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Injury Biomechanics in Railway Backrest Table Design

M. Carvalho[1] and J. Milho[2,3]

[1]UNIDEMI, Department of Mechanical and Industrial Engineering
Faculty of Science and Technology, Universidade NOVA de Lisboa, Portugal
[2]IDMEC, Instituto Superior Técnico, Universidade de Lisboa,
Lisbon, Portugal
[3]CIMOSM, ISEL, Instituto Superior de Engenharia de Lisboa,
Instituto Politécnico de Lisboa, Lisbon, Portugal

Abstract

The study presented here concerns a parametric study for the analysis of the influence of backrest table design during crashes of railway vehicles, focusing on the protection of occupants of railway coach interiors. A railway accident is described by the primary collision, in which the vehicle is subjected to an abrupt deceleration causing the unrestrained occupants to continue the original motion. Then the occupants are projected through the vehicle until the secondary collision occurs with their contact with some part of the interior of the vehicle or with other occupants. The strategy presented here combines and explores the already developed railway structures for crashworthiness with injury biomechanics. The methodology attends the railway accidents specificities such as the inexistence of restraints and the larger distance between contact features, which decreases the predictability on the kinematics of the occupants. Due to the importance of the vehicle interior features for the potential injury of the occupants during the secondary collision, in particular the seating layout with backrest table for which the experimental sled tests were not performed due to its cost, a parametric study was conducted with a numerical model of a reference simulation scenario characterized by the seating pitch of the first class coach. Simulation results suggest design modifications that are discussed in the scope of the reduction of the biomechanical injury indices for the occupants.

Keywords: railway, crashworthiness, passive safety, simulation, injury, biomechanics.

1 Introduction

The developments of new paradigms for automotive passive safety did not find any match in railway crashworthiness until the last decade of the twentieth century. In fact, a series of European Research and Development projects such as TRAINCOL [1], SAFETRAIN [2] and SAFETRAM [3] were responsible for bringing the railway industry up-to-date with the latest knowledge of structural crashworthiness, solving the structural crashworthiness issues associated to the primary collision.

With the main issues related to the primary collision solved and partly reported by [4, 5], it was time to handle issues involving the secondary collisions, *i.e.* the impact between the railway occupants and the vehicle interiors. While the knowledge developed in automotive and aerospace industry offered many of the necessary insights and the current injury criteria [6] have been identified in road and aerospace occupant passive safety, the fact that passengers have their kinematics guided by the use of seat belts which effectively directs them to the airbags to complement their protection, presents a complete world of differences [7] with respect to unbelted railway occupants. However, though in automotive vehicles the occupants are seat belted and have many passive safety systems to prevent severe injuries [8], some studies have been conducted for cases of unbelted occupants in cases of frontal impact [9]. In case of a railway impact, the unrestrained passengers continue their original motion until they collide with other passengers, including standing passengers, front and side facing occupants, or any structural features that includes tables, seats and poles. These layouts include diverse potential target surfaces during impact and there is no particular posture for the passengers resting positions.

For the work presented here, where virtual testing is developed for the inline seating with backrest table layout, a strong knowledge in vehicle modelling and numerical analysis, experience in simulation techniques and control are mandatory requirements [10]. Moreover, the lack of predictability of the kinematics of the occupants when a railway accident occurs, involves applications much more complex than just conventional rail vehicle dynamics software. The real challenge for this kind of problem is to deliver reliable simulation results in the face of many uncertainties [11]. This requires the choice of appropriate modelling techniques, the application of skill and care to develop the model and simulation inputs, and to establish the relevant measurable output criteria, in order to obtain simulation scenarios that attest the reality.

The project SAFEINTERIORS developed the basis of the railway occupant protection both in terms of the identification of the most relevant injury criteria, their thresholds and also in terms of proposing effective design concepts for the occupant protection [12]. The sled tests proposed are based on some of the work done in the SAFEINTERIORS project, conducted in an alternative less expensive way than those conducted by the SAFETRAIN project [2] with real railway carriages, but still relatively very expansive when sensitivity analysis of certain design variables are required as reported in [13–16]. The computer simulations are faster for parametric studies, and for that reason numerical models where developed, being the model for the inline seating layout validated with the experimental sled test carried by CIDAUT [14]. Another study of a wheelchair occupant in railway crash test that was validated with an experimental test for fixed bay table seating layout with standard occupants suggests that more attention should be given to the severity of the thoracic injuries resulting of the impact with the table [17]. In the particular case presented here, for which the experimental sled tests were not conducted due to its cost, starting from a validated numerical model of the inline seating layout [14] and adding the backrest table numerical model, a parametric study was conducted in order to analyse the influence of its design on the injury level of the occupants during the secondary collision.

