defined as the maximum distance from the accident at which a threshold value of death probability of 1×10^{-6} is present. Pasquill stability class F, 2 m/s wind speed and the assumptions discussed in detail in the "Purple Book" [54] were used for the calculation of the distances reported in Table 4. As shown in the table, the fireball has the highest impact distance.

Due to the high flammability of LPG, a fireball may be the direct consequence of a BLEVE and the assumption is usually made that in road and rail accidents each BLEVE ends in a fireball and each fireball is preceded by a BLEVE. The BLEVE can be a "fired" or a "cold" one, depending on its primary cause (the presence of an external fire for

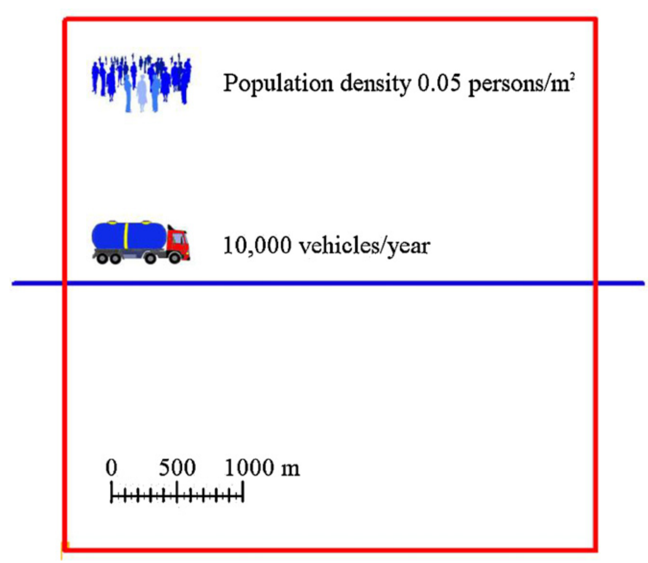

Fig. 5. Case-study 1: map of the test area.

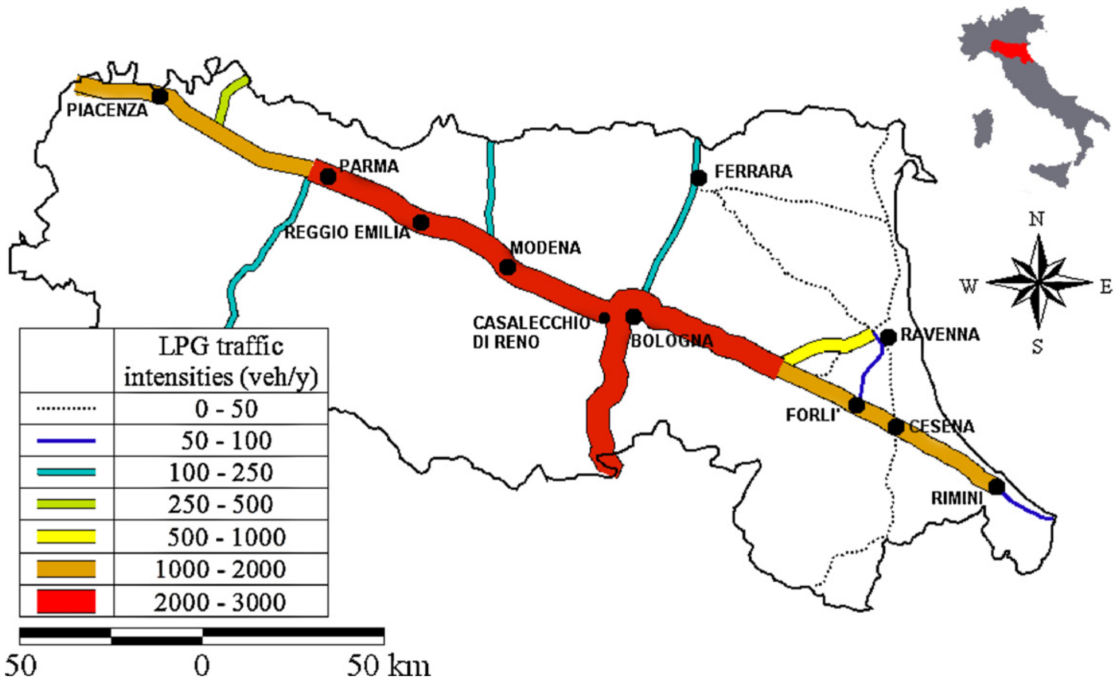

Fig. 6. Case-study 2: the motorway network and the LPG traffic intensity distribution.

