

Towards updated crashworthiness guidelines for safe transport of hazardous cargo on inland waterways

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ABSTRACT: Design and operation of inland waterway ships carrying dangerous goods are governed by the European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways (ADN). In order to limit the risk of transporting these goods, the tank size of an individual cargo tank is limited at 380 m³. Larger tanks up to 1000 m³ are allowed when the consequence of a larger leak after a collision is compensated by a lower probability of a spill by improved crashworthiness of the ship structure. The guidelines on additional crashworthiness were introduced in 2005 and based on the knowledge and state-of-the-art at that time but have at some points become outdated. This paper presents the main findings and conclusions of a study addressing the state-of-the-art in three categories and proposes several updates. Firstly, the available collision energy on the European inland waterways was determined based on ship passages at Lobith showing that on average inland waterway vessels have increased in size and mass over the past 20 years. Secondly, a parameter study using explicit FEA was carried out to investigate the effect of assumptions in the crashworthiness calculations on the energy absorbing capacity of the vessel and a proposal for a more robust calculation method is made. Finally, an investigation on the affected area in case of a tank breach for various substances during a collision was carried out, showing that areas beyond the riverbanks might also be affected when tanks become larger than 1000 m³, depending on the cargo that is transported.

1 INTRODUCTION

Transport of dangerous goods over inland waters is governed by ADN rules (ECE, 2021). With respect to chemicals and gases, the size limit per tank is set to 380 m³ and the minimum required ship structure to ensure sufficient crashworthiness is prescribed. Following the rules, it is commonly and tacitly accepted, a collision will not result in unacceptable consequences for people, asset and environment.

In 2005, ADN Section 9.3.4 came into force allowing individual tanks to exceed a capacity of 380 m³. Alternative designs for improved crashworthiness are required to compensate for the larger consequence of a spill. Using the concept of risk equals probability times consequence, increasing the tank size (and hence consequence of a spill after rupture) must be compensated by reducing the probability of a rupture

by improved crashworthiness. Since then numerous ships have entered service using ADN 9.3.4.

Over a period of 20 years, the probability of a collision and the analysis of the effect of a collision have changed. Experience has been gained in the design and analysis process. Engineering and review by class showed that not all parts of the rules were laid out unambiguously, especially with regards to details of the structural calculations. Almost 20 years after the introduction of ADN Section 9.3.4, shipping and shipbuilding have developed. Other goods are to be transported, including the alternative fuels for the energy transition, larger ships, more traffic, alternative materials and developments of the software were no longer to be ignored. And finally, the industry looks continuously at reducing cost of transport. Tanks exceeding 1000 m³ may be interesting to reduce building weight and cost, as well as operational cost.

These three aspects also cover the core of the Quantitative Risk Assessment (QRA). Probability and consequence are to be calculated in order to find the risk of a certain operation. A consequence is considered less acceptable at increasing amount of casualties, cost or environmental damage. Same for probability: the likelier an event, the less acceptable. When both consequence and probability are too high, mitigation measures are to be taken to reduce either or both the effect and likelihood. This approach to risk is as relevant for transport of dangerous goods as it is for the use of alternative, and mainly more dangerous, fuels.

A project was undertaken to update ADN 9.3.4 on the three aspects: update of the available energy on the river (probability of collision), the structural calculation method (probability of rupture of tank after a collision) and the effect of a spill, also for tanks exceeding 1000 m³ (consequence). A group of ship owners, shipyards, class societies, engineering companies, a tank provider and research institute TNO joined forces to provide state of the art information for updating section 9.3.4 of ADN.

First, collision energy statistics are updated. The 2005 amendment was based on 1998 data, and 20 years later it is clear the amount of shipping, as well as the size of individual ships and push barge combinations has increased. Section 2 is dedicated to explaining the background of the current data and how it is used to update the representation of the available energy on the river. The differences are explained, and how they affect the analysis.

Second, with the partnering engineering companies, a series of FE calculations have been performed in order to formulate the challenges of a reliable crashworthiness analysis, as presented in Section 3. The challenges reported here are focused on scenario choices, i.e. the striking location and angle, and on an inland waterway tanker with independent gas tanks. Effects are discussed and an alternative method is proposed to calculate crashworthiness in case of a model containing both a complicated ship structure and an independent tank.

Third, as presented in Section 4 the effect of a spill after rupture of a tank has been recalculated for tank sizes and substances codified in 2005, as well as for larger tanks and for the “new” substances propane, methane and ammonia. It is shown that the original relation between spill and affected area still holds. The effect of a spill from a tank larger than 1000 m³ is concerning in the view of the authors, as will be discussed.

Conclusions and recommendations are given as summary of the paper.

2 COLLISION ENERGY STATISTICS

Recent data of ship passages at Lobith is available (through the Dutch Waterway Authorities “Rijkswaterstaat”) and is used to reconsider the cumulative

probability density functions (cpdf) of the dissipated energy at a collision. The data contains the draft of the ship as well as the CEMT class for each passage.

