

INVESTIGATION OF OCCUPANT FATALITIES AND INJURIES DURING  
THE IMPACT OF VEHICLE AND ROAD SAFETY BARRIERArtūras Keršys<sup>1</sup>, Algis Pakalnis<sup>2</sup>, Vaidas Lukoševičius<sup>3</sup><sup>1,3</sup> Dept of Transport Engineering, Kaunas University of Technology, Kęstučio g. 27,  
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**Abstract.** The main purpose of any road restraint system is saving human life and minimizing injuries. The efficiency of road restraint system is its capability to hold vehicle on the road, to decrease occupant injuries and damage to the impacted objects. The road restraint systems currently used in Lithuania meet the *European Standard EN 1317*. Acceleration Severity Index (ASI) and Theoretical Head Impact Velocity (THIV) are derivative values used in this standard mainly to describe simulation of vehicle and safety barrier impact situations and to study vehicle crash dynamics. This paper presents simulation of different situations of vehicle and road restraint system crash. Computer impact simulation analysis was performed as well as comparable investigation of conventional injury criterions Head Impact Criteria (HIC) and those used in the *European Standard EN 1317*.

**Keywords:** road restraint systems, safety barriers, injury criteria, computer simulations of impact.

## 1. Introduction

With Lithuania's entering the European traffic system and getting involved into an international market of traffic services the amount of road vehicles, their flows and speeds are increasing right along with the crash probability. Presently theoretical, numerical solutions and dynamic investigations of overground transport's passive safety means and structures absorbing energy are examined rather widely (Cristoforou *et al.* 2010; Ren, Vesenjak 2005; Šušteršič *et al.* 2007). It has to be noticed that experimental or numerical tests of impact of car-car or simplified bearing vehicle structures on obstacles are performed generally. But according to statistics in Lithuania (Prentkovskis *et al.* 2009; Šliupas 2009) ~11% of road accidents occur when the vehicle runs off the road or crashes into the road facility structure. Due to the intensively improving passive safety means the tragic accidents are decreasing, though experimental tests or numerical modeling problems of such structures remain insufficiently examined. In case of vehicle impact on road facility objects, the problems of influence of the appearing inertia forces on vehicle occupants remain very important (Cansiz, Atahan 2006; Huang 2002).

Modern passive road safety structures ensure rather effective absorption of excessive vehicle energy, prevent vehicle runs-off, correct vehicle movement trajectory and do

not allow it to move away from the road. Both in Lithuania and European Union (EU) rigid, half-rigid or deformed road structures used during vehicle crash develop different reaction forces (Bayton *et al.* 2009; Bogdevičius, Prentkovskis 2001). Rigid reinforced concrete or parapet structures, reinforced concrete sides, used especially for this purpose, deform very slightly, therefore, energy is almost not absorbed, dangerous inertia forces are developed and the occupants are not safe against serious injuries. Deformed metal structures are by no means more effective and economical (Fig. 1). The largest advantage of those structures is that it is possible to change deformation more flexibly suppose when mounting additional elements or



**Fig. 1.** Metal safety barriers without inserts used in Lithuania, meeting the safety requirements of *European Standard EN 1317*

doubling structures, to change amount of uprights – adapt high-accident road sections to the existing road conditions (Prentkovskis et al. 2010). Besides, it is much easier to repair metal structures or replace them with other facility solutions. However, all the systems installed on the Lithuanian roads have to meet the requirements of the *European Standard EN 1317-1:1998 Road Restraint Systems – Part 1: Terminology and General Criteria for Test Methods*, based on which investigations of experimental structures have to be implemented. Mostly, experimental investigations of complex structures are rather expensive, though more reliable than the numerical ones. Thus, in order to investigate the process of such a complicated phenomenon as vehicle crash on road facility object more accurately, it is worth performing significantly faster and cheaper numerical experiments.

The aim of this work was to create numerical models, enabling to quickly and rather reliably evaluate behavior of safety barrier during the impact with vehicle.

