Study regarding seat’s rigidity during rear end collisions using a MADYMO occupant model

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Abstract – The aim of this paper is to study the effects of different front occupant backseat’s rigidities in the case of a rear end collision using a multibody virtual model of an occupant. Simulation will be conducted in PC Crash, the most common accident reconstruction software using a MADYMO multibody occupant to simulate kinematics and dynamic of the passenger. Different backseat torques will be used to see how this will influence the acceleration in the head and torso of the occupant. Also, a real crash test is made to analyze the kinematics of the occupant. We believe that the softer seat’s rigidity will reduce not only the head’s acceleration but also reduces the effect of „whiplash” upon the neck due to the fact that the backseat will rotate backwards increasing its displacement and absorb some of the energy generated by the collision. Although a softer seat could reduce the head’s acceleration, a broken seat will increase it due to the fact that the impact of the backseat with the vehicle’s rear seats will generate a second collision. So, in order to achieve a lower acceleration, a controlled torque is recommended and a controlled angular displacement of the backseat is to be used.

1. Introduction
Rear-end collisions are the most frequent types of car-to-car accidents where some form of injury occurs upon the occupant [6]. Usually, in this type of collision the neck and the head suffer the most severe damage due to the phenomenon called “whiplash” that consists of the neck and head’s moving back against the headrest, generating low injuries to the neck, but with long-term consequences [2], [11], [13]. One of the most negative effects of “whiplash” is the long-term injury that can be permanent in some cases. Only in Europe, over 10 million euros were paid by insurance companies to people that reported long-term injuries of “whiplash” [1], [5]. It was observed that, if the backseat moves in accordance with the occupant, a part of the energy is absorbed. Jakobsson designed and built a system to accomplish this, it is called WHIPS and it is mounted on some modern Volvo vehicles [7]. This is done by a mechanism that limits the movement of the backrest slightly, but also moves the backrest upwards to align the head with the headrest [10]. On the other hand, if the backrest’s hinge breaks and moves too much, it will hit the backseat of the vehicle, generating a higher acceleration upon the head. Because of this, the study was realized in order to analyze different torque values of the backseat’s hinge where the acceleration on the occupant’s head varies.

2. Method used
In the simulations, different torque values of the backseat hinge have been chosen to observe the occupant’s kinematics and the head’s acceleration variation as well. This study was conducted in the virtual environment in the PC-CRASH 10.2 program using the MADYMO occupant’s module
integrated into a PC-CRASH [14]. The occupant’s height is fixed to the 50th percentile, and the dashboard geometry is fixed. Its dimensions and seat position are shown in Figure 1.

**Figure 1.** MADYMO occupant’s position and dimensions [4]

The module allows modification of certain parameters regarding the seat-back angle, its rigidity, the head’s restraint, occupant’s mass data, and the airbag deployment times and seat belt pre-tensioning. The MADYMO interface is shown in Figure 2.

**Figure 2.** Interface used to modify MADYMO model parameters

A crash test was made in order to analyze the occupant’s kinematics and to validate the simulation of the impact by using the MADYMO model. The test consisted of a vehicle-to-vehicle rear-end collision with an overlap of 100%. The crash configuration is presented in Figure 3.

**Figure 3.** Crash test configuration

The crash test was filmed with a high-speed video camera, capable of filming at 1000 fps, in order to analyze each phase of the impact and to study the movement of the occupant. After this test had been conducted, a simulation in PC-Crash was also done using the same configuration and compared to the crash test. In Figure 4 the comparison of the occupant’s kinematics is presented between the crash test and the simulation.
In phase 1, the posture of the occupants is seen before the collision, followed by phase 2, when the occupant begins to move towards the inside of the seat, and the head hits the headrest. Also, in this phase, the extension of neck occurs. In phase 3, the chest tends to rebound forward, but it is limited by the seatbelt. Also, the head flexes forward as well. This movement can be seen in both occupants. The parameter of interest in this study is the acceleration of the occupant’s head. The comparative chart between the occupant acceleration in the experimental test and the MADYMO model is shown in Figure 5.

![Figure 4. Occupant’s kinematics comparison between the crash test and simulation](image)

**Figure 4.** Occupant’s kinematics comparison between the crash test and simulation

The start of the collision takes place after 100 ms, point where the occupant's chest travel to the seat and the head reaches contact with the headrest at 130 ms, generating an acceleration peak of 230 m/s². It can be seen that, in both cases, the acceleration has a similar pattern, validating the simulation with an error of 12%.

![Figure 5. Comparison of occupant’s head’s acceleration between the crash test and simulation](image)

**Figure 5.** Comparison of occupant’s head’s acceleration between the crash test and simulation
The acceleration value, according to the impulse duration, shows a maximum limit of 40 g for the head. In the case of pedestrians the situation is more dangerous, at the impact with the ground, much higher head accelerations (120 - 200 g) can cause severe injuries. The head injury risk is assessed using HIC (Head Injury Criteria) criteria on a time interval of 36 ms for the occupant, respectively 15 ms for the pedestrian [8], [9].

