Increasing the safety operation of railway tanks in emergency situations by improving the design of boiler bottom protective elements

Pavol Šťastniak, Juraj Gerlici and Kateryna Kravchenko
University of Žilina, Department of transport and handling machines, 01026, Univerzitná 8215/1, Žilina, Slovak Republic

1 E-mail: kateryna.kravchenko@fstroj.uniza.sk

Abstract. This article presents an analysis of the problem of reliability of tank boilers in an emergency event. The designs of the boiler bottom protection and the prevention of wagon crawls on top of each other in collisions are evaluated. An analysis of the requirements for the tank protective elements is performed. A technical solution to improve the protective shield of the bottom is developed. The proposed solution will increase rigidity and strength of the protective shield structure, reduce the risk of damage to the railway tank boiler bottom when the protruding elements of the adjacent wagon collide. The work presents the results of the stress-strain state of the proposed design protective shield in the case of rail car collision and, accordingly, the force impact of 150 kN according to the RID TE25 standard.

1. Introduction
Railway transport plays an important role in the social and economic development of countries, as the developed railway systems are a precondition for formational economic growth and improvement of its competitiveness [1]. Accidents occur in rail transport as well as in other modes of transport. Carrying dangerous goods involves the risk of an incident due to the fault of other traffic participants, climatic conditions, badly chosen packaging materials or lack of marking [2-5].

The transportation of dangerous materials is essential to the economy of the countries and to the well-being of its people. Dangerous materials are used in water purification, farming, manufacturing, and other industrial applications. As the need for dangerous substances increases, the flows of dangerous goods also grow.

Railroads carry bulk of dangerous materials annually, including millions of tons of explosive, poisonous, corrosive, flammable, and radioactive materials. The need for dangerous materials to support essential services means that the transportation of highly dangerous materials is unavoidable. Rail transportation of dangerous materials is a safe method for moving large quantities of dangerous materials over long distances. The vast majority of dangerous materials shipped by rail tank car every year arrive safely and without incident, and railroads generally have an outstanding record in moving shipments of dangerous materials safely. However, rail shipments of dangerous materials frequently move through densely populated or environmentally-sensitive areas where the consequence of one incident could be loss of life, serious injury, or significant environmental damage [6-8].
2. Analysis of statistical data on accidents in railway transport

Over the 2012-2016 period there have been, on average, just under 1950 significant accidents each year on the EU railways (figure 1). In these accidents, on average, just under 1050 persons are killed and 850 persons are seriously injured each year [9]. According to the statistics of the Eurostat (EuroStat 2020) DATABASE: Annual number of accidents involving the transport of dangerous goods (2004-2015), open between 2006 and 2015, the average number of accidents involving the transport of dangerous goods was 44 (figure 2 and 3) [10].

Figure 1 displays a fall of 3.6% in the number of significant accidents between 2012 and 2016. Percentages are expressed as Compound Annual Growth Rates (CAGR). However, in 2016, not all of these Common Safety Indicators (CSIs) improved across Europe.

The estimated economic impacts of these accidents follow a similar pattern. Figure 1 shows that the rate FWSI/Significant Accident has been improving since 2010, although there is considerable variation between the years and an ascending trend is noticed for the period 2014-2016.

![Figure 1. Significant accidents EU 28, 2010-2016.](image1)

![Figure 2. Annual number of accidents involving the transport of dangerous goods on railways EU 28, 2006-2015.](image2)
Figure 3. Annual number of accidents involving the transport of dangerous goods on railways, by country, 2004-2015.

Having estimated what threat dangerous substances pose to the environment, individuals and the whole infrastructure of transport, it is essential to guarantee the safety of these processes [11, 12].

In a collision, there may be situations where one of the railway vehicles climbs on top of the other and, through its buffers or automatic coupler, collides with the front surface of the tank cover of the other wagon. In such a collision scenario, the packaging may be torn (figure 4), and the dangerous substance may leak into the air or soil.

Figure 4. Damage to the tank bottom when one wagon climbs on top of another a) tank wagons colliding with a track-ram shunting Mussalo Kotka 08.07.2016 [13], b) damage to the end of the tank container in the container wagon (Photo: OTKES) [14].

