HazMat transportation safety assessment: analysis of a "Viareggio-like" incident in the Netherlands

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ABSTRACT

Relevant safety issues are associated with hazardous materials transportation, especially when transport routes cross populated areas. On March 6th, 2015, a passenger train collided with the last rail car of a freight train in Tilburg, the Netherlands. The last car contained 50 t of liquefied 1,3-butadiene. As a result of the collision, the last car showed deformation; a small leakage occurred but fortunately with no relevant consequences. However, extremely severe consequences could have happened, such as in the rail accident that occurred in Viareggio, Italy in 2009. In this work, the case of Tilburg was firstly outlined and explored by qualitative methods, in order to identify possible realistic final scenarios that could have happened. Second, the potential consequences of the identified scenarios were estimated through conventional integral model for physical effects evaluation. Comparison with the Viareggio case was also shown in order to support the discussion of the results obtained. Finally, lessons learned after the incident, policy making considerations, and indications for the risk mitigation of hazardous materials transportation are given.

Keywords:

Hazardous Material Transportation; butadiene; consequence assessment; risk management; fires; explosions

1. Introduction

Transportation of hazardous materials (HazMat) is a crucial activity for the productivity of industrialized countries, being ships, road and rail tankers, and pipelines the common transportation modes (Torretta et al., 2017). During transportation, accidents may occur and propagate among tankers leading to severe fires, explosion or toxic dispersions (Casal, 2018). This may increase the level of individual and societal risk associated to those activities, since the transport network often crosses densely populated areas (Jardine et al., 2003; Ryland, 1999; van der Vlies and van der Heijden, 2013). Due to the relevant safety issues posed by HazMat transportation, the scientific community devoted several efforts to develop quantitative tools for risk assessment of this specific activity. As pointed out in recent works (Landucci et al., 2017; Torretta et al., 2017), the quantitative tools developed for fixed plants were initially implemented for the HazMat transportation (Baksh et al., 2015; Dimauro et al., 2012; Romano and Romano, 2010). Then, based on that approach, different methods were established for risk assessment and several countries adopted specific regulations to manage and control the risk due to HazMat transportation, as pointed out in the comprehensive literature reviews available (ACDS, 1991; CCPS, 1995; CFR Code of Federal Regulations, 2015; CGSB - Canadian General Standards Board, 1997; Erkut et al., 2007; Gheorghe et al., 2005; Mannan, 2005; OPSI, 2009; Purdy, 1993; Uijt de Haag and Ale, 2005). International agreements form the main European references concerning the regulation of HazMats transport, such as the European Agreement concerning the international carriage of Dangerous goods by Road (ADR) (European Commission, 2006a), rail (RID) (European Commission, 2006b) and waterways (AND) (UNECE, 2000).

Several site-specific studies in critical areas supported the implementation of the proposed methodologies (Egidi et al., 1995; HSE-Health Safety Executive, 1981, 1978; RP Authority, 1982). The approaches more frequently applied take into account the combined evaluation of the expected accident frequency and the consequent impact on population of accidents during the HazMat transportation (ACDS, 1991; CCPS, 1995; CFR Code of Federal Regulations, 2015; Mannan, 2005; Purdy, 1993; Uijt de Haag and Ale, 2005). Simplified semi-qualitative assessment based on the same concept were also proposed (Bubbico et al., 2006, 2004; Erkut et al., 2007; Reniers and Dullaert, 2013; Reniers and Zamparini, 2012. Therefore, the problem of HazMat transportation hazard and risk analysis is well known: both consolidated and innovative methodologies are available and applied.

Nevertheless, despite the aforementioned technical and regulatory tools to support the management of HazMat transport risks, relevant recent occurrences raised public concern about the safety of this activity. The catastrophic events in Lac-Mégantic, Canada (U.S. Department of Transportation, 2013), Wetteren, Belgium (Smedt et al., 2014), and two relevant accidents related to liquefied petroleum gas (LPG) transportation in Italy - Bologna in 2018 (ANSA, 2018) and Viareggio in 2009 (Landucci et al., 2011) - point out the relevance of the problem and the need to evaluate the capability of current tools, either regulations and safety assessment methods, to cope with the severe dangers posed by HazMAt transportation to population, environment and assets.

On March 6th, 2015, a passenger train collided with the last rail car of a freight train in Tilburg, the Netherlands. The last car contained 50 t of liquefied 1,3-butadiene (butadiene, in the following). As a result of the collision, the last car showed a deformation of 1.5 m diameter and 35 cm depth. Also, the inspection hatch at the rear of the car leaked showed a drip irrigation for a short period of time. Fortunately, no damages were experienced by people and assets in the surrounding area as a consequence of the minor release. However, the physical effects associated with the scenarios following the incident[1] could have been extremely severe (large fires, explosions or toxic contamination) if the damage to the tank wagon had been worse, such as in the LPG accident that occurred in Viareggio.

In the present study, the specific features of the Tilburg incident are investigated in detail. The results are analysed and lessons learnt from the incident are discussed. Comparison with the consequences of the severe accident occurred in Viareggio (2009) are provided, in order to i) derive a benchmark for impact associated with hazardous materials transportation; ii) verify and reflect on the current assumptions adopted for hazardous materials transportation impact assessment, especially when dealing with loss of containment events evaluation. The need for appropriate regulation, mitigation and emergency planning of dangerous good transportation by railway is finally critically examined in the light of the events sequence.

2. Description of the reference cases

2.1 The Tilburg case

On March 6th, 2015 a freight train was travelling from the Chemelot Industrial estate (a large chemical cluster in the south-east part of the Netherlands) to the Kijfhoek marshalling yard via the Brabantroute. The Brabantroute is a primary railway route in the south part of the Netherlands used for passenger as well as freight transport. The freight train was briefly side tracked for an intermediate stop in the city of Tilburg. Here, a passenger train collided with the last wagon of the freight train, which contained fifty tonnes of butadiene. There were no serious injuries and although there was a leak and loss of containment, the scale remained limited.

[1] In the present work, the term “incident” denotes an abnormal event that evolved into limited damages to plant, equipment and property, but did not result into damages to workers or population; the term “accident” identifies an event affecting persons in terms of psychophysical damages, thus resulting in injuries and/or fatalities.

2.1.1 Focus on the causes of the incident

According to the DSB (Dutch Safety Board, 2016), who thoroughly evaluated the incident, the following contingencies played a role in the chain of events that led to the incident:

- The incorrect length of the freight train that was specified for the request of the intermediate stop, as a result of which the freight train was side tracked to a section that was too short for the freight train. This caused the train to occupy a switch so that the signal for the passenger train remained at red (i.e., avoiding the passage of other trains on the line);
- The driver of the passenger train did not notice the red signal and approached the line without reducing the speed (about 45 km/h) and started to brake only at the last moment, without significant speed reduction when the collision occurred;
- The section of the tracks in which the freight train stopped did not enjoy additional protection against red signal passages by means of the automatic train protection system adopted in the Netherlands and named "ATB-Vv" (*Automatische TreinBeïnvloeding - Verbeterde versie*; Automatic train control - improved version).

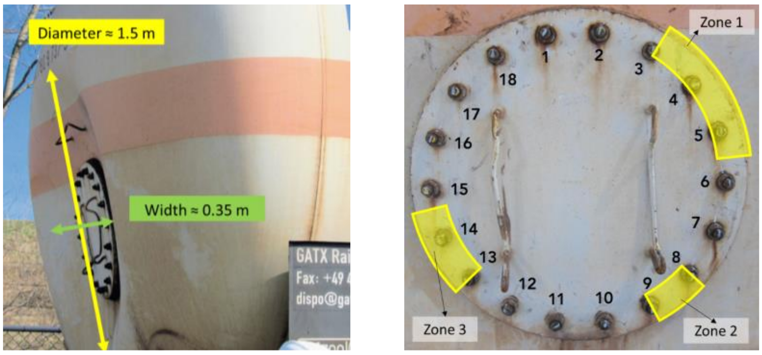
The ATB-Vv collects signals from the line and overrides the driver's controls in case of failure to observe speed limit, with immediate emergency brake application. If the signal had been equipped with ATB-Vv, during the last 120 m prior to the red signal, the system would have recognized that the driver was not activating the braking system on time, providing automatic train halting to avoid the collision.

