Selected aspects of the control of the human body motion in the vehicle subjected to the blast load

Artur Iluk[1]

Abstract In the paper, some selected aspects of the human body motion in a vehicle subjected to a blast load are discussed, especially as related to the dominant injury area, the vertebral column. As far as the blast attenuating seat is concerned, various strategies of human body acceleration are presented and tested against the biomechanical criterion – Dynamic Response Index (DRIz). The profile of the force acting on the passenger is optimized with the use of a simple model. The results show that for this criterion, the two-staged acceleration process is optimal with the first impulse compressing the spine and second impulse keeping the spine compressed.

The full system containing the human body model (deformable Hybrid III ATD) and the blast attenuating seat were prepared in the LS-DYNA explicit code. The numerical simulations of the body motion for the range of boundary conditions and various damping element stiffness were conducted and results were discussed including obtained DRIz values. The importance of the cushion stiffness and seat belts role was emphasized and the ability of constant force damping system to generate two-pulse acceleration profile was discussed.

Keywords blast attenuating seat, vertebral column injury, DRIz, numerical simulation

I. INTRODUCTION

The process of vehicle load by a blast wave exhibits some similarity to road collisions. Both phenomena are abrupt, highly dynamic and potentially lethal. In both cases the proper control of the human body motion without exceeding biomechanical safety criteria and preventing contact of the body with the vehicle structure are essential. In fact, the main difference is the direction of the load. In the case of the blast wave formed by a mine or Improvised Explosive Device, the human body is often accelerated in a vertical direction, rare in road collisions. Because of this dissimilarity, the mechanisms of injury and methods for injury mitigation are different.

As stated in [1], the best available model for thoraco-lumbar spine injury assessment is the Dynamic Response Index (DRI) introduced by Stech and Payne [2]. The primary purpose of this model was the evaluation of the risk of injury during the ejection of a seat from a plane. The similar direction and profile of the load acting on the human body allows adopting this model to evaluate effects of mine blast load. The evaluation of the human body response to the dynamic load is based on the simple mass-spring-damper system shown in figure 1. The Dynamic Response Index calculated only for vertical acceleration is described as DRIz.

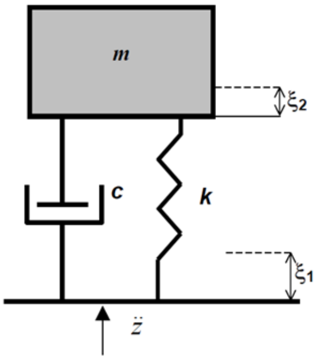

Fig. 1. DRIz model structure [2].

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The equation of the motion for this model is:

$$\ddot{z}(t) = \ddot{\delta} + 2 \cdot \zeta \cdot \omega_n \cdot \dot{\delta} + \omega_n^2 \cdot \delta \qquad (1)$$

where

$\ddot{z}(t)$ – vertical acceleration at the seat

δ – compression of the system, $\delta = \xi_1 - \xi_2$

ζ – damping coefficient, $\zeta = \frac{c}{2 \cdot m \cdot \omega_n}$

ω_n – natural frequency, $\omega_n = \sqrt{\frac{k}{m}}$

The value of DRIz is calculated as a function of maximum compression δ_{max} of the system during full load process, natural frequency ω_n and gravity acceleration g:

$$DRIz = \frac{\omega_n \cdot \delta_{max}}{g} \qquad (2)$$

The values of damping coefficient $\zeta = 0.224$ and natural frequency $\omega_n = 52.9$ rad/s were selected by Stech for the model as values for a representative population of Air Force pilots with a mean age of 27.9 years [1]. The value of the DRIz parameter at the level of 17.7 refers to a 10% risk of AIS (Abbreviated Injury Scale) 2+ injury. Criterion DRIz applied to a blast test is intended to be used with acceleration measured with the pelvis vertical accelerometer Hybrid III Anthropomorphic Test Device (ATD), (referred to hereafter as HIII).

The injury to the passenger of a vehicle subjected to a blast load has been analyzed in numerous works. The spine loading was investigated in [3], [4] with the use of LS-DYNA and MADYMO codes. The transmission of the energy from a blast wave to the vehicle structure was presented in [5], [6] and [7]. It was reported that for various load profiles applied to the seat base, the main parameter influencing the spine injury is the maximum velocity of the blast-accelerated base of the seat.

The selection of the velocity as the influencing factor is based on the observation that the first phase of energy transfer between the blast wave and the vehicle (a few milliseconds) is much shorter than the acceleration of the occupant (about 100 ms). For this reason, there is a possibility to decouple these phases:

a) acceleration of the vehicle,

b) at approximately constant velocity of the vehicle, acceleration of the occupant.

In [8] and [9] various methods of the blast load simulation were checked with a simple analytical model and criterion DRIz for range of the seat velocities up to 8 m/s.

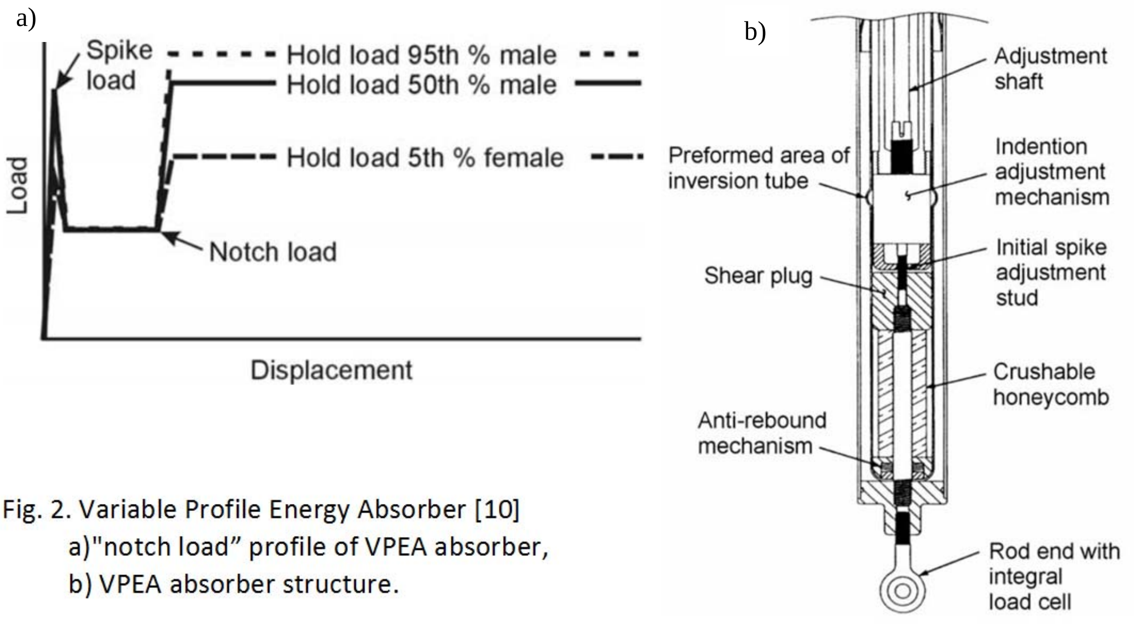

Fig. 2. Variable Profile Energy Absorber [10]
a)"notch load" profile of VPEA absorber,
b) VPEA absorber structure.