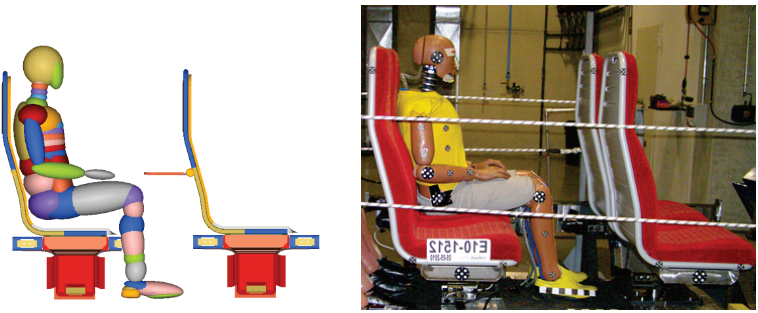
In order to achieve scenarios for crash simulations in which each part of the system is modelled with the most appropriate numerical methodology, the computer software MADYMO [18] was used, being one of the first that allows coupling finite element with multibody models. This integrated simulation environment is an advantage, avoiding numerical problems discussed in reference [10], such as stability issues and the influence of the extrapolation order in the information exchange between the modules in a modular co-simulation setting. Additional care must be taken to ensure that the numerical algorithms handle contact both from the point of view of its geometric conditions [19] but also in what the time integration is concerned [20], when using commercial software. The numerical procedures implemented in the MADYMO software are appropriate to handle properly the contact mechanics which is another feature that is fundamental to support the correct simulation of the numerical models.

2 The numerical model

2.1 Inline seating with backrest table model layout

The inline seating with backrest table layout of the interior of a railway coach analysed here uses the numerical model that was validated with the referent experimental layout [14], consisting of a finite element model of two rows of first class pitch seats, being supported by a cantilever beam that is fixed to the wall. The occupant is represented using a multibody description of an Anthropomorphic Testing Device (ATD), commonly named dummy seated at the wall side. The ATD's are available in the MADYMO model library [18] and had been previously validated against experimental tests of properly calibrated physical ATD, for use in frontal crash. The occupant of the numerical model, represented in Figure 1a is adjusted in the seating position in order to reproduce the experimental layout, represented in Figure 1b, though the experimental layout absences the backrest table.

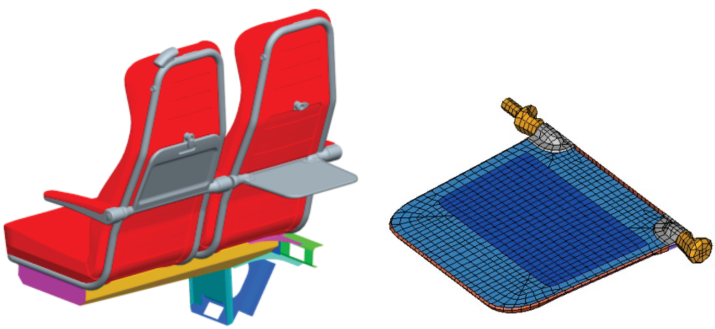
The actual length of the backrest table, as depicted in Figure 2a, is considered small when compared with those that offer a wide table top with a very good support for laptop computers. The current design shown in the reference scenario is made to prevent a potential impact in the abdomen area, being rather short. A previous systematic sen-



(a) (b)

Figure 1: Inline seating layout: a) numerical model (with backrest table); b) experimental test by CIDAUT (without backrest table)

sitivity analysis of the inline seating layout with a backrest table was completed [13], considering the pitch distance and table length variation. The scenarios of higher risk for these occupants are those for variations of table length superior to 120 mm, with a consequent reduction of space in the direction of the pitch. Therefore the scenario with a backrest table length increment equal to 120 mm depicted in Figure 2b is also analysed in this work, which must be acted upon by design modifications, aiming to improve the passive safety.



(a) (b)

Figure 2: a) Geometric model of the row of seats mounted on a cantilever beam with backrest table; b) Finite element model of the table with 120 mm increment in length

2.2 Railway collision dynamics

In order to model the railway vehicle dynamics during a secondary impact scenario, it is required to define an accurate acceleration time history of the crash event. For this purpose, an acceleration crash pulse is defined [21] considering the representativeness of the most relevant accidents in railway which is established in the European Railway Industry Standards [22].

For the experimental testing, a reverse catapult is used, to minimize the physical limitations of the in-house testing facilities. Moreover, variability associated to the crash pulse during experimental testing is considered, provided that acceleration is kept inside corridors limited by 5 g and 6 g, and the variation of velocity is limited below 6 m/s. Therefore, the proposed crash pulse, represented in Figure 3, corresponds to a maximum acceleration of 5.5 g and leads to a maximum speed change of 5.5 m/s. This pulse was applied in the reverse catapult and the corresponding experimental pulse measured by accelerometers is represented in Figure 3 [21].

The validity of the proposed pulse is accepted by being close to the average of the corridors for acceleration, as well as for the measured experimental pulse. Moreover, the actual procedures for dynamic test of passenger seats and tables established recently [23] defines an upper limit of the acceleration corridor of 7.5 g, and the lower limit of 5 g as represented in Figure 3, with the contingency of a minimum free flight velocity of 5 m/s attendance. These requirements appropriate for with the application of the proposed crash pulse.

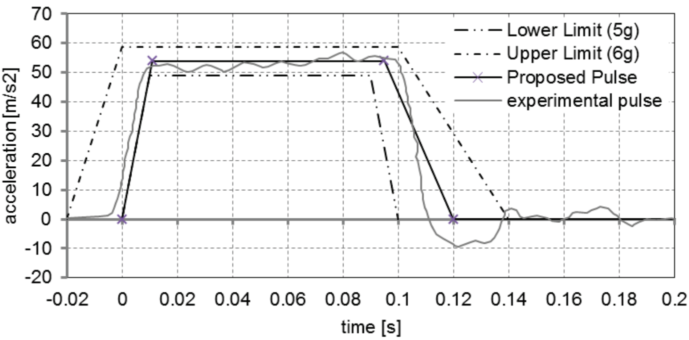


Figure 3: Crash pulse acceleration profiles for secondary collision [21]

2.3 Multibody model for the anthropomorphic testing devices

The ATDs are more than being human supports in physical or virtual testing environments serve as measuring devices for the loading that a vehicle occupant withstands during a crash event. A wide number of ATD exist for different crash configurations, such as frontal and side impact, and for various human sizes, such as the 95th and 50th male percentile or the 5th female percentile.

