Prediction of injury to passengers of railway rolling stock based on modern physical simulation methods

S G Shorokhov, O I Bondarenko and V V Kobishanov
Bryansk State Technical University, 7, Boulevard 50 let Oktyabrya, Bryansk, 241035, Russia

E-mail: oljapolushko54@gmail.com

Abstract. A technique for assessing the levels of injury to passengers and train crew members in emergency collisions is proposed. It is based on the use of physical methods for simulating fast-flowing non-linear processes of material deformation in emergency situations and anthropometric dummies. Based on the analysis of world and domestic experience in the study of injuring people in emergency situations in transport, an anthropometric 50 percentile male Dummy Hybrid III was adopted as a research tool. Its mathematical model is developed. It was verified by data from field experiments. The developed dummies are integrated into mathematical models for the development of emergency scenarios. As objects of study, the most promising types of rail car layout and two locomotive options were considered for the domestic rolling stock. Based on the simulation results, the values of the criteria for injuring passengers and members of locomotive crews in emergency situations are obtained. The most dangerous positions of passengers in the car during longitudinal collision of trains for the considered layout options are determined. It has been established that the most serious injuries are suffered by passengers and members of locomotive crews as a result of their interaction with car interior items and controls of the driver’s cab.

1. Introduction
The analysis of domestic and world statistics on injuries to passengers traveling by rail showed that the most common are injuries resulting from longitudinal collisions of trains with obstacles in the form of cars at level crossings or units of rolling stock on tracks. For this reason, these two emergency scenarios were adopted as reference in the regulatory documentation for the design of rolling stock supporting structures and means for ensuring passive safety. At the same time, an analysis of the consequences of such emergencies shows that passengers are injured due to falling from shelves to the floor, hitting tables or other elements of the compartment’s interior, including ripped off mounts, collisions with other passengers, and are also injured as a result of falling luggage.

The severity of injuries is determined by a combination of factors, such as the collision speed, the obstacle nature, the rolling stock design and others and are subdivided into: severe – in 6% of cases; moderate severity – about 17%; light – 79% (of which light injuries are injuries with short-term health disorder – 55%, and 24% – without short-term health disorder) [1]. In the group of severe injuries, head and limb injuries in the form of fractures are observed in 75% of cases. Less commonly observed are injuries of the internal organs and chest. At the same time, the collision of trains with high speeds leads to 7% of fatal cases and 57% of cases of severe bodily injury [1]. In this case, the head part of the train is the most traumatic, as it experiences the greatest dynamic stress. In this regard, the risk of...
serious injury to members of the locomotive crew is even higher. The main reasons for such injuries, including fatal ones, are the shock interaction of crew members with cabin interior items, and controls. In this regard, the urgent task is to predict the consequences of emergency collisions for passengers and members of locomotive crews at the design stage of the rolling stock interior. Based on the results of forecasting, constructive solutions of the internal interior of rolling stock which reduce the risks of injuring people in emergency collisions can be developed and implemented. 

In world practice, full-scale tests (crash tests) using anthropometric dummies of various complexity and purpose are used to assess the safety of cars in emergency situations. The most progressive and sufficiently versatile are the Dummy Hybrid [2], SID, BioSID [3], BioRID [4], THOR [5] dummies, which make it possible to assess with a high degree of certainty the levels of possible injury to people in emergency situations.

2. Development of a mathematical model of an anthropometric dummy

Three types of adult male dummies are used to assess the safety of ground vehicles from the Dummy Hybrid III family, the 5th, 50th and 95th percentiles, while the 50th percentile Hybrid III 50th Percentile Male dummy corresponds to an “average” adult male and is considered to be the most common test dummy.

When constructing a computer model of an anthropometric dummy, the following assumptions and limitations were made:

- parts of the human body are absolutely solid, that is, they are not deformed under any circumstances;
- geometric parameters and mass of model elements (their length, etc.) coincide with the corresponding parameters of the human body parts;
- model elements are connected in kinematic pairs by spherical or cylindrical joints.