Most of the research is devoted to the validation of some different simulation methods and verifications of existing structures. There are few publications investigating the influence of the seat parameters and structure on the safety of the passenger. Desjardin [10] described efforts to develop a shock attenuating seat for helicopter pilots with a concept of Variable Profile Energy Absorber (VPEA) with the “notch load” profile depicted in figure 2a. No explanation was given for the mechanism for such an attenuating technique, and a different injury criterion based on maximum acceleration was used. The practical realization of the profile leads to a complicated mechanical shock absorber shown in figure 2b.

In the design of absorbers, the influence of seat structure stiffness seems to be neglected by the unspoken assumption that the force profile generated by an attenuating absorber is identical to the force profile applied to the human body. In this paper, the optimal profile of attenuating force and the relation between absorber force and actual force applied to the body is investigated.

II. DRIz MODEL RESPONSE

The main goal for the blast attenuating seat is prevention of injury to the vertebral column. The secondary goal is the attenuation of shock within limited space available inside a vehicle. For minimization of the required stroke, it is necessary to design a strategy of control of the human body inside the vehicle subjected to blast load.

In order to find the optimal profile of the attenuating force for the DRIz model, various acceleration profiles were investigated. Because movement of the seat mounting points during blast strongly depend on the design of the vehicle, an assumption was made that the seat mounting points after the blast are rapidly accelerated to a given velocity, and an attenuating device should safely accelerate the body to the same velocity [8].

The optimization was carried out using the following assumptions:

- the seat was treated as a rigid body,
- maximum DRIz≤17.7 was chosen,
- vertically accelerating seat from 0 to 5 m/s or 7 m/s was used,
- only upwards acceleration was allowed,
- the stroke of the seat required to reach desired velocity was minimized.

The values 5 and 7 m/s were selected because, for the seat without the special damping devices, the maximal DRIz value is approximately equal to fourfold of the initial seat velocity in m/s [11]. For the limiting value DRIz=17.7 the seat without damping is appropriate up to the velocity of 4.4 m/s.

The optimal profile of acceleration requiring the shortest stroke of seat to equalize the vehicle and passenger vertical velocities is shown in figure 3. It consists of two acceleration pulses. The first pulse with the constant acceleration **D** and duration **t1** initiates the compression of the spine. After the first pulse, the accelerating force is reduced to zero until the spine, due to the inertial forces, reaches a desired compression at the time **t2**. When the value DRIz=17.7 is reached, the second pulse with the acceleration equal to 17.7 g is applied to maintain a compression of the spine at the desired level until the vertical velocity of the seat reaches the vertical velocity of the seat base (the vehicle wall velocity) at the time **t3**.

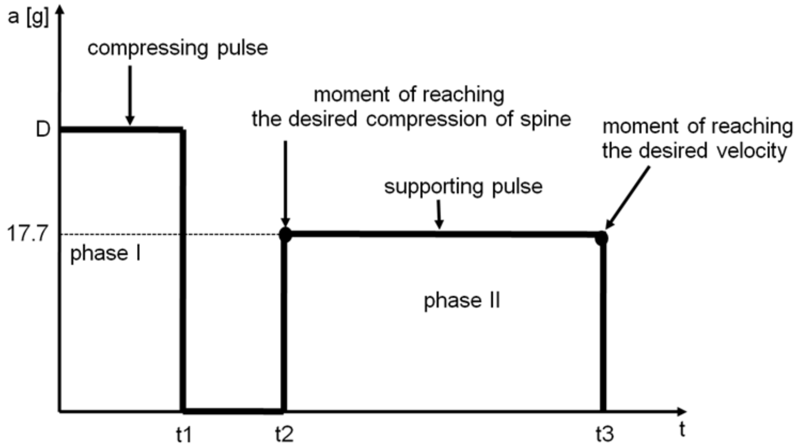

Fig. 3. The optimal profile of the acceleration according to DRIz criterion.

For the double-pulse profiles of acceleration, the duration of the first pulse is much shorter than the natural frequency of the loaded system. In such case, shape of the first pulse has no influence on the structure response, if the total applied impulse of force

$$I = \int_0^{t1} F \, dt \tag{3}$$

and duration is conserved. In figure 4d alternative shapes of the first pulse are presented: rectangular and triangular, with identical force impulse and duration of the first pulse. The resultant DRIz profiles for both pulse shapes are identical.

The second pulse supporting the compression of the spine works at maximum allowable spine compression and should be more stable.

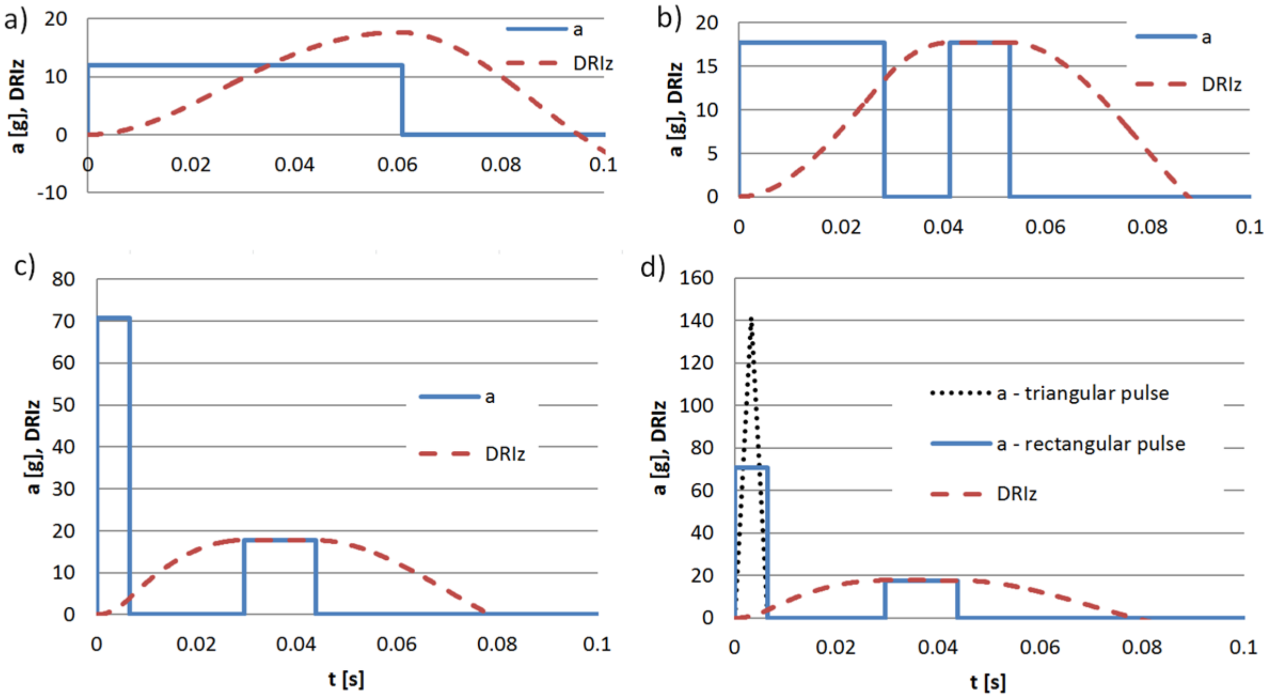

Fig. 4. The characteristic profiles of acceleration and corresponding profiles of DRIz for different amplitudes of the first pulse acceleration **D**:
a) **D**=11.9 g, b) **D**=17.7 g, c) **D**=70.8 g, d) alternative shapes of the first pulse.