The update of the distribution of the dissipated energy for a given collision (assuming a probability of 1) is based on the following assumptions: the collision is fully inelastic, each vessel has a block coefficient of 0.9, the added mass is included in the DWT (deadweight tonnage) and is 10% of the displacement and the struck vessel has zero speed. Furthermore, the data of 2017 is considered representative for traffic in the coming years, because 2017, in contrast to later years, was a considerably good year for inland waterway shipping. Later years were all characterized by a reduction of the transported tonnes per year due to external effects. 2018 and 2019 were characterized by a reduction due to low waterlevels (Binnenvaartcijfers, 2020) and 2020 and 2021 by changes in the cargo demand due to the CoViD-19 pandemic (CCR, 2021). For the long term (>10 years), the data from 2017 is expected to provide a good estimate of traffic intensity when compared to the long-term prognosis by the CPB (Manders and Cool, 2015). Next to that it is assumed that the traffic data of passages at Lobith provides a conservative estimate of the distribution of traffic in the European inland waterways, considering it includes the traffic over the Rhine and Waal combined.

The dissipated energy E_{diss} in [J] for a fully inelastic collision between a striking vessel with a finite, non-zero speed $v_{striking}$ in [m/s] and mass $m_{striking}$ in [kg] and a struck vessel with zero Speed Through Water (STW) and mass m_{struck} in [kg] is expressed in Equation 1, corresponding to ADN 9.3.4 (ECE, 2021).

$$E_{diss} = \frac{1}{2} m_{striking} v_{striking}^2 \left(\frac{m_{struck}}{m_{striking} + m_{struck}} \right) \quad (1)$$

Each of the parameters of the striking vessel is discussed below. The mass of the struck vessel is an input parameter.

2.1 Speed of the striking vessel

The speed of the striking vessel is based on the reported achievable speed of each CEMT (Conférence Européenne des Ministres de Transport) class for deep water (≥ 5 m) as is reported by the German Bundesanstalt für Wasserbau (BAW, 2016). The reported achievable speed is listed for navigation on the Rhine river and other canals in Western Germany. The maximum achievable speed of a vessel indicates the STW, by which data on the current is not needed for the analysis.

2.2 Mass of the striking vessel

The data of passages at Lobith reports the CEMT class for approximately 10% of the passages and the draft for all passages. This means that 90% of the CEMT class attributions is unknown. A comparison

is made to other data sources to justify the extrapolation of 10% of the data to 100%. Rijkswaterstaat (RWS) has made a prognosis (Rijkswaterstaat, 2013) of the future demand for berths for each CEMT class at Lobith for 2020, next to reporting the known demands in 2012. This is shown in Figure 1, where the contribution of most of the bins above a kinetic energy of 42 MJ is higher for the analysis based on the 2017 data than listed in the RWS prognosis. It can be concluded that the data from 2017 with individual passages assumed a larger contribution of high-energy encounters by which the analysis based on the 2017 data is conservative.

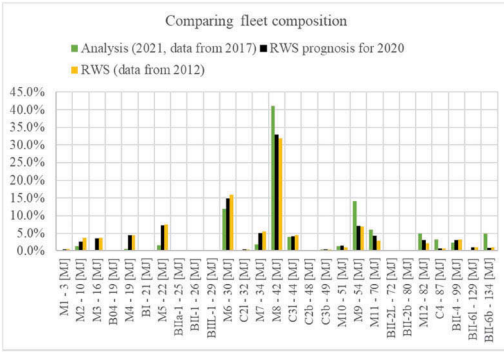


Figure 1. Comparison of the fleet composition over the CEMT classes, ordered from low kinetic energy to high kinetic energy.

The draft of each passage is used to calculate the DWT of the ship when passing Lobith. The database contains an excessive amount of ships with an unrealistically small draft of 0.99 m. This data has been replaced by the maximum draft of inland water transport of the corresponding CEMT classes, which is 3 m (BAW, 2016). The corresponding distribution of the displacements is presented in Figure 2.

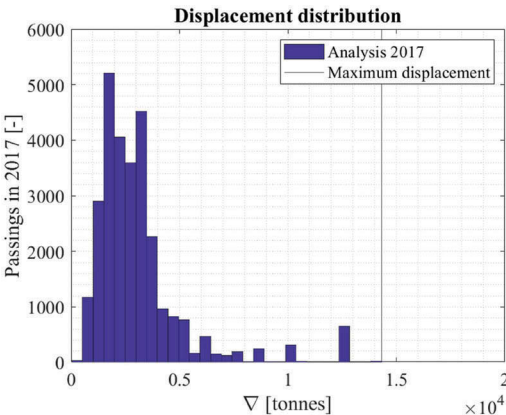


Figure 2. Displacement distribution (excl. 10% added mass).

2.3 Updated energy statistics

Figure 3 presents the resulting updated cumulative probability results, indicating the probability of exceeding the dissipated energy indicated by the bin. The results in Figure 3 are presented for a collision speed equal to the characteristic speed of the vessel, as obtained from the BAW (2016) documentation. Scaling towards lower collision velocities can be done using the relation in Equation 1, indicating the quadratic relation of the speed of the striking vessel with the dissipated energy.