In the sector of freight carriage by rail, the problem of transporting dangerous goods is found to occur mainly in the area of the structure and the equipment of tank wagons and tanks. In order to mitigate the effects of adverse events, including damage to the bearing structure of vehicle platforms and the transported goods as a result of, for example, travelling at an excessive speed or derailment, the vehicles feature a range of structural solutions and sub-assemblies classified as passive safety mechanisms [16-20]. Tank wagons used for transport of dangerous materials can be made more resistant to damage in accidents through the use of a thicker steel tank and other protective features [15, 21].

3. Classification of structures to protect the end of the rail tank car boiler from collision damage

A common scenario of a rail accident involves one railway vehicle running into another at an excessive speed, which leads to their structures becoming deformed and – quite frequently – their buffers missing.
each other in the vertical plane, which results in neighbouring vehicles climb one on top of the other. To prevent this highly harmful phenomenon, leading to, among others, leakage of the tank of a wagon carrying dangerous goods, freight wagons are constructed in a way to feature special solutions preventing the occurrence of climbing [16]. They are mounted on the wagon front usually. These devices are generally called over-buffering protection devices. Another type of protection is known by the term protective shield, which serves as a barrier to the tank body.

Over-buffer protection and a protective shield serve to reduce damage in the event of a railway vehicle crash. The purpose of these devices is to eliminate, as far as possible, damage caused by a collision. Both devices are idle in normal operation, they are activated only when the railway vehicles move towards each other in the vertical direction.

The design of the protective elements of both the over-buffering protection device and the protective shield is very different. These elements work only in emergency situations, therefore, these structures must have a minimum weight and a sufficiently simple structure for easy disassembly.

The significant variety of designs can be divided into the following groups (figure 5):

a) Over-buffering protection:
   - permanently installed:
     - made in the form of a cone [European patent EP 2033868A1];
     - rectangular shape [European patent EP2808222A1];
     - with grate or teeth [European patent EP 2727792B1, European patent EP 3530544A1];
   - triggered in a collision [Anti-climbing device 2020 Innova Systems And Technologies].

b) Protective shield:
   - made with repetition of the tank profile [Patent US4466356A];
   - average height [Patent US3994239A];
   - high [European patent EP0816197A2];
   - with shockproof materials (e.g. elastomer) [Patent DE19833935A1].

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**Figure 5.** Classification of structures to protect the tank boiler end from collision damage.
A protective shield is a device used to protect the tank of a tank-wagon that transports dangerous goods. The shield is located at the ends of the railway vehicle above the main frame. It protects the tank bottom from punctures that could occur as a result of railway vehicles climbing on top of each other, while it is active only in the event of failure of the over-buffering protection, or in its absence. The tank ends are usually still perforated to increase safety.

4. Basic requirements for the design of the protective shield
The tanks of wagons must be protected against stacking and derailment in the event of an accident or at least limit damage to the tank from protruding structural elements (buffers) of an adjacent wagon. The requirements for the protective shield, a measure to limit damage when jumping over buffers are defined in the requirements of the Code for the International Carriage of Dangerous Goods by Rail (RID) in Chapter TE25 [15].

According to the requirements of RID in Chapter TE25, the measures to limit damage in the event of an accident are:

- Use of a protective shield at each wagon end. The protective shield must cover the relevant width of the tank in each case up to its appropriate height. In addition, the width of the protective shield must be at least as great along the entire height of the shield as the distance defined by the outer edge of the buffer plates. The protective shield must, at a height measured from the upper edge of the buffer support, cover either 2/3 of the tank diameter or at least 900 mm and must additionally be fitted with a device at the upper edge to catch the rising buffers. The wall thickness of the protective shield must be at least 6 mm. Lastly, the shield and its attachment points must be designed in such a way as to minimize the possibility of the bottom to be punctured by the shield.

- Protective shield at both ends of wagons equipped with automatic couplings. If a protective shield is used at both ends, it must cover the tank end to a height of at least 1100 mm, measured from the upper edge of the buffer plate, the couplings must be fitted with anti-slip devices to prevent unintentional disconnection and the protective shield must be at least 1200 mm wide. The protective shield must have walls at least 12 mm thick and its points of attachment must be such as to minimize the possibility of the tank ends piercing the protective shield itself.