"fired" BLEVE, all other possible causes for "cold" BLEVE). As shown in Section 2, it is reasonable to assume a reduced probability for the "fired" BLEVE if a thermal coating is adopted to protect the tank. Nevertheless, the probability of the "cold" BLEVE may be considered not affected by the adoption of a thermal protection. Thus, in the presence of coated tanks, a reduction factor should be applied to the fireball probabilities usually assumed in the quantitative TRA.

The data on past accidents reported in Table 1 show that the fraction of "fired" BLEVEs in HazMat transportation incidents is of about 0.86, the fraction of "cold" BLEVEs being of 0.14. By multiplying the fireball probability (0.80 in the "Purple Book) by 0.86 and 0.14, the observational value of, respectively, the "fired" and "cold" BLEVEs' probabilities are obtained, which result equal to 0.69 and 0.11. Assuming a conservative value of 75% of efficiency (i.e. a 25% of failures) of the thermal insulation in preventing the "fired" BLEVE, the occurrence probability of this scenario is reduced to 0.17. Summing this value with the "cold" BLEVE occurrence probability, a value of 0.28 is thus calculated for the residual occurrence probability of the fireball in the case of coated tankers. All the other parameters used for risk calculation in the quantitative TRAs performed are reported in Table 4 and were not modified among coated and uncoated tankers.

Individual risk curves and societal risk plots may be calculated joining the data on hazmat transportation and on population vulnerability to the characterization of the source term summarized by the parameters reported in Table 4 [7–9]. Societal risk is usually expressed through F/N plots (being F the cumulated frequency of events causing N or more expected fatalities) or as a single point value – an integral parameter IP – inferred from the F/N curve through Eq. (1):

$$IP = \sum_{N=1}^{N_{\max}} F(N) \cdot N^{(\alpha-1)} \tag{1}$$

The term $N^{\alpha-1}$, with α usually ranging from 1 to 2, is called the "risk aversion multiplier", since high values of α imply high values of IP, thus reflecting the increasing aversion towards large-scale disasters causing multiple fatalities. If α is taken equal to 1, making no explicit allowance for scale aversion, the integral represents the "Expectation Value" EV, i.e. the average annual predicted

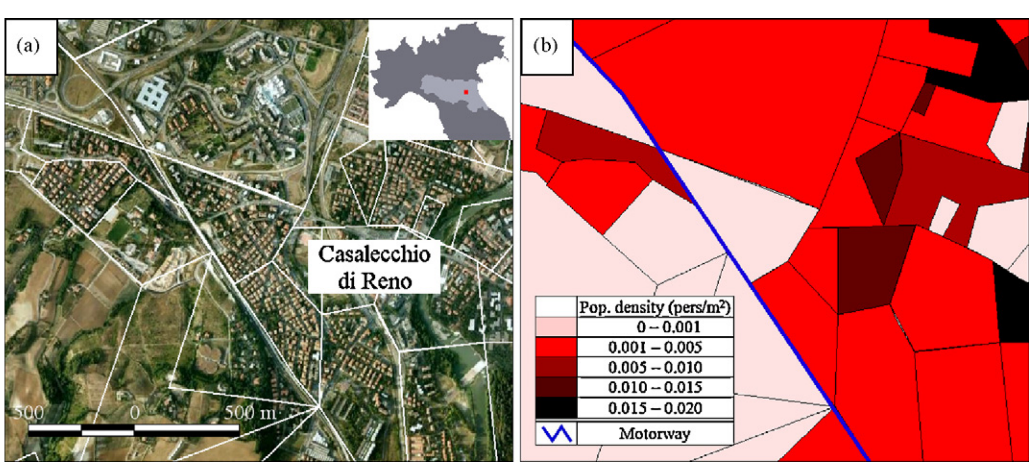

Fig. 7. Case-study 3: (a) aerial photo of the area; (b) map with the motorway and the population distribution in evidence.

frequency of deaths, which coincides with the area beneath the plot of F against N. If α is assumed equal to 2 the "Risk Integral" RI is obtained [1,55]. In the following, for both the cases of uncoated and coated tankers, the F/N curve, the Expectation Value EV and the Risk Integral RI were used to quantify and compare the risk due to LPG transportation in the different case-studies considered. The individual risk distribution in each area considered was mapped and the reduction of the individual risk values ΔIR due to the adoption of coated tankers was calculated as follows:

$$\Delta IR = \frac{IR_N - IR_C}{IR_N} \cdot 100 \tag{2}$$

where IR_C is the individual risk calculated in the case of coated tankers and IR_N is the individual risk calculated considering uncoated tankers.