The increasing values of the first acceleration pulse **D** results in reaching the optimal compression of the spine sooner (DRIz=17.7, time **t2**). Those increasing values also result in a shorter stroke of the attenuating device required to equalize the velocities of the body and vehicle. Direct comparison of the DRIz profiles is presented in figure 5.

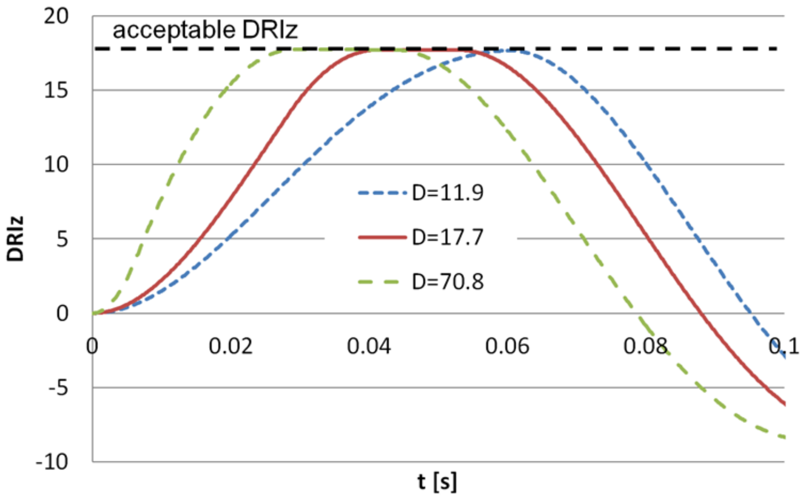

Fig.5. The DRIz values for different acceleration of first pulse **D**.

Application of higher values of **D** influences the duration of the first pulse **t1** and gap between pulses **t2**-**t1**. Required duration of the first pulse and gap is shown in figure 6.

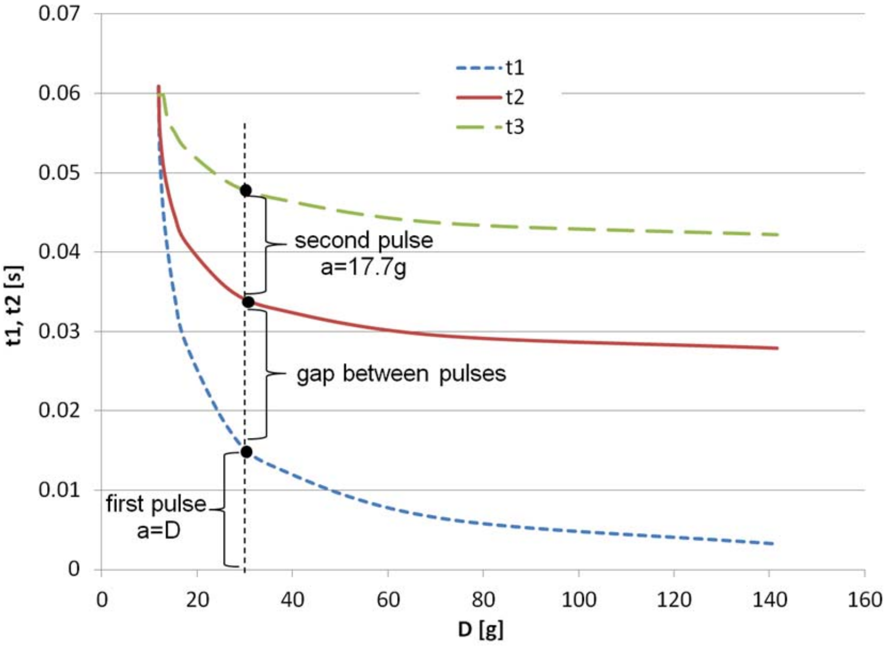

Fig. 6. Required duration of the first acceleration pulse **t1** and the start time of second pulse **t2** as a function of the amplitude of first pulse **D**.

For higher values of the first acceleration pulse, the full compression of the spine is reached earlier. The required stroke of the attenuating device is in this case shorter. The relationship between required stroke of the seat and amplitude of the first pulse for two different vertical velocities of the vehicle is shown in figure 7.

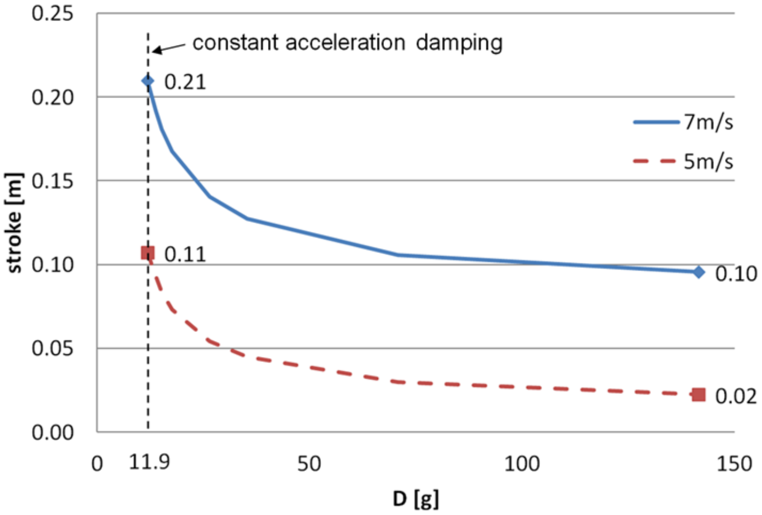

Fig. 7. The required stroke of seat as a function of the amplitude of first acceleration pulse **D** for the vertical velocities of vehicle 5 m/s and 7 m/s.

The required stroke of the seat is decreasing asymptotically with increasing acceleration of the first pulse. For high values of **D**, the stroke required for safe acceleration of the body to the velocity 7 m/s is only half of the stroke of the seat damped with constant force.

The DRIz is a criterion that takes into consideration the duration of the load, like the Head Injury Criterion. In the same manner as in HIC, even extremely high but short acceleration is not dangerous. This kind of criterion seems to be more appropriate for complex and elastic mechanical systems such as the head or vertebral column. Criteria based on a maximum force or moment are more appropriate to stiffer body components such as the femur or tibia.