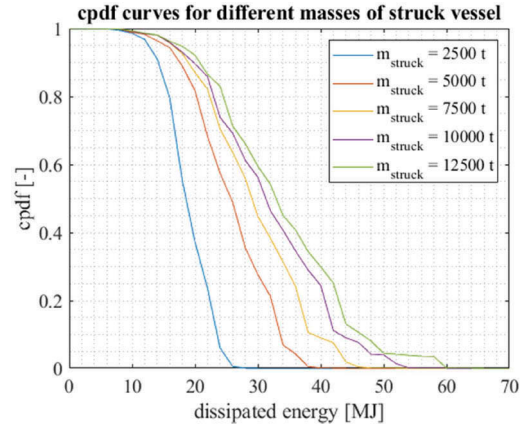


Figure 3. Cpdf curves for a preset mass of the struck vessel. The striking vessel is sailing at 100% of the attainable speed.

2.4 Comparison to ADN 9.3.4

The approach in the current ADN regulations (ECE, 2021) differs from the newly proposed numbers on the following parts:

- *Speed of striking vessel:* This is based on maximum attainable speed for each vessel type in contrast to the trial speed as a function of the displacement that was used.
- *Mass of striking vessel:* This is based on the number of passages per deadweight class (divided in 8 bins) accounting for up and downstream traffic combined in contrast to the use of wide-binned outdated data. Figure 4 shows the increase in the contribution of high DWT vessels in the fleet, as well as the increase in total passages at Lobith.
- *cpdf presentation:* The cpdf curves are reported using the actual discretised data in contrast to a 3rd order fitted polynomial.

In Figure 5, the cpdf curve for a struck vessel of 8000 tonne following the presented analysis is compared to the curve from the current ADN 9.3.4. Figure 5 shows that both the maximum energy and the shape of the distribution has changed. The updated analysis accounts for the actual discretised mass and speed distributions, which does not justify a fitted curve as was done for the current ADN.

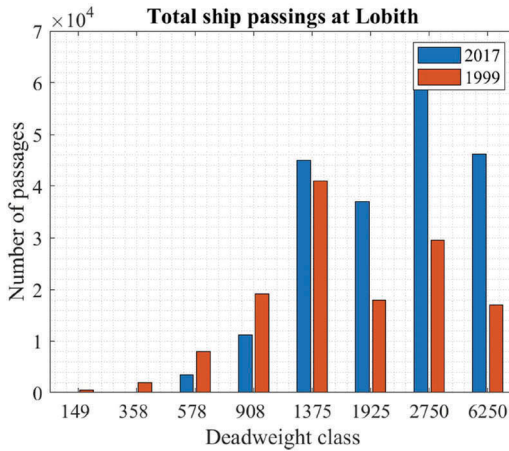


Figure 4. DWT classes with the ADN data (based on 1999) and the updated statistics from 2017. Bins are conform the ADN.

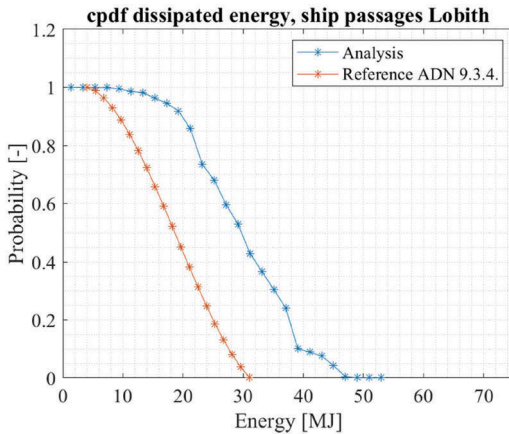


Figure 5. Cpdf comparison of the reported dissipated energy in the ADN and based on the novel analysis for a struck vessel with a mass of 8000 tonne.

2.5 Implications of updated energy statistics for inland vessel design

The results of the analysis are deliberately conservative, i.e. overestimate the dissipated energy by applying (i) the maximum attainable vessel speed to the striking vessel, (ii) assuming an inelastic collision and (iii) basing the fleet composition (CEMT classes) on 10% of the data and justifying this by its conservative nature compared to other data sources. The probability of being struck at an energy level exceeding the crashworthiness level of the vessel has increased compared to 2005. Consequently, halving the probability of exceeding the crashworthiness limit, will require more structural reinforcement compared to the current ADN 9.3.4.

3 CRASHWORTHINESS ANALYSIS

Once the probability of a collision with a certain amount of collision energy has been determined, the next step is to determine the probability of tank rupture given this collision. To determine the probability of tank rupture, the energy absorbing capacity before tank rupture of the struck vessel is calculated by means of an FE crash analysis following the guidelines in ADN Section 9.3.4 (ECE, 2021). In the analysis, the struck vessel is fixed in place and the striking bow is assumed to be rigid moving with a prescribed velocity of 10 m/s such that runtime are short, but the results are still quasi-static.

Various aspects on how to model the structure and analyse the energy absorbing capacity have been prescribed in the ADN regulations (ECE, 2021). However, the effect of some modelling choices have shown in the past to result in large differences in the energy absorbing capacity until tank rupture during collision. One scenario, the perpendicular impact with a V-bow vessel in between two webs, is investigated more closely. Figure 6 shows the FE model including the striking V-bow that was used in the calculations. The model represents a typical inland waterway vessel with scantlings as prescribed by the ADN regulations. The structure is made of Grade A shipbuilding steel for which the material model and failure criterion are given in the ADN regulations. The model consists of 4-noded quadrilateral shell elements and the analyses have been done in LS DYNA r12.