2.1.2 Focus on the consequences of the incident: the loss of containment (LOC)

The consequences of the incident on the tank wagon (the possible leakage sources) were analysed through a technical investigation. The analysis was performed in five different phases, in particular:

1. Visual inspection and laser scan of the tank;
2. Tank leak tests;
3. Analysis of the tightening torque bolt connections on the manhole cover;
4. Analysis of the status of the manhole cover seal;
5. Wall thickness analysis and crack detection.

During the first phase, the tank showed mechanical damages on the surface, in correspondence of the buffers and tow coupling, and a deformation of about 1.5 m diameter and 0.35 m depth on the rear of the wagon. Figure 1a shows a picture of the latter major deformation. The tank showed deformations due the crash only. No pre-existent damages related to weak maintenance or deviations from standard requirements were recorded. After the first phase, the leak tests were conducted in two different ways: a first leak test assessed the actual status of the tank after the collision, and a second test was performed after the tightening torque of the bolt fastening was brought back to its default values. Due to the scope of the present study, only results from the first leak test are reported. The DSB provides a complete report of the technical investigation (Dutch Safety Board, 2016). The first test showed a leak only along the seal of the manhole cover. In particular, the test identified three leakage zones, namely: from nut 3 to the midpoint between nuts 5 and 6, between nuts 8 and 9, and from nut 13 and the centre of nuts 14 and 15. The leakage points are shown in Figure 1b. During the third phase, the separation space between the cover and the flange of the manhole was measured. Separation was recorded in the range from 1.40 - 2.30 mm. Finally, the last two phases of investigation showed no critical issues or relevant deviations related to the leak.



a) b)

Figure 1. a) picture of the deformation on the rear of the wagon after the collision; b) leakage zones identified through leak test along the seal of the manhole. Adapted from (Dutch Safety Board, 2016).

2.2 The Viareggio case

In order to benchmark the potential severity of the Tilburg case, one of the most severe European case histories related to the dangerous good transportation is selected as comparative case. In particular, the LPG accident that occurred in Viareggio (Italy), 2009 is taken as reference case. Even if the causes of the accident are fundamentally different from those occurred in Tilburg, the Viareggio accident represents a comparable example of the hazards posed by HazMat rail transportation. Hence, in the present study, the LOC resulting from the wagon derailment in Viareggio was assumed as credible worst case event that could have occurred in Tilburg. A brief summary of the case is given in the following, in order to provide the relevant data adopted in the comparison carried out in the present study. A deeper analysis of the accident can be found elsewhere (Brambilla and Manca, 2010; Landucci et al., 2017, 2011; Manca and Brambilla, 2010).

On Monday June 29th 2009, a freight train composed of 14 tank wagons carrying LPG was passing through Viareggio station. At 11:45 the first tank wagon derailed and overturned after passing the shunts of the station. The derailment caused a long trapezoidal breach, about 420 mm long and from 60 to 20 mm high, on the first wagon shell. The entire inventory of the tank was released from the breach, while no LOC occurred from the other tank vessels. No immediate ignition followed the release, since the drivers had time to shut-down the engine and run away from the railway. The massive flammable cloud that was formed from the evaporation of the released LPG ignited after few minutes, resulting in a severe flash fire and in confined explosions in some buildings. Due to the intense heat radiation exposure and the collapse of buildings, 32 fatalities and property loss were the result of the accident (Landucci et al., 2017).

3. Methodology

3.1 Overview

The present work has a threefold scope: i) provide an impact assessment for the Tilburg case; ii) analyse the spatial planning in the Tilburg area; iii) provide managerial considerations accounting for the results obtained in tasks i) and ii).

The impact assessment, i.e. task i) whose details are described in Section 3.2, is aimed at the evaluation of damage distances resulting from the LOC considering different scenarios and comparing them against the outcomes of the benchmark case; moreover, reflection on the most commonly adopted assumptions for consequence assessment of transport accidents are discussed. Four possible release sources were analysed, taking into account: the actual LOC through the measured hole geometry (Dutch Safety Board, 2016), two reference LOCs suggested by the guidelines for the quantitative risk assessment for rail transportation of HazMat (Uijt de Haag and Ale, 2005), and a possible derailment-induced release. The latter was implemented considering the geometry of the actual rupture experience after the Viareggio derailment (Landucci et al., 2011). Effects on both humans and buildings/equipment were considered.

The outcomes of the impact assessment carried out in task i) are adopted in task ii) in order to analyse the spatial planning around the area of the incident. More in general, considerations about the current status of regulation around transport routes affected by HazMat transportation are given. Finally, in task iii) reflections on the lessons learned by the incident and policy-making considerations are given based on the outcomes of the quantitative assessment and analysis of land use planning regulation.

3.2 Impact assessment

The impact assessment followed three main steps, namely: 1) identification of credible LOCs and final scenarios; 2) modelling of the potential consequences through commercial integral models for physical effects; and 3) vulnerability assessment through a threshold-based approach for the scenarios identified in the first step.

3.2.1 Identification of the reference LOCs and final scenarios

Table 1 summarizes the types of LOC considered for the present study and the respective release equivalent diameter.

Table 1. Summary of the case studies implemented in the consequences assessment.

Case ID	Description	LOC type	Equivalent diameter (mm)
A	Actual scenario	Continuous	35.7
B	Purple Book G.1	Continuous	76.2
C	Purple Book G.2	Instantaneous	Catastrophic rupture*
D	“Viareggio-type” release	Continuous	147.0

*modelled as instantaneous release of the tank content.

Case A considered the actual release geometry. The results of the investigation on the damaged wagon, reported in Section 2.2.2, were analysed to obtain the reference geometry. In addition to the actual scenario, the reference LOCs related to railway HazMat transportation were identified, following the guidelines described in the “Purple Book“ (Uijt de Haag and Ale, 2005), generating cases B and C. Finally, a “Viareggio type” rupture (case C) was introduced in the analysis as credible leakage induced by derailment. In particular, the same equivalent diameter was considered, as derived from specific observation on the derailed tank car (Landucci et al., 2011). Details on the LOCs identification procedure are reported in Appendix A.

The credible final scenarios, based on the type of release, were identified through conventional event tree analysis (ETA) (Mannan, 2005) considering all the relevant final outcomes (Uijt de Haag and Ale, 2005). Figure 2 shows the ETA developed for the present analysis.

