Review Article

Application of Bumpers in Different Types of Railway Vehicles: A Short Review

Hamza El Etri and Mehmet Erdi Korkmaz
Department of Mechanical Engineering, Karabuk University, Karabuk, Turkey

Munish Kumar Gupta*
Faculty of Mechanical Engineering, Opole University of Technology, Opole, Poland

* Corresponding author. E-mail: m.gupta@po.edu.pl DOI: 10.14416/j.asep.2022.03.004
Received: 16 November 2021; Revised: 12 January 2022; Accepted: 14 February 2022; Published online: 18 March 2022

Abstract
In order to avoid traffic problems in developed countries, railway vehicles play an important role. Passengers, railway workers, goods, cargo utilization, and dangerous materials are being transferred using various railway vehicles, and each vehicle is designed for a specific manner. Such vehicles include different locomotives that work on either electric or diesel power, in addition to different wagons and carriages attached to these locomotives (passenger wagons, sleeping wagons, freight wagons, and several other types, etc.). Railway vehicles run on railroad tracks, these tracks are designed and maintained by specific machines (diagnostic machines, road renewal machines, ballast screening, tamping and regulating machines, etc.). Several methods are applied when coupling wagons or carriages to each other (automatic coupling, semi-automatic traction, and hook clutch drawbar) depending on vehicle type and function. Railroad vehicles are considered a safe transportation system compared to other systems because they use buffers and bumpers to ensure safety. This paper mounts a minor review of railway vehicles, machines used to make railroads, coupling systems, bumpers and, buffers used to ensure railway vehicle's safety, and also focuses on the previous studies conducted to enhance such bumpers and lessen collision effects.

Keywords: Railway vehicles, Bumpers, Buffers, Coupling systems, Wagon designing, Vehicle collision

1 Introduction

Today, railway vehicles have an important place in urban and intercity transportation. Due to their importance, safety installments should be considered such as bumpers that help to reduce the impact of the collision. These design and manufacturing studies are carried out based on international standards and previous research. Bumpers in railway vehicles absorb the forces and transmit them softly to the chassis. The main task of the bumpers is to absorb the impact forces that occur during various impacts, such as a collision between 2 trains that may occur in railway vehicles [1]. In railway vehicles, the impact force between a possible collision and the wagons is quite high. Crashworthy bumpers are used for partial or complete damping of this force, especially in freight wagons. Crashworthy bumpers absorb the impact forces that occur in railway vehicles, especially freight wagons. The aspect that distinguishes these bumpers from the others is that they are capable of withstanding greater force than a conventional bumper [2]. According to this technical review, the effect of bumpers on different types of railway vehicles is thoroughly explained. Moreover, the major focus of the review is to research on the application of bumpers and thin wall tubes seen in automobiles.

2 Railway Vehicles

Railway vehicles are a series of one or more towing vehicles and one or more towed vehicles moving on

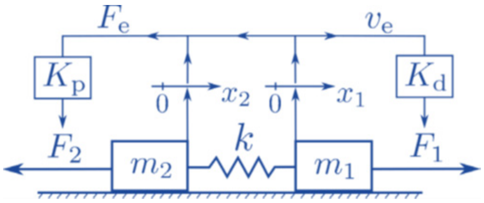

Figure 1: Coupled velocity and force control of vehicle towing (modified from [4]).

the rail. Railway vehicles used in freight or passenger transportation from the past to the present are divided into two as towed and towed vehicles. In addition to these, there are railway construction and repair machines known as construction machines [3].

2.1 *Towing vehicles*

The towing vehicles (Figure 1) used in rail systems are very diverse depending on the nature of the service.

Locomotives are divided into three categories according to their area of use, types of energy used, and power transmission systems. According to their usage areas, towing vehicles are further divided into locomotives used in freight trains, locomotives used in passenger trains, and shunting locomotives.

In addition, locomotives pulling freight and passenger wagons are diversified as steam locomotives, diesel locomotives, and electric locomotives. Today, locomotives work mostly with electricity due to ease of maintenance and towing vehicles at high power or weight. In addition, the ease of use and high-power generation in underground systems makes the use of electric locomotives widespread. Electric locomotives work with direct current or alternating current, depending on the line [5].