Figure 6. FE model for crash analysis.

A parameter study has been carried out in order to investigate a range of parameters: friction coefficient, plasticity model, striking angle, striking location, tank pressure, failure criterion, mesh size and separating the analysis in two steps. For brevity, this paper focuses on the striking angle, striking location and a two-step analysis separating the analysis of tank rupture and the analysis of the corresponding energy absorbing capacity of the ship structure in the following sections.

3.1 Striking angle

The ADN regulations prescribe an impact perpendicular to the ship's side shell (i.e. at a 90 degree

angle). A set of 5 analyses was performed to study the effect of small variations in impact angle on the energy absorbing capacity of the ship structure: at 88, 89, 90, 91 and 92 degrees.

The resulting energy absorbing capacity is shown in Figure 7. First of all, it can be observed that for this specific scenario, a small variation in impact angle has a negligible influence on the energy absorbed by the ship structure for a given indentation. However, when looking at the moment of tank rupture (the black lines), significant differences are observed. And as a consequence, significant differences are found in the total absorbed energy until tank rupture. As can be seen, in this case, the current ADN guidelines resulted in the largest indentation until tank rupture and all variations showed a lower or equal indentation until tank rupture indicating that, in this case, the current ADN guidelines are non-conservative.

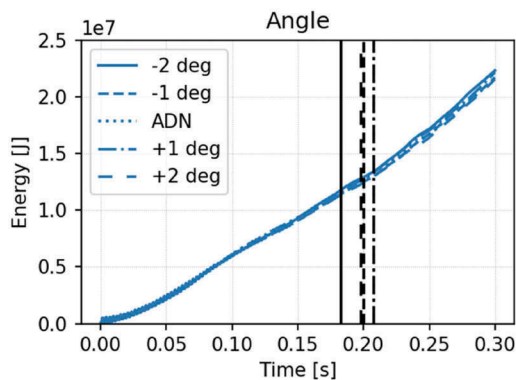


Figure 7. Effect of small variations in the impact angle of the striking bow on the energy absorbing capacity. The vertical line indicating failure.

In order to investigate the sensitivity to the striking angle in more detail, reference is made to the amount of damage observed in the ship structure at an indentation of 1.0m, as shown in Figures 8 and 9. While all analyses result in a comparable energy absorbed by the ship structure for a given indentation, the corresponding deformation mechanisms by which this energy is absorbed show a crack starting in different locations depending on the impact angle.

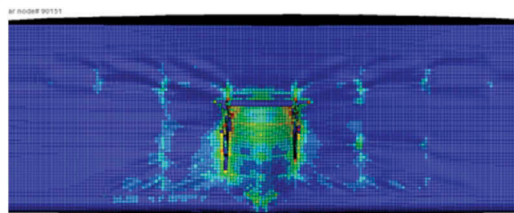


Figure 8. Impact angle variation: 88 deg; Damage, front view, 1.0m indentation.

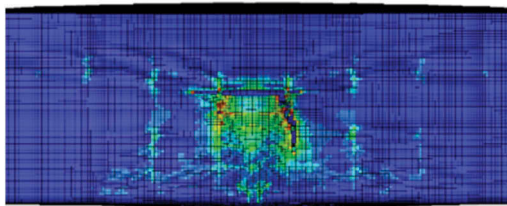


Figure 9. Impact angle variation: 90 deg; Damage, front view, 1.0m indentation.

This is most likely an effect of the numerical discretisation of the structure and how that affects the interaction between the damaged ship structure and the tank. As a consequence, the impact of the ship structure onto the tank will be different for each different striking angle resulting in a different indentation for tank rupture.

3.2 Striking location

In the finite element analyses used to determine the energy absorbing capacity, the ship structure and the striking bow are both discretised in quadrilateral elements. As a consequence, the contact between the striking bow and the ship structure is influenced by the discretisation chosen by the analyst.

Firstly, in order to investigate this effect in longitudinal direction, two cases were analysed: (i) the reference analysis where the mesh of the striking bow and the ship structure are aligned and (ii) an analysis where the striking bow has been shifted longitudinally by half an element (i.e. 50 mm).

Secondly, to investigate the effect of the striking location in vertical direction, the effect of an impact on the stringer is compared to an impact between two stringers. In this case, the reference analysis (i.e. on the stringer) is compared to an analysis where the striking bow has been shifted down by 290 mm such that the vertical section of the V-bow impacts the ship structure in between two stringers.

The resulting energy absorbing capacity is shown in Figure 10. First of all, it can be observed that for this specific scenario, a small variation in longitudinal impact location has a negligible influence on the energy absorbed by the ship structure for a given indentation, but a variation in vertical direction with an impact on or in between two stringers shows a significant difference. Furthermore, when looking at the absorbed energy until tank rupture (the black lines), similar to the variations in impact angle, significant differences are observed.