The velocity of the vehicles was analyzed and presented in Figure 6. The collision velocity was 34 km/h for the striking vehicle (VEH 2) and 0 km/h (stationary) for the struck vehicle (VEH 1).

![Figure 6. Velocity variation of the two vehicles](image)

In can be observed that the collision takes place after 100 ms, when the velocity of the striking vehicle (VEH 2) drops from 34 km/h to 13 km/h at 180 ms, then, a low decrease rate to 0 km/h at 1000 ms occurs. Also, after 100 ms, the stroked vehicle (VEH 1) has an increase in velocity, from 0 km/h, up to 17 km/h at 200 ms, following a lower rate decrease. At 170 ms, it can be seen that both vehicles have the same velocity, of 15 km/h.

In the next phase, three simulations were conducted by using the MADYMO module, in which the torque between the seatback and the seat was set for the three situations and the stiffness was set to normal (1000 Nm), lower (550 Nm) and very low (250 Nm). The kinematics of the occupant and the variation of the back angle for the three situations are presented in Figure 7.

![Figure 7. Variation of the inclination angle of the backrest according to its rigidity](image)
In the case of normal rigidity, the torque is 1000 Nm [4] and the maximum inclination of the backrest is 29 degrees. To simulate a reduced rigidity, the torque was reduced to 550 Nm, resulting in a maximum angle during the collision of 35 degrees, and to simulate a very low stiffness, the torque was reduced to 250 Nm, resulting in a maximum angular displacement of 40 degrees. The comparative analysis of the occupant’s head’s acceleration for the three cases is presented in Figure 8.

Whiplash injuries can be predicted using the correlation between the head and torso rotation angle. NHTSA developed a method to predict the probability of whiplash in accordance with the head-torso rotation based on sled tests conducted in a controlled environment using crash test dummies and different seats and headrests. In Figure 8 the probability of whiplash is presented [12].

![Figure 8. Probability of “whiplash” in accordance with the head-torso rotation angle [12]](image)

In can observed that for a 100% whiplash probability the head-torso angle is around 84 degrees. At this angle, there is very large change that injuries will occur such as muscle tear, vertebra dislocation and fractures. These types of injuries are not life threatening but they do generate long term symptoms and limitations such as pain, dizziness, anxiety, muscle stiffness and head rotation turn limit [3].

In the simulation, the headrest position was not altered (normal position) and as such, the whiplash effect was greatly reduced by the headrest. During the collision the head and torso were aligned and thus, the torso-head angles was almost 0. This can be observed in Figure 9.

![Figure 9. Center of gravity axis change for the head and torso of the occupant during the collision](image)
Before the collision, the head and torso CG axis can be observed, they are at an angle of 23 degrees (Figure 10). When the collision occurs, the head moves back and it is stopped by the headrest, thus the two axis align and reduce the whiplash effect. In Figure 10 the movement of the head and torso is presented.

**Figure 10.** Head and torso angle variation during the collision

Because the torso and head have the same axis, the angle is counted for both of them in regards to a vertical axis. In the initial condition, the torso is at a 14 degree angle in the normal position and rotates at different angles for the different seat rigidities analysed (26 degrees – normal, 31 degrees – low rigidity and 36 degrees – very low rigidity).

From this point of view, the whiplash effect is minimal and can be neglected due to the fact that the occupant model had the headrest adjusted correctly and only the seat rigidity was modified. This is why the head acceleration was taken into account and analysed as the main parameter for the occupant.

3. Results
The results consist of the head’s acceleration comparison between the three cases. In the graph presented in Figure 11, the head’s acceleration was obtained, compared and analysed.
Figure 11. Comparative analysis of head’s acceleration according to the torque of the backrest

In the case of normal rigidity, the head’s acceleration is 230 m/s², at 130 ms. In the case of low rigidity, maximum head’s acceleration is 170 m/s² at 140 ms, and in the case of very low rigidity, the acceleration peak is 160 m/s² at 160 ms. It can be seen that acceleration peaks are attained at different times due to the increased angular displacement of the occupant. The reduction in headline acceleration is shown in Figure 12.

Figure 12. Percentage reduction of head’s acceleration and percentage increase of occupant’s angular displacement according to the backrest stiffness

It can be observed that, if the backrest stiffness is reduced, the acceleration is also reduced by 26%, while the angular displacement increases by 20%, and in the case of very low backrest stiffness, the acceleration decreases by up to 30% and the angular displacement increases by 38%.

4. Conclusions

After conducting the experimental test, the simulation was successfully validated, using the same impact configuration, with an error of just 12%. By modifying the backseat torque, a reduction in head’s acceleration was obtained. In the case of a lower rigidity seat, the torque was of 550 Nm, the acceleration reduction was of 26% and in the case of a very low rigidity, the torque was of 250 Nm, the acceleration reduction was even higher, up to 30%. The reduction takes place due to the increase
of the angular displacement of the backrest, resulting in the absorption of collision energy. Angular displacement of the backrest shows an increase of approximately 21% in the case of lower rigidity, and 38% in the case of very low rigidity. It can be concluded that, by reducing the torque of the backrest, the head’s acceleration of the occupant is also reduced, but with an increase of an angular backrest’s displacement.

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