Technic solutions analysis and development of the innovation design protective elements of railway tank wagons

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Abstract. The absence of protective elements on railway tank wagons in case of accidents can lead to significant losses and adverse effects on the environment. This is especially the case for railway wagons for transportation of ignition matters. The article deals with the analysis and the development of the protective elements structures. Two variants of protection are developed - anti-climbing devices and protective shields. Innovation patented design variants are presented. New materials are used in protective constructions, such as aramid, non-Newtonian fluid. A series of measurements and simulation analyses for the integration of protective elements have been made. For the selected constructions, the results of strength researches of constructions are presented. The advantages of the proposed designs are evaluated.

1. Introduction

In general, accidents or collisions occur during transport, the impact of which can have a major impact on the environment and the population (figure 1). According to report on railway safety and interoperability 2020 [1] for 2018, Member States reported a total of 55 accidents and incidents involving dangerous goods of which 9 involved a release of the dangerous goods being transported during the accident (figure 2).

Accidents of tank wagons are not common but can have catastrophic consequences. An example is an accident in May 1991 in the English town of Bradford-on-Tone [2], in which the failure of one of the
tank wagons led to the mass derailment of vehicles (figure 1). Highly flammable liquids were transported in the tanks, which caused a large-scale explosion and fire. The pollution was significant.

If we focus on tank wagons, which usually transport various chemicals harmful to the environment, their most sensitive part are the ends of the tank packaging [3, 4, 5]. There are usually situations where one of the vehicles climbs to the other and through its buffers or automatic coupler collides with the front surface of the tank cover of the other wagon (figure 3) [5, 6, 7]. In such a collision, the packaging may break and the dangerous goods may leak into the soil and air.

Based on cases where similar incidents have occurred, there has been a demand for freight wagon manufacturers to increase the protection of transported goods. For this reason, protective devices have started to be introduced. Typical representatives are anti-climbing devices and protective shields (figure 4). 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 vehicles move towards each other in the vertical direction.
The gradual development of technologies, production processes, and materials does not bypass this part of the development, and it is also important to monitor current and anticipated developments in the market in the field of goods transport [5-10]. The paper further focuses on a new design solution protective devices of tank wagons.

2. Requirements and regulations for the tank wagons protective devices

Devices for the end part of the tank wagon protection from damage in collisions are always located at the wagon ends. When designing new designs, the normative free spaces specified in the Convention concerning the International Carriage of Dangerous Goods by Rail (RID) [11]. For example, no rigid part of a railway vehicle may be located within the Berne rectangle intended to ensure the safety of personnel when coupling or uncoupling wagons.

The minimum size of the Berne rectangle:
- in the case of fully compressed buffers, free space shall be at least 300 mm, measured perpendicular to the plane of the front buffers, and defined in the longitudinal direction of the wagon.
- the width is 400 mm;
- the height must be at least 2000 mm above the rail head.

The width of the anti-climbing device design must comply with the RED Rules, i.e. it must be not less than the width of the buffer plate. The UIC 526-1 standard defines the dimensions of the space for a standard buffer, with a buffer plate width of 450 mm. The design of the anti-climbing devices must be as light as possible and easy to dismantle after a collision.

According to the requirements of RID TE25 design of anti-climbing device:
- shall permit the free taking of curves by another wagon fitted with the anti-climbing device in a curve of 75 m radius;
- shall function independently of the condition of the load and the wear and tear of the wagons concerned;
- shall withstand a vertical force (upwards) of 150 kN;
- shall be located above every buffer.

The requirements for the protective shield and the measure to limit damage when climbing over buffers are also defined in the requirements of RID in Chapter TE25 [RID]. Shells of tank-wagons shall also be protected against the overriding of buffers and derailment or, failing that, to limit damage when buffers climbing.