Most of the ATDs available today were developed for automotive testing, in which the kinematics of the occupants is guided, with seatbelts seat arrangements, or other restraint systems, to the target regions of the vehicle, such as airbags or other highly compliant zones. In railway applications the kinematics of the occupant is not guided by seatbelts or restraint systems and, consequently, the selection of a currently existing ATD to be used in any particular crash configuration may be problematic. In face of the different possible seats and tables arrangements the various phases of the impact may lead to the use of the range for which they have been developed and validated. The good news is that only crash configurations corresponding to frontal or rear impacts are of interest in railway passive safety studies.

In this work only the inline seating configuration is addressed and for the reference validated scenario the Hybrid III dummy is recommended for use in this type of configuration. The Hybrid III [24, 25] is composed of moving parts as illustrated in Figure 4 representing the head, neck, thorax, lower torso, upper and lower arms, hands, upper and lower legs and feet. Internal moving parts are also included, representing the thoracic and lumbar spine, ribcage, sternum and abdomen. The moving parts are coupled between each other using kinematic mechanical joints that mimic human articulations and internal interactions. Hybrid III is also defined for different sizes, the 50th percentile being of particular relevance to this work.

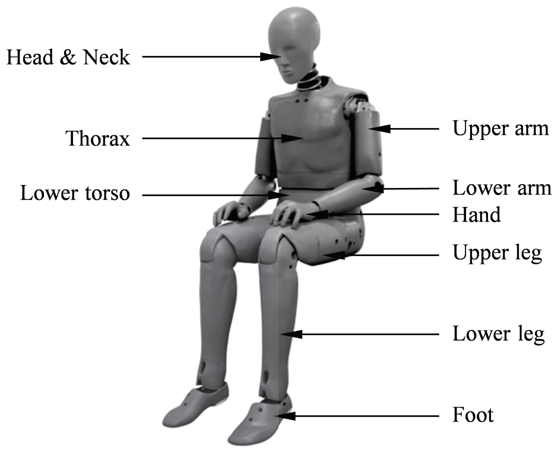


Figure 4: The Hybrid III Anthropomorphic Testing Device (moving internal parts not displayed)

In the particular case of this work a contact feature exists that is the backrest table which increases the potential of injury in the abdomen region. Unfortunately, the

Hybrid III does not have a biofidelic abdominal insert, and there is no compliance requirement related to the abdomen. The THOR dummy, the anticipated future frontal crash regulatory part, has an abdomen possessing some bio fidelity and measurement capability in its current iteration of the midsized male. However, the most appropriate type of abdominal insert to use and the associated injury metric are still a subject of debate [26]. In this work a numerical model of the Hybrid III RS is also used which is a modification of the 50th percentile adult male Hybrid III dummy with a THOR insert (thorax, abdomen and pelvis) and frangible abdomen depicted in Figure 5. The frangible part is modelled with a finite element model. The Hybrid III RS is a development, non-regulated ATD that has been used extensively by the rail community and is being used by companies manufacturing rail vehicle furniture who seek to meet advanced safety requirements [27].

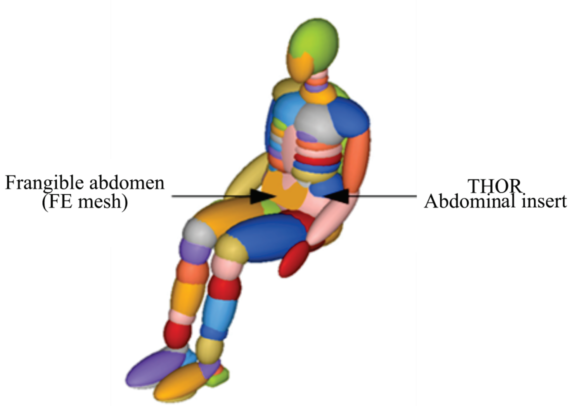


Figure 5: Numerical model of the Hybrid III RS ATD

2.4 Railway injury evaluation criteria

Injury biomechanics studies the effect of mechanical impact on the human body. Therefore, this research involves experiments and calculations for the identification and explanation of injury mechanisms, the quantification of mechanical response of body components to impact and the determination of tolerance levels to impact.

In railway occupant protection, three levels for injury thresholds are considered and deemed as: moderate, serious and severe. The moderate limit represents the threshold for the onset of an injury requiring hospital treatment. The serious injury threshold corresponds to injury with long term consequences and the severe limit represents the threshold for an injury that poses a significant threat to life [28].

Relatively to the injury criteria in the abdomen region a reasonable body of work dedicated to understanding and preventing injury to the abdomen, at least within the automobile environment is available. Some of the most recent work on the abdomen has focused on measuring the material properties of solid and hollow viscera, and understanding the interaction between organ systems during impact. What is less readily available is the correlation between injury and injury metric. Not all studies have attempted this correlation and from those that have, there is no agreement as to which metric is superior. These types of data have direct application to the development of computational models, as well as forwarding the understanding of injury mechanisms and injury tolerances [26].

The measure of the severity of the simulation scenario uses the injury criteria (including the criteria for the abdomen region) relevant for railway passive safety for the general adult population being the thresholds for each injury type presented in Table 1.

