Simulation of child passenger collision in the rail vehicle interior

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Abstract. Passive safety of rail vehicles is described by two documents. These requirements for structural crashworthiness are covered by EN 15227 standard. The GMRT 2100 standard (currently mandatory in UK) summarizes the requirements for interior safety. The actual legislation deals only with an injury of an average adult male (50 percentile). An assessment of interior passive safety for the wider population (5 and 95 percentile) will be other logical steps (in the near future). This approach is well known from automotive industry. This study identifies the most dangerous factors for child passenger collisions in the interior of a rail vehicle. Virtual simulations, finite element method and multibody simulations are used for that. It is possible to overtake the current trends and to carry out a rail interior safety assessment for children due to the excellent scalability of the VIRTHUMAN model. The data of the vehicle design were obtained from the local producers. The vehicles which are used in this research were developed recently and they are generally used. The injury criteria are used for probability of injury evaluation. Some first recommendations for rail interior design safe for children are provided at the end of this paper.

1. Introduction
The paper describes the simulation of the rail vehicle collision scenario according to the GMRT 2100 standard [1]. Only 50-percentile adult male is considered in current standards. The developers of rail vehicles are usually inspired by the European Standard EN 1176-6:2017 "European safety standard for playground equipment and impact absorbing playground surfacing", when a new vehicle with department intended for child passengers is designed. Hence requirements in this standard are not connected with rail transportation, it is possible to overtake the current trends and to carry out a rail interior safety assessment for children. For this simulation, an interior model consisting of seats with table was created. Interesting part of the modelled interior is the seat padding foam material, which was validated experimentally in previous work [2]. Part of the description is a chosen geometry, material constants, and a finite element calculation network. In addition, the report describes the scaling of the VIRTHUMAN human body model to represent a child passenger. For the explicit simulations the commercial SW Pam-Crash [3] was used. The scaled child model is seated in the seat. Two variants representing the actual seat of the child on the seat are considered. The standard simulations themselves are presented in two configurations, with a folded and unfolded table. The simulations results are significantly influenced by the passenger initial position. It is obvious than this position is difficult to predict. Therefore, the two standard initial positions (observed by experiment) and more non-standard positions are considered. The results are evaluated in terms of kinematics and prediction of injury to the passenger. Based on these, a general recommendation is made to improve the safety of the selected interior type. Some recommendations for rail interior design safe for children are provided at the end of this paper.
2. The rail vehicles passive safety

In an accident, there is generated a large acceleration in the railway vehicle, which is caused by changing its speed. Unrestrained passengers continue to move in the railway vehicle at a constant speed until they reach to a conflict with the interior elements. "The size and the direction of the resultant acceleration which would cause a collision, depend on the type of an accident and other impacts of a train unit." There are two main types of impacts. The primary impact appears, if a train crashes into a large set of stationary or moving objects, which is the source of the generated slowdown. The secondary impact appears, if there are the derailment and overturning sets of certain vehicles, or their impact to the other vehicles of the trainset. Then there are generated different combinations of a vertical, transverse and longitudinal deceleration in this type of impact. The primary impact is often followed by a number of secondary impacts (figure 1). Sometimes there is also possible to occur some of secondary impacts, as there was the case of the train accident in Hatfield. It was caused by the derailing because of broken rails, where the first three car units remained almost untouched on the track in the accident. Due to the complexity of the resulting motions and acceleration during the secondary impacts, there has been considered only the primary impact in most studies of the interior safety. The size of the overall deceleration within the primary impact depends mainly on the following parameters:

- the relative velocity between colliding vehicles,
- the weight of colliding vehicles,
- the collision mechanism and the structural behavior of the train construction,
- the longitudinal deformation, the stiffness or colliding objects.

A lot of research works are focused on the improvement in the structural behaviour of railway vehicles structures by the impact today. Requirements for the vehicle design deal with the new European standard EN 15227. In short, we can say that primarily there is an effort to prevent the danger of a climbing vehicle collision in the energy absorption, the retention survival space, the reducing of the deceleration pulse and reducing of the derailment risk. This standard strives to limit the acceleration acting on the crew for majority of the conflict scenarios up to 5 g. However, the specific load pulses for evaluating the behaviour of vehicle interior features are not treated by any standard yet.

The number of rail vehicle accidents is minimal in contrast to the quantity of road vehicle accidents. It is possible to get better results with a greater volume of the measured data. In the assessing of the rail vehicle interior safety, there should be considered a separate collision scenario for each vehicle there. Although it is definitely important to evaluate the train accident as an accident of each train vehicle unit. The passengers are injured as a result of what happens to their vehicle, not as the result of the whole train movement.