On the other hand, according to power transmission systems, locomotives are divided into hydraulic and electric power transmission systems. Hydraulic power transmission systems are used in diesel-powered railbuses, diesel and electric train sets, shunting locomotives. Electric power transmission systems are used in diesel and electric systems [6].

2.2 *Towed vehicles*

Vehicles that carry passengers and cargo used on railways and cannot move on their own are called

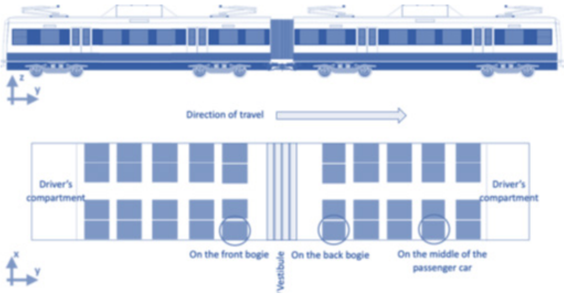

Figure 2: Compartment passenger wagon [8].

wagons. Wagons are manufactured taking into account agreements such as The International Union of Railways (UIC), Rail Incident Commander (RIC), Rail Inspection Vehicle (RIV), Technical Specifications for Interoperability (TSI). Wagons, which cannot move on their own and are moved by a towing vehicle, are divided into two main groups, including passenger wagons and freight wagons.

In order to ensure that passengers travel more comfortably, passenger wagons are designed to be speed-resistant and comfortable. It is manufactured with various features depending on whether the journey is short or long. Passenger wagons include compartment wagons, couchette wagons, sleeping wagons, Pulman wagons, dining wagons, suburban and lounge wagons (Figure 2) [7].

The interior of the compartment wagons (Figure 2) is divided into a certain numbers of sections, namely compartments. In each of these sections, two or three people can sit opposite to each other. Figure 2 shows the interior sector of a compartment passenger wagon.

There are many sections, such as compartment wagons and couchette wagons, among others. The seats in these wagon types, on the other hand, can be configured so that the occupants can lie down comfortably.The couch wagon is utilized in rail systems that provide passengers with a more comfortable environment.

Another type of passenger wagon divided into compartments is the sleeping wagon. In addition to single or double beds in each compartment, these wagons can also have parts, such as a sink, work desk, and shower. Pulman wagons, on the other hand, are wagons made in the form of a saloon without being divided into compartments. There are armchairs at the edges of these halls and a walking path in the middle.

On the other hand, in the dining wagons, there is a kitchen section suitable for all kinds of cooking and dining halls with tables where two or four people eat together. Suburban wagons are suitable for sitting or standing and they are suitable for short distance journeys [9]. On the other hand, saloon wagons are wagons that can be rented by an individual or a group, with a sitting room, dining area, and a place to sleep. Freight wagons are manufactured in different types according to the characteristics of the cargo. At this point, freight wagons will protect the weather-affected goods; will do the filling and unloading as soon as possible; be able to carry long or bulky items with flowing and leaking materials and they are manufactured in a way that will protect those goods that will deteriorate and rot quickly.

There are various types, such as freight wagons, closed wagons, high-sided open wagons, bottom, and side discharged open wagons, platform type, special type wagons, cooler wagons, and cistern wagons, which are manufactured as closed or opened type according to the external weather conditions. Closed wagons are wagons that are used for the transport of goods that may be affected by external conditions and that have doors and windows to load or unload the goods [10].

The height of the high-sided open wagons is 1.5 m. It is used for the transportation of goods such as coal and sand, which are not affected by external conditions. Another open-top wagon type is the wagon type with unloading from the bottom or the side. These wagons are also used to transport goods that are not affected by external factors, such as coal and sand. In this type of wagon, unloading is carried out in facilities suitable for bottom or side unloading. Other types of vehicles including automobiles and buses and lengthy commodities e.g. iron or logs (which can be transported by platform-type wagons), and platform wagons are used to move containers or other heavy loads. Grains and other powdered substances can also be delivered in special carts. Refrigerated wagons are also used to transport perishable items like fruits, vegetables, and seafood. In addition, cistern wagons are used to transport substances, such as liquid or gaseous fuel, acid, milk, and oil. Other towed vehicles are generator wagons that provide electricity generation in passenger trains, heating wagons, ballast wagons that provide the transport of ballast used in railway maintenance or renovations, and long rail transport wagons that provide the transport of long and welded rails from the rail factory.

Figure 3: Road renewal machine [12].