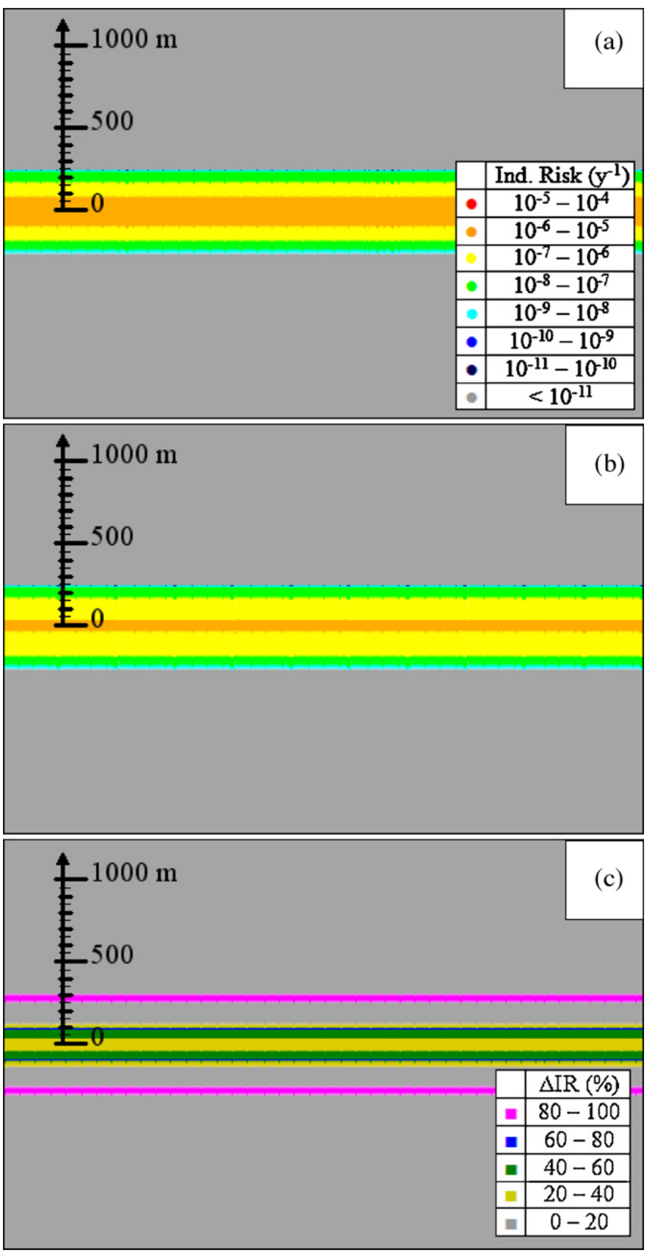

Fig. 8. Case-study 1: (a) individual risk distribution for non-coated tanks; (b) individual risk distribution for coated tanks; (c) percentage reduction in individual risk ΔIR due to coating.

The TRAT-GIS 4.1 software was used for risk calculations. The tool allows to calculate individual risk maps and the societal risk due to hazmat transportation in a defined area taking into account the actual distribution of the on-road and resident population. A detailed description of this software tool is reported elsewhere [56,57].

3.2. Description of the case-studies

Three case-studies were selected to analyze the potential impact of coating on the risk caused by the transportation of flammable liquefied gases. A first case-study (case-study 1) was introduced defining a fictitious area with a homogeneous population distribution crossed by a road used for LPG transportation (Fig. 5). A square area of 4 km × 4 km was considered, divided in two equal rectangles by a road where 10,000 LPG tankers/year (each carrying 23 t of LPG) are transported. An accident frequency of 3.31×10^{-7} events/km/vehicle was assumed, in analogy with the other case-studies. A high value of the residential population density (0.05 persons/m^2) was assumed to emphasize societal risk values. The case-study was introduced due to its simplicity, that easily allows the analysis of the effect of coating on individual and societal risk reduction.

Case-studies 2 and 3 represent two real-life scenarios, that were defined using the actual data on population distribution and transportation of LPG. Case-study 2 is derived from the actual LPG transportation scenario in the Emilia-Romagna region, in the North of Italy, and allows the analysis of the effects on coating at a regional level. For this case-study the regional motorway network (having a total length of about 840 km) was considered. An accident frequency of 3.31×10^{-7} events/km/vehicle was assumed, derived from the analysis of local data on past accidents provided by the company that manages the motorway [58]. The release probability after an accident was assumed equal to 0.05 [59]. Information on resident population was derived from the last national census [60] and meteorological data were obtained from local historical records [61]. Information on the LPG shipments was obtained by an accurate survey carried out by local public authorities and involving the major LPG storage plants present in the region [62]. On the basis of this report, 5078 shipments of LPG were considered to take place each year on the motorway network, travelling on 74 different routes, for a total distance of more than 660,000 km/year. Fig. 6