It is also necessary to choose the proper incidents that will be considered. The term "accident" or "incident" often means the fire or the train derailment without a subsequental collision. The passengers are not usually injured in these types of accidents. On the contrary, it sometimes leads to the passengers' injuries without causing a collision (the emergency braking). It is proposed that the term "accident" may include all the accidents of a rail vehicle, which result in an injury. Sometimes there could be the injuries caused after a collision, such as in a situation when the vehicle catches fire, the passenger, who is unable to leave the railway vehicle, could die. So it may happen that the originally minor injuries such as concussion will turn into fatal. Therefore, it is necessary to take into account the evaluation of the railway in the next course:

- the injuries caused by the emergency braking before the initial impact,
- the initial primary vehicle collision that leads to the secondary injury impacts,
- the injuries caused by trying to escape from the vehicle,
- the injuries due to being trapped inside the vehicle.

The primary impact is usually followed by a number of secondary collisions. However, only a low number of the secondary impacts can appear sometimes, as it was in the case in Hatfield rail crash. There was a derailment due to the broken rail, where the first three vehicles of the unit remained almost untouched on the track in the accident. According to the given complexity of movements and the
resulting acceleration of the secondary impacts, in most studies there are considered only the primary impacts concerning the interior safety. The slowdown in the overall size of the primary impact depends primarily on the following parameters.

3. The rail vehicles structures legislation
The passive safety is marginally related to various regulations and standards. From the perspective of the interior, it is worth mentioning DIN 5510-2, UIC 564-2 and EN 13501-1:2007 for non-combustible interior materials. The further requirements are specified in terms of a dynamic seat load through the UIC 566 and UIC 567th in an ergonomic point of view. The special demands are made on the passive safety of the driver's cab. There is a requirement to the windscreen strength as UIC 651 and the other security elements according to UIC 617 (e.g. the escape routes). In terms of passive safety, the structures were partially included into the standard ČSN 12663 in advance, and they particularly relate to the calculations of housing stock. However, a new standard ČSN EN 15227 [4] has been introduced recently. The referring measures in this document represent the last resort of protection on condition of all options fail to prevent the accidents. These standards describe the requirement for the interiors only partly. The legislative which can summarize all requirements for the safe rail interior still does not exist.

4. The human body model
The model (called “VIRTHUMAN”) is suitable for the evaluation of the safety risk in common crash scenarios [5]. The shape of the model is based on the real data from a scanned human body (database CESSAR) with parameters close to 50th percentile figurine. The model is developed by using a multibody approach (MBS). The biggest advantage of this approach is a short computing time. The individual parts of the body (as thorax, pelvis) are usually created as a single rigid body, or are created as a conglomerate of few rigid bodies. Thank to Multibody Structure it is quite simple to place the body model and prepare a crash scenario. The new model has all parts segmented individually (figure 1). Each segment can be pressed separately and each segment has its different stiffness and damping. Thank to this feature, the different response of a soft tissue can be simulated.

![Figure 1. Virtual model of human body](image)

The biomechanical response is improved by validations. The validations are based on data from cadaver tests. Only the public available sources are used for this purpose. The human body is verified in two approaches. First, there are validated only parts of the body (thorax, head, pelvis, etc.). Then, there is validated the human body model as the whole by using the standard sled tests. Thank to this
approach, the biomechanical response of the human body model “VIRTHUMAN” is close to the response of the real human body. Most of human body models and dummies are developed for specific collision scenarios. The new developed human body model is suitable for a general use. The model allows to simulate the front or aside collision of the standing or sitting occupant. The model “VIRTHUMAN” is based on 50th percentile human body parameters, but the whole model is smoothly scalable [6, 7]. The methodology of the automatic virtual human creation allows to create a body corresponding to the age and weight of any European on the base of scaling (figure 2).