Body Region	Injury Criterion	Thresholds values (Mod/Serious/Severe)
HEAD	Resultant Head Acceleration (3ms) (g)	80/-/220
	HIC15	150/500/1000
NECK	Neck Shear Force (N)	2770/-/4170
	Neck Axial Force (N)	1900/-/3100
	Neck Bending Moment in Flexion (Nm)	88/189/310
	Neck Bending Moment in Extension (Nm)	47/57/135
THORAX	Deflection of chest relative to spine (mm)	42/53/75
	Localized Rib Viscous Criterion (m/s)	0.4/0.5/1.0
ABDOMEN	Abdomen Compression (mm)	-/34/42
UPPER LEG	Femur uni-axial Load (N)	4000/7600/10000
	Knee Joint Displacement (mm)	-/16/-
LOWER LEG	Tibia Axial Load (N)	4000/8000/-
	Tibia Index	1.0/1.3/-

Table 1: Injury indices and thresholds values [28]

2.5 Finite element model for the railway vehicle interior

The use of multibody models for vehicle structural impact using the plastic hinge approach is well documented in references [4, 5, 29]. However, before structural multibody models can be used they have to be properly validated and have not been demonstrated that they can be used in the framework of redesign or optimization involving their structural characteristics. Because the foreseeable use of the models developed here is the improvement of the railway seats the use of nonlinear finite elements that include the geometric details and material mechanics characteristics of the structural arrangements is preferred here. The structure of the railway seats is basically composed of a steel tubular structure that supports steel bars and spring like steel nets that hold the foam seats and back that contain the occupant, as depicted in Figure 6a. The structural arrangement that constitutes the railway seat is mounted on a beam cantilevered to the railway vehicle wall as pictured in Figure 6.

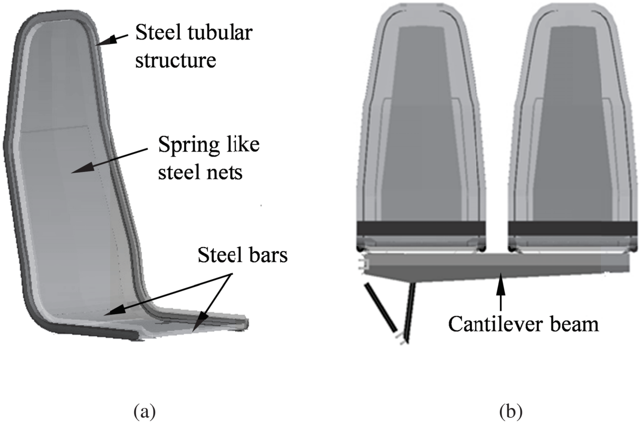


Figure 6: Typical railway seat used in an inline seating configuration: (a) seat components; (b) seat mounted in a cantilever beam

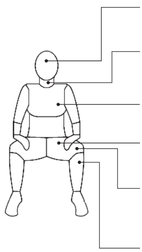
2.6 Interaction between multibody and finite element models

Interaction between finite element models for the railway seats structures and the multibody models for the Hybrid III dummies is established using contact models. A set of contact surfaces is defined for the calculation of the external forces exerted on the models when the multibody bodies contact the structures discretized using finite elements. These surfaces are ellipsoids with the form depicted in Figure 1a for the components of the Hybrid III crash dummy. For the structures, these surfaces are defined by the external contouring nodes of the finite element mesh as presented in Figure 6 for the seats and the cantilever beam and shown in Figure 1b for the backrest table. Initially, and because gravity is considered, the ATD is supported by the rigid model of the seat with a contact friction law that represents the kinematics of the head and chest for the validated numerical model of the inline seating layout [12]. The numerical procedure for contact detection and contact force evaluation are defined using the MADYMO MB-FE contact algorithm [18].

2.7 Results of the validated inline seating layout

The biomechanical injury indices results obtained for the validated model (MADYMO) are presented in Figure 7 and compared with experimental results of the layout obtained by CIDAUT [14].

For the interested reader, in the work developed by the authors [14], selected frames



Body Region	Injury Criterion	MADYMO	Exp.	Relative error (%)
HEAD	Resultant Head Acceleration (3ms) (g)	50.8	57.2	-11
	HIC15	239.6	268.7	-11
UPPER NECK	Neck Shear Force (N)	1614	1300	24
	Neck Axial Force (N)	1030	850	21
	Neck Bending Moment (Nm)	41.0	46.2	-11
CHEST	Deflection of chest relative to spine (m)	0.0	0	0
	Localized Rib Viscous Criterion (m/s)	0.0	0	0
FEMUR	Femur uni-axial Load (right) (N)	2320	2450	-5
	Femur uni-axial Load (left) (N)	2901	2480	17
KNEE	Knee joint displacement (right) (N)	11.1	4	178
	Knee joint displacement (left) (N)	13.4	13.5	-1
TIBIA	Tibia axial load (right) (N)	-776	-450	72
	Tibia axial load (left) (N)	-666	-550	27
	Tibia index load (right) (N)	0.70	0.16	678
	Tibia index load (left) (N)	0.90	0.7	350

Figure 7: Injury indices relative errors of the validated model [14]

for the kinematics of the validated virtual testing model and experimental testing are presented and compared, the emphasis being the same instants: contact of the legs with the back of the front seats, contact of the head with the front seat, maximum neck compression and rebound from the contact, confirming the similarity of both kinematics from experimental tests and virtual testing. The relative difference in the value of HIC is 11% with the experimental results, validating the virtual testing model. All injury indices, with exception for HIC and knee displacement are below the injury threshold for moderate limit level. HIC values are below serious limit level, requiring hospital treatment, which suggests future design improvements targeted to decrease this index. Knee injuries are near the serious threshold limit, though these injuries are never considered life threatening. This validated scenario supports the construction of the backrest table layout scenario, for which there are no experimental results.

