Influence of the Headrestrain Position in Case of Rear End Collision and its Effects Upon the Whiplash Phenomenon

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***Abstract*— The purpose of this study was to determine the injury potential in the case or rear end collision of the occupants head and neck by analyzing the distance between the head and headrest using two virtual multibody occupants. For this study, a rear impact was simulated virtually using PC Crash, the most common program used for accident reconstruction. The study was made by using 2 virtual multibody models, a basic multibody occupant included in PC Crash and a MADYMO occupant model. The distance of the headrest to the head varied from being close to the head (at about 110 mm from the normal position) to not using a head rest at all. This will simulate the position of the occupant when driving, while some drivers adapt a more close position to the steering wheel (head being far from the headrest) while others adapt a more relaxed position (head is near the headrest). The angles of the head and neck were measured and compared to medical limitations of them. Also the neck injury criteria (NIC) was calculated to evaluate the injury potential of the head rest distance variation.**

Keywords*— *Head restrain, acceleration, whiplash, rear impact, head position, headrest, madymo, multibody

I. INTRODUCTION

Road safety is considered a major public health problem. Statistics show that more than 3,000 people worldwide die each day due to the death of accidents [1]. In rear end collisions between two vehicles, the most common type of injury for the occupants is the fracture of the cervical spine. This phenomenon goes by the name of "Whiplash". Even the lower speed collisions can lead to prolonged neck injuries [2]. Post-injury pain and disability are some effects of whiplash, along with others such as cold hyperalgesia, post-injury anxiety and catastrophizing [3]. In 1993, a study was conducted on victims of rear end collisions. Almost a quarter of them have confirmed that in crashes noted as property damage only, symptoms of neck strain injury were present [4].

The reduction of whiplash injuries in occupants who visit the emergency rooms, that had headrests adjusted correctly, was not proven. In 1989, Morris [5] analyzed 106 patients following a rear end collision and discovered an increased number of whiplash injuries in those crashes were no headrest was present; although, Olney, Marsden [6], Hildingsson and Toolanen [7] discovered that the headrest did not protect the occupants from imminent neck injury. Adjustable headrests can reduce the injury risks by 10%. In theory, if the headrest is adjusted correctly, to limit the angle and movement of the head and neck during a rear end collision, it should reduce the injury risk caused by whiplash phenomenon.

In 1995, Bostrom [8] has proposed a formula for assessing the injury risk to the neck in rear impacts, by linking head movement relative to the vertebra of the neck (T1) by analyzing trauma arising in the lymph cervical spine caused by changes in pressure transient into the spinal canal. The formula is based on the difference between the longitudinal acceleration (X-axis) of the center of gravity of the head, and the acceleration of the vertebra T1 is therefore representative of the movement of the neck during the withdrawal phase.

$$NIC = a_{rel} \cdot 0.2 + v_{rel}^2 \quad (1)$$

$$a_{rel} = a_{rel}^{T1} - a_{rel}^{head} \quad (2)$$

$$v_{rel} = \int a_{rel}\, dt \quad (3)$$

Where a_{rel} is the relative acceleration, v_{rel} is the relative velocity, a_{rel}^{T1} is the relative acceleration for the T1 vertebrae and a_{rel}^{head} is the head relative acceleration. The maximum value of NIC in the first 150 ms of the impact is issued NIC_{max} and it was considered for many years the primary evaluation in whiplash injury. The maximum value of the human neck limit is $NIC_{max} = 15\ m^2/s^2$.

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 [9], [10].

The human neck has limitations regarding its movement in the flexion and extension phases. In figure 1 those limitations are presented. In rear end collisions both phases are present, first is extension of the neck and second is flexion.

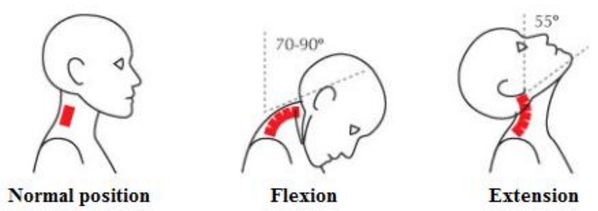

Fig. 1. Limitations of the human neck [11]

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The medical limitations are as followed, for flexion the maximum values are 70 to 90 degrees and for the extension phase about 55 degrees. Above those values, depending on the body type, cervical spine and muscle strain injuries can occur.