With the simplifying assumptions made, based on the data given in [6, 7], the original solid-state model of the anthropometric dummy Hybrid III 50th Percentile Male was developed (figure 1).

![Figure 1. Developed model of the Hybrid III 50th Percentile Male Dummy.](image)

A distinctive feature of the obtained model is the presence of a hinge modeling the hip joint. A dummy is a combination of absolutely rigid bodies with real weight and geometric characteristics (head, neck, upper body, shoulder, hip, etc.), united by hinges into a single model. The parameters of solids were taken in accordance with the data given in [6]. Articulated joints imitating human joints were described using rotational and generalized power joints with specified elastic-dissipative characteristics [8-10]. To accurately describe the kinematics of movement of the human body parts in the dummy model, rotation restrictions of its components are introduced in accordance with the real capabilities of human joints [11, 12]. The possibility of contact interaction of dummy elements with each other using a set of special contact elements of the sphere-sphere type is also taken into account allowing to limit the penetration of the dummy parts into each other during their mutual movement.
For a more accurate analysis of the degree of possible injury to passengers during solid-state modeling, the mechanical characteristics of the biological tissues of the human body under the influence of shock loads were taken into account by introducing power contact elements between the dummy model and the interior elements of the compartment or the cab of the locomotive. Since the muscles of the body perceive the main impact of shock forces, the elastic-dissipative properties of the dummy material elements were taken into account in accordance with [10, 13] when setting contact stiffness parameters.

The developed model of the anthropometric dummy allows us to analyze the levels of dynamic effects on dummy elements: linear and angular displacements, speeds and accelerations, as well as contact impact forces. On the basis of the dynamic forces obtained when modeling the dummy elements, the level of passenger injury in emergency situations [6] is estimated based on the calculation of universal indicators – injury criteria [14]. The criteria formulated in the regulatory documentation of the US National Highway Traffic Safety Administration (NHTSA) [14] were used in the paper. Within the framework of the adopted approaches, the following criteria for injuring a passenger are distinguished: a criterion for traumatic brain injury (HIC), a criterion for injuring a neck (Nij), a criterion for injuring a chest (CTI), a criterion for injuring a hip (FFC).

When calculating the criteria for injury, acceleration, tensile and compressive axial forces, as well as bending moments acting on the dummy elements are taken into account. Moreover, for each criterion, based on an analysis of the consequences of accidents, normalized values are established [14].

The adequacy of the developed anthropometric dummy model was assessed by comparing the results of field tests conducted by the US Federal Railways Administration (FRA) [14] with the calculation results. The tests conducted by the FRA are aimed at assessing the safety of various options for passenger seats. The test bench is a platform on which two rows of chairs are mounted at a distance of 81 cm from each other. The front row of seats during the test was empty, on the back there were anthropometric mannequins. Armchairs are rigidly fixed to the platform. The speed of the platform when it hits an obstacle is 36 km / h. The test bench and dummies have got specialized equipment for fixing forces, accelerations and deformation of elements upon impact.

For comparison with the results of full-scale tests, a solid-state model that repeats the test conditions was designed. As a result of the simulation, the time dependences of the dynamic forces acting on the dummy elements were obtained, which made it possible to calculate the criteria for injury: traumatic brain injury, injury to the neck and hip. During verification, the values of the criteria obtained experimentally and by calculation were compared. The comparison results show their qualitative and quantitative compliance, the difference does not exceed 27%, which indicates the adequacy of the developed anthropometric dummy model.