Though such simulation is a task of large scope and time-consuming, it gives a possibility to solve and evaluate much more problems – mechanical characteristics of the repaired barriers, behavior during a crash, natural weather and road conditions, influence of road geometry or soil, reliability of bolted joints, etc.

**2. European Standard EN 1317 and injury criterions**

The United States procedures are prescribed in *NCHRP Report 350* (Ross et al. 1993), the European Committee for Standardization (CEN) procedures are presented in the *European Standard EN 1317-2:1998 Road Restraint Systems – Part 2: Performance Classes, Impact Test Acceptance Criteria and Test Methods for Safety Barriers*. This standard provides a common basis for the data collection of vehicle impact test and the collation of the relevant European studies and researches with a view to improving future specifications and reviewing measurement of impact severity. According to the standard, safety barriers shall restrain and change vehicle’s trajectory, without complete breakage of the principal longitudinal elements of the system. Elements of the safety barrier shall not penetrate the passenger compartment of the vehicle.

*Standard EN 1317* establishes three main criteria:

- safety barrier restraint level – standard prescribes for restraint levels for different vehicles (Table 1);
- impact influence criterion, i.e. acceleration severity index (ASI), theoretical head impact velocity (THIV) and post impact head deceleration (PHD);

- working barrier width (max barrier displacement in horizontal direction). Eight deformation classes of protective barriers are defined.

CEN test procedures prescribe that ASI criterion shall be calculated as (Nasution et al. 2009)

$$ASI_{(t)} = \left[ \left( \frac{a_x}{x_l} \right)^2 + \left( \frac{a_y}{y_l} \right)^2 + \left( \frac{a_z}{z_l} \right)^2 \right]^{0.5}, \quad (1)$$

where  $a_x, a_y, a_z$  – the 50 m/s<sup>2</sup> average component vehicle accelerations.

The threshold accelerations are 12 g, 9 g, and 10 g for the longitudinal (x), lateral (y), and vertical (z) directions, respectively.

Since it uses only vehicle accelerations, the ASI inherently assumes that the occupant is continuously contacting the vehicle, what is typically achieved with the use of seat belt.

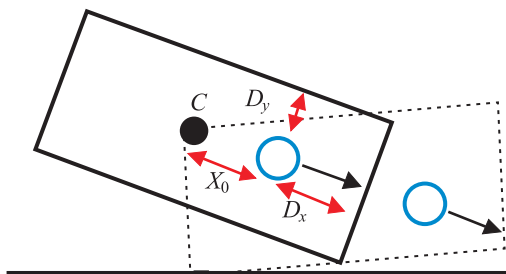
The max ASI value over the duration of the vehicle acceleration pulse provides a single measure of collision severity that is assumed to be proportional to occupant risk. To provide an assessment of occupant risk potential, the ASI value for a given collision acceleration pulse is compared to established threshold values. ASI criterion is dimensionless value and scalar function of time, which is always positive. Although a max ASI value of 1.0 is recommended, a max ASI value of 1.4 is acceptable (*European Standard EN 1317-2:1998 Road Restraint Systems – Part 2: Performance Classes, Impact Test Acceptance Criteria and Test Methods for Safety Barriers*).

The theoretical head impact velocity (THIV) concept has been developed for assessing occupant impact severity for vehicles involved in collisions with road vehicle restraint systems. The occupant is considered to be a freely moving object (head) that, as the vehicle changes its speed during contact with the vehicle restraint system, continues moving until it strikes surface within the interior of the vehicle (Fig. 2). The magnitude of the velocity of the theoretical head impact is considered to be a measure of the vehicle to vehicle restraint system impact severity.

The head is presumed to remain in contact with the surface during the remainder of the impact period. In so doing it experiences the same levels of acceleration as the vehicle during the remaining contact period (post-impact head deceleration PHD). The PHD is calculated as the peak value using a 10ms moving average of the resultant vehicle acceleration after the THIV impact.