5. The numerical model used for simulations
The new model of a real rail vehicle interior was created. The 3D CAD data were obtained from the manufacturers of the rail vehicles in the Czech Republic as [8–10]. Because the seats layout is the same throughout the whole vehicle, it is possible to model only a single seat. The accelerating pulse was chosen in the middle of the theoretical corridor. This corridor is described by prof. Hardy in "Safety Assessments of Passenger rail vehicles in future" and also [1, 11]. There was used a software package Pam-Crash for the calculation for the pre-processing and the post-processing. The time step of calculation was set to $10^{-4}$ ms. The hourglassing was controlled by the output energy. The hourglass energy was less than 5 %. The steel structure of a seat was created through 2D elements. The upholstery was modeled by using 3D elements. The material steel structure was modeled as a piecewise linear hardening by using a Cooper Symons rule. In this type of simulation, there is not necessary to define the failure criteria there. The material of the upholstery was modeled as some foam with strong nonlinearities, considering the different characteristics by unloading. The most difficult problem of this material was the great softness. The risk of a negative element was compensated by a contact type of anticollaps. The other contacts were defined as contacts of deformable solids. The new model of the human body, developed in the project “VIRTHUMAN”, was used for the simulations. The collision scenarios were chosen with a regard to all options of a modeled rail vehicle interior. At first, there was simulated a collision of the passenger sitting in the direction of an acceleration. Next, there was simulated a collision of passenger sitting in the opposite direction of an acceleration. Finally, the collision of standing passenger was simulated. The main parts of these simulations are shown in figures 3 and 4.
6. The validation of foam material

The material model validated by experiments is suitable for seat padding in explicit simulations [12]. The present experiment enables us to assess whether the behaviour of a material model corresponds to the reality [13]. In addition, the material model data can be adjusted to obtain better correlation between collision simulation and the real-world situation. To validate foamed material data, an FEM calculation was carried out, which effectively simulates the experiment. A model of a striker (a rigid body) has been created. The striker model is attached by means of a 1D element to a kinematic joint with a single degree of freedom. These bodies with weights identical to those of the real experimental parts represent the pendulum. The striker hits a cuboid created with solid eight-node elements. This cuboid represents a model of the relevant part of the seat made of a foamed material. Its height is clearly defined (by the height of the part).

The material data is first validated at a higher speed. Figure 5 shows the results of the validation and calculation. Clearly, the behaviour of the non-validated material is rather close to the experimental findings. The strain-rate \( \dot{\varepsilon} \) at the point of impact can be estimated with the aid of the initial striker velocity and the initial height of the part (Eq. 1):

\[
\dot{\varepsilon}(t) = \frac{d\varepsilon}{dt} = \frac{d}{dt} \left( \frac{L - L_0}{L_0} \right) = \frac{v(t)}{L_0}
\]

where \( \varepsilon \) denotes engineering strain, \( L_0 \) is the initial width of the foam, \( L \) is the instantaneous width of the foam, and \( v(t) \) is the instantaneous rate of compression of the foam at time \( t \). Figure 5 shows results of the calculation for the initial speed of 3.9 m s\(^{-1}\). The behaviour of the model is close to the experimental findings. By adjusting the material parameters, much better correlation can be obtained. This is clear from figure 5 which compares the non-validated profile and the validated profile where the latter overlaps with the experimental results at some points.
Figure 5. Impactor acceleration during the fall from the initial height of 880 mm.

The most important inputs for the next simulations are the parameters of foam material model (table 1) for foam seat padding made from Elastoflex W 5662 covered with Holdsworth BHLH 31634. The material model validated by experiments is suitable for seat padding in explicit simulations.

Table 1. The final validated material model parameters with conventions of SW Pam-Crash.

| UNIT | (MM) | (KG) | (MS) | (KELVIN) |
| MATYP | RHO | ISINT | ISHG | ISTRAT |
| 45 | 4E-7 | 3 | 2 | 0 |
| QVM | IDMPD |
| 1 | 0 |
| E | UNLFAC | HYDRO | KSI | SLMULT | Fo |
| 0.02 | 0.25 | 0 | 0.7 | 0 | 3.0 |
| Q1 | Q2 | Q3 | ERATc1 | ERATc2 | ERATt1 |
| 1.2 | 0.06 | 0.01 | 0 | 1 | 0 |
| LCc1 | LCc2 | LCt1 |
| X | Y | X | Y | X | Y |
| 0. | 0. | 0. | 0. | 0. | 0. |
| 0.2 | 3.5·10^{-5} | 0.2 | 9.5·10^{-5} | 0.2 | 3.16·10^{-5} |
| 0.4 | 4.5·10^{-5} | 0.4 | 0.00111 | 0.4 | 0.000414 |
| 0.6 | 7.0·10^{-5} | 0.6 | 0.000159 |
| 0.75 | 0.00013 | 0.75 | 0.000254 |
| 0.8 | 0.00029 | 0.8 | 0.000446 |
| 0.85 | 0.000485 | 0.85 | 0.00159 |