5. Technical proposal for a protective shield design
on the basis of the analysis of the design of protective shields, a promising design of the protective shield has been developed. The design takes into account the requirements of the rail tank car manufacturer, as well as RID rules. An application for an invention (a2020 03605 from 16.06.2020 UKRPATENT) and utility model (u2020 03804 from 24.06.2020 UKRPATENT) has been filed for this technical solution.

The method of fixing this structure is based on the use of two consoles 13. To ensure the best strength properties of the consoles 13 and protective shields of the rail tank car, it is advisable to place the consoles 13 around the axis of the buffers. Console 13 is attached to the rail tank car by welding in two places, by means of one of the transverse plates 1 (figure 6) with the frame of the rail tank car and by means of the main vertical stiffening plate 2 with the bearing structure of the buffer. The second transverse plate 1 connects the main vertical stiffening plate 2 with the auxiliary vertical stiffening plate 3.

Depending on the design of the rail tank car, the thickness of the console elements may vary. For example, for tank truck Za (c) ns 98 m³ (Tatragónka Poprad) the best thickness is 10 mm.

The height of the protective shield of the rail tank car above the upper edge of the buffer must be not less than 900 mm. The width of the protective shield of the rail tank car, as well as the height are subject to the rules of RID TE25. Accordingly, the width should be at least such as the distance between the outer surfaces of the buffer plates.

The design of the protective shield of the rail tank car must have the lowest possible weight. Therefore, according to the strength calculations, the lowest weight of the structure for the rail tank car Za (c) ns 98 m³, will be achieved when the thickness of the metal sheet 4 is 6 mm.
To ensure high stiffness of the structure in the longitudinal direction, metal sheet 4 is made of a peak shape and cut in the shape of a trapezoid. Several stiffeners are placed on the front side of the protective shield of the rail tank car.

![The protective shield design.](image)

The main reinforcement of the structure are three vertical stiffeners 5, which are located opposite the buffers on the left and right hand sides of the trapezoid of metal sheet 4 and in the upper part have gripping elements 6. In addition, the vertical stiffeners 5 are arranged so that they are directly connected to the main vertical stiffening plate 2 of console 13 and the frame of the rail tank car. In the event of an accident, the buffers of the adjacent rail car rise above the frame of the rail tank car and must be captured by the gripping elements 6, as shown in figure 7.

![The process of capturing the buffers of adjacent rail car.](image)

The connection of the vertical stiffeners 5 is realized, in addition to the metal sheet 4, by joints at three levels of height. The first connection is located on the upper edge of the protective shield of the rail tank car and is realized by means of a plate 7, which is placed on its entire upper part and fixed on a metal sheet 4 by means of triangles 8. The second connection is in the area of the rail car buffer capture. The last connection is at the bottom in the connection area with the consoles 13.
To strengthen the structure of the protective shield of the rail tank car on its outer surface horizontal ribs 9 in two rows and side vertical ribs 10 are fixed on the edge of the protective shield of the rail tank car along its entire height, in the lower part of metal sheet 4 there are holes 11 which are parts of the frame rail tank car.

When two cars collide (figure 8 a, b), one of them will begin to rise above the second (figure 8, c). This will lead to the capture of buffers of one of the rail cars by the elements of the second rail car protective shield (figure 8, c, d). In this situation, it is possible that there will be a plastic deformation of the protective shield. At the rear, the protective shield is pressed against the rail tank car bottom, so that the force from the buffer plates is decomposed into a larger plane. This will preserve the integrity of the rail tank car bottom.

When the rail cars collide, one of the rail cars will start approaching the other and the buffers of the oncoming rail car will be captured by the gripping elements 6 of the rail tank car protective shield, there will be forces that will be transmitted to the rail tank car frame through screws 12 in the holes.

Material EN S 355 can be used for the construction of the rail tank car protective shield with insignificant economic costs and sufficient yield strength for this design. In addition, it should be borne in mind that in the event of a rail car collision, the protective screen may be destroyed and will interact with the rail tank car bottom.

![Figure 8. The collision.](image)

6. **Strength analysis of the protective shield**

Strength analysis was performed in ANSYS 19.2. The shield geometry was inserted into a numerical program, which was created as an assembly in the Catia V5R20 program.