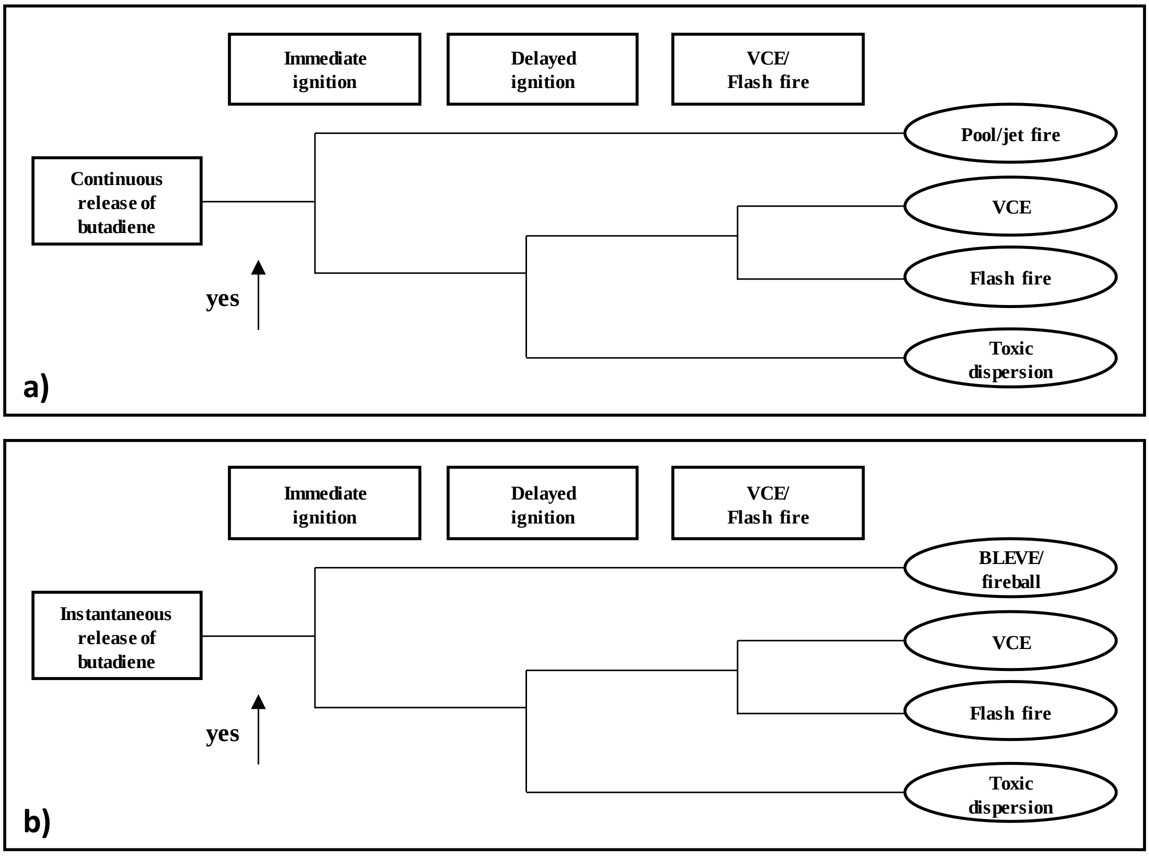


Figure 2. ETA implemented in the present analysis for a) continuous release and b) instantaneous release, of pressurized flammable/toxic gas (i.e. butadiene). BLEVE = Boiling Liquid Expanding Vapour Explosion; VCE = vapour cloud explosion

3.2.2 Consequence assessment settings

The physical effects associated with the final scenarios identified in Figure 2 were estimated through consolidated integral models for the consequence assessment (CCPS, 2000; Mannan, 2005; van den Bosch and Weterings, 2005). The software package DNV GL® Phast 8.11 (in the following, Phast) was adopted.

Table 2. Summary of the meteorological conditions implemented in the present analysis.

Parameter	**Unit**	**F/2**	**D/5**
Pasquill Stability class	-	F (stable)	D (neutral)
Wind speed at 10 m	(m/s)	2	5
Ambient Temperature	(°C)	6.1	6.1
Ambient Pressure	(kPa)	101.3	101.3
Humidity	%	80	80
Surface roughness length	mm	1000	1000
Solar radiation	kW/m^2	0.595	0.595

A key step in the consequence assessment was setting the proper meteorological conditions. Due to lack of specific data on atmospheric conditions at the moment of the accident, two reference meteorological conditions were adopted, namely F/2 and D/5, as detailed in Table 2. More information on the meteorological conditions and simulation set up are reported in Appendix A.

3.2.3 Vulnerability estimation

In order to evaluate the impact of the final scenarios, a threshold-based approach was adopted. Both effects on humans and on buildings were considered.

For the impact assessment on humans, the literature reports several thresholds data sets, some of them adopted in specific legislations (Christou et al., 1999; Decreto 09/5/2001 N. 151, 2001; SFK/TAA Germany, 2005). In order to define a damage threshold set of generic validity, a vulnerability-based approach was adopted, as carried out in previous studies (Pula et al., 2005; Shariff and Wahab, 2013; Shen et al., 2018). In particular, three levels of probability of death (i.e., expressing vulnerability) were first set: 0.1%, 1%, and 10%, representing minor, moderate, and severe damages, respectively. Probit functions (see Table 3) were then adopted to calculate the threshold of physical effects corresponding to the three vulnerability levels.

Table 3. Models for human vulnerability (Committee for the Prevention of Disasters, 1992; Mannan, 2005) adopted in the impact assessment. Y = probit; D = dose; t_e = exposure time (s); Q = heat radiation (kW/m^2); Ps = peak overpressure (bar); C = concentration (mg/m^3).

Vulnerability vector	Probit equation	Dose
Heat radiation	Y = -14.9 + 2.56 ln(D)	$Q^{4/3} \times t_e$
Overpressure	Y = 5.13 + 1.37 ln(D)	P_s
Toxic release	Y = -23 + ln (D)	$C^2 \times (t_e/60)$

The calculated thresholds damages for humans adopted in the present impact assessment are summarized in Table 4. It is worth mentioning that in absence of probit relations for the flash fire scenario, literature thresholds were adopted in order to integrate the dataset (Decreto 09/5/2001 N. 151, 2001). The exposure time (t_e) was assumed equal to 1 min and 30 min for heat radiation and toxic exposure, respectively.

For the vulnerability assessment of buildings, the thresholds suggested by the Dutch guidelines (Committee for the Prevention of Disasters, 1992) were taken as reference, evaluating moderate and severe damages at the structures due to radiation and overpressure. The reference intensities for the evaluation of physical effects on buildings are summarized in Table 4.

Table 4. Threshold values for the evaluation of human vulnerability; n.a. = not applicable; u = unlikely to cause damages (Committee for the Prevention of Disasters, 1992).

Scenario	Unit	Thresholds set damages to humans			Thresholds set damages to buildings	
		Minor	Moderate	Severe	Moderate	Severe
Pool Fire	(kW/m^2)	6	8	11	2	15
VCE	(barg)	0.09	0.17	0.36	0.17	0.35
Jet Fire	(kW/m^2)	6	8	11	2	15
Fireball	(kW/m^2)	6	8	11	u.	u.
Flash Fire	-	n.a.	½ LFL	LFL	u.	u.
Toxic dispersion	ppm	21000	31000	52000	n.a.	n.a.

Given the thresholds in Table 4, the damage distance of a given scenario was calculated as the maximum distance at which the physical effect reached the reference value (see Appendix B). Finally, once the impact of all possible accidents was estimated, the results were plotted on the map of the site. Results of the vulnerability assessment are shown in Section 4.1.

3.3 Spatial planning around railway lines

More than in other major European countries, rail transport of hazardous substances in the Netherlands is organised right through city centres, creating a strong link between rail transport, urban planning and the (re)development near railways (see for example (de Wilde, 2006)). This reflects how external safety is managed in the Netherlands, where they focus on a risk based policy. For example, the Dutch have adopted generic standards for external safety, which are based on transport parameters as well as on parameters of people residing in urban areas (see (van der Vlies, 2011) or (van der Vlies et al., 2018) for a thorough elaboration on the institutionalization of ‘standards’ concerning external safety). The term ‘external’ is used to denote that these risks involve civilians residing in areas adjacent to these risky activities. If a person working with hazardous substances has an accident, this would be referred to as internal safety or occupational risk.

More recent, in 2015, the Basic Network Act took effect. As a result, among others, the national authorities implemented so-called risk ceilings. A risk ceiling is the maximum amount of individual risk (IR) that the adjacent areas of a railroad may endure as a result of transport of hazardous materials. Risk ceilings (the IR 10^{-6}, 10^{-7} and 10^{-8} contours) are expressed in meters from the centre of the rail cluster. These distances are the result of calculating risks for a specified amount of transported hazardous substances per rail segment, and also the environment is taken into account. The calculated results are used as a reference value. For example, in Figure 3 one can see that the IR 10^{-6}, 10^{-7} and 10^{-8} contours have distances of 0, 0 and 15 meters respectively, depending on the specifications of the rail segment (i.e. a segment between Amersfoort Oost and Deventer West). This is then compared with the maximum amounts of hazardous substances, expressed in so-called tank wagon equivalents, which may be transported per year per category of substances. The categories are defined grouping substance with similar hazards and identifying a reference substance for each category (see Figure 3). As shown in Figure 3, for the mentioned rail segment this is limited to the equivalent of 10 wagons of category A (flammable gas) and 400 category C3 (very flammable liquid) substances per year[2].

