Modeling of nonlinear shock deformation of passenger car bodies with emergency exits

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Abstract. Original design solutions for passenger car bodies equipped with emergency exits have been proposed. The operability and safety of the proposed structures is evaluated based on the modeling of the load bearing structures in emergency situations. Two options for the development of an emergency are considered: a collision with a car on a level crossing and rollover. The analysis of loading was performed by the finite element method in a dynamic nonlinear formulation. The finite element models of the supporting structures of the bodies of passenger cars with evacuation exits and without them have been developed. Model verification was performed by field bench tests. The dynamic loading was estimated in a dynamic setting by the explicit integration method based on the central difference method with keeping the accelerations constant within the step and quadratic approximation of the displacement vector for three consecutive moments of time. The data obtained as a result of the study on the stress-strain state of the supporting structure indicate the operability and safety of the proposed solutions. A variant of the body structure of a double-decker car is protected by a patent for a utility model.

1. Introduction

At the first stage of the work, an analysis of world experience in the field of studies of the behavior of passengers and railway personnel in emergency situations related to its roll-over on a side wall was carried out. Active work in this direction is carried out by world leaders in the field of rolling stock safety by the US Federal Rail Administration (FRA) [1-3], the British Association according to railway safety standards (RSBB) [4, 5], Cranfield University [6], the University of Vienna [7] and others. The results of research by specialists are taken into account in a number of national standards [8, 9].

Along with theoretical studies, specialists of these scientific organizations carry out a significant amount of field tests, including using specialized stands created in the USA and Great Britain, as well as involving volunteers.

An analysis of the study of foreign experts showed that in order to ensure a sufficient speed of evacuation of passengers and the train during its lean-to in the event of an emergency, it is necessary to provide additional emergency exits.

Domestic passenger rolling stock has significant differences from foreign analogues both in terms of the layout of cars and in terms of body structure.

In this regard, the work evaluated the design solutions that ensure the evacuation of passengers from new-generation passenger cars manufactured by “Tver Carriage Works” OJSC in the event they are rolled-over sideways due to emergency situations.
In the event of an emergency, according to the designs of domestic passenger railcars, the evacuation of passengers is carried out through the front doors located in the car’s lean-to and emergency exits. Emergency exits in passenger cars are windows equipped with special devices to ensure their destruction or dumping with minimal effort. When a passenger car is tipped over to the side wall as a result of an emergency, some of the exits are blocked (exits on the side wall that is under the car), and access to the other emergency exits is complicated, since they are located on the opposite side wall, which has a ceiling position. With an internal width of the car exceeding 2.8 m, a passenger located on one side wall does not have the ability to freely reach the exits on the opposite wall. In this position, the passenger can get to the emergency exits when providing special assistance from the outside of the car or using elements of the interior of the car with special devices.

If a passenger is injured as a result of an accident and cannot evacuate independently from the car through emergency exits located in the upper position, it becomes extremely difficult. To evacuate passengers in such situations, it is proposed to equip the cars with additional emergency exits located on the roof of the car and in the frame of a two-story car. Such an arrangement of exits allows passengers to leave the car body in a shorter time when it is on its side.

2. Constructive decisions for bodies of passenger cars with additional emergency exits

As objects for the proposed modernization, a new-generation compartment carriage model 61-4440 and a two-story passenger car with seats for model 61-4492 manufactured by Tver Carriage Building OJSC are considered.

The analysis of the layout of the car, the layout of the supporting structures of the body, system elements, power supply, lighting, ventilation and fire alarm located in the space under the roof and in the frame of the two-story car made it possible to determine the areas for the possible location of additional evacuation exits. For the car model 61-4440, the location of the additional emergency exits is above the corridor (Figure 1).

Based on the analysis of studies conducted by foreign experts [10], it was concluded that two additional evacuation exits A and C are enough to ensure the evacuation of the maximum number of passengers provided for by the technical documentation for the car (36 people) (Figure 1). Taking into account the manufacture of “Tver Carriage Works” OJSC on the basis of the body of non-compartment carriages of model 61-4447 with a population of 54 passengers, the location of three evacuation exits A, B, C is proposed.

The dimensions of the evacuation exits are taken based on ensuring unhindered evacuation of passengers from the car, including those injured using special devices (stretchers, immobilization shields (backstrap)). At the same time, they should minimize the weakening of the supporting body structure and not require significant equipment upgrades in the ceiling space and on the frame of a two-story car.
Taking into consideration these limitations in the design of a passenger car, it was proposed to provide three additional rectangular evacuation exits in the roof of the body over a large corridor with dimensions (in clear) of 600 × 730 mm located at a distance of 6510, 11810 and 17210 mm from the end beam of the brake end of the car (figure 1).

Additional evacuation exits on the roof are closed by covers, providing tightness, thermal insulation and body strength. The mechanism for fastening the covers of evacuation hatches ensures their reliable fastening during the normal operation of the car and eliminates their spontaneous opening under all types of operating loads. In emergency situations, the mechanism for fastening the cover of the evacuation exit ensures its unhindered opening and reset when maximum force is applied to the unlocking lever of 50 N.

Since the presence of additional evacuation exits in the car roof leads to a decrease in its load-bearing capacity, an analysis of the operability of the variants of load-bearing structures of passenger car bodies proposed in this work is considered.