The essential requirements of RID TE 25 for the design of a protective shield are:
- shall protective shield at each end of the wagon;

Figure 4. Known designs of the tank wagons protective devices.
- the protective shield shall cover the width of the tank in each case, up to the respective height. In addition, the width of the protective shield shall, over the entire height of the shield, be at least as wide as the distance defined by the outside edge of the buffer heads;
- the height of the protective shield, measured from the top edge of the headstock, shall cover either two-thirds of the tank diameter or at least 900 mm and shall, in addition, be equipped at the top edge with an arresting device for climbing buffers;
- the protective shield shall have a minimum wall thickness of 6 mm;
- the protective shield and its attachment points shall be such that the possibility of the tank ends being penetrated by the protective shield itself is minimized.

3. Innovative technical solutions for protecting the ends walls of tank-wagons in collisions
To protect the integrity of the tanks, a number of innovative directions and patented design ideas have been developed for further research. The research was carried out in two directions: anti-climbing devices (Patents of Ukraine №№ 123129, 143189, 143478, 144784, 144227) and protective shields (Patents of Ukraine №№ 144785, 144786, 144604, 145401, 145644). Depending on the design of wagons will be profitable one or another the design of protective devices. The manufacturer will be able to choose a more suitable technical solution of protective device design depending on the financial and design capabilities. In this paragraph, only ideas are presented that require additional research for implementation in operation.

3.1. Technical proposals for the design of anti-climbing devices.
3.1.1. Anti-climbing devices with high-modulus synthetic fibers. The essence of the technical solution is to install on the gripping anti-climbing devices of the casing of a material containing high-strength and high-modulus synthetic fibers (figure 5, a), also having a low weight and strength five or more times greater than steel (depending on the selected material, such as aramid fibers. Due to the fact that the gripping elements are closed by a high-strength casing, they can be made with holes on the entire surface, which will significantly reduce the weight of the entire structure. This preserves all the necessary properties of the structure to fulfill the purpose of not crawling wagons in a collision (Patents of Ukraine № 144784).

Technical result:
- increase the strength of the construction by five times or more depending on the high-strength modular synthetic fibers used in the casing material, which allows absorbing higher shock loads in emergency situations;
- facilitation of the entire construction through the use of holes in the gripping elements.

Figure 5. Technical proposals for the design of anti-climbing devices:
  a) with high-modulus synthetic fibers; b) with rubber element
3.1.2. Anti-climbing devices with rubber element. Fixing on the inner surface of the anti-climbing gripping device a rubber element, which in cross-section has the shape of a cone. The outer surface of the rubber element is made with a pattern in the form of inclined grooves, and the angle of the grooves is made in the shock direction (Patents of Ukraine № 144227). Due to the different directions of the impact force on the upper and lower gripping element, the angle of the grooves on the upper and lower gripping element is made in the mirror (figure 5, b).

Technical result:
- reduce the force of impact and vibration by using a rubber element and energy dissipation during impact;
- reduce impact noise by damping the rubber element respectively and scattering and absorbing part of the impact energy
- reduce the likelihood of one wagon collision into another by using a pattern on the outer surface of the rubber element at the small impact force.

3.2. Technical proposals for the design of protective shield

3.2.1. The protective shield with rubber element. The essence of the technical solution is the outer surface of the protective screen is provided with a sheet of elastic material (e.g., rubber), which absorbs the kinetic energy of the collision during damping (Patents of Ukraine № 144785). The working surface of this sheet is made with a non-slip pattern (figure 6).

![Figure 6. The protective shield with rubber element: a) Placement of the protective shield on the wagon; b, c) the working surface of the protective shield with a non-slip patterns.](image)

- increasing the efficiency of the protective shield by damping the sheet of elastic material and scattering the kinetic energy of the collision;
- the use of the anti-slip pattern on the surface of the sheet of elastic material will limit the sliding of the protruding elements of adjacent wagons on the surface of the protective screen and, accordingly, save the railway tank from damage and reduce the likelihood of derailment.

3.2.2. The protective shield with aramid fibers. The outer surface of the protective shield is provided with a rubber plate, which is reinforced with aramid fibers (Patents of Ukraine № 144786).

Technical result:
- increasing the efficiency of the protective shield by using the strength properties of aramid fibers.
- improving the safety of rail tankers and protecting them from damage.