							Substance category						
			IR 10^{-6}	IR 10^{-7}	IR 10^{-8}		A	B2	B3	C3	D3	D4	
155600 : 464517	207590 : 474798	Route 30, Amersfoort Oost – Deventer West					10	0	0	400	0	0	0-24
155600 : 464517	155751 : 464660	EK: Amersfoort Oost – Barneveld aansl.	0	0	15								
155751 : 464660	166056 : 463827	EL:	0	0	12								

Substance category	A	B2	B3	C3	D3	D4
Description	flammable gas	toxic gas	very toxic gas	very flammable liquid	toxic liquid	very toxic liquid
Reference substance	propane	ammonia	chlorine	pentane	acrylonitrile	acrolein

Figure 3. An extract from the Basic Network Regulation (Regeling Basisnet) showing IR and allowed tank wagon equivalents per rail segment "Amersfoort Oost- Deventer West".

In the Netherlands, a legally binding norm for IR is implemented for vulnerable objects such as homes, schools, hospitals, large office complexes etc. The norm implies that an unprotected person who resides near a railroad for a full year may not endure a risk of death of more than 10^{-6} or once in every one million years and that no vulnerable objects may be built within the 10^{-6} contour. With the Basic Network Act, a program was implemented to buy up all the properties within the 10^{-6} contour, which was limited to several dozens of properties. In the Tilburg case, no norms are exceeded, nor vulnerable objects remediated.

Apart from the IR, the Dutch external safety policy traditionally also distinguishes the Group Risk (GR). This is the cumulative probability for each year that at least 10, 100 or 1000 people die as a direct result of their presence in the influence area of an establishment or transport route if an incident happens with hazardous substances. Therefore, the GR is influenced by the people in the vicinity of a risk. Prior to the Basic Network Act, this was visualised on a logarithmic scale by using the F/N curve, where F represents the frequency of an accident and N the number of people expected to die as a result of that accident. In the new Basic Network Act, the GR is also expressed

[2] Although factual, these are rather low numbers for a whole year. There are also rail segments where many tens of thousands of different matter categories may be transported.

in terms of contours. Figure 4 depicts the interaction of GR and IR: an object (for example a school with 1000 students) is located on the IR 10^{-7} contour. When this school is open fulltime (24/7 and 365 days per year) at this location, the possibility that 1000 people would be subject to a fatal accident involving hazardous substances is once every 10 million years. The school is not built within the 10^{-6} contour, thus the IR norm is not exceeded.

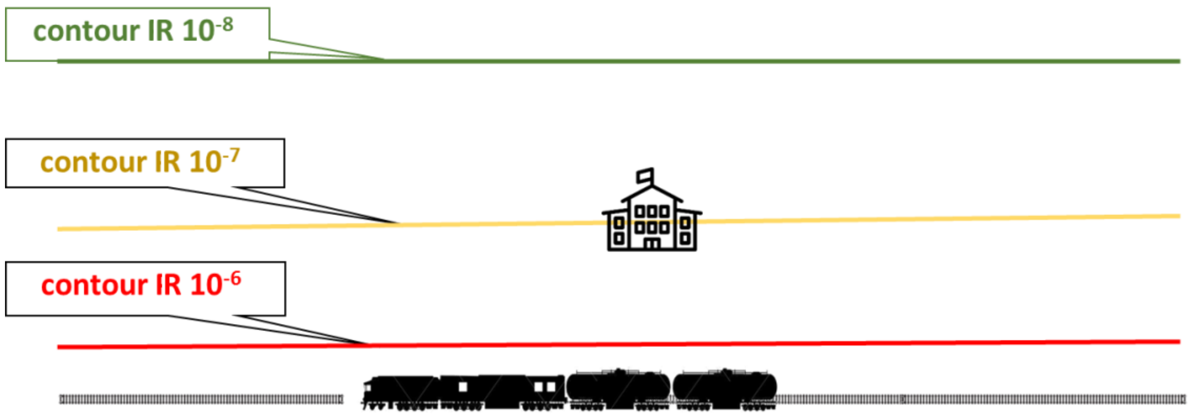


Figure 4. An illustration between the relation of IR contours and GR.

The GR is not a limiting value or norm, instead it is an orientation value which allows deviation. The values in the table are hence a reference for local authorities that they may differ from and instead may be used to evaluate their local development plans and weigh to what extent they find the developments acceptable or not.

Obviously, this risk-based policy primarily focusses on low possibility high effect scenarios. The abstract possibility of once every million years makes it in practice a difficult norm or guideline to live up to (van der Vlies, 2011). Also, because there is hardly any focus on the distances of scenarios, this makes it, due to the density of the country, attractive for local politicians and spatial planners to build near the transport route[3]. Therefore with this article, we would like to focus on the potential impact of a scenario on the adjacent built area by analysing the Tilburg case.

[3] The last couple of years, the Dutch government is integrating all environmental acts into one massive Environment and Planning Act (‘*Omgevingswet*’). In this act, there are also new developments concerning external safety which imply a more effect based policy. This means that local governments may induce measures to newly developed property, such as blast resistant glass or heat resistant walls to (longer) withstand incidents with hazardous materials. This however can only be mandatory for new development

4. Results and discussion

4.1 Potential severity of the incident

The results of the impact assessment are shown in terms of vulnerability maps obtained through the approach described in Section 3.2. Figures 5 and 6 show the results of the estimated worst-case scenario of each release type, through the vulnerability maps obtained for citizens and for buildings, respectively. The worst-case scenario was determined after having calculated each individual scenario identified through the ETA (see Figure 2) adopting the vulnerability thresholds reported in Table 4.