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 2 the probability of whiplash is presented [12]. It is considered that modern vehicles with active headrests can meet the acceptable limit of 12 degrees maximum, indicating a probability of whiplash of 7 %.

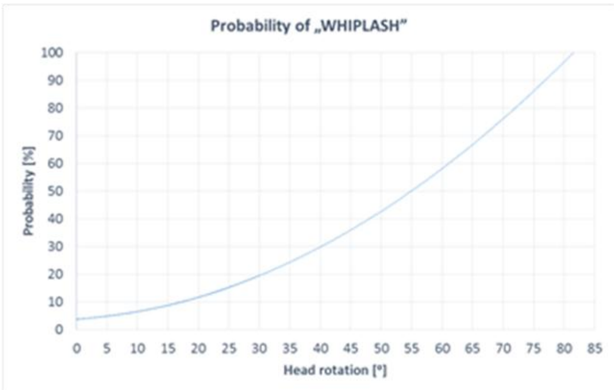

Fig. 2. Probability of “whiplash” in accordance with the head-torso rotation angle [12]

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 threating but they do generate long term symptoms and limitations such as pain, dizziness, anxiety, muscle stiffness and head rotation turn limit [13].

II. METHODS USED

The method used for this study was to create a simulation of a rear end collision with an occupant and modify the distance between the head and headrest to analyze the outcome. The simulation was created in PC-Crash and was done by using 2 similar vehicles and impacted them at the velocity of 35 km/h. This is the average impact velocity in these types of collision, especially in urban areas [14]. In the impacted vehicle the occupant model was placed.

Fig. 3. Experimental test collision configuration

The occupant was a multibody human male [15] were all body parts consists of ellipsoids interconnected with joints in an identical way a human body is connected. In figure 4 is a comparison between the human body and the multibody model with joints.

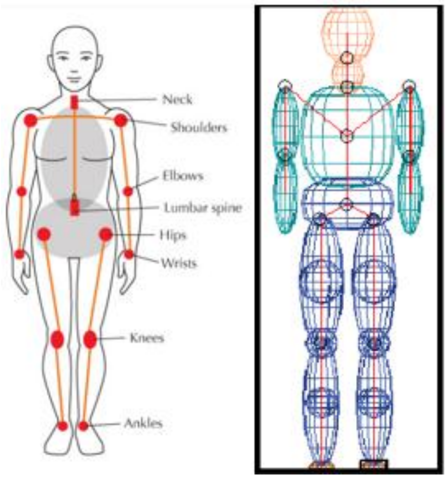

Fig. 4. Comparison between the human body and the multibody with connecting joints

The position of the occupant in the vehicle was done according to the normal position of a human occupant in a vehicle as shown in figure 5.

Fig. 5. Occupant position in the vehicle

In figure 6, the normal position of the occupant is presented with the headrest distances. Unadjusted, the headrest has a longitudinal distance of 110 mm from the back of the head and 60 mm transversal distance from the top of the head. This will consist the reference condition of the study. From this configuration the variation will be done.

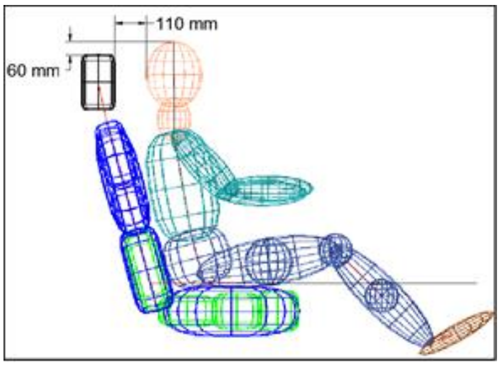

Fig. 6. Normal position of the headrest

Multiple simulation were done to analyze the distance between the headrest and the occupant head and also calculate the neck injury criteria. Also, as a comparison, a MADYMO multibody occupant was also used in the simulation to analyze

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the same variation of the headrest. MADYMO is a MAthematical DYnamic MOdelling software application used in crash test applications [16]. In figure 6 the Madymo model is presented. This model has a more biofidelic kinematic and dynamic of the human body by using the finite element calculation (FEM).