When comparing the corresponding damage to the ship structure, it was shown that similar to the small variations in impact angle, a small longitudinal shift of the impact location might result in a different damage mechanism and, as a consequence, a different interaction between the damaged ship structure and the tank. As is to be expected, a variation in vertical

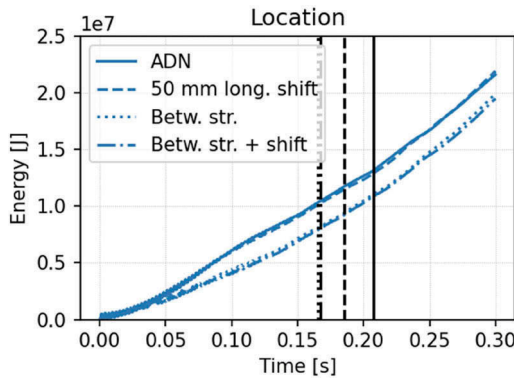


Figure 10. Effect of small variations in the impact location of the striking bow on the energy absorbing capacity.

direction with an impact on or between two stringers has a significant influence on the damage mechanism and subsequent interaction between the damaged ship structure and the tank.

3.3 Two-step analysis

The previous sections have shown that the indentation for tank rupture, and consequently the energy absorbing capacity of the ship structure, appear to be heavily influenced by the interaction between the damaged ship structure and the tank. An example result of the damaged ship structure following this interaction is shown in Figure 11, illustrating the complexity of this interaction, which is difficult to capture accurately in finite element analyses. As a result of element deletion, local pieces of structure remain, which subsequently impact the tank and influence tank rupture. In order to circumvent this challenge, a two-step approach is proposed:

1. Determine the indentation until tank rupture
2. Determine the energy absorbing capacity of the system at the indentation determined in step 1

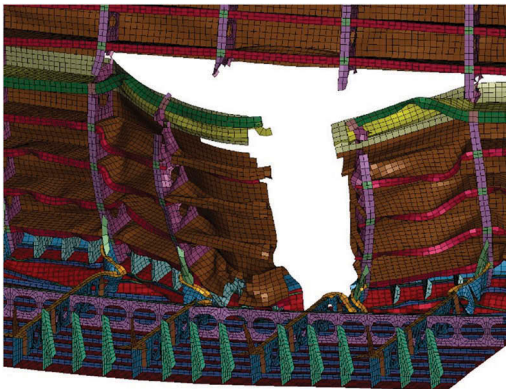


Figure 11. Example of a typical damaged and deformed ship structure after a crash analysis.

In order to determine the indentation until tank rupture, two scenarios are recognized: (i) the damaged structure folds away such that the striking bow directly impacts the tank and (ii) the ship structure is in between the striking bow and the tank. Therefore, the following analyses are proposed in step 1, as illustrated in Figure 12: (i) direct impact between the striking bow and the tank and (ii) impact without failure of the ship structure to avoid local pieces as a result of element deletion. Based on these results, an indentation until tank failure can be determined, after which an impact analysis including failure of the ship structure can be used to determine the corresponding energy absorbing capacity.

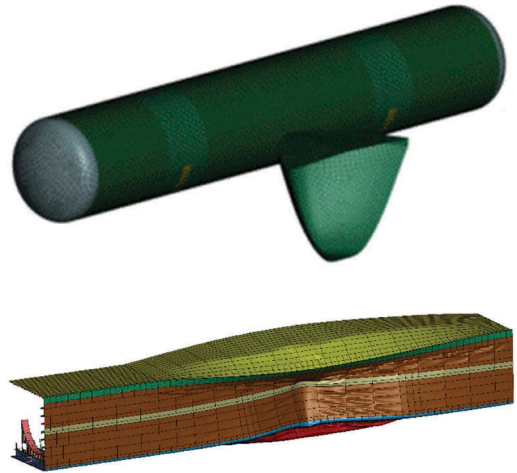


Figure 12. Direct impact (top) and impact without failure (bottom).

The resulting energy absorption vs indentation is shown in Figure 13. As can be seen, when applying a criterion based on a forming limit curve (FLC), as defined in the ADN regulations, no failure is observed in the tank for both the direct impact and the impact without failure of the ship structure at

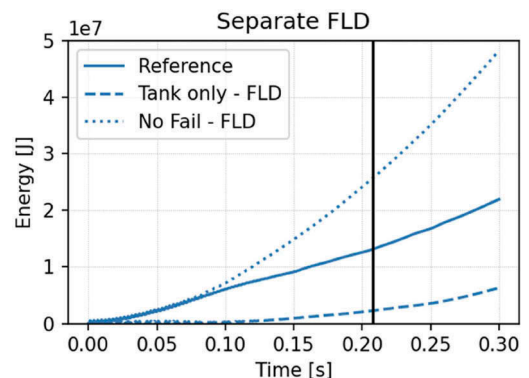


Figure 13. Separate analyses - Tank failure based on FLD. The vertical lines indicate the moment of tank rupture.

3.0 m indentation, while failure was observed in the reference analysis at 2.1 m.

This clearly indicates the importance of the interaction between the ship structure and the tank, but also shows that a more detailed investigation is required to better understand this interaction before this procedure can be applied in practice. However, once this interaction is better understood, the same approach could be applied to any tank or tank structure.

3.4 Discussion

Based on the parameter study that was carried out, the following main conclusions were drawn with respect to the impact angle, impact location and a potential two-step analysis of the energy absorbing capacity of the ship structure.