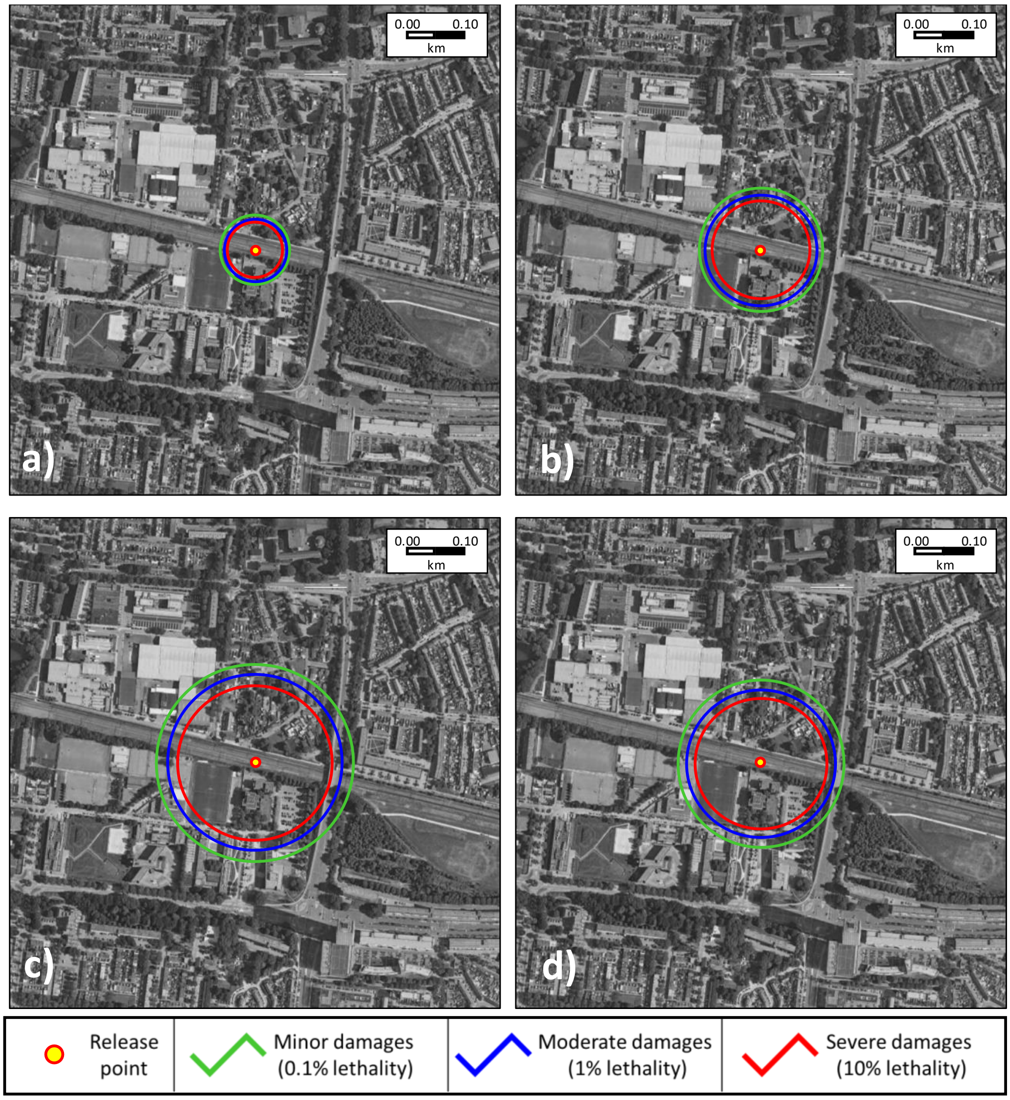


Figure 5. Human vulnerability assessment of the worst-case scenario (pool fire) obtained for the case studies: a) case A; b) case B; c) case C; d) case D (see Table 1 for case ID).

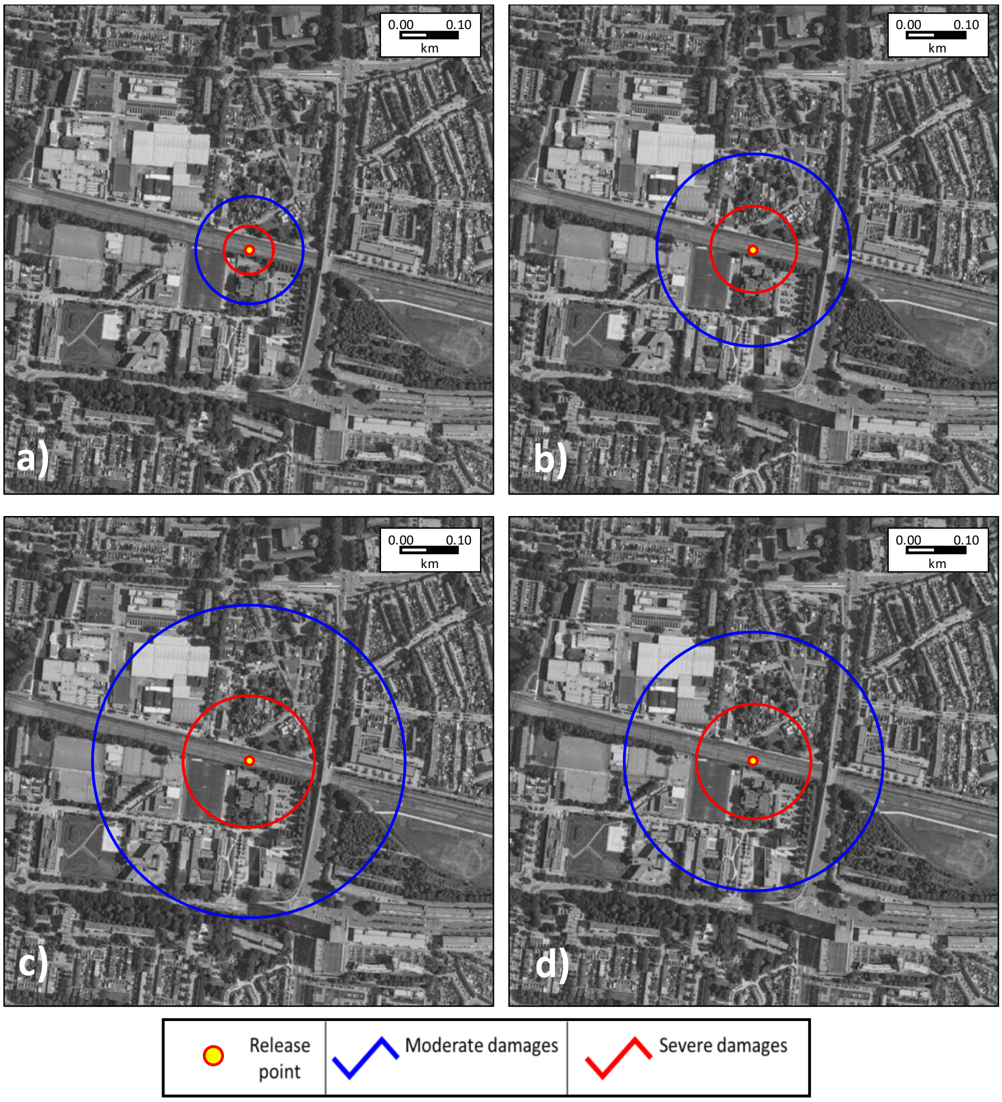


Figure 6. Buildings vulnerability assessment of the worst-case scenario (pool fire) obtained for the case studies: a) case A; b) case B; c) case C; d) case D (see Table 1 for case ID).

The radius of each circle in the map represents the maximum distance at which the reference threshold was obtained. In this way, the circles represent the effect zones accounting any possible wind direction. The worst-case scenario resulted in a large pool fire for all the cases, despite other final outcomes feature distances in the same order of magnitude. The complete set of consequence assessment results is reported in Appendix B.

The outcomes of the actual release scenario (case A) have limited impact and only partially affects the residential area surrounding the railway (see Figure 5a); moreover, limited damages to buildings are predicted (see Figure 6a). However, when more severe, but credible, release conditions are considered, damage distances drastically increase. In the conventional scenarios adopted for risk assessment in the Dutch framework (i.e., cases B and C), the distances increase about 1.8 and 2.7 times with respect to case A and affect the surrounding areas (see Figures 5b and 5c for case B and

C, respectively). Similar results are obtained for the analysis of damages to buildings for cases B and C (Figures 5b and 5c, respectively). Whereas, the damage distances associated with case D, in which the Viareggio release type was considered, are similar to the ones obtained in case C (15% difference in the extension of severe effects). This may be due to the large release section considered for case D. Hence, this confirms the credibility of the assumption of the catastrophic release as an indication of the worst-credible rupture, potentially induced by impact after transport vessels derailment, collision, and, more in general, severe transport accidents.

The analysis of potential consequences of the Tilburg incident was integrated with a comparison against the actual impact of the Viareggio accident. In this case, the flash fire, i.e. the final outcome of the event tree corresponding to the actual Viareggio scenario, is considered. Despite the different substances involved (i.e., butadiene and LPG) and differences in the urban context and specific meteorological conditions affecting the flammable gas dispersion, the comparison is aimed at providing a benchmark evaluation of the severity and impact of the accidents associated with the transportation of hazardous materials and to evaluate the current status of land use planning around transport lines in the Dutch context.