3 Results of the analysis of the backrest table layout

The reference scenario of the study presented here uses the numerical model that was validated for a reference experimental layout [14], for which the occupant is a Hybrid III 50th percentile adjusted in the position represented in Figure 1a and a backrest table is included. The finite element model of the actual backrest table is connected with kinematic joints to the front seat. For this reference scenario the kinematics of the occupant and the injury indices are analysed.

Since the actual length of the backrest table is considered small by the railway industry, and considering the conclusions of the sensitivity analysis done previously [13], the scenario with a backrest table length increment equal to 120 mm is also analysed in this work.

In the particular case of this work, the backrest table increases the potential of injury in abdomen area and there is no particular posture for the occupants resting positions. Therefore, other parameters to be analysed are the position of the occupant which is a numerical model that combines a Hybrid III dummy with a THOR frangible abdominal insert depicted in Figure 5.

3.1 Reference scenario

Selected frames of the animation of the results of the virtual testing are presented in Figure 8, helping to appraise the kinematics of contact, by a sequence of contacts. The emphasis is put on the instants of the contact of the legs with the back of the front seats, the head with the front seat and maximum neck flexion. Notice that due to the occupant positioning adjusted to the position of the experimental test of the inline seating layout without backrest table, the contact of the occupant's body with the table causes its revolution about the support axis, avoiding the contact with abdomen area. Though there is no particular resting position, the analyses starts with this configuration in order to compare with the results obtained with the validated model for the inline seating layout.

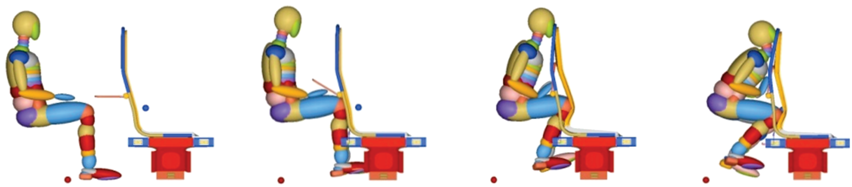
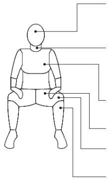


Figure 8: Selected frames of the virtual testing results for the reference scenario of the layout of the inline seating with backrest table

The changes for injury criterion, presented in Figure 9 when compared with the values of the validated inline seating layout model indicate a significant change only for head injuries. For the reference scenario, the value of HIC is above the serious threshold value corresponding to injury with long term consequences. This increase in the value of HIC compared with the scenario without backrest table is due to an earlier instant when the head contacts with the front seat, in the upper frame of the steel tubular structure. At that moment the deformation of the structure is much less when compared with the validated inline seating layout model. This suggests that some modifications in the upper frame of the seat must be implemented in order to decrease the values of head injury.

3.2 Table length scenario

Figure 10 presents selected frames of the animation of the results of the virtual testing in the instants of the contact of the legs with the back of the front seats, the head with



Body Region	Injury Criterion	Reference Backrest table scenario	Validated inline seating model	Threshold values mod/ser/sev
HEAD	Resultant Head Acceleration (3ms) (g) HIC15	82.7 600.3	50.8 239.6	80/-/220 150/500/1000
UPPER NECK	Neck Shear Force (N) Neck Axial Force (N) Neck Bending Moment (Nm)	1576 963 32.7	1614 1030 41.0	2770/-/4170 1900/-/3100 47/57/135
CHEST	Deflection of chest relative to spine (mm) Localized Rib Viscous Criterion (m/s)	0 0	0 0	42/53/75 0.4/0.5/1.0
FEMUR	Femur uni-axial Load (N)	3110	2901	4000/7600 /10000
KNEE	Knee joint displacement (mm)	14.6	13.4	-/16/-
TIBIA	Tibia axial load (N) Tibia index load (N)	312 0.93	776 0.9	4000/8000/- 1.0/1.3/-

Figure 9: Injury indices of the reference scenario vs. validated inline seating model and threshold limit values

the front seat and maximum neck flexion, which occurs in the same time instants. Notice that the only change relative to the reference scenario is the increment of the backrest table length of 120 mm. Therefore the kinematics is similar to the reference scenario; again the contact of the occupant's body with the table causes its revolution about the support axis, avoiding the contact with abdomen area.

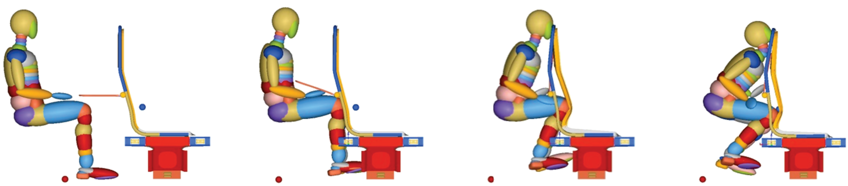
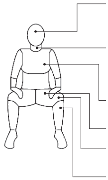


Figure 10: Selected frames of the virtual testing results for the table length increment scenario

Due to the fact the structure has a larger table, though kinematics is similar, it is required to post process the results for the injury indices which are presented in Figure 11. Comparing these results with the scenario with a smaller table, the reference scenario, the metrics for the injury in the head region decreases expressively to a level below the serious threshold value. It is important to analyse this scenario with a larger table that offers a wide table top with a very good support for laptop computers. Therefore the occupant positioning may differ as a consequence of being in a working position so in the next section two different positions are analysed.