3.2.3. The protective shield with innovative technical solution. The protective shield is made C-shaped, in the cavity of which is placed an additional protective metal sheet behind which is a rubber shell,
which is filled with non-Newtonian liquid (Patents of Ukraine № 144604), the strength of the rubber shell is provided by a casing made of aramid material and mounted on top of the rubber shell (figure 7).

![Figure 7](image)

**Figure 7.** The protective shield with innovative technical solution:

- **a)** placement of the protective shield on the wagon;
- **b)** the protective shield.

Technical result:
- scattering of impact energy in the event of a collision of wagons;
- restriction of upward movement of the protruding elements of adjacent wagons and preservation of the integrity of the tank-wagon.

3.2.4. **The protective shield with innovative technical solution.** The protective shield is made of an arrow shape with stiffeners made on the outside with gripping elements to protect against vertical movement of the protruding elements of the climbing wagon (Patents of Ukraine № 145401). Attaching the protective shield to the tank frame is performed using the console (figure 8, a).

![Figure 8](image)

**Figure 8.** The protective shield: a) the arrow shape; b) the flat shape.

Technical result:
- reducing the risk of damage to the boiler bottom of the tank wagon in the event of a collision of the protruding elements of the adjacent wagon, which may occur in collisions;
- ensuring high stiffness of the structure in the longitudinal direction due to the use of the arrow shape of the protective shield of the tank wagon;
- use for various tank-wagon designs, due to the use of special holes for the placement of wagon elements (e.g. vehicle frames);
- simple production of the protective shield and installation on the tank-wagon, due to the fact that the form of separate parts of a design is rather simple;
- ensuring the integrity of the tank wagon bottom, due to the fact that all the stiffeners and reinforcing structural elements are placed on the front side of the protective shield of the tank-wagon, respectively, the rear side of the protective shield of the tank-wagon is made without irregularities that could damage tank in case of collision.

3.2.5. The protective shield with flat shape. The protective shield has a flat shape and expands in width from bottom to top, is fixed to the frame of the wagon with brackets and rear supports, on the outside of the protective shield are stiffeners (figure 8, b).

Technical result (Patents of Ukraine № 145644):
- reducing the risk of damage to the bottom of the tank wagon in the event of the collision of the protruding elements of the climbing wagon, which may occur in collisions;
- ensuring the strength of the protective shield through the use of stiffeners;
- providing simple production of the protective shield and installation on the tank-wagon, due to the fact that the form of separate parts of a design is rather simple;
- ensure the integrity of the bottom of the tank wagon due to the fact that all the stiffeners and reinforcing elements of the construction are located on the front side of the protective shield. The rear side of the protective screen is made without irregularities that could damage the tank in case of a collision.

4. Design and modelling of the stress-strain state of protective elements for a specific wagon Za(c) ns 98 m³ (Tatravagonka a.s., 2020)
The Za (c) ns 98 m³ wagon is a four-axle tank wagon with a volume of 98 m³ manufactured by Tatravagonka a.s. Poprad (figure 9), complies with the TSI-WAG regulations, valid UIC regulations, ERRI recommendations, the agreement on the mutual use of freight wagons in international transport AVV (RIV) and EN standards. The wagon is designed for unrestricted operation on all European lines with normal gauge and for climatic conditions with temperatures T1 (-25 °C + 40 °C) according to TSI-WAG. The wagon meets the conditions for the GE designation, according to TSI-WAG (Tatravagonka a.s, 2019).

4.1. Estimation of free space for the placement of protective elements
The width of the design must comply with the RID regulations, i.e. it must be at least as wide as the width of the buffer plate. The UIC 526-1 standard specifies the size of the space for a standard buffer, the width of the buffer plate is 450 mm. Based on the mentioned standard to facilitate the creation of the design, a model of the free space for the buffer was created (1). Furthermore, the free space for the taillight (2), the space located on the left riser (3), and, last but not least, the Bern rectangle (4) were...
modelled. The tail light is not located equally on both ends of the wagon (figure 10), its height offset is 150 mm.