The presented optimal acceleration profile contains in the first phase acceleration with high amplitude. Although the DRIz criterion passes, the other suggested criteria such as maximum acceleration 14.5 g [10] will fail. Because of a short duration and the controlled compression of the spine, the high amplitude of the first pulse seems to be acceptable.

The practical realization of a double-pulse profile is difficult. The purely mechanical dampers as shown in figure 2b are complicated and not able to realize the first pulse with the amplitude higher than the second one. The active dampers, for example, based on magneto-rheological effect [12] can be utilized, but required switching time below one millisecond is difficult to achieve. Additionally, such dampers need efficient power sources and are not able to decrease a damping force to zero.

In the second part of this paper, the possibility of application of the double-pulse acceleration profile by a simple constant force load limiter will be presented.

III. MODEL OF SEAT-PASSENGER SYSTEM

To investigate the behavior of a more realistic system taking into account the elasticity of the seat (cushion, elastic support structure), the model of the full system seat-passenger was developed with the use of finite element method code LS-DYNA. The human body was modeled by the elastic 95th percentile HIII. The version heavier than the standard 50th percentile HIII was selected because in military practice a 50th percentile soldier traveling in an armored vehicle is wearing additional equipment with weighing 20-25 kg and therefore his total combat mass is very close to the 95th percentile HIII. For this reason the well standardized 95th percentile HIII instead of the 50th percentile HIII with non-standard additional mass has been used.

The blast attenuating seat consists of two parts: the base connected rigidly to the wall of the vehicle and the movable part occupied by the belted HIII. The attenuating device is mounted between the parts of the seat.

The cushion with the thickness of 50mm was modeled with the use of solid elements with MAT_LOW_DENSITY_FOAM material model with stiffness entered as tabular data. Before the start of the blast load, the cushion was pre-stressed to achieve a static equilibrium with the weight of the HIII. .

In a vertical acceleration, the cushion of the seat plays a more important role than in a frontal road collision. In a road collision a body is moving in the forward direction and the cushion of the seat is unloaded. In the case of a blast load, the body is moving toward the cushion, and the cushion stiffness can potentially influence the acceleration of the body. In order to verify this, two real characteristics of the foams used in a vehicle seat were investigated. The characteristics of the foam stiffness are presented in figure 8.

The attenuation of the blast shock was realized by the damping element with the constant maximum force. In real application, similar characteristics can be achieved with the use of ALPORAS aluminium foam. The static characteristic in compression of the aluminium foam with density 250 kg/m^3 is shown in figure 9. The plateau stress at the level of approximately 2 MPa provides the quasi-constant attenuating force in a wide range of strain.

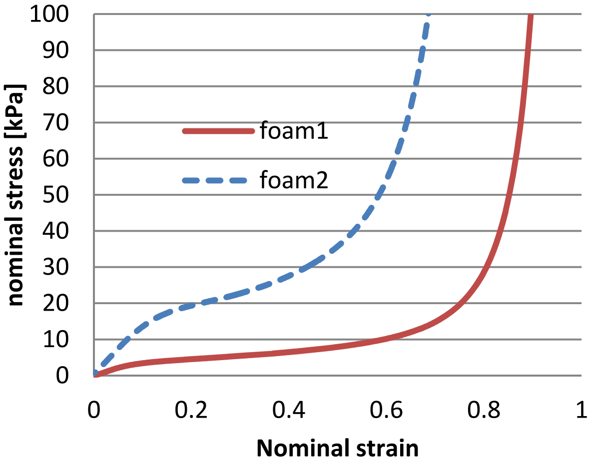

Fig. 8. The stress-strain characteristic of two cushion foams.

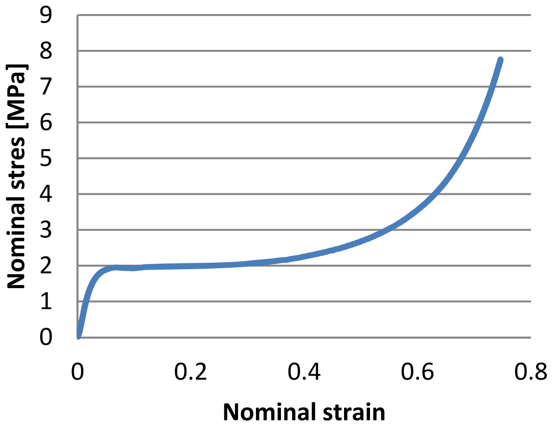

Fig. 9. The stress-strain characteristic of ALPORAS

The nominal attenuating force in the range of 5 to 20 kN was investigated. The stroke of the attenuating device was restricted to a maximum 200mm by the seat structure. For each attenuating force, various profiles of the vehicle velocity were simulated with peak velocities of 3 m/s, 5 m/s and 7 m/s. The view of the complete model which contains the belted HIII and the seat structure with shock absorber is presented in figure 10.

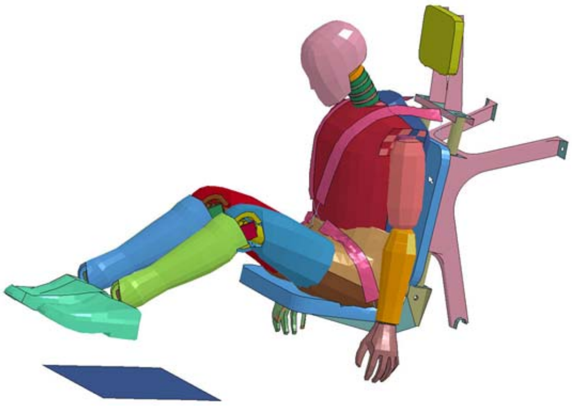

Fig. 10. The complete model of the Hybrid III and blast attenuating seat equipped with a 5-point belt.

IV. RESULTS

The main output from this simulation is the acceleration profile measured in the point close to the center of gravity of HIII. The mounting point of the accelerometer used according to STANAG 4569 [13], [14] measured the input acceleration for the DRIz model. Additionally, the velocities of particular elements of the model and actual damping force in the attenuating element were checked.

The result of simulations with a different cushion foam stiffness showed a negligible influence on the movement of the body and DRIz parameter. The resultant velocities and DRIz profiles are presented in figures 11 and 12. With the high acceleration level generated during a blast load, stiffness of the seat foam is too low to accelerate the body before contact with a steel seat structure. The usage of a cushion foam with much higher stiffness would decrease the comfort of the passenger.

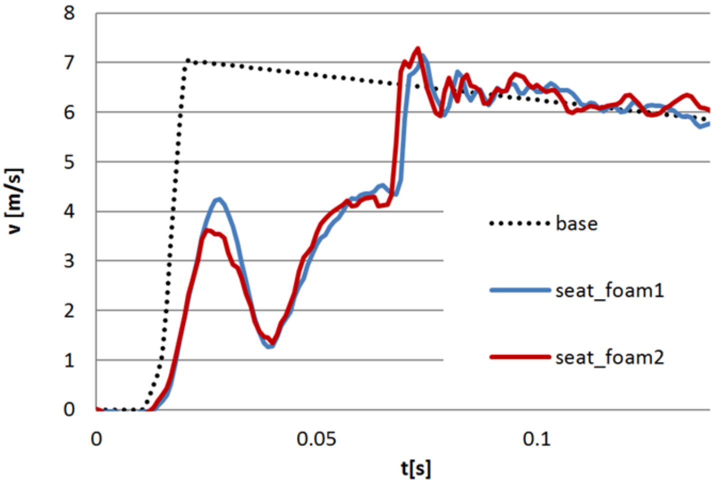

Fig. 11. The vertical velocity of the base of seat (wall of vehicle) and attenuated part of seat for two types of the foam.