Body Region	Injury Criterion	Backrest table length increment 120mm	Reference scenario	Threshold values mod/ser/sev
HEAD	Resultant Head Acceleration (3ms) (g) HIC15	75.9 329.5	82.7 600.3	80/-/220 150/500/1000
UPPER NECK	Neck Shear Force (N) Neck Axial Force (N) Neck Bending Moment (Nm)	1489 695 25.2	1576 963 32.7	2770/-/4170 1900/-/3100 47/57/135
CHEST	Deflection of chest relative to spine (mm) Localized Rib Viscous Criterion (m/s)	3.6 0	0 0	42/53/75 0.4/0.5/1.0
FEMUR	Femur uni-axial Load (N)	3205	3110	4000/7600/ 10000
KNEE	Knee joint displacement (mm)	14.4	14.6	-/16/-
TIBIA	Tibia axial load (N) Tibia index load (N)	274 0.94	312 0.93	4000/8000/- 1.0/1.3/-

Figure 11: Injury indices of the table length increment scenario vs. reference scenario and threshold limit values

3.3 Occupant positioning scenario

Two distinct positions are considered: (1) the occupant in a resting position is depicted in Figure 12, and (2) the occupant is in a leisure/working position with the hands above the table level as depicted in Figure 13. Figures 12 and 13 present selected frames highlighting the instants of the contact of the legs with the back of the front seats, the contact of the abdomen with the table, the contact of the head with the front seat and the maximum neck flexion. Notice that the instant of the contact of the legs with the front seat coincides with the instant that the table contacts the abdomen for both cases.

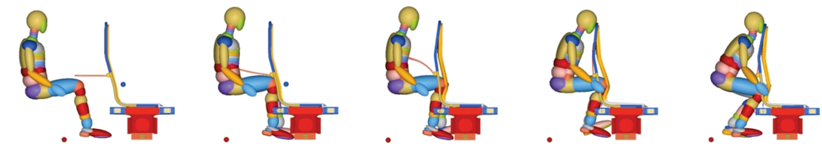


Figure 12: Selected frames of the virtual testing results for the occupant positioning (1) scenario

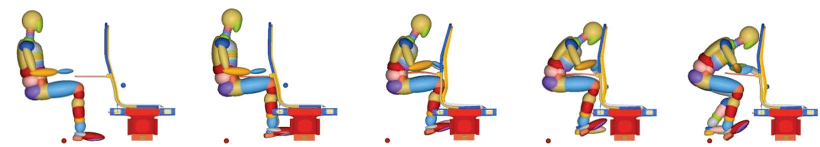
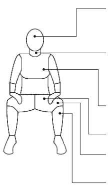


Figure 13: : Selected frames of the virtual testing results for the occupant positioning (2) scenario

In scenario (1) the table is pressed by the abdomen and chest, rotating around its axis, with a consequent influence on the injury in chest region depicted in Figure 12 (indices in chest region are below the moderate threshold values). When the head contacts with the backseat structure the tubular steel frame is bent forward, which means it is absorbing the energy of the legs impact with its plastic deformation. There is a consequent reduction in the value of head injury indices for the occupant, particularly the HIC value is slightly below the moderate limit.

In scenario (2), due to the position of the arms, the occupant embeds the table, which causes a delay in the instant of contact of the head with the front seat. The constraint of the table causes the rotation of occupants body about an axis located in abdomen region, then the head contacts the backseat structure, but below the tubular steel frame, with a consequent reduction in the value of head injury indices, particularly the HIC value decreases significantly. In Figure 14 the injury indices are depicted for both scenarios are depictedand are compared with the threshold values. For both scenarios, the injury indices are all below the moderate threshold value, which means a requirement for hospital treatment. However, since there is no assessment of the injury metrics in the abdomen, which is important due to the kinematics of the occupants, in the next section this scenario is analysed with a dummy that has an abdomen possessing some bio fidelity and measurement capability in its current iteration of the midsized male.



Body Region	Injury Criterion	Pos (1)	Pos (2)	Backrest table length increment	Threshold values mod/ser/sev
HEAD	Resultant Head Acceleration (3ms) (g)	14.3	13.5	75.9	80/-/220
	HIC15	149.8	10.6	329.5	150/500/1000
UPPER NECK	Neck Shear Force (N)	1277	358	1489	2770/-/4170
	Neck Axial Force (N)	1136	854	695	1900/-/3100
	Neck Bending Moment (Nm)	24.0	10.7	25.2	47/57/135
CHEST	Deflection of chest relative to spine (mm)	26.4	8.3	3.6	42/53/75
	Localized Rib Viscous Criterion (m/s)	0.19	0.06	0	0.4/0.5/1.0
FEMUR	Femur uni-axial Load (N)	3151	2666	3205	4000/7600/ 10000
KNEE	Knee joint displacement (mm)	13.7	12.7	14.4	-/16/-
TIBIA	Tibia axial load (N)	432	329	274	4000/8000/-
	Tibia index load (N)	0.98	0.90	0.94	1.0/1.3/-

Figure 14: Injury indices occupant positioning scenarios (1) and (2) vs. table length increment scenario and threshold limit values

3.4 Occupant model scenario

In this section the analysis is made with a numerical model of Hybrid III RS for both positions (1A) and (2A) considered in the above section.