**Table 1.** Different types of tests according to *EN 1317*

Test	Vehicle type	Vehicle mass, t	Impact angle, °	Impact velocity, km/h
TB 11	Car	0.9	20	100
TB 31	Car	1.5	20	80
TB 32	Car	1.5	20	110
TB 42	Truck	10	15	70
TB 51	Bus	13	20	70
TB 61	Heavy goods vehicle	16	20	80



**Fig. 2.** Theoretical THIV and PHD calculation:  $D_x$  – longitudinal distance from head to vehicle;  $D_y$  – transversal distance from head to vehicle;  $X_0$  – distance from the center of gravity of vehicle to the head

Head injury criterion (HIC), parameter specifying possible injury of an occupant of vehicle, is expressed as function of acceleration and impact pulse. The HIC criterion was defined by USA National Highway Traffic Safety Administration and is widely used in numerical experiments and computed for acceleration of 36 ms.

Later, the max time for HIC calculations was reduced from 36 ms to 15 ms. The HIC value is calculated from the resultant acceleration time history of the head center of gravity filtered through a class 1000 filter. The HIC value is then calculated from

$$HIC = \left[ \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a dt \right]^{2.5} (t_2 - t_1), \quad (2)$$

where  $a$  – the acceleration expressed,  $g$ ;  $t_1, t_2$  – any two points in time. It is now usual for an upper limit on the range  $t_2 - t_1$  of 15 ms to be applied.

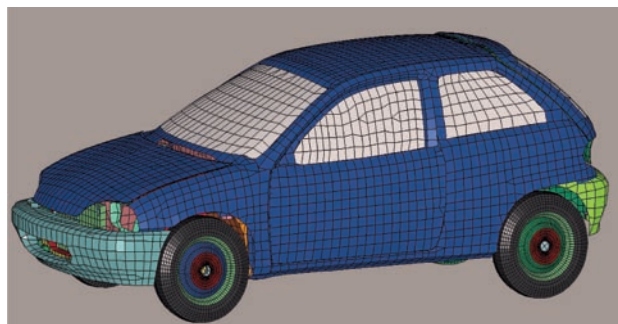
### 3. Description of finite element model

Vehicle models for numerical experiments, performed according to EN 1317, are presented in USA National Highway and Transport Safety Authority library (*Federal Highway Administration (FHWA)/National Highway Traffic Safety Administration (NHTSA), National Crash Analysis Center*) Models developed for the program LS-DYNA are contained here (Sennah *et al.* 2003; Vasenjak *et al.* 2009). For TB11 and other numerical experiments the General Motors GeoMetro finite elements model (FEM) (Fig. 3) was chosen. The model was slightly changed. For the main front and side parts, contacting during impact with the safety barrier, types of elements were changed from the Belytschko-Tsay to the S/R co-rotational Hughes-Liu element to ensure numerical stability during the analysis. Thus, the remote elements are not designed in the model of barrier structure and tire contact with uprights during crash, tire finite element grid was compressed and material models were changed from elastic-plastic (type 24) to elastic (type 1). For Geo Metro shell structures full integrated shell element of 16 types with 8 hourglass formulations was selected.

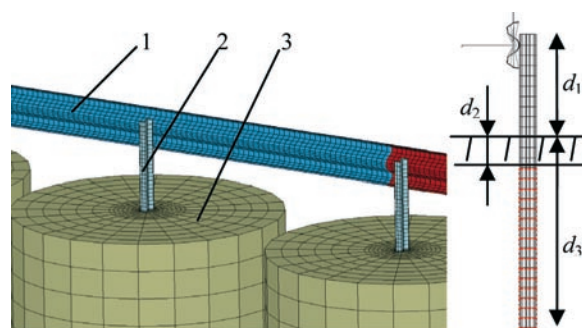
Rails and posts are made of S235 JRG2 steel, with yield strength of 235 MPa. The material properties of the safety barrier use the piecewise linear plastic. Posts have a sigma shaped section and an overall height of 1900 mm. Rails are connected to posts using nodal rigid body spot welds. Linear springs are attached to the ends of the rails to simulate continuance of the guardrail system. Back stretches in the model are assessed by springs, which rigidity in three directions is calculated approx with simplified model. Accelerometers, by help of which acceleration values in three directions of coordinates and ASI and THIV criteria are evaluated, both in real vehicle tests and in numerical experiments are mounted in the center of gravity of a car. The FEM of the road restraint system consists of ten w-beam rail sections with sigma profile posts at standard length of 4000 mm of the total length of 40 m (Opiela *et al.* 2007).