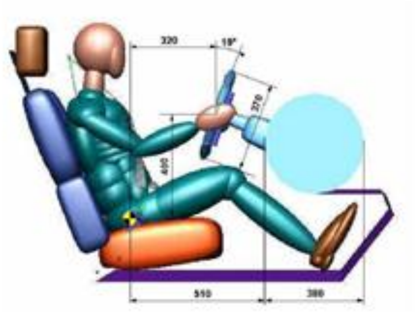

Fig. 7. Madymo model

This model was positioned in the same type of vehicle, in the same test conditions as the other model. After the simulations were completed, the angles of the neck and head could be obtained and also the neck injury criteria calculated.

The method of varying the headrest position is presented in figure 8. A total of 8 simulations were conducted, 3 with the headrest at the distances of 50, 75 and 110 mm from the normal position close to the head and the 3 test with the same distances away from the head. Also 1 simulation with the normal position of the headrest, and 1 with no headrest at all. An additional 3 simulation were conducted using the Madymo model, using the same conditions as the regular multibody model from PC Crash.

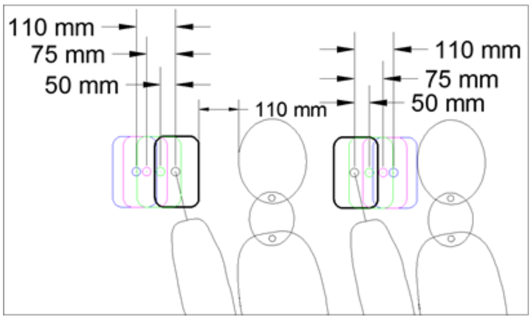

Fig. 8. Variations of the headrest distance

III. RESULTS

The first results were the velocity of both vehicles and also the head acceleration of the occupant in the first vehicle. They are presented in figure 9. During the collision the velocity of the vehicles were the same at some point. This is called velocity equalization.

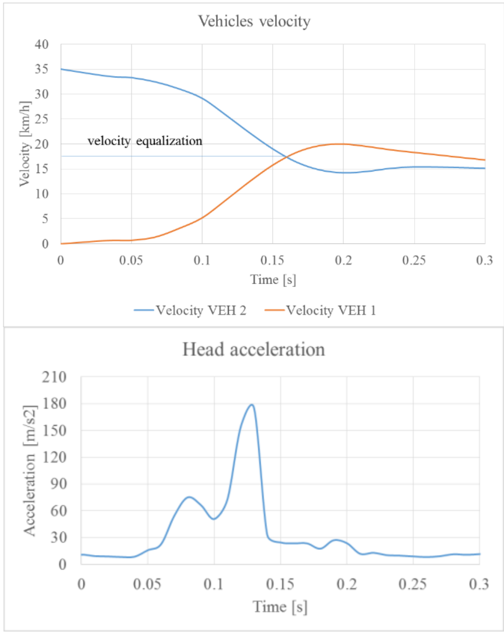

Fig. 9. Vehicle velocities and occupant head acceleration during the collision

In figure 9, the head acceleration of the occupant was 180 m/s2 maximum during the first 150 ms of the collision. Also the total collision duration was about 100 ms, from 0.05 s to 0.15 s.

The occupant head and neck angular displacement during the collision is presented in figure 10. The maximum angle was at 135 ms and it was 39 degrees. As presented earlier, the neck can extend backwards at a maximum of 55 degrees without neck strain injury occurring.

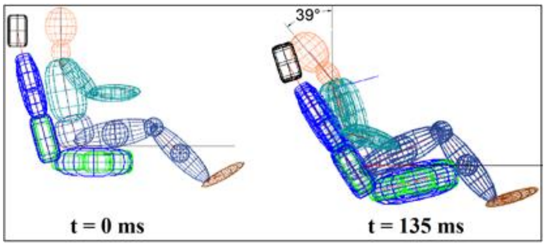

Fig. 10. Occupant neck and head angular displacement during the collision

These are the results when the headrest was in a normal position, unadjusted, presented earlier. Also, for this simulation the neck injury criteria was calculated to evaluate the injury risk.