In Figures 15 and 16 selected frames are depicted highlighting the instants of the contact of the legs with the back of the front seats, the contact of the abdomen with the

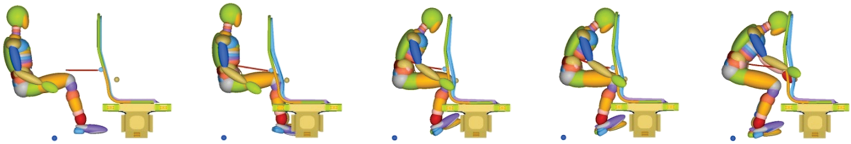


Figure 15: Selected frames of the virtual testing results for the occupant positioning (1) scenario

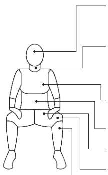
Figure 16: : Selected frames of the virtual testing results for the occupant positioning (2) scenario

table, the rotation of the occupant around abdomen area and the contact of the head with the front seat. Notice that the instant of the contact of the legs with the front seat coincides with the instant that the table contacts the abdomen for both cases, but for scenario (1A) illustrated in Figure 15, the contact with abdomen is in the upper region, instead of scenario (2A) shown in Figure 16, where the contact is made in the lower region. Furthermore the kinematics for both scenarios is different which conducts to different injury indices shown in Figures 17 and 18.

In Figure 17 the injury indices for scenario (1A) are described, which are compared with the referent simulated with the Hybrid III dummy, and with the threshold values. For both scenarios, the injury indices are all below the moderate threshold value, though the value of HIC is reduced. The deflection of abdomen wall relative to the spine is 14 mm, below the serious threshold value. The pressure is distributed in the upper region, as shown in Figure 19a for the instant when the impact occurs. The finite elements with higher pressures correspond to nonrelevant numerical singularities of the finite element method for elements defined in order to connect the element mesh to the rigid model of the abdomen insert.

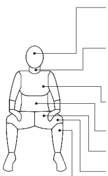
The injury indices for scenario (2A) are presented in Figure 18, which are compared with the referent simulated with Hybrid III dummy, and with the threshold values. Although there is an increment of the injury indices in the head and neck regions, for both scenarios, the injury indices are all below the moderate threshold value. The value of maximum abdomen compression is 31mm, closer to the serious threshold value.

The pressure in the abdomen is distributed in the lower region, as shown in Figure 19b for the instant when the impact occurs. As found for scenario (1A), the finite



Body Region	Injury Criterion	Pos (1A)	Pos (1)	Threshold values mod/ser/sev
HEAD	Resultant Head Acceleration (3ms) (g) HIC15	26.5 22.1	14.3 149.8	80/-/220 150/500/1000
UPPER NECK	Neck Shear Force (N) Neck Axial Force (N) Neck Bending Moment (Nm)	272 1360 13.1	1277 1136 26.4	2770/-/4170 1900/-/3100 47/57/135
CHEST	Deflection of chest relative to spine (mm) Localized Rib Viscous Criterion (m/s)	1.5 0.08	26.4 0.19	42/53/75 0.4/0.5/1.0
ABDOMEN	Abdomen compression (mm)	14	-	-/34/42
FEMUR	Femur uni-axial Load (N)	2801	3151	4000/7600/10000
KNEE	Knee joint displacement (mm)	12.9	13.7	-/16/-
TIBIA	Tibia axial load (N) Tibia index load (N)	472 0.86	432 0.98	4000/8000/- 1.0/1.3/-

Figure 17: Injury indices occupant positioning scenario (1A) vs. scenario (1) and threshold limit values

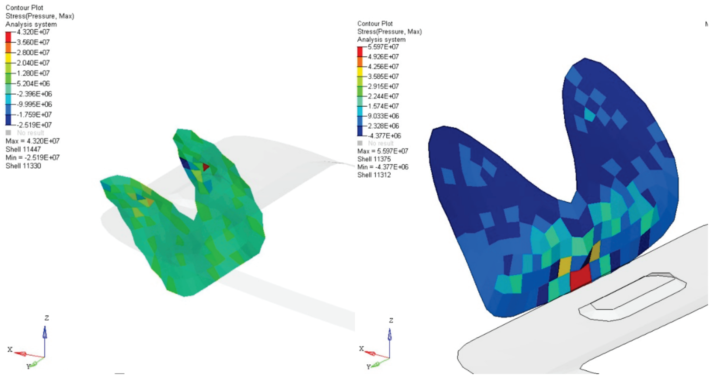


Body Region	Injury Criterion	Pos (2A)	Pos (2)	Threshold values mod/ser/sev
HEAD	Resultant Head Acceleration (3ms) (g) HIC15	59.1 150.1	13.5 10.6	80/-/220 150/500/1000
UPPER NECK	Neck Shear Force (N) Neck Axial Force (N) Neck Bending Moment (Nm)	551 996 22.5	358 854 10.7	2770/-/4170 1900/-/3100 47/57/135
CHEST	Deflection of chest relative to spine (mm) Localized Rib Viscous Criterion (m/s)	2.9 0	8.3 8.3	42/53/75 0.4/0.5/1.0
ABDOMEN	Abdomen compression (mm)	31	-	-/34/42
FEMUR	Femur uni-axial Load (N)	2010	2666	4000/7600/10000
KNEE	Knee joint displacement (mm)	11.3	12.7	-/16/-
TIBIA	Tibia axial load (N) Tibia index load (N)	419 0.81	329 0.90	4000/8000/- 1.0/1.3/-

Figure 18: Injury indices occupant positioning scenario (2A) vs. scenario (2) and threshold limit values

elements with higher pressures also correspond to nonrelevant numerical singularities of the finite element method for elements used to connect the element mesh to the rigid model of the abdomen insert. Due to the observed distinct pressure distributions in the upper and lower abdomen region, there are significant changes in kinematics and consequently in the values of injury indices. Then it is significant to simulate scenario (1B), which is scenario (1A) with the modification of the backrest table for the actual length in order to compare results.