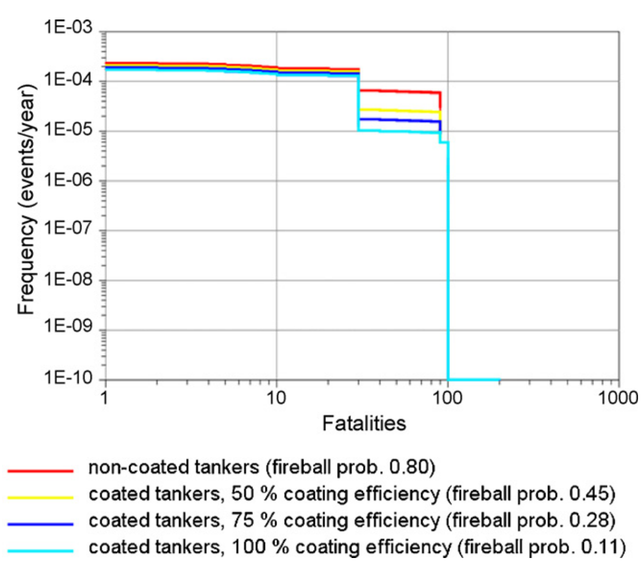

Fig. 9. Case-study 1: F/N curves.

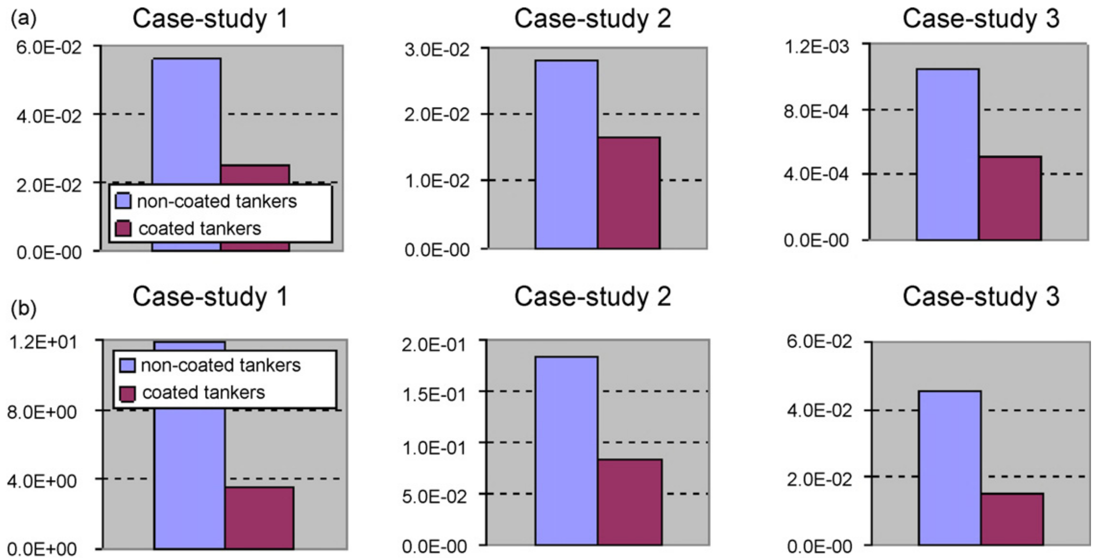

Fig. 10. Case-studies 1, 2 and 3: values of the Expectation Value *EV* and of the Risk Integral *RI*.

shows the regional motorway network and the LPG transportation intensities on each link.

Case-study 3 was derived from the LPG transportation scenario in the district of Casalecchio di Reno, in the Emilia-Romagna region, a populated urban area crossed by a highway used for hazmat transportation (Fig. 7a). This case-study allowed the analysis of the potential risk reduction calculated using data on population distribution and vulnerability more detailed than those usually available at a regional level. A stretch of the A1 motorway, which connects the Emilia-Romagna region to Tuscany, was considered. A traffic of 1857 LPG vehicles/year was considered as the risk source. The same accident and release frequencies of case-study 2 were used. Meteorological data were obtained from local historical records [61]. Detailed census data were used to describe the population distribution [60], which is shown in Fig. 7b.