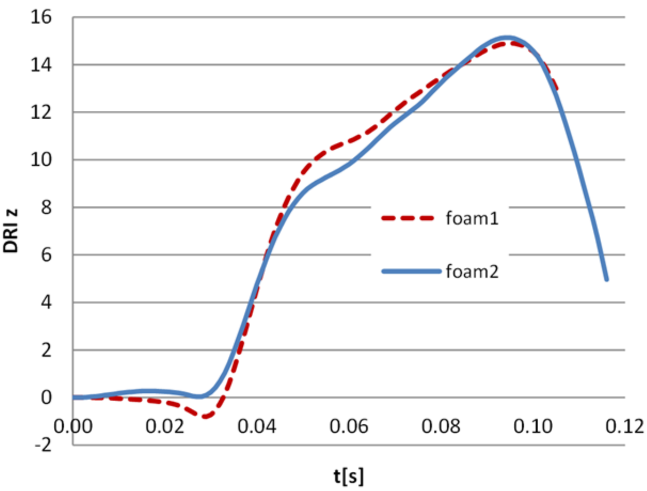

Fig. 12. The influence of cushion foam density on the value of DRIz parameter.

In figure 13, the typical vertical velocity profiles of the base of the seat, attenuated part of seat and center of gravity of the HIII are presented. The body is accelerated, but because of elasticity of the cushion and seat structure, it does not follow strictly the movement of the attenuated part of the seat. The shock wave reaches the seat base at point **A**. At point **B**, the cushion is fully compressed and the acceleration of the body starts. At point **C,** velocity of the movable part of the seat and the body reaches the velocity of the seat base. The elastic energy accumulated in a seat structure ejects the body in the direction of a roof. At point **D** the safety belts stop the body acceleration, and at point **E** the process of shock attenuation is finished and the body follows the movement of the vehicle.

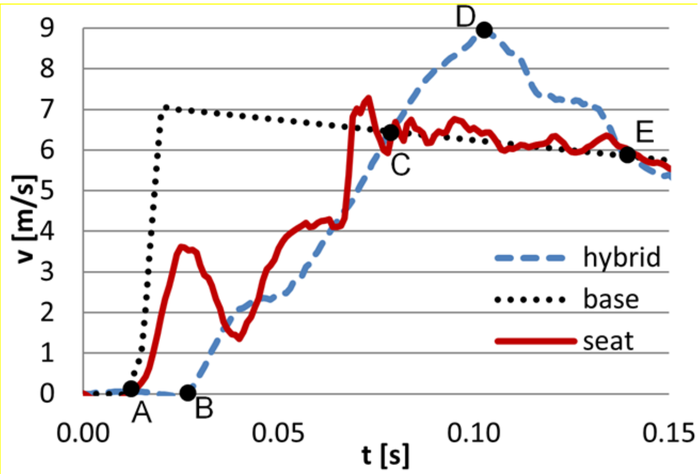

Fig. 13. The vertical velocity of the base of seat (wall of vehicle), attenuated part of seat and Hybrid model for 7 m/s maximum vehicle velocity and damping force 10kN.

The velocity of the body at point **D** is 35% higher than the velocity of the vehicle. It emphasizes the role of the seat belts, which should stop the body in upward movement to minimize the risk of head and neck injury. Additionally, compression of the cushion between points **A** and **B** develops a clearance between the body and the belts, which increases the distance between points **C** and **D**, so the body is stopped later. The loosened seat belts as a result of the seat cushion compression are shown in figure 14.

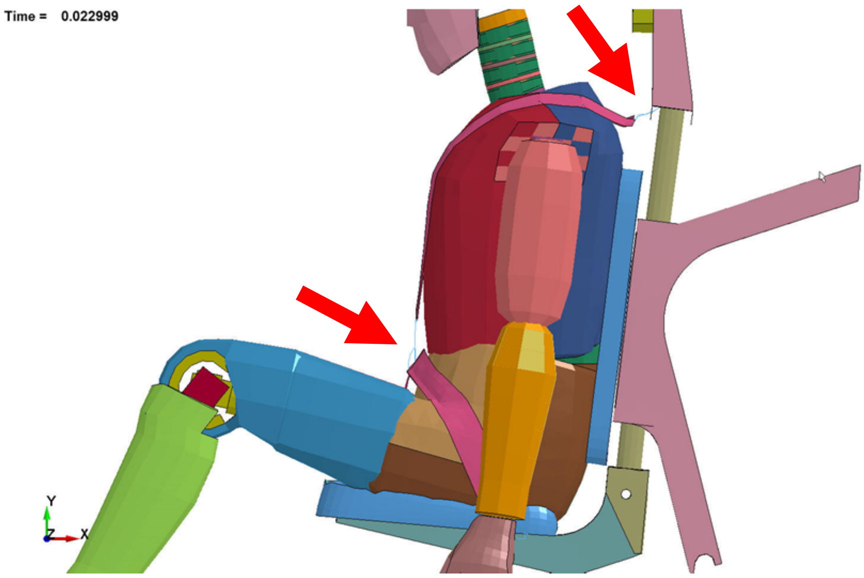

Fig. 14. The loosed belts after a full compression of the seat cushion (point B in figure 13).

The biomechanical criterion for the blast seat attenuation performance is the maximum value of the DRIz parameter. Results for various vehicle wall velocity and attenuating nominal forces are summarized in table I.

TABLE I
MAXIMUM VALUES OF DRIZ PARAMETER

nominal attenuating force	vertical velocity		
[kN]	3 m/s	5m/s	7m/s
5	6.1	8.9	23.0
10	10.1	12.9	15.1
15	12.3	16.4	18.7
20	12.3	18.7	24.1
∞ (seat only)	12.3	20.6	32.5

For 3 m/s base velocity, the seat without attenuating device meets the requirements and the DRIz does not exceed value 17.7. The velocity 5 m/s required a damper with a maximum force lower than 20 kN. For 7 m/s base velocity, only an attenuating force of 10 kN passed the test. Higher damping force resulted in excessive acceleration and softer damper failed because of reaching the maximum available stroke of the seat. The resultant DRIz profiles for analyzed velocities of vehicle wall and attenuating forces are presented in figure 15.