2.3 *Road machinery*

They are railway machines used in the detection and repair of road faults. In railways, it is diversified as construction equipment, fault detection machines, work cars, road renewal machine and trains, ballast screening machines, tamping machines, ballast regulators, ballast ramming machines, and dynamic line stabilizers. Diagrams about issues, such as the status of the line, the quality of the superstructure material, the condition of the road axes are created with the fault detection machines [11].

Business vehicles are diesel-powered railway vehicles that can only go on the railway or both on the railway and on land, can be mounted on wagons, have magnets and hook cranes mounted on them, and can carry vehicles, materials, and passengers, such as workers who repair railways in their chassis. With these vehicles, road maintenance and repair teams and their materials can be transported in a wagon, and with their cranes, materials can be loaded or unloaded into the wagons.

A road renewal machine (Figure 3) is a construction machine that can replace the rail and sleeper on existing railways or is used for laying rail and sleeper on new roads. When driving a wagon, safety wagon and sleeper wagons are added to it, it turns into a road renewal train. These construction machines are brought to the workplace by a locomotive and move with their traction power at the workplace. There are rails on both sides of the traverse wagons that the crane can walk on. The road renewal machine (Figure 3) is used to replace the rail and sleeper of a railway.

Ballast screening machine takes the polluted ballast under the existing road and shift it with the vibrating screens on it, keeping the standard ballast in the line and the non-standard ballasts and slag out of the line. The bad ground that is desired to be removed under the line is corrected by sieving.

Tamping machines are used in horizontal and vertical axis misalignment and the repair of broken roads. By compressing the existing ballast on the road under the sleeper, it is ensured that the ballast provides the best bearing for the road. Taming machines are manufactured and designed according to user needs. By adding small-scale rammers to taming machines, the ballast of the road, which is brought to its axis, is compressed from the outside. In this case, it is ensured that the road serves for a long time without deterioration. The tamping machine is used to repair broken railway roads.

The ballast regulators ensure that the ballast in the line is arranged in accordance with the ballast profile. These construction machines are used to transfer the excess ballast on one side of the line to the other side. Ballast regulators are operated in front and behind the tamping machines.

The ballast ramming machine compacts the ballast on the profile shoulders of the tampered sections of the sleepers by means of its vibratory rammers and this condition is maintained. On the other hand, dynamic line stabilizers ensure that the road is stable; It prevents the line from breaking and escaping [13]. Figure 4 shows a dynamic line stabilizer used to make sure that the railroad is stable.

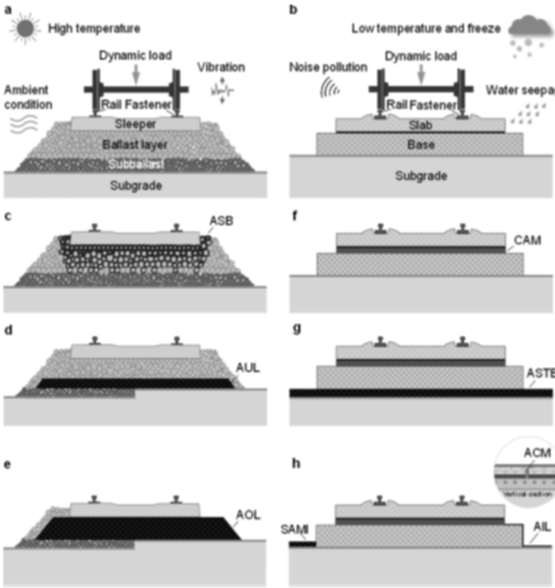

Figure 4: Schematic of dynamic line stabilizer [13].

2.4 *Vehicle fasteners in railway vehicles*

In railway vehicles, the device that connects each vehicles together, transmits the pulling motion, absorbs some of the dynamic forces in pulling, and pushing, is expressed as a "traction device"[14]. There are three types of traction devices, such as hook clutch, semi-automatic clutch, and automatic clutch. Draw frames with automatic coupling transmit pushing motion as well as pulling. The hook-clutch drawbar assembly includes drawbar hook, drawbar, drawbar spring, harness piping, harness shaft, harness nut, and harness stirrup. The systems used in the Cer susta package are of two types including conical coil spring and bracelet spring.