Right simulation of the interaction of soil and uprights is very important and critical factor for calculation results. Interaction between soil and structure was evaluated twice in this work.

In the first case the method for restricting slipping movements 200 mm below the road pavement was used (Fig. 4). In this case the upright may freely bend below pavement, and this is very similar to the real upright deformation during crash. In the second case soil is simulated with the simplest soil material model, solid elements and the Lagrangian mesh selected. In this case the elements are contorted badly, therefore simulation is rather approxi-



**Fig. 3.** General Motors GeoMetro and FEM



**Fig. 4.** FEMs of the road safety barrier: 1 – rails; 2 – sigma posts; 3 – soil;  $d_1 = 700$  mm,  $d_2 = 200$  mm,  $d_3 = 1200$  mm

mate. More accurate evaluation is achieved with the use of Eulerian mesh, but this is much more complicated and needs additional numerical investigations. Friction coefficient between the car and the road pavement is assumed to be equal to 0.6 in all calculation cases, coefficient between the barrier uprights and the soil is selected equal to 0.4. Friction between the safety barrier and the car was not taken into account. For HIC criterion estimation anthropomorphic Hybrid III 50<sup>th</sup> rigid model, representing the 75 kg 50<sup>th</sup> percentile male developed by Livermore Software Technology Corporations (LSTC) was selected. LSTC produce a range of freely available dummy models that are suitable for basic loading analysis.

**4. FEM simulation of the impact of vehicle and safety barrier**

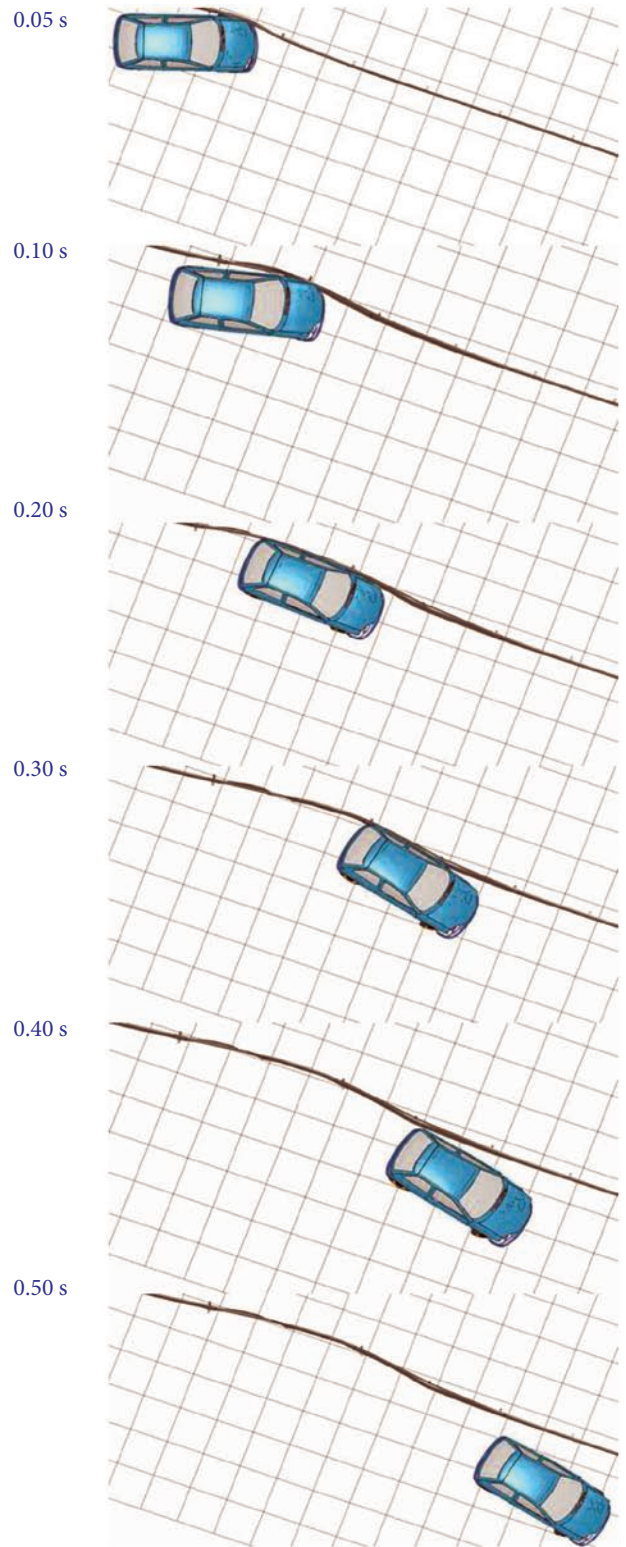
Deformation of metal safety barrier and vehicle trajectory after numerical experiments by TB11 test is presented in Fig. 5. It was determined, that in initial impact stages a vehicle hardly deforms, in contrast to the safety barrier. But later vehicle deceleration increases, deformation of the barrier decelerates and vehicle deformations increase. In this crash stage a vehicle changes its movement direction. Movement trajectory at the beginning is parallel to a barrier axis, after a while the vehicle turns on its vertical axis and under the action of inertia forces returns back to the road.