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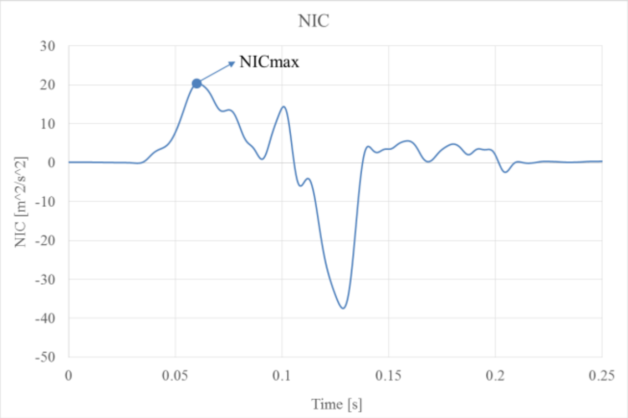

Fig. 11. Neck injury criteria for the normal headrest position

The maximum value for NIC in the first 150 ms was NICmax=20 m2/s2 which is a bit higher than the 15 m2/s2 limit, that would suggest a minor neck strain that will not have a significant impact in long term injury.

After the results for the normal position of the headrest were obtained, the variation of the headrest were made and simulated. The occupant head acceleration was obtained at first for the headrest positioned closer to the head. This is presented in figure 12.

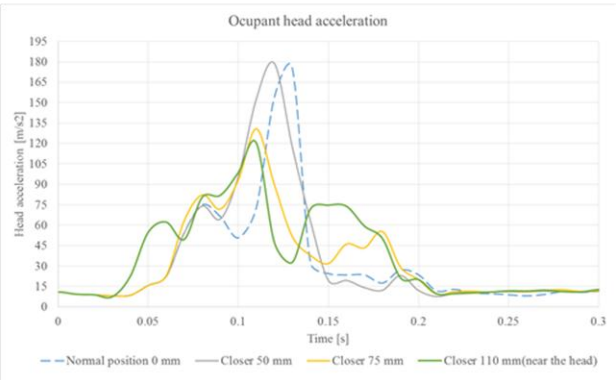

Fig. 12. Occupant head acceleration for the different distances of the headrest positioned closer to the head during the collision

From the figure, it can be observed that if the headrest is closer to the head, the acceleration to the head is lower, which is a good thing. At 50 mm, there is no difference in acceleration value, only that the time interval is a bit earlier, the maximum acceleration is at 110 ms instead of 135 ms as the normal position. The difference can be observed when the headrest is close at 75 mm and even very close at 110 mm. There is an acceleration drop of almost 60 m/s2 when the headrest is as close as possible. Lowering the distance between the headrest and the occupant head will reduce the acceleration values by almost 35%. Also the angular displacement of the neck and head could be obtained and presented in figure 13.

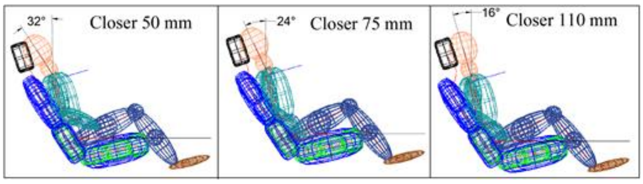

Fig. 13. Angular displacement of the neck and head during the impact at different headrest distances

At 50 mm there is smaller displacement, but not enough to influence the head acceleration as presented earlier, a reduction of just 18%. For the 75 mm, the reduction is a lot higher, up to 40% less displacement than the original position.

It can be observed that closing the distance of the headrest to the head, also reduces the angular displacement of the head and neck, obtaining a total reduction of the angle up to 60% less displacement.

Using the whiplash probability chart developed by NHTSA, the probability was calculated for the close headrest distanced and presented in figure 14.