A small variation of the impact angle results in significant variations in the moment of tank rupture and, hence, the energy absorbing capacity of the ship. The energy absorption vs. indentation was nearly identical for all five variations of impact angle.

The study on striking location showed that a longitudinal shift of the location of first impact by half an element result in a significant difference in the moment of tank rupture, while the energy absorption vs. indentation was nearly identical. The effect of shifting the incoming bow so that it first impacts between two stringers, instead of directly on a stringer, showed less energy absorption and earlier tank rupture.

The results showed that the energy absorbing capacity of the ship is heavily influenced by the interaction between the damaged ship structure and the tank. A two-step approach separating the analysis of tank rupture from the analysis of energy absorption was proposed to address this challenge. An initial investigation of the proposed approach clearly indicated the importance of the interaction between the ship structure and the tank, but also showed that a more detailed investigation is required to better understand this interaction.

In conclusion, all results indicate the sensitivity of these analyses to variations in input and inherent uncertainties. Therefore, in order to address these challenges in the future, a probabilistic approach is proposed to explicitly account for these variations and uncertainties in the resulting output. By running more scenarios, the sensitivity to certain modelling choices can be quantified and accounted for in the overall probability of tank rupture.

Furthermore, all analyses currently assume a non-moving struck vessel and a striking vessel with a prescribed, constant speed, while in reality the external dynamics of both vessels will also affect the results and should be accounted for, especially in case of collisions away from midship.

4 CONSEQUENCE ANALYSIS

To complete the picture of the risks of transporting dangerous goods over water, the consequences of

a spill in terms of effect areas have been studied. Following up on work that had been done in a previous study underlying the current ADN 9.3.4 (ECE, 2021), effect calculations for larger tanks sizes for a set of relevant substances have been carried out.

The current ‘state of the art’ calculation model EFFECTS 11.5.1 (Gexcon, 2021) has been used to calculate the physical effects of outflow, pool evaporation, dispersion, and ignition of vapour clouds. These physical effects lead to consequences for people (lethality and injuries) due to toxic exposure, heat radiation, flame contact and blast effects from explosions. As a measure of the size of the effect areas, the areas of the contours that represent lethal effects for unprotected population that are greater than 1% are considered. Assumptions about scenario parameters such as released quantities, storage conditions, outflow durations, weather circumstances, etcetera are derived from (NIPV, 2021).

The chosen substances cover the whole range of possible consequence scenarios. Table 1 shows the list of substances that have been considered in this study and their properties in terms of storage condition and type of health effect.

Table 1. Overview of used substances with storage conditions (gas & liquid) and hazard (flammable & toxic).

Substance	Gas	Liquid	Flammable	Toxic
Benzene	x		x	x
Propane		x	x	
Methanol		x	x	x
Ammonia	x			x

4.1 Scenarios

The general scenario is that of a collision between ships, which causes a hole in a tank that contains the chemical substance. The hole is large and the liquid or gas that is in the tank flows out rapidly, or even violently if it is a pressurized gas. The liquid spills onto the water surface, forms a pool and starts to evaporate. If the chemical is flammable, it can be ignited immediately, causing a pool fire or jet fire, or delayed, which can cause a cloud fire or vapour cloud explosion. If the chemical is toxic, it may disperse and cause a gas cloud that can cause intoxication in an area downwind from the accident.

Table 2. Investigated substances and scenarios.

Substance	Pool fire	Cloud fire	Jet fire	Explosion	Toxic cloud
Benzene	x	x		x	x
Propane		x	x	x	
Methanol	x	x		x	
Ammonia					x

For methanol, cloud fires and explosions have been considered but these do not lead to the exceedance of the lethality threshold values. Ammonia is not very flammable and causes no significant fire risks.

The calculation model takes into account the following physical mechanisms:

1. Outflow (liquid or jet);
2. Pool evaporation;
3. Atmospheric dispersion;
4. Heat radiation (fire);
5. Explosion.

4.2 Assumptions

To be able to calculate the effects for each of the scenarios and effect mechanisms, a range of input parameters have to be defined. The most important ones are mentioned in this section.

4.2.1 Storage conditions and tank failure

In this study, the tanks containing the chemicals have volumes of 380, 650, 760, 880, and 1000, 2000, 3000 and 5000 m³. The chemicals are stored under ambient temperature. For ammonia and propane, the tanks have a pressure of 8.6 and 6.3 bars, respectively.

Similar to the studies that were carried out for the original inception of ADN 9.3.4, it is assumed that a collision causes a hole in the tank, with a circular shape, oriented in the vertical plane, the lower edge of which is assumed to be at the water line and at the bottom of the tank. This is conservative, because the tank bottom will most probably be below the water-line which reduces the outflow and related consequences. The considered hole size is 2 m².

Table 3. Environmental conditions.