7. The injury evaluation
The passenger injuries in the railway vehicle are mostly caused by the collision of the passenger with interior equipment such as seats, tables, walls and handrails. The injuries and their severity highly depend on what part of a body is injured. Now, there is the place to describe the mechanisms and the injury criteria in terms of five main points here. The injury criteria are given by the Railroad Group Standard GM/RT2100 [1] Issue 5 and the criteria for each body part are given as follows chapters.
7.1. Head Injury Criteria
To prevent head injury, the maximum acceleration of the head shall not exceed 80 g for more than 3 ms and the Head Injury Criterion (HIC) must not exceed the value of 500 over any time interval of 15 ms. The formula for calculating the HIC is given in Eq. (2), where \( t_1 \) represents the start of the time interval, \( t_2 \) represents the end of the time interval, \( A_s \) the resultant acceleration and is equal to acceleration magnitude (in x y z directions):

\[
HIC = (t_1 - t_2) \frac{\int_{t_1}^{t_2} A_s dt}{(t_2 - t_1)^{2.5}}
\]  

(2)

7.2. Neck Injury Criteria
To prevent neck injury, the bending of the neck (\( M_{yc} \)) shall not exceed 310 Nm when under flexion and 135 Nm when under extension. The force on the neck (\( F_y \)) shall not exceed 4170 N when under tension and 4000 N when under compression. At any point in time, the Neck Injury Criterion (\( Nij \)) shall not exceed 1.0. The formula for calculating the \( Nij \) is given in Eq. (3), where \( F_y \) is 6806 N when under tension or 6160 N when under compression and \( M_{yc} \) is 310 Nm when under flexion or 135 Nm when under extension:

\[
Nij = \left( \frac{F_y}{F_{yc}} \right) + \left( \frac{M_{yc}}{M_{yc\max}} \right)
\]  

(3)

7.3. Thorax Injury Criteria
To prevent thorax injury, the maximum resultant of the thoracic acceleration shall not exceed 60 g over any 3 ms interval. The maximum chest deflection shall not exceed 63 mm. The Viscous Criterion (\( V^*C \)) shall not exceed the value of 1.0. The formula for calculating the \( V^*C \) is given in Eq. (4), where \( V(t) \) is the instantaneous chest velocity in m/s, \( C(t) \) is the instantaneous chest compression and \( C = D(t)/229 \), where \( D(t) \) is the instantaneous chest deflection in mm:

\[
V^*C = 1.3 \times V(t) \times C(t)
\]  

(4)

The Combined Thoracic Index (\( CTI \)) shall not exceed the value of 1.0. The formula for calculating the \( CTI \) is given in Eq. (5), where \( A_{int} \) is 90 g, \( D_{int} \) is 103 mm, \( A_{max} \) is the resultant chest acceleration and \( D_{max} \) is the maximum chest deflection:

\[
CTI = \left( \frac{A_{max}}{A_{int}} + \frac{D_{max}}{D_{int}} \right)
\]  

(5)

7.4. Abdomen Injury Criteria
To prevent abdominal injury, the peak abdominal compressive deflection shall not exceed 40 mm. The \( V^*C \) at any time shall not exceed 1.98. The formula for calculating the \( V^*C \) is given in Eq. (6), where \( V(t) \) is the instantaneous abdominal velocity (m/s), \( C(t) \) is the instantaneous abdominal compression and \( C(t) = D(t)/D_{AIB} \), where \( D(t) \) is the instantaneous abdominal deflection and \( D_{AIB} \) is the depth of the uncompressed abdomen test device:

\[
V^*C = V(t) \times C(t)
\]  

(6)

7.5. Leg Injury Criteria
To prevent leg injury, the maximum tibial compression force shall not exceed 8 KN. The peak femur compressive force shall not exceed 4.3 KN and the Tibial Index (\( TI \)) at any time shall not exceed a value of 1.3. It is permissible for the femur compressive force to exceed 4.3 KN up to a maximum value of 5.7 KN subject to the maximum TI value linearly decreasing from 1.3 to 1.0 over the range 4.3 to 5.7 KN. The formula for calculating the \( TI \) is given in Eq. (7), where \( M_c \) is 240 Nm, \( F_c \) is 12 KN, \( M(t) \) is the instantaneous resultant tibial bending moment and \( F(t) \) is the tibial compressive force:

\[
TI = \left( \frac{M(t)}{M_c} \right) + \left( \frac{F(t)}{F_c} \right)
\]  

(7)
8. Initial position of the child passenger
It is obvious that the adult 50-percentile mail can be positioned by known standard recommendations described exactly in GM/RT2100 [1]. This initial position is not known for nonstandard percentiles in rail vehicle interiors. Specially for children is not possible to use the known positions from automotive industry, cause the children during road vehicle crash is belted in special seat. It is not possible to estimate the position virtually. Hence the initial position was tested experimentally with subject close to 50-percentille 6 year old child (111 cm, 20 kg).