3.3. Results of the case-studies

Individual and societal risk calculated for case-study 1 are reported in Figs. 8 and 9 respectively. As shown in Fig. 8a, in the case of uncoated tankers individual risk values are higher than 10^{-6} events/year up to distances of 100 m from the road. The adoption of the coating halves the maximum distance at which individual risk is higher than 10^{-6} events/year, reducing it to less than

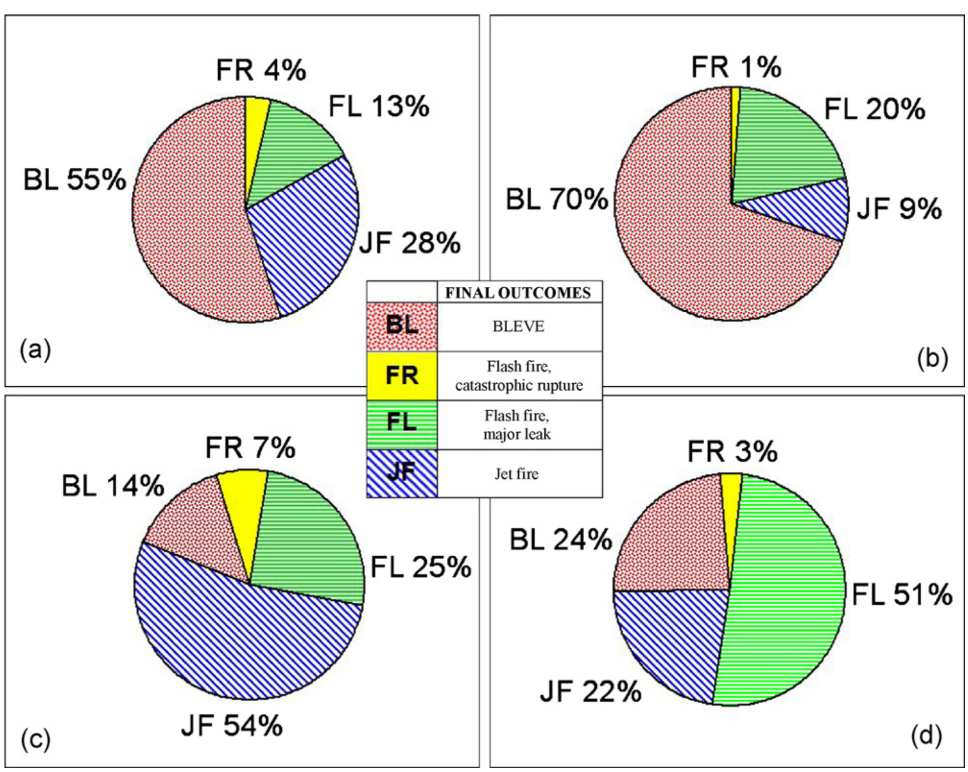

Fig. 11. Case-study 1: contribution of the final outcomes to Expectation Value *EV* (a) non-coated tankers and (c) coated tankers; and to Risk Integral *RI* (b) non-coated tankers and (d) coated tankers.

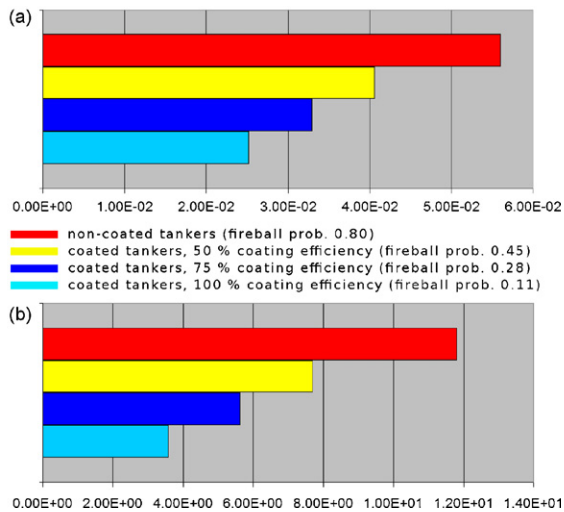

Fig. 12. Case-studies 1: values of the Expectation Value *EV* in events/year (a) and of the Risk Integral *RI* (b) assuming different values for the efficiency of the thermal coating.

50 m, as shown in Fig. 8b. This is evidenced also in Fig. 8c, where the individual risk reduction ΔIR due to the thermal protection is shown. The risk reduction on the road and in the zone immediately next to it to is between 20 and 40%, and is between 60 and 80% at about 100m from the road. As shown in the figure, the highest risk reduction (between 80 and 100%) is experienced at about 270 m from the road. This result is justified by the impact distance of BLEVE, that is the only final scenario having a relevant impact zone up to distances higher than 250 m from the road, as shown in Table 4. Thus, the significant reduction of the conditional probability of this scenario turns out in a corresponding reduction of individual risk at high distances from the road, where the BLEVE is the only scenario contributing to risk. At lower distances (on the road and immediately next to it, up to a distance of 50 m), the jet-fire scenario gives the major contribution to the risk and its conditional occurrence probability is not affected by the adoption of the thermal protection. Thus, as shown in Fig. 8, in this zone no relevant risk reduction is experienced.