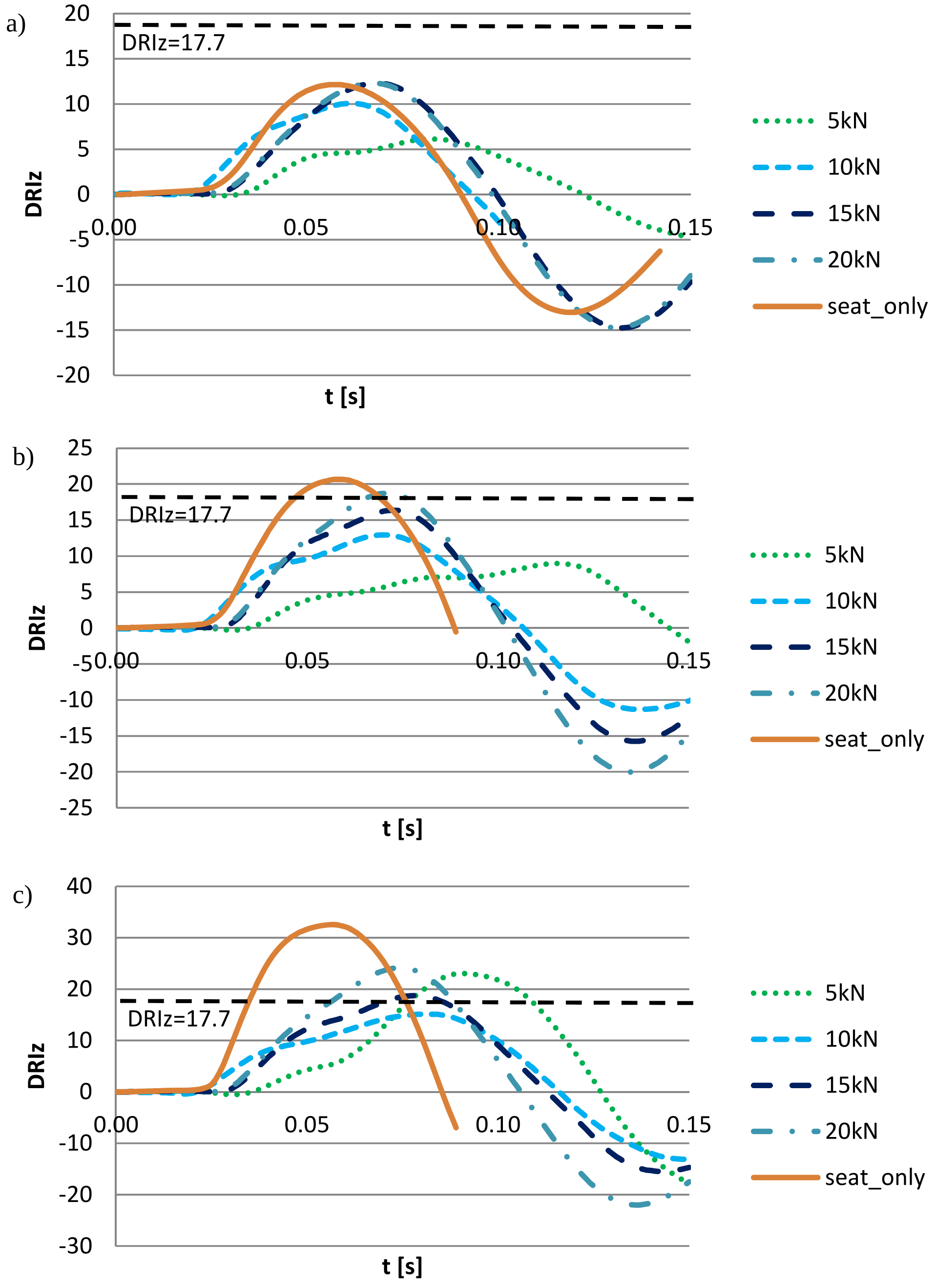

Fig. 15. The influence of an attenuating force on the DRIz parameter for different maximum vertical velocities of the seat base: a) 3 m/s, b) 5 m/s, c) 7 m/s. The profile **seat_only** refers to the seat without an attenuation device; both parts of the seat are rigidly connected to each other.

The seats without a damper exhibit one maximum. For seats with a damper, the decreasing value of the damping force results in an increasing number of local maxima up to three shown in figure 15b for the 5 kN damper. The reason for oscillations is due to unstable values of the actual accelerating force discussed later.

The performance of damping for various attenuating forces was compared in figure 16. For the damper with attenuating force 5 kN, the stroke of seat limited to 200 mm was too short, and the seat bottomed out exceeding the maximum allowed DRIz value.

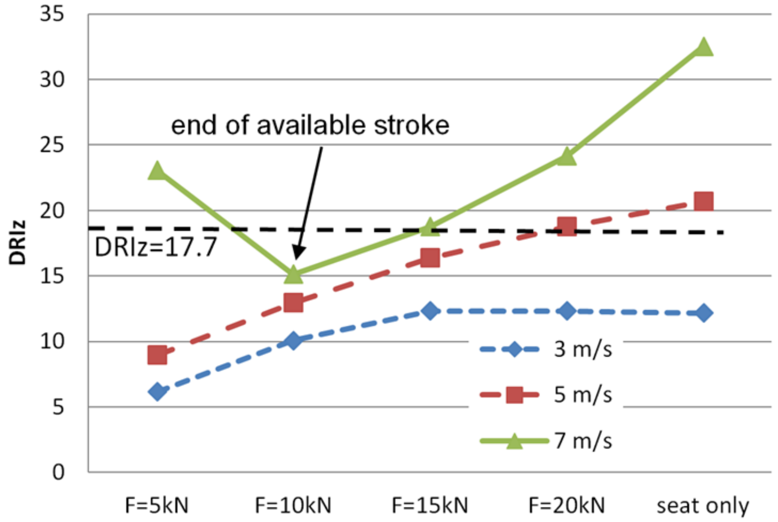

Fig. 16. The influence of attenuating force **F** on DRIz parameters for various vertical velocities.

The DRIz based criterion is an evaluation tool. A better insight in an attenuation process is given by analysis of forces transmitted between the base of the seat and the body. In figure 17, the accelerating forces applied to the center of gravity of the body are presented. The force was calculated by multiplying the input acceleration of the DRIz model by the mass of the accelerated part of HIII (without lower extremities).

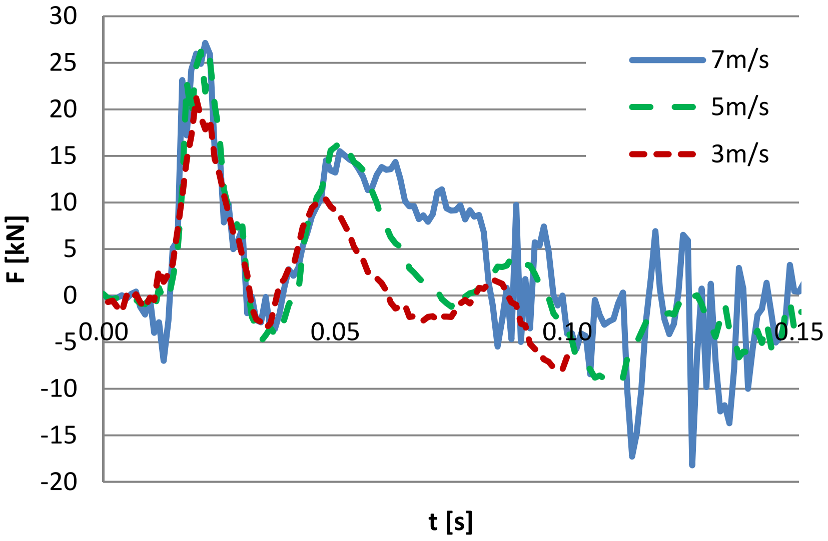

Fig. 17. The profile of accelerating force applied to the body by the seat with the 10 kN damper for various vertical velocities of the seat.