As a performance criterion, the conformity of the supporting structure of the car body to the requirements of EN 12663 [11] is taken.

3. The study of the dynamic loading of the bodies of passenger cars with additional emergency exits

The operational strength of the supporting structure was evaluated on the basis of the developed plate finite element models consisting of 130 thousand elements connected by 126 thousand nodes, which has 750 thousand degrees of freedom for the car model 61-4440 and 72 thousand elements united by 63 thousand nodes, and having 380 thousand degrees of freedom for the car model 61-4492 (figure 2).

![Finite element models of cars with emergency hatches](image)

**Figure 2.** Finite element models of cars with emergency hatches.

The adequacy of the results obtained using the proposed models was assessed by comparing them with the results of full-scale bench tests.

The paper analyzes the stress-strain state of the car body with evacuation hatches from the loads recommended by [11].

A comparison of experimental and calculated data showed their qualitative and quantitative agreement, the difference did not exceed 14.2%, which confirms the adequacy of the developed finite element models.

The analysis of the stress-strain state of the initial load-bearing body structures equipped with emergency exits within the framework of the requirements of [11] showed that their presence does not affect the global stress-strain state of the body. At the same time, local voltages in the output zone are within the limits allowed by the standards. Significant deformations of the contours, hatches, capable of creating an obstacle to their opening are not found.

Since the use of evacuation hatches is provided after an emergency, it is necessary to consider the load on the structures of the hatches, as well as their covers during emergency collisions and lean-to of bodies onto the side wall.

The analysis of the loading of exit zones in emergency situations was carried out for the two most likely development scenarios: a collision with a car at a level crossing and lean-to onto the side wall of cars. At the same time, finite-element design schemes for the bodies were supplemented with finite-element models of hatch covers (figure 3).
The interaction of hatch covers with a body model was described by the introduction of special rod end elements. The presence of seals was taken into account by introducing volumetric finite elements with the property of a nonlinear elastic material along the contour of the hatch covers. The properties of volume elements were described on the basis of experimentally obtained force characteristics of the seal material.

The forces effecting the supporting structures of the car bodies in a collision with a car at the level crossing were taken, in accordance with the recommendations given in [12-15].

When simulating the lean-to of a car onto a side wall, the model was supplemented with a supporting surface with elastic-dissipative characteristics corresponding to the characteristics of an elevated approach made of crushed stone of a fraction of 25–40 mm (figure 4). The longitudinal $a_x$ and angular $a_\omega$ accelerations of the body at the initial moment of calculation were taken in accordance with the simulation results of a similar emergency given in [16].

The simulation was carried out in a nonlinear dynamic formulation by explicitly integrating the equations of nodal displacements based on the method of central differences with keeping the accelerations constant within the step and quadratic approximation of the displacement vector for three consecutive time instants. In the calculations for the elements of the supporting body structure, an elastic-plastic material was used. Its plastic properties were described on the basis of a simplified Johnson-Cook model of plasticity [17, 18].

4. Conclusions
As a result of the simulation, patterns of changes in stress and strain in the supporting structure over time are obtained. As an example figure 5 shows pictures of the stress-strain state of hatches and covers in emergency situations. The table shows the maximum equivalent stresses and strains in the areas of emergency hatches.

![Figure 3. Finite element model of an emergency exit hatch cover.](image3)

![Figure 4. Car body structure with additional cutouts.](image4)

![Figure 5. The picture of the stress-strain state of the hatch and roof structure in the area of the emergency hatch.](image5)

a) outside view  
b) inside view
The analysis of the results indicates that the maximum equivalent stresses in the supporting structure of the body in the areas of evacuation hatches do not exceed the permissible values. The stresses in the hatch fastening elements and the locking device are also significantly lower than permissible. The strains of the supporting structure in the area of hatches for the considered variants of the bodies are elastic, and their size does not prevent their opening after an emergency. The findings indicate the operability of the proposed design of emergency exits. A patent for utility model № 191688 has been received for the body structure of a double-deck car with evacuation exits.

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Table 1. Results of modeling the stress-strain state of bodies.

| Car model | Stress, strain, MPa | Hatch | Collision with a car | Lean-to the side wall | Hatch |
|-----------|---------------------|-------|----------------------|----------------------|-------|
|           | Hatch #1 | Hatch #2 | Hatch #3 | Hatch #4 | Hatch #1 | Hatch #2 | Hatch #3 | Hatch #4 |
| 6L-4440   | Stress, MPa | 124 | 124 | 124 | 124 | 164 | 129 | – | – |
|           | Strain mm  | 0,71 | 0,86 | 0,86 | 0,86 | 0,71 | 1,26 | 1,19 | 1,07 | 0,99 |
| 6L-4447   | Stress, MPa | 125 | 118 | 97,3 | 97,3 | 162 | 126 | 101,8 | – |
|           | Strain mm  | 1,18 | 1,03 | 0,92 | 0,92 | 1,32 | 1,26 | 1,16 | – |
| 6L-4492   | Stress, MPa | 107 | 98 | 81 | 81 | 120 | 109 | 101 | 94 |
|           | Strain mm  | 1,06 | 0,94 | 0,86 | 0,86 | 0,71 | 1,26 | 1,19 | 1,07 | 0,99 |

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