To assess the levels of possible injury to passengers during longitudinal collisions of trains with obstacles, two variants of solid-state models of trains were developed within the framework of the accepted collision scenarios. The first version of the train consists of a six-axle electric locomotive EP2K and four passenger cars: models 61-4458 with a standard layout, models 61-4458 with an improved layout, as well as two compartment cars model 61-4440. The second option is characterized by replacing the EP2K locomotive with a two-system six-axle high-speed passenger electric locomotive EP20. The overall dimensions of the interiors of passenger compartments of cars and its elements correspond to the technical documentation of the manufacturer. Computer models of anthropometric dummies are included in the generated passenger car model (figure 2). When specifying the dummy contact parameters with the surrounding surfaces, the stiffness characteristics of the obstacles – parts of the interior of the passenger compartment – were taken into account. For this, power contact elements of the point-plane type are introduced into the model. The values of the stiffness and dissipative parameters of the contact elements are determined based on the characteristics of the dummy materials and the interior of the compartment. In this case, the value of the damping coefficient is taken equal to 10% of the value of contact stiffness. This approach is used in world practice when simulating the dynamics of the interaction of solids [15].
Figure 2. Location of dummy in mathematical models of passenger’s cars models: a – in the compartment of the wagon; b – in the wagon with increased comfort seats; c – in the standard wagon with seats.

Within the framework of a similar methodology, the models of locomotives are supplemented by subsystems that describe the geometry of the compartment’s interior and anthropometric dummy models, placed in the driver’s and assistant’s seats.

3. Simulation results
In mathematical modeling of an emergency situation, we obtained graphs of dynamic forces acting on dummy elements. As an example, figures 3-6 show graphs of compressive forces, bending moments and accelerations obtained when simulating a train collision with a freight car. Based on the data obtained, injury criteria are calculated (table). Since the developed model lacks the ability to determine chest deformity, a safety assessment was carried out according to the criteria for traumatic brain, neck and hip injuries.

Figure 3. Graphs of changes in the dummy head acceleration over time

Figure 4. Graphs of changes in the forces acting on the dummy neck over time
The analysis of the simulation and calculation results showed that under the design scenarios of a collision, a passenger who is in a sitting position at the window in the direction of the train does not receive injuries that threaten life and health. The calculated values of none of the considered criteria exceed the normalized values, which indicates acceptable passenger safety conditions. However, for the correct assessment of the safety of the interior of the passenger car compartment in emergency situations, an analysis of the various possible positions of the person in the compartment at the time of impact is necessary [16].

**Table 1.** Criteria for injuring passengers in a train collision with an obstacle.

| Position of a dummy in accordance with figure 2 | Collision with a car | Collision with a wagon |
|-----------------------------------------------|----------------------|------------------------|
|                                              | HIC                  | Nij        | FFC | HIC | Nij | FFC |
| 1                                             | 90                   | 0.074      | 98  | 423 | 0.21 | 36  |
| 2                                             | 227                  | 0.38       | 2516| 1102| 1.47 | 8936|
| 1 (near the window)                           | 93                   | 0.076      | 421 | 428 | 0.21 | 1085|
| 2 (near the window)                           | 48                   | 0.13       | 2137| 189 | 0.46 | 7005|
| 3                                             | 72                   | 0.085      | 85  | 364 | 0.18 | 41  |
| 4                                             | 246                  | 0.17       | 1836| 913 | 0.58 | 4567|
| 3 (head to the door)                         | 84                   | 0.082      | 101 | 369 | 0.17 | 52  |
| 4 (head to the door)                         | 384                  | 0.19       | 1087| 1187| 0.78 | 3567|
| 5                                             | 76                   | 0.052      | 71  | 369 | 0.16 | 43  |
| 6                                             | 231                  | 0.31       | 795 | 624 | 0.54 | 3271|
| 5 (head to the door)                         | 72                   | 0.61       | 76  | 329 | 0.15 | 34  |
| 6 (head to the door)                         | 261                  | 0.34       | 894 | 703 | 0.49 | 3842|
| Compartment wagon                           |                      |            |     |     |     |     |
| Standard wagon with seats                    | 10                   | 59         | 0.16| 2264| 194 | 0.53| 7184|
| 11                                            | 57                   | 0.14       | 2138| 181 | 0.61| 6988|
| 12                                            | 63                   | 0.15       | 2272| 161 | 0.49| 7052|
| 13                                            | 78                   | 0.14       | 2205| 209 | 0.54| 7107|
| Wagon with increased comfort seats           | 7                    | 64         | 0.15| 1863| 179 | 0.58| 6368|
| 8                                             | 52                   | 0.16       | 1791| 150 | 0.53| 6211|
| 9                                             | 68                   | 0.15       | 1803| 172 | 0.56| 6234|
| EP2K locomotive driver’s cab                 | Driver               | 821        | 0.74| 2638| 1087| 0.83| 8953|
| Assistant driver                             | 869                  | 0.78       | 2706| 1136| 0.86| 9106|
| EP20 locomotive driver’s cab                 | Driver               | 795        | 0.67| 2009| 1019| 0.80| 8764|
| Assistant driver                             | 824                  | 0.71       | 2136| 1093| 0.83| 9004|