The peak values of accelerating force are much higher than the maximum force on the load limiting damper. The overload is a result of inertia of the movable part of the seat. It is accelerated between points **A** and **B** (fig. 11), and finally impacts the body. After the impact at point **B** and rebound, the amplitude of the second impact is lower and more effectively damped by the force limiter.

The comparison of the damping force and the actual accelerating force is presented in figure 17. Additionally, the optimal force profile is shown. This profile was calculated by multiplying the double-pulse acceleration profile defined by the vertical line in figure 6 by the accelerated mass of HIII. The actual accelerating force applied through the seat to the body is surprisingly similar to the optimal one according to the DRIz criterion. This similarity exists mainly for the 10 kN damper where the higher and lower values of damping force lead to a different shape of acceleration profile. This fact corresponds with best performance of the 10 kN damper for all evaluated vertical velocities.

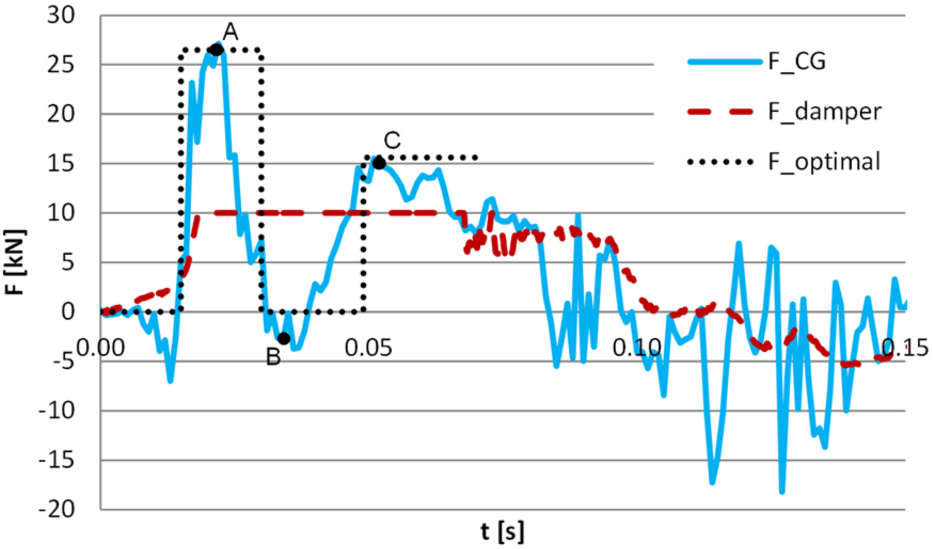

Fig. 17. The comparison of damping force **F_damper**, the actual accelerating force applied to the body **F_CG** and the optimal force profiles **F_optimal** for the 10 kN damper and vehicle vertical velocity 7 m/s.

The first peak **A** corresponds to the first impact of the seat into the body after full compression of the cushion. The short gap **B** after the first pulse is a result of rebound. The second contact of the seat with the body is more damped and causes the second pulse of force **C** with lower amplitude, which decreases to zero at the end of the attenuating process. Different shapes of the damper force and the actual accelerating force emphasize the influence of cushion thickness and the elasticity of the seat structure on the attenuation process.

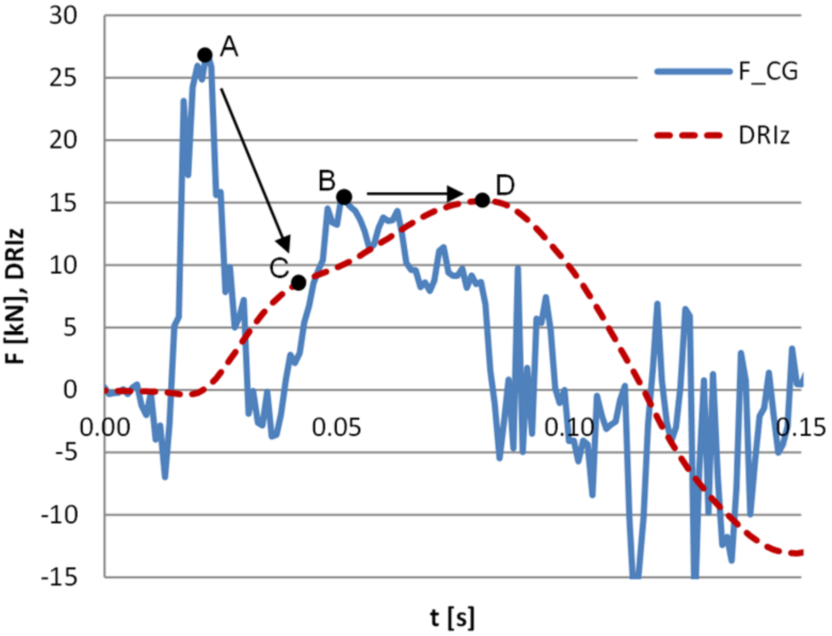

Fig. 18. The DRIz values and the actual force applied to the body **F_CG** for 10 kN damper and 7 m/s impact velocity

The comparison of actual force applied to the body and the DRIz history presented in figure 18 reveals direct correspondence of the two pulses of forces **A** and **B** with two maxima of DRIz profiles **C** and **D,** respectively. In order to reach the optimal profile of DRIz, the amplitude of local maximum **C** should be increased up to the level of the second maximum **D**. It requires increased value of the first impulse **A** applied to the body. Modification of the shape of this pulse of force can probably be achieved by modification of the seat structure stiffness and thickness of the cushion.

V. DISCUSSION

The limitation of this acceleration profile is the DRIz model's reliability. In particular, the DRIz model allows the application of extremely high acceleration in a short time. For example, the best result (the shortest required stroke of the seat) shown in figure 7 is reached for the first acceleration pulse with the amplitude 140 g and duration 4 ms. The question is whether such a high acceleration level is acceptable.

In available literature there are few data for maximum allowed acceleration, which can be applied axially to the spine in such a short time. The Eiband tolerance curve [15], based on various sources (volunteer tests, hog and chimpanzee experiments), is compared in figure 19 with the optimal first pulse parameters curve described in the first part of the paper (fig. 6, curve t1).