The semi-automatic clutch drawbar acts both as a buffer and as a drawbar hook. The tying takes place automatically with a buffer and the uncoupling takes place manually by means of a lever. In addition, the harness on it allows connection to a wagon with a hook grip. In the semi-automatic draw frame coupling, the harness heads are placed in the “clutch-ready position”. For this, the release arm is taken perpendicular to the rail and if the wagon is on a straight track, the heads of the harnesses are taken to the axis of the wagon. In the wagon curve, the axes of the harness heads are placed in the grip position.

Fully automatic traction (Figure 5) is found on some electric units and railbuses. It acts as a buffer and drawbar hook. Binding and unbinding happen automatically. In addition to the mechanical connection, the electrical connection with the air connection takes place automatically when the bonding takes place. Figure 5 shows an automatic clutch traction assembly during both open and closed knuckle conditions.

2.5 *Bumpers*

Bumpers provide damping of the forces coming in the direction of the rail and transmitting them softly to the

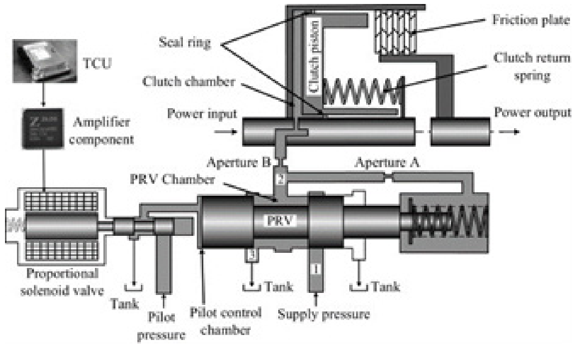

Figure 5: Automatic clutch [15].

chassis. The bumpers are fixed to the bumper cross member with four bolts. The parts that make up the body of the bumpers are made of forged or cast steel, and the clasps or bracelets inside are made of spring steel. Wrapped conical, helix, and bracelet springs are generally used in bumpers [16].

A typical bumper consists of a bumper support plate, a bumper outer body, a bumper connecting plate bolted to the wagon, and a shock absorber inside. Shock absorbers are diversified as helical spring, ring spring, elastomer, hydraulic shock absorbers.

2.6 *Collision buffers*

Collision bumpers are the type of bumper found in freight wagons carrying dangerous goods. In the case of large impact forces (greater than 1.5 MN), the collision bumpers deform plastically and do not return to the starting point. When large forces act on the bumper, plastic deformation occurs in the bumper's outer body to absorb some of the collision energy [17]. The crashworthy buffer of a train is normally used to absorb collision energy.

The collision buffer is a buffer consisting of two tubes. One of the tubes has an impact plate mounted at its ends, while the other tube has a connecting plate to be fixed on the wagon. On the other hand, there is a spring between the impact plate and the inner tube.

Collision buffers are simple and low-cost structures in which a large amount of energy is stored or used. These bumpers, which can be easily mounted on the vehicle, can absorb energy in two phases with elastic and plastic deformation. It prevents overloading of the vehicle, its structure, and components during strong impacts and collisions [17].

The two thin-walled tubes are also of different lengths. Thus, while the amount of elastic deformation in the spring (Figure 5) comes to an end, plastic deformations in the tubes do not occur simultaneously in order to maintain the constant force formed during plastic deformation.

3 Design of Bumpers

Bumpers are structurally composed of three main parts. These are expressed as “buffer cap”, “thin-walled tube” and “spring”.

According to Hosseini and Tehrani's research, the “thin-walled tube” is very effective in preventing deformation as a result of the impact and absorbing the kinetic energy generated by the impact. Especially as energy absorbers, these structures have been used in different ways in different areas [18]. On the other hand, by developing a simplified model for square pipes examined by Pyrz and Krzywoblocki [19], the value of “Average Impact Force” in the structure was obtained.

The material properties, effects of geometry, and boundary conditions of the thin-walled tube in the bumper in an axial collision and axial buckling in the bumpers were investigated by Jensen *et al.* [20] . Consequently, axial torsion in the thin-walled tube is another factor in the buffer design. One of the factors affecting the design of the buffer structure is external inversion. According to Haidari and Tehrani [21], as a result of their research, the wall thickness of the tube is shaped according to the external inversion stress of the corner radii on the cap. Hosseini and Tehrani have investigated in detail the axial buckling and external inversion regarding the bumper design they have examined in their article [21]. Figure 6 is a schematic design of a bumper designed by Haidari and Tehrani [21].