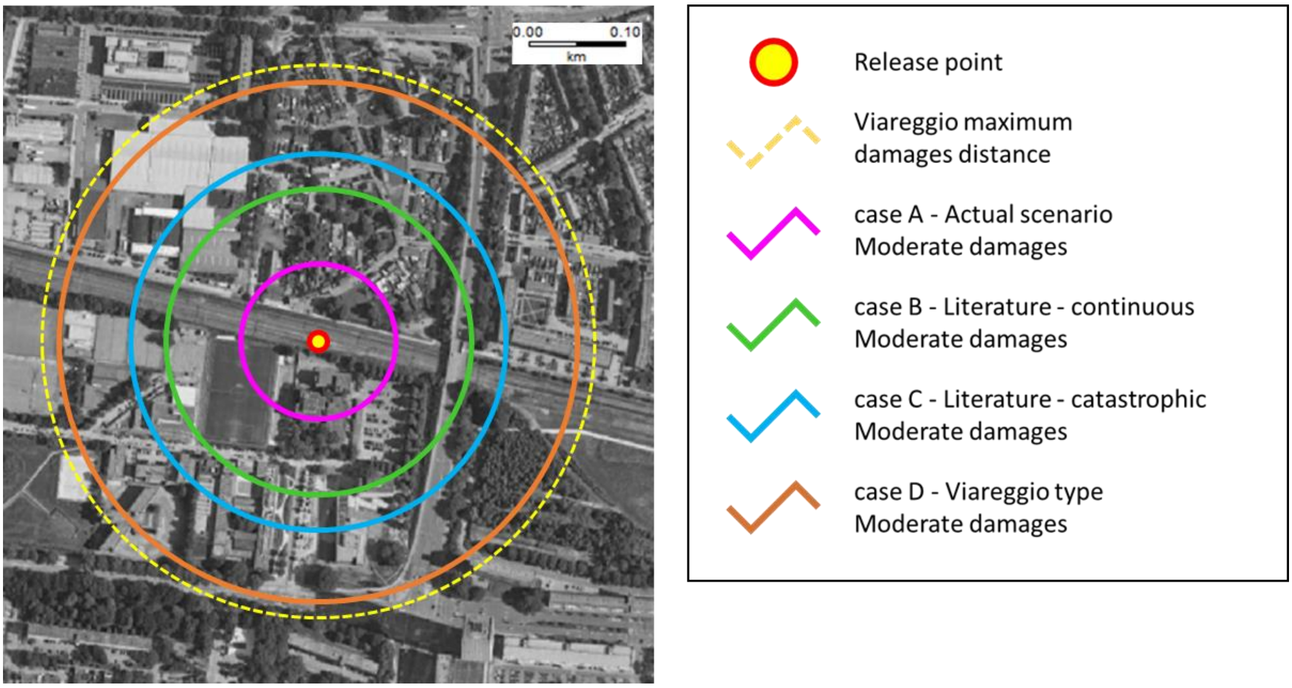


Figure 7. Comparison between the impacts of the flash fires that occurred in Viareggio (Landucci et al., 2011) and the flash fires estimated for cases A-D. The contours represent the estimated impact corresponding to moderate damages (1% lethality), (i.e. ½ LFL, see Table 4).

The comparison among the potentiality of Tilburg incident and the actual impact of the flash fire following the Viareggio derailment is reported in Figure 7. In particular, the moderate damages zones (corresponding to the extension of ½ LFL, see Table 4) for the four cases are represented by solid lines. Whereas, the actual Viareggio damage zone is drawn as the dashed circle in Figure 7. The radius of the Viareggio consequence represents the maximum damage distance from the release point experienced in the accident (see (Landucci et al., 2011) for more details).

As shown in Figure 7, the foreseen flash fire extension for the actual release scenario (case A) is quite limited as expected, being about 3.7 times lower than the maximum extension of a Viareggio damage zone. Moreover, the potential damage zone of case A does not affect the surrounding residential areas, as already evaluated for the worst-case scenario (see Figures 5a and 6a).

However, quite good agreement exists in the maximum extension of flash fire damages with the simulation of the same release type ("Viareggio type" release in case D). On one side, this denotes the reliability of conventional approaches for consequence assessment based on integral models, despite the relevant simplifications related to the lack of obstacle considerations. The reader is referred to (Hanna et al., 2009; Pontiggia et al., 2011, 2009) for a more comprehensive examination of integral models and their performance in presence of obstacles on large scale geometries. On the other side, the commonly adopted release schematization of the accident scenarios (in particular, the Purple Book approach adopted for transportation risk assessment in the Netherlands (Uijt de Haag and Ale, 2005)) induces a more limited severity for the specific scenario under concern. In particular, the flash fire radius in case D is 1.8 and 1.5 higher than the one of cases B and C, respectively. The discrepancy of the results of cases D and C may be due to the schematization of the dispersion model, which is different between a large, but finite, release section (case D) and an instantaneous release (case C).

Nevertheless, in the severe release scenarios (cases B, C and D), the flash fires resulted in an extensive impact on the residential area. This highlights the criticality of hazardous materials transport across populated areas due to the relevant severity of the potential scenarios. Hence, the results underline the relevant need to evaluate the current status of land use planning around transport lines.

4.2 Lessons learned

4.2.1 Prevention and mitigation strategies: some reflections

The findings of the consequence assessment reflect what basically is already known for years: that there are scenarios that can cause serious havoc and even more important, casualties when they take place. Up to now, it was unknown how large the effects could have been in the Tilburg case. However, it is an illusion that urban areas can or should be changed overnight. This will not happen in our lifetime and perhaps also not over a century and is very costly and not cost-effective (van der

Vlies, 2011). This however does not mean that further risk mitigation strategies, aimed at prevention of disasters, should not be implemented. And there are examples in practice that aim to do so. As discussed by (Liu et al., 2013), the combined adoption of tank car safety design improvement, such as improved control systems, upgrading track infrastructure, routing, and improving emergency response practices may contribute with interacting effects to the overall shipment risk reduction.

In order to systematically address the possible mitigation strategies aimed at preventing events such as the ones in Tilburg and Viareggio, Landucci et al. (2017) developed a bow-tie analysis in which relevant safety barriers are identified and their qualitative performance assessment is provided. The bow-tie was elaborated and updated in order to analyse the Tilburg case, as shown in Figure 8. The numbered arrows present the relations between causes and final consequences. Safety measures can act as a line of defence and interrupt the accident chain. The chain of events associated with the Tilburg case is shown in red colour and the effectiveness of the barriers is shown in Table 5 with a qualitative scale. Security-related scenarios, i.e., associated with external intentional attacks to the tank car, are excluded.

From the analysis Figure 8 and Table 5 it can be concluded that the improved automatic control system (providing an emergency stop of the train) is a good measure to reduce the probability of the release events following the train collision, although not giving full protection. Similarly, improved training, maintenance and inspection combined with specific safety management plans would be effective although not giving full protection.