With respect to societal risk, Fig. 9 shows that the *F*/*N* curve is lower in the case of coated tankers. In addition to the assumption of a 75% of efficiency of the thermal coating in avoiding the "fired" BLEVE, for case-study 1 also the values of 100% and of 50% efficiency

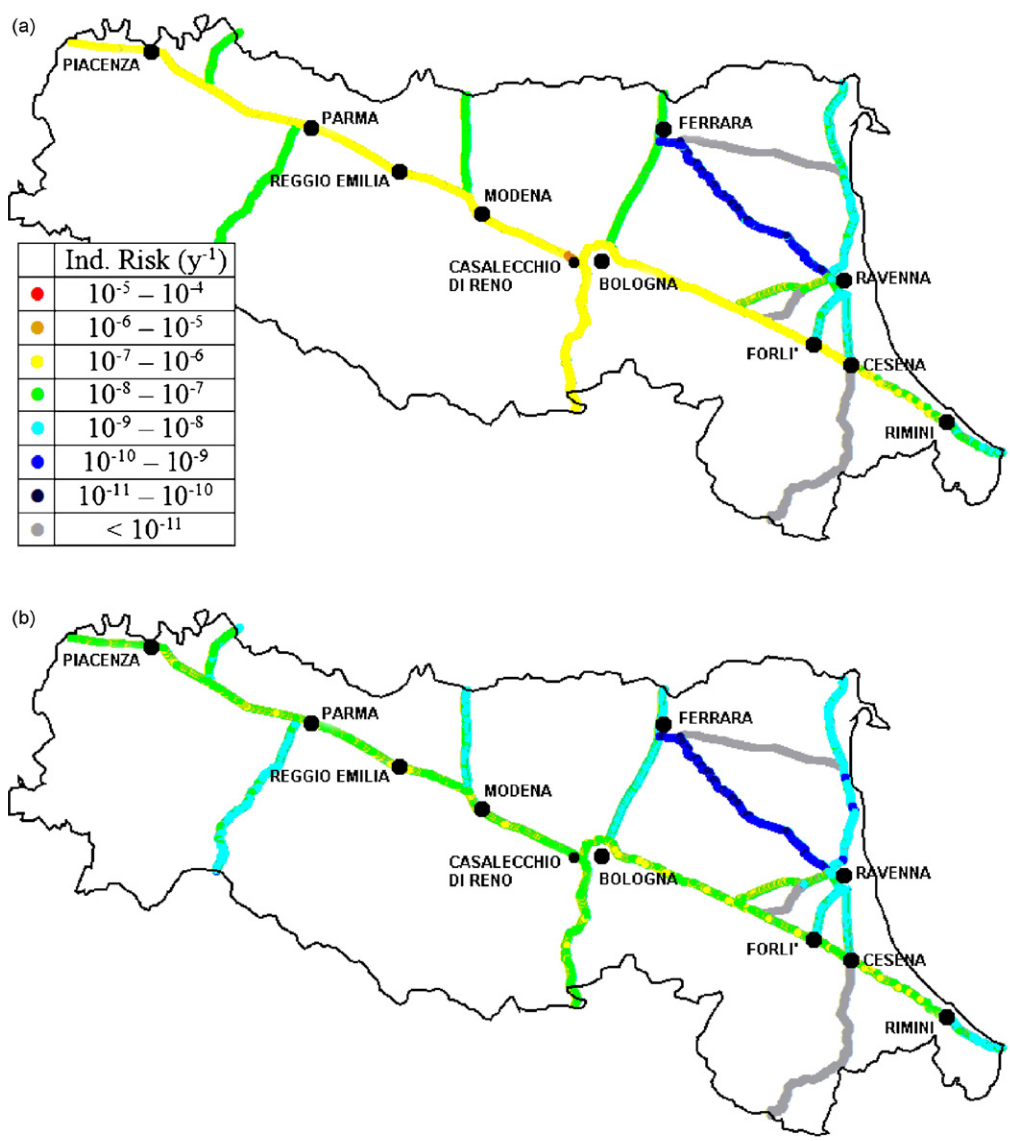

Fig. 13. Emilia-Romagna case-study: individual risk values on the road in the case of: (a) non-coated tankers; and (b) coated tankers.

(corresponding to residual fireball probabilities of, respectively, 0.11 and 0.45) were taken into account. The major decrease of frequency, *F*, due to coating (which is nearly of one order of magnitude in the case of 75% of efficiency of the thermal insulation) occurs for fatality values, *N*, in the range between 30 and 100. This is well justified by the lower frequency of the BLEVE scenario in the coated case, since this scenario, due to its wide impact area, contributes to the high values of *N* of the societal risk plot.