In addition, Hosseini and Tehrani used carbon steel AISI 1018 as the material in the rigid parts of the bumper, which they designed and analyzed [21]. Hosseini and Tehrani chose this material in line with the information in the articles they reviewed [21]. For the spring, elastomer structures are in question, and due to the lack of rigid material, they have been defined in the LS-Dyna program.

Hosseini and Tehrani analyzed the thin-walled tube as a finite element model in the LS-Dyna program

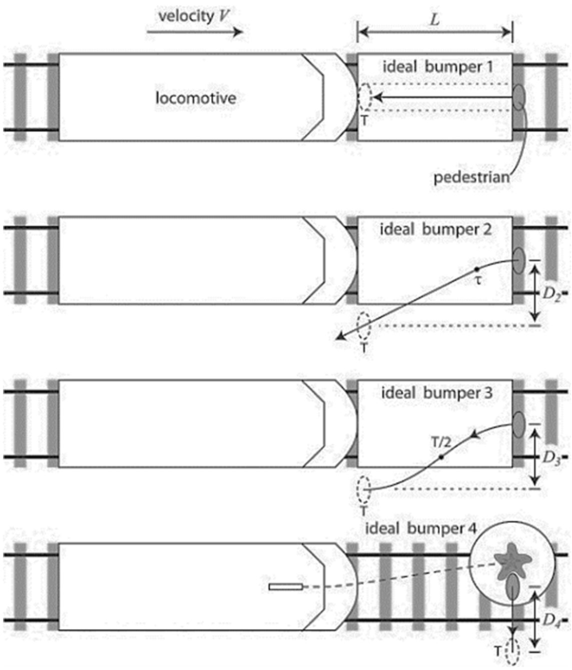

Figure 6: Bumper design [21].

[21]. Here, it is modeled with the element type "Belytschko-Tsay Four-Node, Shell Element With Five Integration Points" along the wall thickness surrounding the tube. "Quadrilateral elements" were determined as the mesh type. "Self-contact interaction" and "Automatic Single Surface" are defined in order to prevent the "interpenetration" situation on the wall of the tube. "Node – to – surface" and " surface – to – surface" contacts are defined to define the contacts between the head and support plate and the tube. In addition, the "Cowper & Symond" material model is based on the yield and tensile strength of the material. The equation of this material model [Equation (1)] is as follows [21].

$$\frac{\sigma_d}{\sigma_s} = 1 + \left(\frac{\varepsilon}{C}\right)^{1/q} \tag{1}$$

In Equation (1), the "Cowper & Symond material model" is expressed as the ratio of dynamic yield stress to static yield stress. "Cowper & Symond" coefficients (C = 40 1/s; q = 5) were entered according to this material model. Also in the article, the coefficient of friction is 0.2 [21]. The buffer length is 620 mm and the stroke is 110 mm.

According to Reid, in thin-walled tubes, there are three separate stresses arising from axial buckling, external inversion, and axial splitting tests, and these three factors are taken into account in the bumper design [22].

The friction coefficient for the tube is accepted as 0.15. On the other hand, with the axial buckling test performed by Reid, the tube was compressed by a maximum of 70 mm. The sample reaches its compression value of 70 mm after producing more than 500 kN of resistance [22].

In the external inversion test performed in the same article, three different radii support plates were used. A support plate with a radius of 10 mm was used, and cracks occurred in the tube by flaming. On the other hand, the average force values of 85 and 80 kN, respectively, were obtained in the tubes in which support plates with radii of 4 and 6 mm were used [22].

In the axial splitting test, the force and compression amount in the tubes where the support plates with 4 and 6 mm radius radii are subjected to axial splitting by being compressed to the support plate with a radius of 10 mm. Here, each line type changes according to the stopping distances of the tubes to the support plate during the experiment [22].