**Figure 5.** Graphs of changes in moments acting on the dummy neck over time

**Figure 6.** The graph of changes in compressive forces acting on the dummy hip over time
To assess the most dangerous positions of a passenger’s body from the point of view of his injury, an analysis of the influence of the passenger’s body position on the degree of his injury when a train collides with an obstacle is made. When simulating, the most unfavorable situation – the passenger is in the first compartment of the first car behind the locomotive – is considered. The 19 most probable passenger positions in a passenger car are studied. Passengers are in a compartment on four shelves with their heads to the window, passengers are on the shelves with their heads to the doors. Passengers are sitting by the window, by the door on the lower shelves, passengers are on each of the seats in a row of a car in a passenger compartment (figure 2). Additionally, the location of the dummy in the cabs of electric locomotives EP2K and EP20 is considered.

The simulation results are summarized in a table.

4. Conclusions
The analysis of the simulation results shows that a collision between a passenger car and a freight car under conditions corresponding to design scenario №2 can lead to serious harm to the health of train passengers. In the studied positions of the body, the passenger can get a concussion and a fracture of the skull bones, which is confirmed by exceeding the criterion of a traumatic brain injury of the normalized value for positions №2 and №4 (head to the door). In position №4, the calculated value of the HIC criterion differs slightly from the normalized one, which indicates a high degree of risk of traumatic brain injury.

The simulation results indicate that the criterion for hip injury for all considered positions of the passenger body in the compartment is in the allowable range of the parameter. The most dangerous according to this criterion are the provisions №2. In other positions, compressive loads are applied to the hip of the dummy without causing serious injury.

The analysis of the data obtained shows that the most dangerous in the totality of the considered criteria are the passenger’s position along the train. In these provisions, the dummies are affected by significant dynamic loads, leading to the onset of injuries of varying severity. The most dangerous situation is position №2, in which, according to the simulation results, the criteria for traumatic brain injury and neck injury were exceeded. The position of the passenger body against the train travel is characterized by small movements of the dummy, which reduces the level of exposure to dynamic loads during movement.

An analysis of the levels of injury to the dummies located in the driver's cab showed that the greatest levels of dynamic effort arise due to the collision of members of the locomotive crew with elements of the control panel. In this case, the excess of the normalized criterion of head injury in a collision with a car and the criterion of injury to the neck and head in a collision with a car is recorded.

The totality of the results allows us to conclude that it is advisable to use computer models of anthropometric dummies, which makes it possible to assess the likelihood of a possible injury to passengers and members of the locomotive crew in emergency collisions with a sufficient degree of reliability. The main reasons for injuring passengers and members of locomotive crews is their collision with interior elements of the passenger compartment and the driver’s cab. Therefore, when designing modern passenger rolling stock, it is necessary to take into account the influence of interior elements of the passenger compartment and the driver’s cab on the safety of people in rolling stock.

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