In this task stage, besides particularities of soil simulation, influence of boundary conditions and stiffness of back stretch was also examined. By numerical experiments it was found out that the length of working stretch of numerical model has great influence on the stiffness of barrier and also on the most important criterion describing occupant ASI.

The shorter the examined stretch in the model, the more rigid the model, the higher influence of length on the criterion. Difference of ASI parameter between 24 m and 40 m length stretches, with all other boundary conditions identical, makes up about 40%. In this stage of the work stiffness of back stretches was estimated for the road 40 m in length. For calculations, when the joints of back stretches fixed rigidly, slipping movements fixed and joints unfixed, were selected. The obtained results show that difference between the results obtained under different boundary conditions of back stretches is insignificant ASI criterion differs by ~0.01, except the case without fixing of back joints. ASI criterion differs about 2% for models with fixed back joints and unrestraint ones. It should be noticed, that in case of unrestraint back stretches, vehicle’s trajectory is very different also – the car overturns and does not return back to the road. Two more cases were examined for further estimations. Simulation of back stretches taking into account just longitudinal elements described in publication (Tabiei, Wu 2000) was considered:

$$K = \frac{EA}{L}, \tag{3}$$

where  $E$  – steel elasticity modulus, Pa;  $A$  – barrier cross-section area, m<sup>2</sup>;  $L$  – length of back stretch, m.



**Fig. 5.** Top view of the impact of vehicle and safety barrier: impact angle 20°, velocity 100 km/h

The downward back stretch was simulated in great details. After stiffness simplified calculations for the latter model in three directions and comparison to numerical experiments performed earlier, springs’ stiffness in three directions was selected. Interaction of soil-upright was simulated also in several ways. The model, when joints’

slipping movements are restricted at 200 mm below pavement, seemed to be rather rigid in comparison to the other two models – 3D solid elements and Lagrangian mesh describing soil-upright interaction. Two variants were selected here – connecting upright and soil joints and taking into account 0.4 of friction between upright-soil. However, it was defined that the latter models are rather inaccurate due to FE grid contortion and for further research a more rigid and more accurate soil simulation principle was selected.

### 5. Investigations of injury criteria

In this stage of investigation the injury criteria were examined. Estimation was performed with the use of LS-DYNA program postprocessor. Numerical simulation variants TB11 and those not meeting the *EN 1317* criteria were chosen for the investigation: increased vehicle speed, impact angle to safety barrier, elastic deformation of the fragmentation not taken into account and taken into account in material mathematical model, as well, changed yield strength of barrier structure. This allows a more accurate evaluation of numerical model used and finding out how accurate the matching of calculations of FE of various mathematical models and experimental investigations, described in publications, is. Dependences of ASI criterion of some calculation variants on time, after filtering directional acceleration results by SAE 60 filter, are given in Fig. 6, and calculation results are shown in Table 2.