Abramowicz and Jones presented the following formulas [Equations (2) and (3)] for the theoretical buckling of thin-walled tubes after a detailed study [23].

$$\frac{P_B}{\sigma_0 * \left(\frac{t^2}{4}\right)} = 20.79\left(\frac{D}{t}\right)^{t/2} + 11.9 \tag{2}$$

$$\frac{\mathrm{H}}{\mathrm{R}} = 1.76\left(\frac{\mathrm{t}}{2}\right)^2 \tag{3}$$

In Equation (2), the compressive force applied during buckling is related to the yield stress of the material, the diameter of the tube, and the wall thickness of the tube. Here, the buckling is assumed to consist of three fixed (material) bending points separating the two outward-moving parts in a section of length 2H subjected to circumferential elongation [23]. Another study on thin-walled tubes is the article published by Gao *et al.* [24]. They discussed the experimental investigation of an active-passive integration energy absorber. In railway vehicles, the active-passive

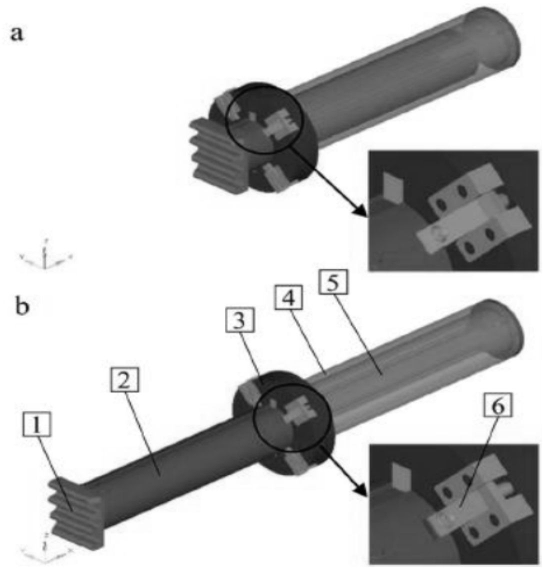

Figure 7: Active–passive integration energy absorber and parts [24].

integration energy absorber device located between two connected wagons by a traction device is located on the right and left of each wagon. Thin-walled tubes in the assembly are located in a separate device. There are six separated parts in the analyzed absorbent structure (Figure 7). These are the support assembly (1), the discharge tube (2), the support part (3), the guide tube (4), the reversible actuator (5), and the stop (6) parts, respectively [24]. Active-passive parts of the integration energy absorber are shown in Figure 7.

Figure 8 shows the function of an energy absorber with active-passive integration. As shown in (a), the absorber does not affect the coupling of the two vehicles during normal operation. Before the rail car collides, the reversible actuator extends the discharge tube along the guide tube and inserts it into the stop groove to lock the discharge tube as shown in (b). Increasing the length of the discharge tube frees the coupler limits in the longitudinal dimensions of the absorption tube, resulting in a significant increase in the discharge tube's deformation path (stroke). When a collision occurs, the support assembly undergoes an initial impact, and as shown in (c), some of the initial collision energy is absorbed by the pressure on the surface of the discharge tube. As shown in (d), the two clutches collide, the energy generated by the collision in the deformed pipe is released, and the shear bolt of the

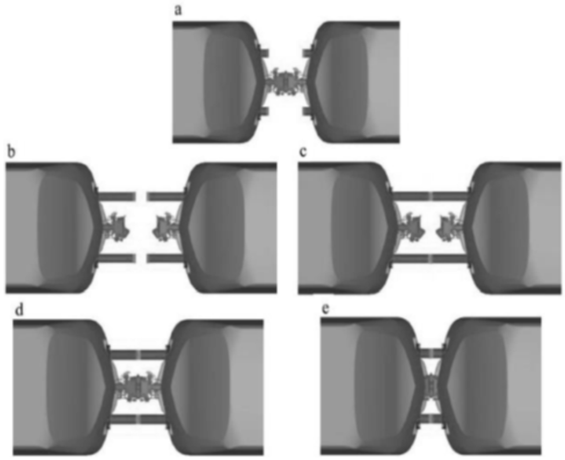

Figure 8: Collosion scenario and absorber [24].

clutch is damaged by the impact. When the coupling returns to the car, the discharge tube absorbs most of the impact energy. As seen in (e), the coupler is entirely retracted within the rolling stock, at which point the front ends of the rolling stock begin to collide and the non-vital components at the ends of the rolling stock undergo plastic deformation to dissipate the remaining impact energy. Because the absorber absorbs the majority of the kinetic energy in the impact, damage to the ends of railway carriages is considerably reduced [24]. Figure 8 depicts the collision situation as well as the absorber's response.