![Figure 10. Models of free spaces on the wagon Za (c) ns 98 m³: 1-space for the buffer, 2 - space for the end lighting of the wagon, 3 - space on the left riser, 4 - Bernese rectangle.](image)

### 4.2. Design of protective elements

#### 4.2.1. The anti-climbing device

The anti-climbing device consists of 19 parts. The base plate (1) copies the surface of the buffer carrier on the top and is bent into such a shape that it does not come into contact with the space for the end lighting of the tank wagon. The base plate contains two openings above the buffer, through which the passage bracket holders can pass. The advantage of these holes is the reduction of the weight of the construction. The main stiffness rids (2) are located along the edges of the construction, there are holes in them to reduce the weight. Two rows of additional stiffening ribs are installed to increase the stiffness of the construction (3). The catching part is formed by a tooth segment (4), which is reinforced by triangular reinforcements under each tooth (5). In addition to the base plate, the stiffness rids was also connected by a front wall (6) carrying the already mentioned tooth segment. At the bottom of the device there is a connection of the main stiffness rids by means of a rod (7), which serves not only for reinforcement, but can also serve as a replacement for the handle for the pusher, when passing under the buffer (figure 11). Thanks to this solution, it is not necessary to connect the base plate in its bottom part. The anti-climbing device is symmetric with relatively to the buffer axis.

The end elements of the design have the shape of teeth. The teeth are distributed on the front surface of the design so that in the event of a collision of wagons at the same height level, they interlock and there is no mutual collision with the teeth compared to the placed protection. Ideally, in which it assume the collision at the same height level with zero transverse displacement, there will be no contact of the anti-climbing protections. This prevents strain on the protection in the longitudinal direction of the wagon. When the vehicles are moved laterally transversely, a situation can arise where the teeth of the anti-climbing devices meet each other. In this case, the teeth shape is largely designed so that the teeth tend to enter the tooth gaps opposite the located protection (figures 12, 13).

The design of the anti-climbing device in the area of the left riser has been considerably modified to maintain free spaces. The handle for the pusher (7) is moved 90 mm lower. In the event of an accident and collision of buffers, under the action of the force of impact, one of them begins to rise (figure 13). When installing the gripping elements on both wagons, the teeth of the gripping elements of both wagons are engaged. The impact of the collision is initially perceived by the buffers, then the teeth with stiffening ribs come into work.

If the gripping elements are installed on only one wagon, then in the event of an accident and collision of buffers, with the help of the gripping element limited vertical movement of the wagon buffer, which hits the wagon with installed anti-climbing device.
High-strength design steel marked EN S500 was used to construct the designs. The material was chosen on the basis of the requirement to avoid permanent deformations under a static load of 150 kN upwards and downwards. By using the given material, the weight of the design was reduced. The weight gain of the wagon using this protection is 308.2 kg.

4.2.2. The protection shield. The construction of the shield is created by welded joints. The shield is characterized by an arrow-shaped bend (figure 14). The arrow shape increases the overall stiffness of the construction. The main plates forming the wall have the shape of a trapezoid and carry several stiffness rids on their front side. The main reinforcement of the design are three vertically oriented stiffness ribs, on both edges of the shield. The shape of these reinforcements also serves to catch the rising buffers (figure 14).
The design is made of separate pieces of sheet metal, these sheets form a shield assembly. The shape of the individual parts of the design is relatively simple. The advantage is therefore simple production and considerably increased stiffness in the longitudinal direction due to the arrow shape. The protective shield can be used at both ends of the wagon. The shape of the design does not increase the risk of piercing the tank bottom, there are no stiffness ridges on the backside. The weight of the shield itself is 234.95 kg.

Figure 13. Principle of operation of protection devices.