8.1. First common initial position (variant I)
In the beginning of long time experiments the tested subject took position quite close to the standard position of adult 50-percentille male. The most significant difference was in the head high and in the angle of the lower legs (figure 6). As input for next simulations was used the position from the pre-simulation on the figure 7.

![Figure 6](image_url)
**Figure 6.** The First standard initial position of tested subject observed experimentally.

![Figure 7](image_url)
**Figure 7.** The relevant pre-simulation of first standard position with the same position of H-point.

8.2. Second common initial position (variant II)
It is necessary to note, than the position of tested subject was changed significantly after some time or after few repetition. The second position (figure 8) was different in the position of h-point of the tested subject. The position of this point is usually very important for interior passive safety tests and simulations. It is not so easy to make final decision about initial position. It will be recommended to provide the experiment with more tested subject in real transportation. For this reason are both initial positions (as pre-simulation of variant I (figure 7) and variant II (figure 9)) considered in the next simulations.

![Figure 8](image_url)
**Figure 8.** The second standard initial position of tested subject observed experimentally.

![Figure 9](image_url)
**Figure 9.** The relevant pre-simulation of first standard position with the same position of H-point.
9. Results of simulations

9.1. Standard initial positions

It was simulated lot of scenarios, although the most significant of them was the two versions of standard initial positions and two positions of table (open and closed) [14]. The most serious injury can be described on the results according to EuroNCAP methodology [15] (table 2) of second initial position of (version II in figures 10 and 11).

![Figure 10. The result of simulation with second initial position with closed table.](image)

![Figure 11. The result of simulation with second initial position with open table.](image)

| Table setting | Head HIC36 | Neck moment (Nm) | Chest deflection (mm) | Abdomen force (kN) | Pelvis | Femur L force (kN) | Femur P force (kN) | Knee L | Knee R | Tibia L | Tibia R moment (Nm) |
|---------------|------------|------------------|-----------------------|-------------------|--------|-------------------|-------------------|--------|--------|--------|-------------------|
| Closed        | > 3000     | 310              | < 18                  | < 0.5             | 4.6    | 5.9               | < 3.8             | < 3.8  | < 112  | < 100  |
| Open          | 1593       | -59              | 37                    | 2.8               |        |                   |                   |        |        |        |

9.2. Non-standard initial positions

Some another injury risks are connected with a non-standard initial positions. It is obvious than especially for children the initial position can be very variable. For this reason another non-standard positions was considered. The safety risk for standing child passenger is shown on the figure 12. This scenario is danger by the possible next falling, but the simulation result can by significantly affected by the small change in initial condition (what can simply lead to nonprecious predictions – the graph on figure 13).

The result of child passenger injury caused by sitting on the knees of adult passenger. Relatively unfavourable is the contact oh the adult passenger head with the head of child passenger (figure 14). The most significant injury is caused by table in open position. The abdomen injury is marginal. Interesting fact is than table can be partially closed after collision (figure 15), what is prohibited by standard GM/RT2100.
Figure 12. The collision of standing child passenger with the seat.

Figure 13. The displacement of head cog for simulations with very small change in initial conditions.

Figure 14. The contact of child passenger head with adult passenger head.

Figure 15. The result of very unsafe constellation (with prohibited movement of table after collision).

10. Conclusion
The final consideration is based on the results of the simulations (paragraph 9). The rail transportation is very different in the contrast with automotive industry. The requirement for special child restraint system in rail vehicle is unreal. Although the safety performance of standard interior (not designed for child passenger) is not as bad, it exists significantly worst scenarios.

The most significant safety risk for child passenger is connected with the table in the open position (figure 11). This part represents significant safety risk (for child passengers) which is amplified if the child passenger is sitting on the knee of adult passenger. The table can be partially closed after collision (figure 15), what is also prohibited by standard GM/RT2100. It can be shown than this collision scenario can be still danger even during emergency barking (statistically more often). The considered table design is reason of significant head injury even in the closed position (table 2). This result is caused by one design of table and can-not predict result for very different design, but the change (of actually simulated
design) is highly recommended. For example, very simply step will be to omit the tables in the departments intended for child passengers.

The aim of next simulations is to show safety risk of standing passenger. It is this type of simulations exist real risk of non-precious results. Therefore, the simulation time was significantly reduced. After the fall over the next seat the model is able to show very different results for very small changes in initial conditions (Figure 13). This problem must be studied in the next research to observe the possible chaotic behavior. That can predict potential simulation problem for another researcher.

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