Parameter	Value
Water temperature	9 °C
Air temperature	9 °C
Pasquill stability class	F
Wind speed	1.5 m/s
Solar irradiation	0 W/m ²
Roughness length	0.1 m

4.2.2 Threshold levels for toxicity, radiation, flame contact and overpressure

The toxicities and the explosion limits of the chemicals are listed in Table 4 and are based on different sources: the LEL (Lower Explosion Limit) values as well as the IDLH (Immediately Dangerous to Life and Health) values and the LC01 (Lethal Concentration for 1% of the population) value for ammonia are all taken from the DIPPR database which is a part of EFFECTS (Gexcon, 2021); the LC01 toxicity of benzene is from (Casal, 2007) and the LC01 toxicity of methanol is from (RIVM, 2021). Propane gas is not considered to be toxic.

Table 4. Toxicities and explosion limits.

Substance	LEL (ppm)	LEL (mg/m ³)	LC01 (ppm)	LC01 (mg/m ³)	IDLH (mg/m ³)
Benzene	12000	38975	3936	12784	1623.9
Propane	21000	38503			3850.3
Methanol	71800	95659	19209	23181	7993.8
Ammonia	150000	106220	2396	1696	212.4

For fires the consequences that should be considered are direct flame contact and heat radiation. It is assumed that direct flame contact will result in 100% lethality. Exposure to a heat load exceeding 35 kW/m² will result in 100% lethality. For lower heat loads the percentage of lethality depends on the exposure duration. Based on exposure duration of 20 seconds and excluding the protection of clothes a radiation heat load of 10 kW/m² will result in the maximum consequence distance (i.e. 1% lethality). Protection from clothes is not taken into account, which is a conservative assumption, especially when combined with Pasquill class F which occurs almost exclusively during night time.

For explosions, a threshold overpressure level of 100 mbar (0.1 bar) is used.

4.2.3 Other assumptions

In the analysis several conservative assumptions have been made.

The maximum pool size is chosen to be ‘unlimited’, while in reality it may be confined by riverbanks.

The moment of ignition of gas clouds is assumed/ chosen to be the moment where it results in the largest effect area, for a cloud fire, and the moment that it has the largest explosive mass for a vapour cloud explosion.

Concerning the strength of explosions, a major factor that determines this strength is the extent to which the cloud is in an environment that has obstacles that limit its expansion. This is governed by the so-called curve number. Considering the possibility that there may be some confinement from, for example, a bridge, curve number 4 is chosen.

4.3 Results

For brevity, only the results for benzene and propane are discussed in more detail, since they cover all scenarios. A summary of all results is presented based on which the conclusions are drawn.

4.3.1 Benzene

Benzene is a substance that is both flammable and toxic as a gas. Stored as a liquid under atmospheric pressure and temperature, it may form a burning (if ignited) or evaporating pool after loss of containment occurs and the generated vapour can become a flammable/explosive and toxic cloud.

Figure 14 shows the effect areas for all tank sizes, for the pool fire scenario. In this case the vessel is located in her sailing position and we see that, for this specific location representative of inland waterways in the Netherlands, for the tank sizes larger than 1000 m³ the radiation contours may reach the shore. This means that lethal effects may occur to the population on land, within the assumptions made in this analysis.

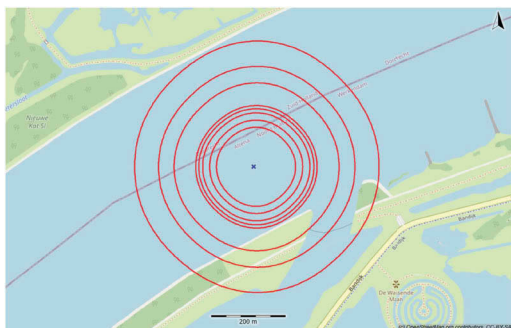


Figure 14. Benzene pool fire with 1% lethality radiation contours for all the tank sizes (from smallest to largest: 380, 650, 760, 880, 1000, 2000, 3000 and 5000 m³).

Similar calculations have been done for the cloud fire, explosion and toxic cloud scenarios. The results of all these calculations are summarized in Figure 15.

As already mentioned, the dimensions of these effect areas mean that the risks from heat radiation or toxic concentrations are not limited to people on board ships, but also the population on land may be exposed.

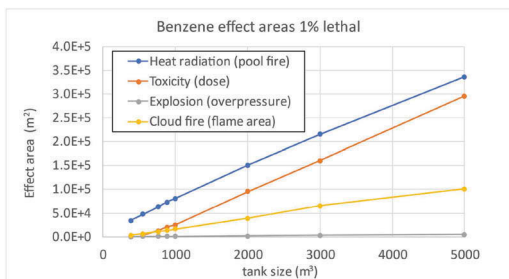


Figure 15. Benzene: effect areas (1% lethal) as a function of tank size.

4.3.2 Propane

Because propane is stored at atmospheric temperature under high pressure, a hole in a tank causes a violent outflow of gas. If the gas is ignited immediately, this causes a large jet fire. If the gas is ignited after the outflow has stopped, a cloud fire or vapour cloud explosion may occur. Figure 16 shows an example of the effect areas for these scenarios for a tank size of 1000 m³.