Structurally, this shock-absorbing mechanism is similar to conventional multi-stage shock-absorbing systems. However, the additional crushing area is provided to reduce the collision severity as compared to conventional mechanisms. This, in turn, reduces the severity of the collision and allows the railway vehicles to absorb the additional kinetic energy of the collision. Additionally, the crush area is provided by the double-acting cylinder reversible actuator extending and retracting the discharge tube using compressed air in the storage tanks. The pressure tube is made of AA7075-T4 and AISI 1045 material, and the stop is made of high-speed steel [24].

4 Conclusions

While railway vehicle transportation system is a sort of fast, large capacity, almost environmentally friendly, and safe system. It is important to take into consideration a major problem, which is vehicle collisions. Railway collisions are a complex issue covering various topics, this made collisions of railway vehicles to be a major research topic for several researchers. The use of more safe bumpers, the use of stronger materials, better designs with a stronger ability to absorb collision energy made researchers focus on finding solutions for such important problems due to its dangerous impact on humans (passengers), goods (cargo utilities), and dangerous materials (toxic substances, gas, and even military-related materials end equipment, etc. Therefore, a strong collision might lead to dangerous catastrophes especially in the case when transporting passengers (high-level capacity) or in the case of dangerous materials (toxic substances), which will lead to enormous danger. Collision bumpers in freight wagons deform plastically when subjected to relatively high forces (larger than 1.5 MN), then they return to the starting point after deformation. This mechanism helps in absorbing some of the energy generated during a collision. Such bumpers mainly consist of two tubes, one with an impact plate, the other with a connecting plate. These bumpers are composed of thin-wall tubes, which are a major part of bumpers since they play an effective role in preventing deformation. This paper is an endeavor to summarize different research conducted in the field of railway collision improvements. The review focuses on studies concerning bumpers and thin wall tubes and how to improve them. Some researchers carried out the development of new simplified models for square pipes of bumpers, others focused on material properties, the boundary condition of thin wall tubes, the effect of geometry when subjected to axial collision. In addition, studying the relation between external invasion and its impact on wall tube thickness was conducted too. A future suggestion from this review is that an attractive issue can motivate researchers to explore different approaches to strengthen bumpers and reduce the effectiveness of collisions on railway vehicles, as suggested in this review.

References

[1] R. A. MacNeill, S. W. Kirkpatrick, R. T. Bocchieri, and G. Gough, "Development of a prototype retrofit bumper for improved Light Rail Vehicle safety," in *Joint Rail Conference*, 2015, pp. 1–8, doi: 10.1115/JRC2015-5810.

[2] W. Johnson and A. G. Mamalis, *Crashworthiness of Vehicles*. England: Mechanical Engineering Publications, 1978.

[3] E. Andersson, M. Berg, S. Stichel, and C. Casanueva, *Rail Systems and Rail Vehicles: Part 2: Rail Vehicles*. Stockholm, Sweden: KTH Royal Institute of Technology, 2016.

[4] B. Szaksz and G. Stepan, "Stability charts of a delayed model of vehicle towing," *IFAC-Papers OnLine*, vol. 54, no. 18, pp. 64–69, 2021, doi: 10.1016/j.ifacol.2021.11.117.

[5] F. J. G. Haut, *Electric Locomotives of the World*. UK: Bradford Barton, 1977.

[6] M. Cipek, D. Pavković, M. Krznar, Z. Kljaić, and T. J. Mlinarić, "Comparative analysis of conventional diesel-electric and hypothetical battery-electric heavy haul locomotive operation in terms of fuel savings and emissions reduction potentials," *Energy*, vol. 232, 2021, Art. no. 121097, doi: 10.1016/j.energy.2021.121097.

[7] Y. H. Chang, C. H. Yeh, and C. C. Shen, "A multiobjective model for passenger train services planning: Application to Taiwan's high-speed rail line," *Transportation Research Part B: Methodological*, vol. 34, no. 2, pp. 91–106, 2000, doi: 10.1016/S0191-2615(99)00013-2.

[8] A. Rodríguez, R. Sañudo, M. Miranda, A. Gómez, and J. Benavente, "Smartphones and tablets applications in railways, ride comfort and track quality. Transition zones analysis," *Measurement*, vol. 182, 2021, Art. no. 109644, doi: 10.1016/j.measurement.2021.109644.

[9] S. Coxon, K. Burns, and A. D. Bono, "Design strategies for mitigating passenger door holding behavior on suburban trains in Paris," in *33rd Australasian Transport Research Forum Conference*, 2010, pp. 1–15.