As Fig. 6 (curve a) shows, after numerical experiments by TB11 regulated test done, a curve of ASI criterion has a jump – in this impact stage, a wheel strikes the upright bearing a barrier. The performed investigations show that when simulating structures without a rigid insert between a barrier and upright, exact FEM of tire and simulation of interaction of impact of upright and tire may influence the results obtained.

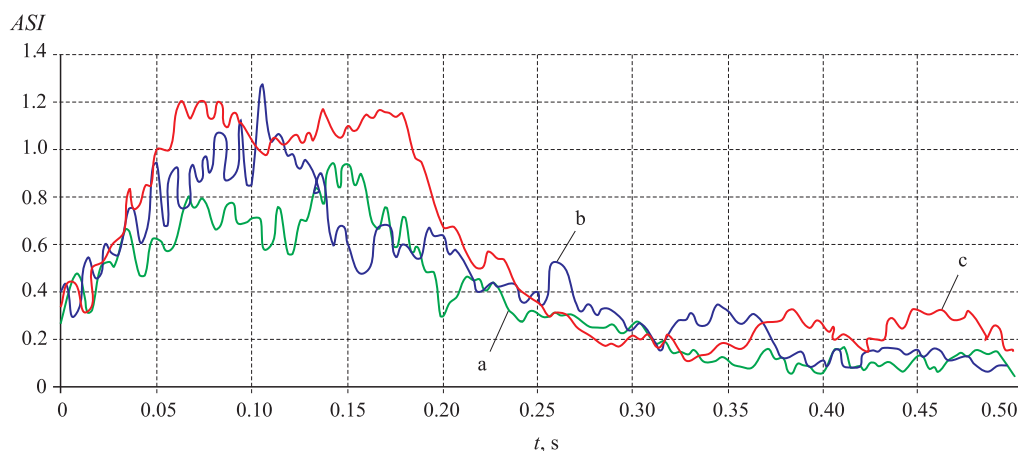
With the increasing vehicle speed up to 130 km/h (Fig. 6 (curve b)) the influence of upright and wheel impact is insignificant, but the value of ASI criterion increases greatly. Intermediate results are obtained tilting a vehicle at 40° angle to barrier axis (Fig. 6 (curve c)).

**Table 2.** Test types below the *Standard EN 1317*

Simulation description	ASI	THIV, km/h	PHD, g	Departure speed, km/h
20°, 115 km/h	1.24	27.9	20	92.4
20°, 115 km/h w/o fail. strain	1.18	27.9	19.6	91.4
20°, 130 km/h	1.27	28.5	18.9	93.8
20°, 130 km/h w/o fail. strain	1.33	28.9	22.8	79.4
30°, 100 km/h	1.21	28.9	22.9	79.2
40°, 100 km/h	1.32	43.4	9.10	63.4
$\sigma_{\text{yield}} + 20\%$	0.90	27.4	17.2	52.6
$\sigma_{\text{yield}} - 20\%$	0.87	25.7	16.2	77.4

On the basis of recommendations of the above mentioned standard, for a impact severity level, determining occupant security level, the value of ASI criterion for metal barrier structures should not exceed 1,  $\text{THIV} \leq 33 \text{ km/h}$  and  $\text{PHD} \leq 20\text{g}$ . For THIV and PHD the following data is chosen: longitudinal distance from head to vehicle 800 mm, transversal distance from head to vehicle 300 mm and distance from center of gravity of vehicle to the head 600 mm. Results of numerical simulation presented in Table 2, reflect general tendencies and forecast very well. While changing simulation parameters, which do not meet those prescribed in *EN 1317*, the values of injury criteria in some cases exceed the permitted ones. It is especially noticeable in case of ASI criterion, which is commonly considered as the main parameter representing possibilities of the safety of road barrier.