The combined results of all effect area computations for propane are shown in Figure 17. It shows that the

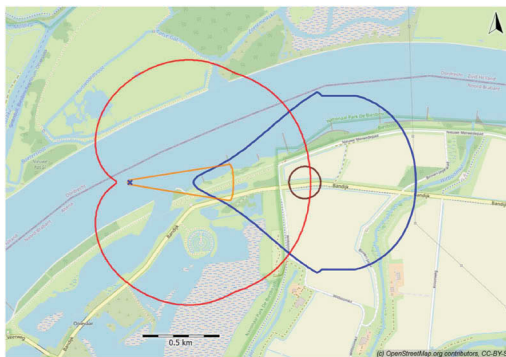


Figure 16. Propane effect areas for all considered scenarios, for tank size 1000 m³. The contour of the jet fire (flames) is shown in orange; the 1% lethality contour for heat radiation in red; the cloud fire contour (at maximum size) in blue and the 100 mbar explosion overpressure contour in brown.

effect areas are largest for the cloud fire scenarios. The effect areas for the jet fire scenarios for the tank sizes of 380 – 1000 m³ have been left out because the exposure times for those scenarios are less than 20 seconds.

The effect areas for the 100 mbar contours belonging to the vapour cloud explosions are relatively small.

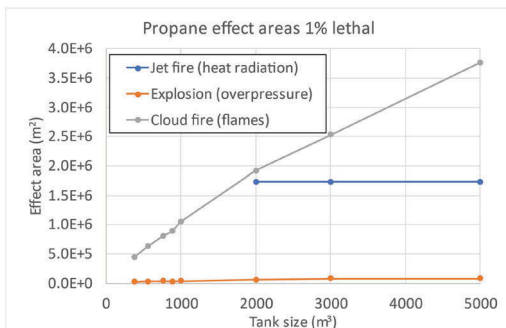


Figure 17. Propane: effect areas (1% lethal) as a function of tank size.

4.3.3 Envelope results for all substances

Figure 18 shows the largest effect areas for all substances vs. tank size. As can be seen, the largest effect area is the one for the propane cloud fire, with an area of almost 4 km² at a tank size of 500 m³. It should be noted, however, that the results also showed that the distances up to which a substance can cause health effects in these scenarios is largest for ammonia. This has to do with the very elongated shape of the hazard areas, which is caused by the high-speed jet of gas and the stable atmospheric circumstances which cause the vapour cloud to disperse very slowly. The calculated maximum distance from the source of the 1% lethality contour for the 5000 m³ tank size is 10.4 km for ammonia.

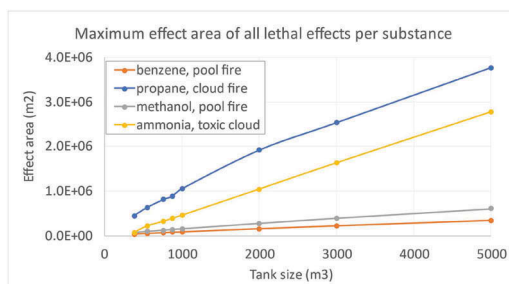


Figure 18. Largest effect area for all scenarios vs. tank size.

4.4 Discussion

As shown by the presented results, there are areas along the inland waterway where an increase in the maximum tank size beyond 1000 m³, will result in effect areas that extend well beyond the river banks and, thereby, might affect people living along the river. Based on this, the recommendation is to maintain the restriction on maximum tank size of 1000 m³ under the ADN regulations.

For larger tank sizes, a complete risk assessment is required based on which derogations for a specific substance onboard a specific vessel along a specific route could be considered.

5 CONCLUSIONS

The guidelines on additional crashworthiness were introduced in 2005 and based on the knowledge and state-of-the-art at that time and have at some points become outdated. This paper has presented the main findings and conclusions of a study addressing the state-of-the-art in three categories.

An update of the collision energy statistics to reflect the distribution of inland waterway vessels that currently sail the European Inland Waterways has shown that inland waterway traffic has increased both in number of vessels and in the mass of the vessels. As a consequence, in case of a collision, the struck vessel has a higher probability of exceeding its crashworthiness limit. Lowering this risk, will require more additional structural reinforcements than currently needed. The parameter study that has been carried out to investigate the crash analysis to determine the energy absorbing capacity of the struck vessel has shown that small variations and uncertainties in input parameters such as the striking angle or striking location can have a significant impact on the resulting energy absorbing capacity until tank rupture. In order to address these challenges in the future, a probabilistic approach is proposed to explicitly account for these variations and uncertainties in the resulting output.

One of the effects that has a large influence is the interaction between the ship structure and the tank, which is also heavily dependent on the way both the ship structure and tank are discretised. A two-step

approach separating the analysis of tank rupture from the analysis of energy absorption has been investigated to address this challenge and showed that a more detailed investigation is required to better understand this interaction.

Based on the consequence modelling study increasing the permissible tank size limit beyond 1000 m³ is not recommended, since the affected areas will extend well beyond the river banks and, thereby, might affect people living along the river. For larger tank sizes, a complete risk assessment is required based on which derogations for a specific substance onboard a specific vessel along a specific route could be considered.

In conclusions, the study presented in this paper has shown that the current guidelines on additional crashworthiness of inland waterway vessels carrying hazardous cargo in large tanks are in need of an update to reflect the current state-of-the-art. Furthermore, with the recent transition to alternative fuels onboard ships that all have one or more hazardous characteristics, a similar procedure will also be necessary to ensure safe operation of ships sailing on alternative fuels.

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