[10] M. Paczek, A. Wróbel, and A. Buchacz, "A concept of technology for freight wagons modernization," *IOP Conference Series: Materials Science and Engineering*, vol. 161, no. 1, 2016, doi: 10.1088/1757-899X/161/1/012107.

[11] Q. Li, Z. Shi, H. Zhang, Y. Tan, S. Ren, P. Dai, and W. Li, "A cyber-enabled visual inspection system for rail corrugation," *Future Generation Computer Systems*, vol. 79, pp. 374–382, 2018, doi: 10.1016/j.future.2017.04.032.

[12] R. Mohammadi, Q. He, and M. Karwan, "Data-

driven robust strategies for joint optimization of rail renewal and maintenance planning," *Omega*, vol. 103, 2021, Art. no. 102379, doi: 10.1016/j.omega.2020.102379.

[13] X. Xiao, D. Cai, L. Lou, Y. Shi, and F. Xiao, "Application of asphalt based materials in railway systems: A review," *Construction and Building Materials*, vol. 304, 2021, Art. no. 124630, doi: 10.1016/j.conbuildmat.2021.124630.

[14] L. Li, D. Thompson, Y. Xie, Q. Zhu, Y. Luo, and Z. Lei, "Influence of rail fastener stiffness on railway vehicle interior noise," *Applied Acoustics*, vol. 145, pp. 69–81, 2019, doi: 10.1016/j.apacoust.2018.09.006.

[15] T. Ouyang, G. Huang, S. Li, J. Chen, and N. Chen, "Dynamic modelling and optimal design of a clutch actuator for heavy-duty automatic transmission considering flow force," *Mechanism and Machine Theory*, vol. 145, 2020, Art. no. 103716, doi: 10.1016/j.mechmachtheory.2019.103716.

[16] B. E. Paden, P. M. Kelly, J. A. Hines, D. Bothman, and C. Simms, "On the feasibility of life-saving locomotive bumpers," *Accident Analysis and Prevention*, vol. 89, pp. 103–110, 2016, doi: 10.1016/j.aap.2015.12.025.

[17] P. Xu, C. Qu, S. Yao, C. Yang, and A. Wang, "Numerical optimization for the impact performance of a rubber ring buffer of a train coupler," *Machines*, vol. 9, no. 10, 2021, doi: 10.3390/machines9100225.

[18] S. Pirmohammad, "Collapse study of a pair thin-walled prismatic column subjected to oblique loads," *International Journal of Automotive Engineering*, vol. 1, no. 4, pp. 267–279, 2011.

[19] M. Pyrz and M. Krzywoblocki, "Crashworthiness optimization of front rail structure using macro element method and evolutionary algorithm," *Structural and Multidisciplinary Optimization*, vol. 60, no. 2, pp. 711–726, 2019, doi: 10.1007/s00158-019-02233-7.

[20] Ø. Jensen, M. Langseth, and O. S. Hopperstad, "Experimental investigations on the behaviour of short to long square aluminium tubes subjected to axial loading," *International Journal of Impact Engineering*, vol. 30, no. 8–9, pp. 973–1003, 2004, doi: 10.1016/j.ijimpeng.2004.05.002.

[21] A. Haidari and P. H. Tehrani, "Crack driving force calculation for a railway wheel considering thermoplastic properties of the wheel material TT," *IJRARE*, vol. 7, no. 1, pp. 29–39, Jun. 2020, doi: 10.22068/IJRARE.7.1.29.

[22] S. R. Reid, "Plastic deformation mechanisms in axially compressed metal tubes used as impact energy absorbers," *International Journal of Mechanical Sciences*, vol. 35, no. 12, pp. 1035–1052, 1993, doi: 10.1016/0020-7403(93)90054-X.

[23] W. Abramowicz and N. Jones, "Dynamic axial crushing of circular tubes," *International Journal of Impact Engineering*, vol. 2, no. 3, pp. 263–281, 1984, doi: 10.1016/0734-743X(84)90010-1.

[24] G. Gao, W. Guan, J. Li, H. Dong, X. Zou, and W. Chen, "Experimental investigation of an active–passive integration energy absorber for railway vehicles," *Thin-Walled Structures*, vol. 117, pp. 89–97, 2017, doi: 10.1016/j.tws.2017.03.029.