Fig. 10 shows the values of the expectation value, *EV*, and of the risk integral, *RI*, calculated by Eq. (1) from the societal risk curves, both in the case of uncoated and coated tankers. As shown in the figure, a reduction of the *EV* as high as 55% is estimated in the case of coated tankers. The *RI* shows an even higher reduction (about 70%) if coating is adopted. These results may be well justified if the contributions of single scenarios to the overall values of *EV* and *RI* are estimated. As shown in Fig. 11, BLEVE is the most important scenario in the case of uncoated tankers, contributing to 55% of the final *EV*, and even more to the *RI*. Fig. 11 evidences that the adoption of coating strongly reduces the contribution of the BLEVE scenario to the overall risk, that goes down to 14% for the *EV* and to 24% for the *RI*. These preliminary results suggest that passive fire protections could produce significant reductions of the individual and societal risk associated to road and rail LPG transportation scenarios. For case-study 1 the values of EV and RI have been evaluated also assuming different values of the efficiency of the thermal insulation, i.e. of the residual fireball occurrence probability, as shown in Fig. 12.

The results of case-study 2 (Emilia-Romagna region) are summarized in Fig. 13, that shows the individual risk values on the road calculated in the case of uncoated tankers (Fig. 13a) and coated tankers (Fig. 13b). If coated tankers are considered, a high reduction of individual risk may be estimated on most of the motorway routes considered at a regional level. This may be of particular importance when the routes cross densely populated zones, as the outskirts of Bologna (more than 370,000 inhabitants). As a matter of fact, as shown in Fig. 10, the values of the *EV* and *RI* calculated from societal risk curves obtained for the case-study show again a reduction higher than 50% if coated tankers are considered.

Analyzing the results reported in Fig. 13a for the Emilia-Romagna region, it can be noted that the town of Casalecchio di Reno, selected for the third case-study, is one of the “hot spots” where individual risk values are higher than 1×10^{-6} events/year. The results of the detailed calculations performed for case-study 3 are shown in Figs. 14 and 15, reporting respectively the individual risk maps and the *F*/*N* plot. The results confirm that individual risk values are higher than 1×10^{-6} on the road and in its vicinity if uncoated tankers are considered (as those presently used in Italy for LPG transportation). Individual risk values are comprised between 1×10^{-7} and 1×10^{-6} events/year up to 100 m from the road and are higher than 10^{-11} events/year up to 300 m from the road (Fig. 14a). Since the motorway crosses residential areas, with peaks of population density as high as 0.02 persons/m^2, these results turn out in a rather critical situation. In fact, if an acceptability value of 10^{-6} events/year for individual risk in residential areas is considered, as required in the Netherlands by the Fourth Dutch National Environment Policy Plan [63], in Casalecchio di Reno this standard is not fulfilled. With the application of the coating, individual risk values may decrease of nearly an order of magnitude. As shown in Fig. 14b and c, reporting respectively the individual risk map