The selected frames depicted in Figure 20, highlight the moment of contact of the legs with the front seat is not at the same time as the contact of abdomen with backrest table. The rotation of the occupant's body around the contact axis is retarded, and consequently the head contact with the upper back structure is when the seat frame is whiplashing. Though the maximum pressure and the maximum abdomen compression decrease slightly, the injury indices increase significantly in the head region although



(a) (b)

Figure 19: Frangible abdomen insert finite element mesh – a) pressure results for (1A) scenario (t=146ms); b) pressure results for (2A) scenario (t=136ms)

below serious threshold value. The remaining indices in the leg regions are similar for both analyses, as shown in Figure 21.

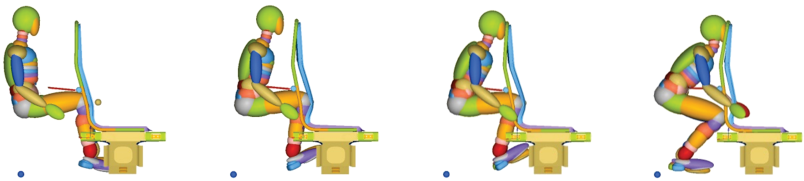
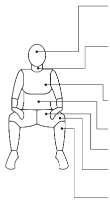


Figure 20: : Selected frames of the virtual testing results for the occupant positioning (1B) scenario

4 Conclusions

The inline seating with backrest table layout has been methodically analysed during a crash of a railway vehicles, focusing in the identification of the potential sources of injury for railway occupants. Simulation results suggest design modifications that are discussed in the scope of the reduction of the biomechanical injury indices for the occupants.

The challenge of railway accident simulation is to deliver reliable results in the face of many uncertainties due to the lack predictability on the kinematics of the occupants. First a reference scenario is analysed for which a previously validated numer-



Body Region	Injury Criterion	Pos (1B)	Pos (1A)	Threshold values mod/ser/sev
HEAD	Resultant Head Acceleration (3ms) (g)	40.5	26.5	80/-/220
	HIC15	255.9	22.1	150/500/1000
UPPER NECK	Neck Shear Force (N)	1570	272	2770/-/4170
	Neck Axial Force (N)	526	1360	1900/-/3100
	Neck Bending Moment (Nm)	32.4	13.1	47/57/135
CHEST	Deflection of chest relative to spine (mm)	1.5	1.5	42/53/75
	Localized Rib Viscous Criterion (m/s)	0.02	0.08	0.4/0.5/1.0
ABDOMEN	Abdomen compression (mm)	13	14	-/34/42
FEMUR	Femur uni-axial Load (N)	2820	2801	4000/7600/10000
KNEE	Knee joint displacement (mm)	13.6	12.9	-/16/-
TIBIA	Tibia axial load (N)	453	472	4000/8000/-
	Tibia index load (N)	0.88	0.96	1.0/1.3/-

Figure 21: Injury indices occupant positioning scenario (1B) vs. scenario (1A) and threshold limit values

ical model of the inline seating layout is used, with the addition of the finite element model of the actual backrest table. The finite element model of the actual backrest table is connected with kinematic joints to the front seat. Since the actual length of the backrest table is considered small by the railway industry, a scenario with a backrest table length increment is analysed. Kkinematics for both scenarios show that the metrics for the injury in the head region decreases to a level below the serious threshold value. These scenario simulation results suggests that any improvement in the passive safety features of the vehicle interior should be obtained with the characteristics of the upper part of the back of the seat structure, where collision of the head is more likely to occur.

For the reason that there is no particular posture for the occupants, another parameter to analyse is their positioning. Therefore two distinct positions are considered for analysis: a resting position and a leisure or working position. There is an improvement in the injury indices for the critical body regions, but the potential of injury in the abdomen area is increased. The ATD used in experimental testing is Hybrid III and does not have a biofidelic abdominal insert and consequently no assessment of the injury metrics is made of the abdomen.

For completion of the study the scenario with a dummy that has an abdomen possessing some bio fidelity and measurement capability in its current iteration of the midsized male is analysed. The numerical model combines a Hybrid III dummy with a THOR frangible abdominal insert. This numerical model of the occupant is currently under development and in the lack of experimental results is not validated. Additionally there is still no consensus on the correlation between impact force and abdomen injuries. For this reason, though there is reasonable work dedicated to understanding and preventing abdomen injury for road vehicles, the absence of passive safety devices in railway interiors increases the uncertainty of the kinematics and a complete solution remains elusive for the backrest table design. Nonetheless, the presented study provides an insight on understanding and prevention of the injury in the abdomen, which is critical for the design of improved injury assessment tools such as ATD's and computer models.

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