Figure 14. View of the wagon model with protective devices, bottom a), top b), from the rear of the protective shield without tank c), detail of the location of the bolts of the protective devices d).
4.3. Modelling the stress-strain state of protective elements

The strength analysis of the structure was performed using the finite element method (FEM). The analysis was performed in the computer program ANSYS 19.2. The mesh size was 6 mm. Due to the dimensions of the structure, the network chosen in this way is sufficient. The force corresponds to the size specified in the RID regulation, i.e. 150 kN. Due to the dimensions of the structure, the network chosen in this way is sufficient. The force corresponds to the size specified in the RID regulation, i.e. 150 kN.

The results show maximum stress is 355.26 MPa. The stress is located at the bending point of the main stiffness rid of the design (figure 15). The maximum stresses did not exceed the yield strength of the selected material, i.e. it was lower than 500 MPa. The stress of 350 MPa was not exceeded in the places of welds. The maximum elastic displacement at its critical point is 3.17 mm. The displacement in the vertical direction is located at a similar point and has a value of 2.97 mm (figure 16). The obtained deformations do not affect the functional properties of the structure.

![Figure 15. The anti-climbing device stress - in the area of the brake mechanism when a downward force is applied](image1)

![Figure 16. Deformation of the anti-climbing device - in the brake mechanism area](image2)
The material EN S355 was chosen for the design of the protective shield. The reason for choosing said material is mainly from economic costs because the protective shield reaches larger dimensions than the anti-climbing device. The given material has a sufficiently high yield strength of 355 MPa. The yield strength of the welded structure is 248.5 MPa. Another reason for its choice is the assumption that the protective shield is designed mainly to catch climbing buffers and in the event of an impact is calculated from its later plastic deformation, but also its contact from the tank wagon bottom.

Due to the size of the shield construction, the net was set at 10 mm. The course of stresses in the design is most pronounced in vertical stiffness rids. Critical stress points are located in the upper parts of the stiffness rids catching the buffers. The maximum stress value is 342.27 MPa. To determine the stresses at the welds, an analysis of the elements around the buffer's catch was performed. The maximum stress value of 242.2 MPa was reached in the welds between the stiffness rids and their reinforcing plates.

From the point of view of catching the buffers, the resulting deformations of the entire design are especially important. The maximum analysed displacement is 2.15 mm. The place of occurrence of the largest displacement is on the upper edge of the design (figure 17). The displacement in the vertical direction did not exceed 1.19 mm and, in the longitudinal direction 1.8 mm.

![Figure 17. Deformation of the protective shield](image)

### Conclusion

According to the analysis of accidents during the transportation of dangerous goods by railroad wagons, the issue of maintaining the integrity of tanks in case of collisions is very relevant both from an environmental and economic point of view.

The main regulatory requirements for the development of protective devices for tanks in case of collisions are analysed. One of the basic requirements is the impact force, which must be equal to 150 kN. In addition to the RIG TE25 normative document, when developing designs, it is necessary to take into account the customer's requirements, which differ depending on the tank wagons' design.

A number of patented technical solutions for the design of the anti-climbing devices and protective shields have also been developed. The design proposes the use of modern materials and innovative designs, allowing to obtain maximum protection of the tank surface in the event of collisions. The design proposes the use of high-strength materials, including aramid fibers, as well as a non-Newtonian fluid, which changes its properties depending on the applied force. In further studies, a more detailed study of
the properties and characteristics of these materials is planned, taking into account their use in protective devices for wagons.

Some variants of the protective elements design have been developed for the specific wagon Za (c) ns 98 m³ (Tatrawagonka a.s., 2020). The proposed design of the anti-climbing device for one tank wagon consists of weight of 308.2 kg. The weight of the protective shield is 234.95 kg. The analysis of the stress-strain state of both designs has shown their reliability in collisions with a static force of up to 150 kN. At applied loads, the protective shield is sufficiently rigid and no plastic deformations occur. The ability of the shield to catch climbing buffers is not significantly affected by this load. From the results of the displacement of the protective shield, a maximum value of 2.15 mm was recorded at the upper edge of the protective device. Also, the displacements in the vertical and longitudinal directions did not reach significant values. The given displacement results indicate the largest deviations of the entire protective shield construction. Due to its dimensions, the deformations are low enough.

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