In accordance with the dimensions of the construction, the mesh size was 10 mm. Based on the requirements of the protective shield, the main stressed part is the vertical stiffening ribs. The load from the rising buffers is applied to these stiffening ribs and at the same time these reinforcements reach up to the places where the shield is attached to the rail car frame. For this reason, the mesh size is 6 mm on the given parts of the structure.

When selecting the boundary conditions, the shield was fixed behind the elements located around the screw holes (figure 9). A force of 150 kN was applied to the edges of the vertical stiffening ribs catching the buffers.

Stresses distribution in the construction is most expressive in the ribs of rigidity. Critical stress points are located in the upper parts of the stiffening ribs catching the buffers. The maximum stress value is 342.27 MPa (figure 10).
To determine the stresses at the welds, the analysis of the elements around the buffer catch is given. The maximum stress value in the welds between the stiffening ribs and their reinforcing plates is 242.2 MPa (figure 11).

In terms of capturing the buffers, the resulting deformations of the entire structure are the maximum displacement. The maximum analysed displacement is 2.15 mm. The place of occurrence of the largest displacement is on the upper edge of the structure. The displacement in the vertical direction did not exceed 1.19 mm and in the longitudinal direction of the rail car 1.80 mm. The distribution of the total deformation construction is shown in figure 12.

Figure 9. Boundary conditions of the protective shield.

Figure 10. Protective shield stresses analysis.

The most important result from the analysis is the distribution of the stress. The calculation revealed that the maximum stress was 342.27 MPa. This value does not exceed the yield strength of the EN S355 material used. Due to the construction of welded joints, the stresses in the most stressed welds are verified. The most critical welded joints were the places where the main stiffening ribs were connected with their auxiliary bent plates, i.e. the place where the rising buffers were caught. The critical stress in the given welds is 242.2 MPa. This means that the yield strength of the welded structure for EN S355 was not exceeded in the welds.

Another important finding is the relatively low overall deformation of the structure. From the displacement results, a maximum of 2.15 mm was recorded at the upper edge of the protective device.
The largest displacement in the vertical direction is 1.19 mm. In the longitudinal direction of the rail vehicle, the maximum displacement is 1.80 mm. The given displacement results indicate the largest deviations of the whole structure. Due to its dimensions, the deformations are low enough.

![Stress in the area of the most stressed welds.](image1)

**Figure 11.** Stress in the area of the most stressed welds.

Under the loads specified by the manufacturer, the protective shield is sufficiently rigid and no plastic deformations occur in it. The deformation values of the structure are relatively small. The ability of the shield to catch rising buffers is not significantly affected by this load. The final weight of the protection shield is 234.95 kg.

![Deformation of the protective shield.](image2)

**Figure 12.** Deformation of the protective shield.

7. **Conclusion**

The analysis of emergency situations in railway transport showed the need to develop new designs that protect the rail tank body from damage during collisions. For this, existing designs for protecting the bottom of rail tanks from damage are evaluated. On the basis of the requirements of regulatory documents and manufacturers of railway cars, the design of a protective shield for the end part of railway tanks is proposed. The protective shield is made of separate pieces of sheet metal. Its construction is designed to protect the tank bottom as effectively as possible.

The calculations showed the reliability of the structure under the action of 150 kN forces, specified in requirements RID TE25. Critical stress points are located in the upper parts of the stiffening ribs catching the buffers. The maximum stress value is 342.27 MPa. The final weight of the protection shield is 234.95 kg.

The developed design of the protective screen makes it possible:
• to reduce the risk of damage to the rail tank car bottom in the event of collision of the protruding elements of the adjacent car, which may occur in accidents;
• to provide high rigidity of the protective shield in the longitudinal direction due to the use of the peak form of the rail tank car protective shield;
• to provide durability of the protective shield of the rail tank car due to use of stiffening ribs and strengthening elements of the design (triangles, plates);
• to be used for different designs of rail tank cars in connection with the use of special holes for placement of rail car elements (for example, vehicle frames);
• to ensure simple production of the protective shield and installation on the rail tank car, due to the fact that the shape of individual parts of the structure is relatively simple;
• to ensure the integrity of the rail tank car bottom due to the fact that all stiffeners and reinforcing structural elements are placed on the front side of the rail tank car protective shield, respectively, the rear side of the protective shield is made without irregularities that could damage the rail tank car in case of an accident.

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