THIV and PHD criteria are depending strongly not only on the inertial vehicle's and stiffness – force barrier possibilities but also on the geometric parameters of vehicle and its occupants. Transversal distance from head to vehicle equal to 300 mm which is measured between a dummy head and windscreen sometimes does not exceed 100 mm, and longitudinal distance from head to vehicle depends greatly on position of occupant seat along vehicle axis. Due to such uncertainty the latter two criteria are considered more theoretical values.



**Fig. 6.** ASI parameter vs time plot: a – TB11 test; b – 20°, 130 km/h; c – 40°, 100 km/h

When the vehicle speed and impact angle is increased, injury criteria exceed the prescribed limits both with and without the evaluation of elastic deformations of the fragmentation of structure. Decreasing tendencies of the criteria are fixed by changing the mechanical characteristics of material structure – by increasing or decreasing yield strength. Analysis of results demonstrates that analogical results are obtained for vehicle departure speed. As this value does not represent the vehicle occupant injury, it demonstrates very well the restraining possibilities of safety barrier.

In order to evaluate the occupant head injury a simplified model (Fig. 7) was selected with the help of which the regularity of variation of ASI and HIC criteria was estimated rather approximately. For simulation of seats, safety belts and dummy elements of rigid type were used.

The regulated experimental tests of vehicles and barriers are not yet performed by using special dummies designed namely for such tests.

FEMs of the Hybrid III dummy initially were designed and calibrated for frontal vehicle impact on the obstacles. The use of Hybrid III dummy for simulation of cross crash of the vehicle and the safety barrier has not been sufficiently examined also.

For the vehicle cross crash against the road facility object and for the more accurate calculations of values of dummy injury criteria the additional investigations are necessary. ASI criterion, developed in 1960 in US, is calculated in the center of gravity of vehicle, therefore the controversial problems and uncertainties arise in various cases. At present this parameter is not used to evaluate occupant security in US, though procedures of the European Committee for Standardization CEN specify ASI as the most important possible criterion enabling to evaluate injury.

HIC calculation results, obtained in this work, confirm the forecast. Initial investigations demonstrate merely the relation of HIC and ASI criteria and the nature of their variation. The main parameters correlate rather well at low values, i.e. when ASI parameter increases linearly the HIC parameter also increases, but later the variation becomes exponential (Shojaati 2003).

Latter investigations were performed with the use of rigid Hybrid III dummy and very simplified rigid nu-



Fig. 7. Safety barrier simulation with rigidly belted Hybrid III dummy

merical model of the seat. In order to revise solutions it is necessary to evaluate additional parameters of interaction between the dummy and the seat. For this purpose, it is necessary to develop a more detailed model of safety belt with pretension, slip rings, retractor elements, revised mechanical characteristics of belt material, design rigidity and friction characteristics of the dummy and the seat, to develop a more detailed FEM of the seat, to describe more accurately the dummy and vehicle interaction, to simulate side-door windows.

## 5. Conclusions

Vehicle impact on road facility object was analyzed in this work. Program package LS-DYNA was used for the calculations. A rather detailed numerical model of metal road safety barrier was developed and the injury criteria under different crash conditions were also determined. The main advantage of solutions to similar numerical problems is a possibility of description or examination of crashworthiness simulation in great details, and this is rather complicated by the conventional analytical methods.

The developed numerical models of safety barriers enable preliminary evaluation of the structure's rigidity during the vehicle crash into the obstacle. FEMs reflect experimental researches, described in various publications, rather well. Numerical models demonstrate strong dependence of the results obtained on the mechanical characteristics of material. In order to analyze vehicle crash into the obstacle and general structure behavior by the developed FEMs more specifically, it is recommended to perform more detailed numerical investigations of soil simulation, to define experimentally mechanical characteristics of safety barriers and to analyze characteristics used in mathematical models.

The currently used standards and regulations, describing experimental vehicle impacts on road obstacles, analyze vehicle dynamics, however, they do not analyze in detail requirements to occupant security. The occupant injury criteria were estimated in accordance with the current standards as well as the regulated vehicle impact tests using Hybrid III 50<sup>th</sup> dummies.

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