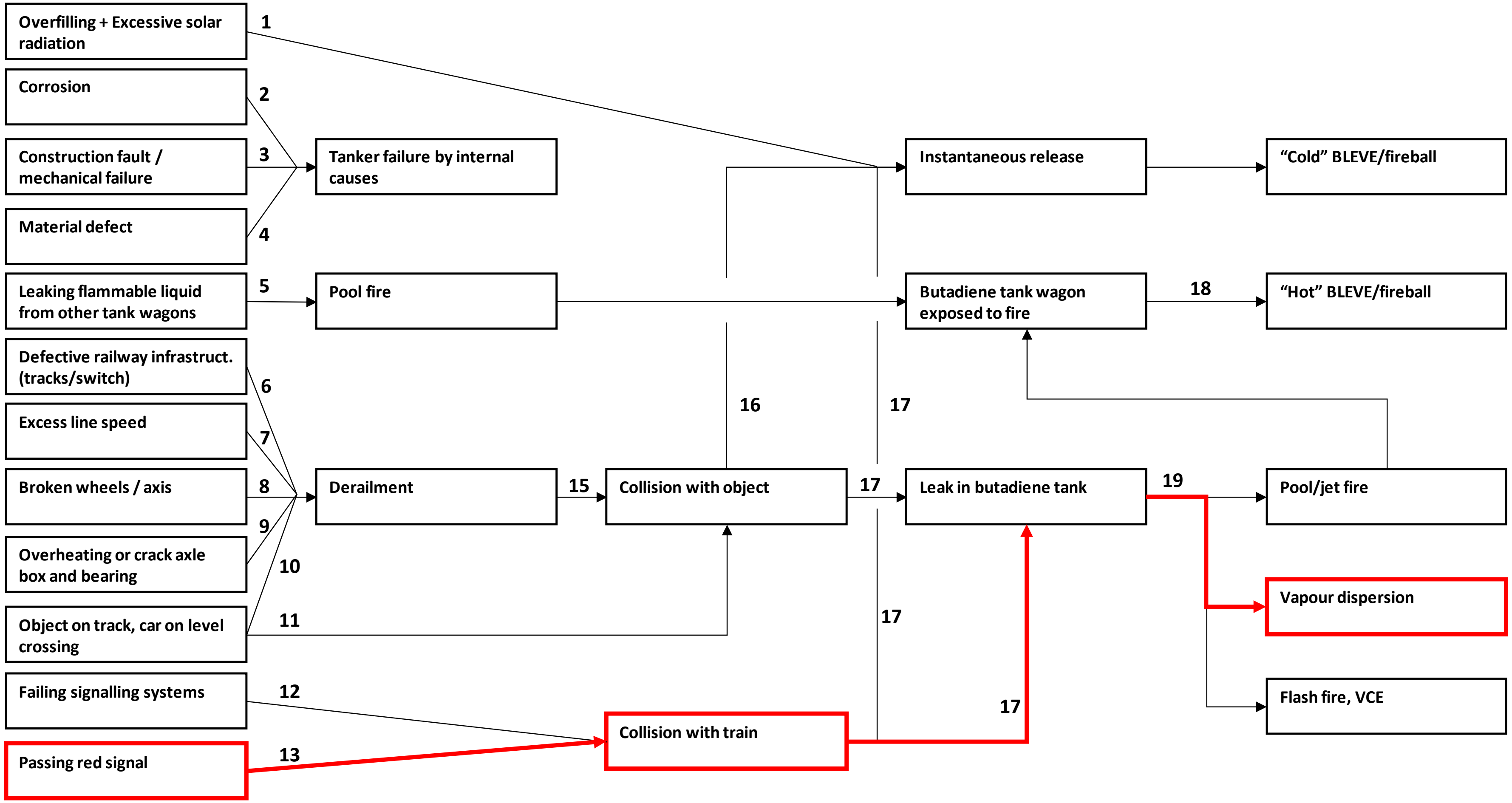


Figure 8. Integrated bow tie diagram for an accident involving a butadiene tank car. The red bold line highlights the development of the Tilburg incident. Adapted from (Landucci et al., 2017).

Table 5. Qualitative performance assessment of safety barriers that may act as a line of defence for Tilburg-type accidents. Number under "line of defence" refers to barrier position in Figure 8. Adapted from (Landucci et al., 2017).

Measure	Line of defence	Vapour disp.	Flash fire, VCE	Jet/pool fire	"Hot" BLEVE	"Cold" BLEVE
Overfill protection	**1**					+++
Pressure relief valve	**1, 18**				+	+++
Enhanced "Hot box" detection systems	**8, 9**	+	+	+	+	+
Control systems for brakes wagon	**8, 9**	+	+	+	+	+
Crash elements tank wagons flammable gasses and liquids	**5, 17**	+	+	+	+	++
Improve side impact resistance wagon, head shields on wagon	**5, 17**	+	+	+	+	++
Over-buffering/end impact resistance tank wagons flammables	**5, 17**	+	+	+	+	++
Complete thermal protection	**18**				+++	
Segregation flammable liquid wagons and flammable gas wagons	**14**				++	
Remove sharp rigid objects along railway track	**15**	++	++	++	+	+
Avoid level crossings	**10, 11**	+	+	+	+	+
Derailment detection + emergency stop	**11**	++	++	++	++	++
Improved automatic control system	**13**	+	+	+		+
Improved training of train engineer	**7, 13**	+	+	+		+
Maintenance and inspection	**1-15**	+	+	+	+	+
Additional checks during periodic inspection	**1-15**	+	+	+	+	+
Safety management system	**1-15**	+	+	+	+	+
Post-release mitigation actions (walls, spray curtains, etc.)	**19**	++	++	+		

After the incident in Tilburg, the enhanced version of the automatic train protection system *ATBvv* was installed, for example (see Section 2.1.1 for more details on *ATBvv*). Also, the safety region (*Veiligheidsregio*, the administrative body responsible for fire brigades) conducted several studies to review how well they are prepared for these types of scenarios. As stated before, not as a result of the incident, the Dutch government is looking at creating a more effect-based policy. These are just a couple of examples of what is done at different levels of government to prevent the worst case scenarios. Safety however is not the same as certainty and although the transport of hazardous materials is safe due to all the measures that are taken to prevent accidents from happening, one cannot guarantee that the worst case scenario will never happen, as emerges from the analysis of Figure 8.

4.2.2 Policy making considerations

After the DSB completed its accident investigation, policy responses focused exclusively on improvements in chemical transport by rail, see (Dutch Safety Board, 2016; Ministry of Infrastructure and Environment, 2017, 2016) and the response of the private companies involved to the Dutch Safety Board (Prorail, 2017). This is a logical result of the type of accident investigation: a mandatory legal requirement in the Netherlands after all rail incidents is that the railway safety experts of the DSB conduct a formal investigation that logically focuses on railway safety, taking into account that extra precautions are warranted for chemical transport. In case the incident would have damaged its environment, a much wider investigation scope would probably have applied (see (Elliott and Mcguinness, 2002) for the logic of investigation and inquiry assignments).

The DSB's recommendations did not explicitly consider the potential implications of the accident for the surrounding residential environment, neither did the follow up by policy makers and private actors responsible for transportation. In their responses, the responsible authorities and private actors point at the problems of international coordination (for instance the Dutch authorities cannot oblige international partners to ensure that the last wagon of a chemical transport does not carry hazardous materials) and the limits of voluntary network cooperation (Ministry of Infrastructure and Environment, 2016; Prorail, 2017). The safety region of Midden-West Brabant has developed considerable capacity and expertise to fight chemical industrial accidents and provide the emergency response should such an incident occur (Anteagroup, 2015).

The safety region's risk assessment report of 2015, a public communication tool to inform citizens about the safety risks present in their living environment, pays attention to chemical-industrial incidents as one of its main seven categories. It does not specify risks induced by rail transportation because the emphasis of its assessment is on the consequences not the causes (Anteagroup, 2015). Yet many residential building blocks and several primary schools are located in the immediate vicinity of the Tilburg railway tracks (< 250 m, see (Risicokaart, 2019)). However, the authority for urban planning is not a safety region competence but a local political matter, confined by national and provincial legislation.

Political and policy making rationales do not align well with risk analysis rationales (Terry, 1998). The abstract possibility of an incident (an uncertain loss) needs to be weighed against the certain gains of building in the city centre, and efficiently and cost-effectively transporting essential (though hazardous) goods between Europe's industrial hubs, such as the German Ruhrgebiet and the port of Rotterdam. Prospect theory and the negativity bias in politics instruct us that decisions that affect voters negatively outweigh decisions to safeguard or provide a public good (Weaver, 1986; Tversky and Kahneman, 1981; Vis, 2011). There is no doubt that a real incident such as the

Viareggio disaster affects the lives of local residents as well as their political representatives. Near-misses such as in Tilburg do not result in radical policy and political changes, probably because such changes imply unpopular regulations and restrictions in the short-term, weighed against the more abstract gains in terms of future safety. However, over the years, near misses seem to have changed public risk perception and media coverage, instigating debate about whether intensifying areas adjacent to railroads can be done in a safe manner in a densely urbanized country such as the Netherlands.