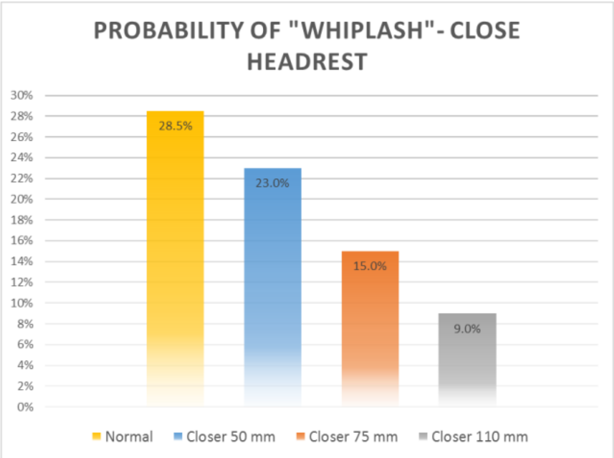

Fig. 14. Probability of “whiplash” for close headrest

Examining the chart it was obvious that reducing the distance between the head and headrest reduces the whiplash effect by almost 20% (from 28.5% to 9%). In the normal position, the probability obtained was 28.5% which is considered to cause a couple of symptoms such as muscle pain and neck mobility limitation for a short period of time. Also, the neck injury criteria was calculated for the close distances to evaluate the injury risk. This is presented in figure 15.

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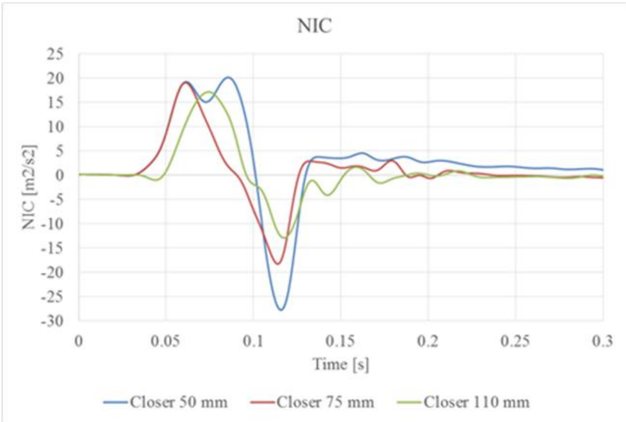

Fig. 15. Neck injury criteria diagram for the closer distances

From the diagram it can be observed that at 50 and 75 mm, NICmax = 18 m2/s2 in the first 150 ms of the simulation, which is higher than the limit of 15 m2/s2, but still lower than the normal position of the headrest. The lowest value of NIC is at 110 mm, where the value is just about 16 m2/s2, just at the maximum value. This indicates that the whiplash risk is very low, to nonexistent, minor risk injury to the neck and head of the occupant.

The next simulations that were conducted was with the headrest away from the head. The acceleration values of the occupant for the headrest positioned away from the head is presented in figure 16.

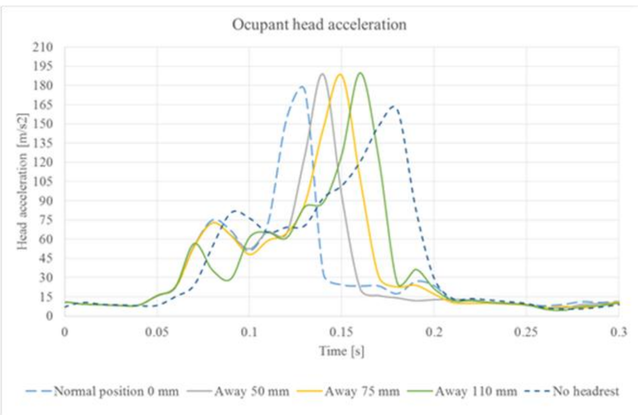

Fig. 16. Occupant head acceleration for the different distances of the headrest positioned away from the head during the collision

In this diagram, it can be observed that moving the headrest away from the occupant head, will result in a slight increase of acceleration. The difference is that the acceleration value peak is delayed, from the original 135 ms, up to 160 ms. All 3 distances taken into account, 50, 75 and 110 mm have the same acceleration values. A fourth simulation was conducted were the headrest was no used at all, and a decrease in acceleration was obtained, lower than the normal position, up to 2% lower acceleration value. Also the neck and head angular displacement is obtained and presented in figure 17, similar to the previous case.