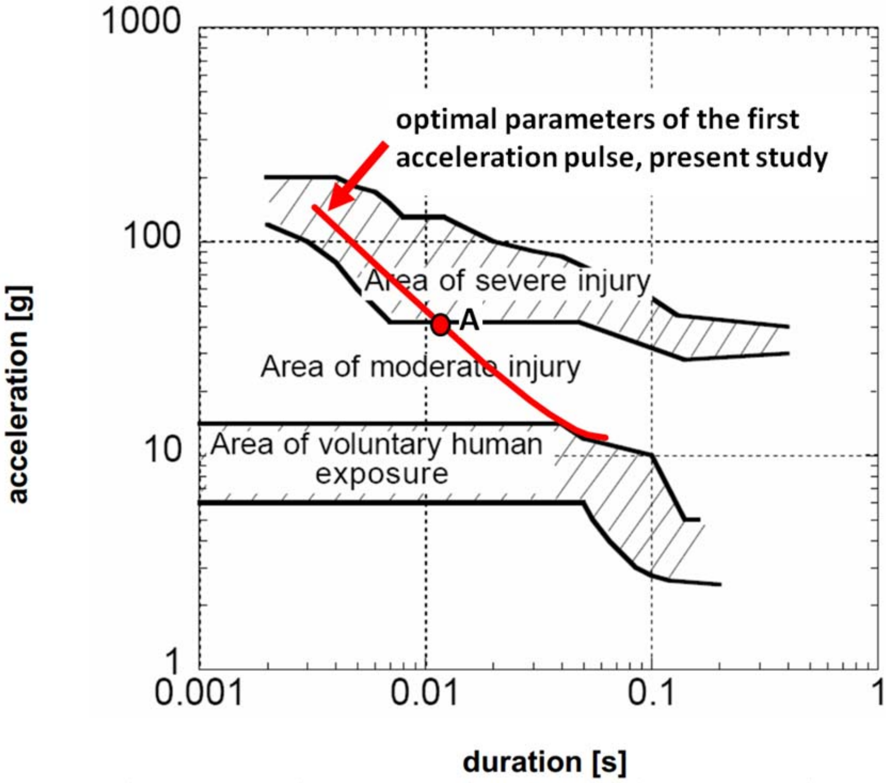

Fig. 19. The Eiband tolerance curves [15] (in black), the curve representing optimal first pulse parameters according to the DRIz criterion (present study, in red), **A** – optimal point according to DRIz criterion in the area of moderate injury

Because of higher amplitude of the first pulse results in the shorter stroke of the seat, the optimal point in the moderate injury area (point A, figure 19) represents the first acceleration pulse with the amplitude 48 g and duration 10 ms. The optimal dual pulse accelerating force profile corresponding to point A (fig. 19) in comparison to the actual accelerating force for 7 m/s impact velocity are shown in figure 20.

The second limitation of the model is the technical possibility of realization of this profile, discussed partially in the second part of the paper. The presented ability of the constant damping force system to generate a dual pulse acceleration profile leads to relatively simple and reliable mechanical dampers, for example based on the mentioned aluminium foams.

The clearance between the body and the belts (fig. 14), developed by the compression of the cushion, results in the excessive vertical body velocity, 35% higher than the velocity of the seat pan. This phenomenon can probably be minimized by application of the seat belt pre-tensioners. On the other hand, the forced minimization of the clearance can potentially change the duration between pulses generated by a constant force damping system. In case of the application of such devices, the sensitivity of the dual-pulse response to the pretensioner parameters should be carefully investigated.

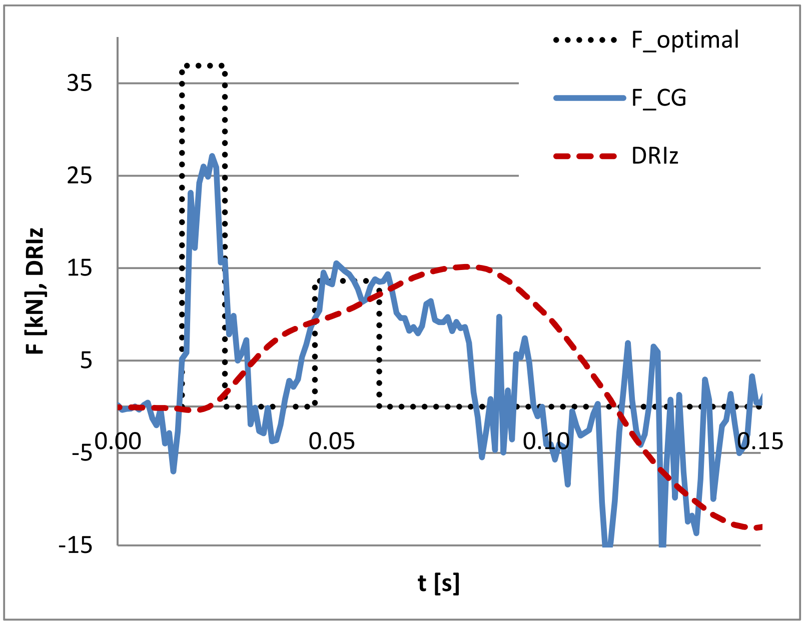

Fig. 20. The comparison of DRIz values, the actual accelerating force applied to the body **F_CG** and the optimal force profile corresponding to point **A** (fig. 19) for D=48 g.

In the paper the possibility of the design of a constant damping force seat responding with dual pulse are presented. The sensitivity analysis has been conducted for the cushion foam stiffness (figures 11 and 12) and shows the negligible influence of the cushion stiffness on the DRIz value. The specific dual pulse response of the full occupant/seat system relies on the elasticity of the seat support structure. Presented behavior occurs for the damping system with the given maximum force and the mass of the occupant. The sensitivity of the dual-pulse response to the seat structure stiffness as well as the response of such structure for the different mass of occupants will be the subject of future work.

VI. CONCLUSIONS

On the basis of a simple model, the optimal profiles of acceleration of the human body were developed according to the Dynamic Response Index criterion. To minimize a required stroke of the blast attenuating seat, two pulses of acceleration should be applied to the human body: first, to initiate the compression of the spine, and second, to keep compression at the desired level, with the gap between pulses. The profile of the first pulse of the acceleration was compared with available data and optimal pulse amplitude equal to 48 g with duration 10 ms was selected.

In order to check the behavior of a more realistic system, the full model of deformable seat with a constant maximum force attenuating device, cushion, seat belts and Hybrid III ATD was developed. The influence of cushion stiffness and attenuating force for various vertical velocities of the vehicle were investigated. The simulation with the use of LS-DYNA explicit code for various boundary conditions showed the best performance of a system with attenuating force 10 kN. The influence of the cushion stiffness on the DRIz value is negligible, but dynamic deflection of the cushion generates additional clearance between the human body and seat belts, and decreases efficiency of the belts.

The ability of a constant force damping system mounted in a properly designed seat (structure stiffness, cushion thickness) to generate the two-pulse acceleration profile close to the optimal one was presented. The dependency between the stiffness of seat structure, the thickness of cushion and the shape of acceleration pulse should be investigated.

VII. REFERENCES

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