In recent years a transition occurred from a risk-based policy, which was documented in previous building regulation (Bouwbesluit, 2012) and well-known in the scientific community (Pasman and Reniers, 2014), towards a more effect-based policy, with -in some cases- legally mandatory safety measures to buildings (RIVM, 2019). However, these mandatory dispositions are only meant for newly built situations and not to all the buildings in the Netherlands currently at risk.

5. Conclusions

The study analysed the incident that occurred in Tilburg in 2015, in order to assess what could have happened on the surrounding environment if the near-miss had led to a large loss of containment. The work aimed at supporting a critical discussion on the current policy making process on the risk assessment of HazMat transportation. Moreover, a critical reflection on the recent transition from a risk-based policy towards an effect-based policy in the Netherlands and implications on building safety was carried out.

To give a tangible view of Tilburg's possible consequences, the impact of the credible accidental scenarios following the collision was estimated, mapping the results on the urban area surrounding the incident location. Moreover, the comparison with the flash fire event that occurred in Viareggio (2009) was also provided, obtaining similar potential impact. This comprehensive assessment highlighted a relevant risk posed by the incident to the civil installations in the surrounding, leading to a main critical observation on the current policy making process of the risk assessment in the HazMat transportation field. Namely, the need of consider the potential impact of possible incidents on the surrounding environment before a real accident, such as the Viareggio disaster, affects the population at risk. In fact, after the Tilburg near-miss event, policy makers responsible for transportation only considered the improvement of the railway safety. Despite these measures may be effective in achieving relevant risk reduction, as discussed in the present study, the latter can be further strengthened by systematizing a consequence-based approach for the land use planning.

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Appendix A – Consequence assessment set-up

A.1 Identification of LOCs

As reported in Section 2.2.1, the investigation on the damaged wagon resulted in the quantification of the real extension of leakage area. In particular, two relevant parameters were measured during the investigation, namely: the length of the manhole cover from where the loss occurred and the separation distance between the cover and the flange. For the definition of the actual LOC (case A), the leak width was conservatively assumed equal to the maximum measured distance between the cover and the flange, which was recorded at 2.3 mm. Then, the overall perimeter of the leak was estimated summing the lengths of the leakage zones (see Figure 1b). Assuming a standard manhole of DN500 (FFB, 2018; GBRX, 2018), the sum of the lengths resulted in an overall leak extension of approximately 0.44 m. Finally, the width was multiplied by the perimeter obtaining a leakage area of $1.0 \cdot 10^{-3}$ m^2 (about 36 mm of equivalent diameter). For the Viareggio type rupture, case D, data reported in (Landucci et al., 2011) were assumed as reference geometry for case D in Table 1. The other release sections, i.e., cases B and C, were based on literature indications (Uijt de Haag and Ale, 2005).

A.2 Meteorological conditions

As reported in Section 2.2.1, F/2 and D/5 conditions were taken as reference meteorological conditions for the modelling of physical effects. The letter indicates the Pasquill-Giffort atmospheric stability class (Mannan, 2004), while the number indicates the wind speed in m/s at 10m. Solar radiation and ambient temperature were evaluated through a statistical analysis of past-meteorological conditions in the Netherlands during March. The maximum expected value was set for the solar radiation according to data reported in (Committee for the Prevention of Disasters, 1992). Whereas, the average value recorded from 2009 to 2018 was taken into account for the temperature (KNMI, 2018). The surface roughness length was set according to the guideline of "Purple Book", for the terrain surrounding the railway (Uijt de Haag and Ale, 2005). Table 2 summarizes the meteorological set-up of the present analysis.

A.3 Definition of substances and storage conditions

The tank wagon involved in the Tilburg incident was storing butadiene (Dutch Safety Board, 2016). Butadiene is a flammable substance, gaseous in atmospheric conditions, usually transported as liquefied gas under pressure. It is harmful if inhaled due to its acute inhalation toxicity. An Immediately Dangerous to Life or Health Concentrations (IDLH) can be defined for the butadiene based strictly on safety considerations (CDC, 2018). Lethal concentration (LC) data for human were extrapolated, from the available data for animals (CDC, 2018), through the procedure reported in the guidelines from (Committee for the Prevention of Disasters, 1992). Table A.1 reports the relevant properties of the butadiene implemented in the models for the consequences assessment.

Table A.1. Properties of butadiene implemented in the study.

Property	Unit	Value	Reference
Composition		pure 1,3-butadiene	-
Liquid density	kg/m^3	639	(DNV GL, 2017)
Storage temperature (S.T.)	°C	6.1	(DNV GL, 2017)
Saturation Pressure at S.T.	bar	1.49	(DNV GL, 2017)
LFL	% v/v	2	(DNV GL, 2017)
IDLH	ppm	2,000	(CDC, 2018)
LC50 (human)	ppm	220,308	(CDC, 2018)

Appendix B – Detailed results of the consequence assessment

The estimated damage distances for all the Tilburg case studies are discussed in the following. Vulnerability assessment was based on the threshold values reported in Table 4. Results of the human vulnerability assessment are given in Table B.1, whilst Table B.2 reports the results obtained for the buildings vulnerability assessment. Results are given with respect to the reference weather conditions (F/2 and D/5). Scenarios not mentioned in the Tables have been excluded by the ETA, for the given release scenario.

Table B.1. Human vulnerability assessment expressed by probability of death (%). Damage distances (m) of the four considered case studies: A - Actual scenario; B - Literature scenario, continuous release; C - Literature scenario, catastrophic release; D - Viareggio type rupture; n.a. = not applicable; n.r. = not reached.

Weather condition	**Vulnerability (%)**	**Damage distance (m) for each individual scenario**					
		Pool fire	**VCE**	**Jet Fire**	**Flash fire**	**Fireball**	**Dispersion**
Case study A							
F/2	0.1	126	106	64	n.a.	-	51
	1.0	113	92	60	79	-	37
	10	101	84	55	54	-	n.r.
D/5	0.1	109	76	57	n.a.	-	n.r.
	1.0	99	62	53	42	-	n.r.
	10	89	54	49	14	-	n.r.
Case study B							
F/2	0.1	226	188	126	n.a.	-	106
	1.0	202	173	117	157	-	86
	10	178	164	109	114	-	58
D/5	0.1	202	128	113	n.a.	-	58
	1.0	182	113	104	90	-	45
	10	162	104	96	60	-	25
Case study C							
F/2	0.1	356	227	-	n.a.	247	142
	1.0	315	213	-	193	214	123
	10	274	204	-	145	182	98
D/5	0.1	358	217	-	n.a.	247	139
	1.0	320	203	-	194	214	117
	10	281	194	-	142	182	93
Case study D							
F/2	0.1	303	296	227	n.a.	-	187
	1.0	270	282	210	267	-	156
	10	238	274	195	200	-	114
D/5	0.1	285	186	204	n.a.	-	107
	1.0	256	172	188	159	-	87
	10	228	164	172	110	-	61

Table B.2. Building vulnerability assessment. Damage distances (m) of the four considered case studies: A - Actual scenario; B - Literature scenario, continuous release; C - Literature scenario, catastrophic release; D - Viareggio type rupture.

Weather condition	**Type of damage**	**Damage distance (m) for each individual scenario**		
		Pool fire	**VCE**	**Jet Fire**
Case study A				
F/2	Moderate	196	44	87
	Severe	89	28	52
D/5	Moderate	159	44	80
	Severe	80	28	45
Case study B				
F/2	Moderate	333	46	172
	Severe	157	29	101
D/5	Moderate	303	46	158
	Severe	146	29	89
Case study C				
F/2	Moderate	569	46	-
	Severe	239	29	-
D/5	Moderate	555	46	-
	Severe	251	29	-
Case study D				
F/2	Moderate	473	44	310
	Severe	209	28	181
D/5	Moderate	431	44	287
	Severe	205	28	159