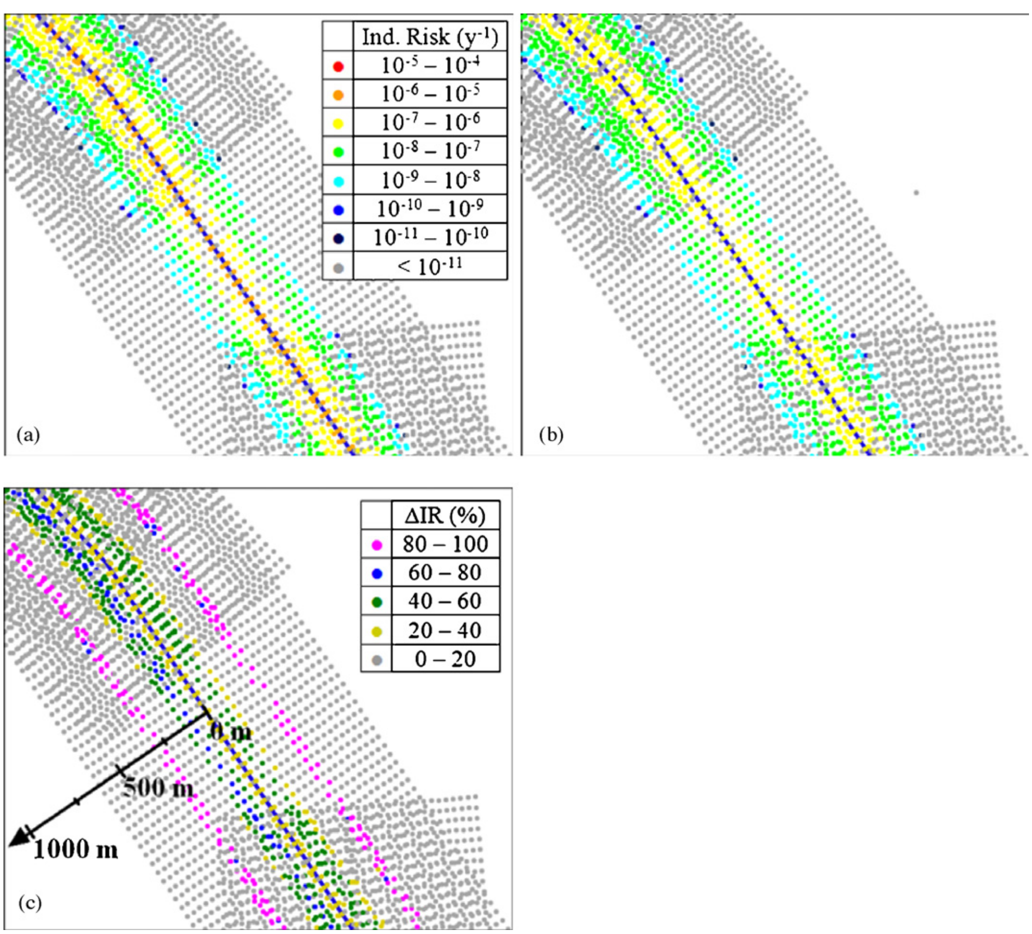

Fig. 14. Case-study 3: Individual risk calculations. (a) *IR* for non-coated tankers; (b) *IR* for coated tankers; (c) differences in individual risk values are also reported (c) Δ*IR* plot.

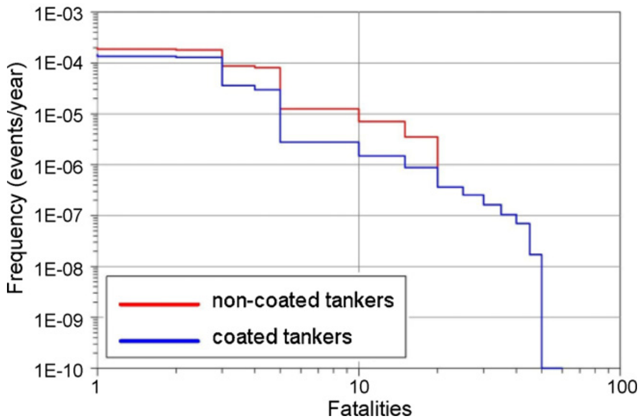

Fig. 15. Case-study 3: societal risk *F*/*N* curves.

obtained considering coated tankers and the ΔIR values, if coated tankers are adopted a 60% decrease in the individual risk value up to 100 m and of 80 ÷ 100% up to 270 m from the road are expected. In particular, in the case of Fig. 14b it is evident that individual risk is always lower than the safety threshold criterion suggested by the Dutch legislation.

In Fig. 15 the *F*/*N* curves are shown for the case of coated and non-coated tankers. Comparing the curves, it can be noted that, as in case-study 1, the adoption of coating results in a lower *F*/*N* plot. The maximum reduction of *F* is of about one order of magnitude. As shown in Fig. 10, a significant reduction is also obtained for the Expectation Value *EV* and for the Risk Integral *RI* calculated from the societal risk curves.

Thus, the results obtained from all the case-studies considered confirm that the introduction of thermal coating leads to significant reductions (up to an order of magnitude) of individual and societal risk values associated to LPG transportation.

4. Conclusions

The potential reduction of the risk in LPG road transport due to the adoption of passive fire protections was investigated. Experimental data available for small scale vessels fully engulfed by fire were extended to real scale tankers using a finite elements model. The results of mathematical simulations of real scale fire engulfment scenarios that may follow road or rail accidents involving LPG tankers proved the effectiveness of the thermal protection in avoiding the "fired" BLEVE scenario. The presence of a thermal coating greatly increases the "time to failure", allowing for a time lapse that in the European experience is considered sufficient to start of effective mitigation actions by fire brigades. The results obtained were used to calculate the expected reduction of individual and societal risk due to LPG transportation in real case scenarios. The results confirmed that the introduction of passive fire protections turns out in a significant reduction of risk, up to an order of magnitude in the case of individual risk and of about 50% if the expectation value is considered. Thus, the adoption of passive fire protections, not compulsory in European regulations, may be an effective technical measure for risk reduction, and may contribute to achieve the control of "major accidents hazards" cited by the European legislation.

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