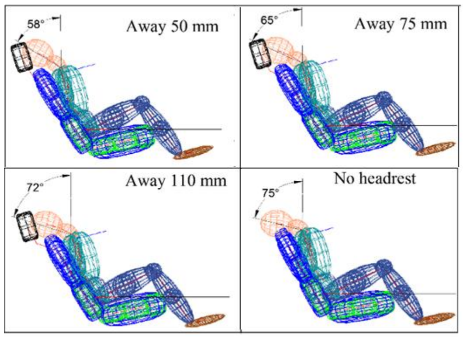

Fig. 17. Angular displacement of the neck and head during the impact at different headrest distances

When the headrest distance is increased, the angular displacement of the head and neck is greater. It ranges from 58 degrees in the case of 50 mm up to 75 degrees where the headrest is missing. From the normal position, an increase of 50% in angular displacement was obtained. All values obtained are above the human neck limit of 55 degrees, as such, whiplash injury would occur and long term injury will be present, even down to neck vertebra and muscle rupture. If the headrest is not present, there are chances that the occupant neck could hit the top of the upper seat resulting in neck vertebra displacement.

In a similar way to the first case, using the whiplash probability chart developed by NHTSA, the probability was calculated for the away headrest distanced and presented in figure 18.

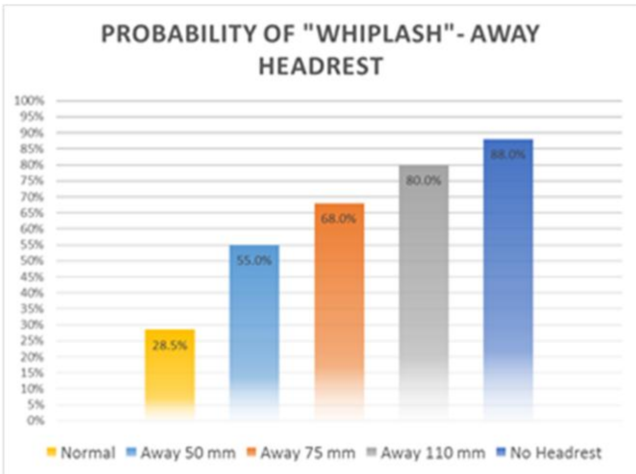

Fig. 18. Probability of “whiplash” for away headrest

Increasing the distance between the head and headrest will greatly increase the whiplash effect by up to 60% (from 28.5% to 88%). Between the distance of 110 mm and the lack of headrest there is little difference of just 8% in the probability of whiplash. At this level it is predicted that the occupant could suffer severe whiplash injuries such as vertebrae displacement and permanent muscle fatigue as mentioned earlier.

For this case, the neck injury criteria was also calculated to evaluate the neck injury, even though, the angular displacement show that the occupant would suffer massive whiplash injuries.

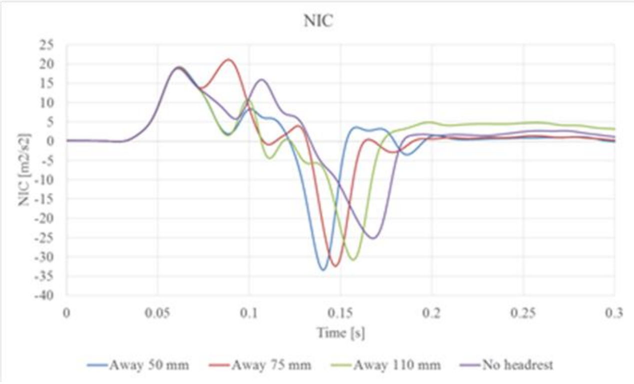

Fig. 19. NIC calculation for away distances

From the figure it can be observed that at all distances, all have a NICmax=19.5 m2/s2, with the exception of the 75 mm distance, where NICmax=21 m2/s2. Between 5 ms and 120 ms where the headrest is missing, NIC decreases compared to others, below 15 m2/s2. In this scenario, NIC calculation show that the occupant would suffer whiplash injury but on a lower level. To further compare the neck injury criteria, from both cases a diagram can be obtained to evaluate the overall injury risk. In figure 17 a NIC comparison is presented.

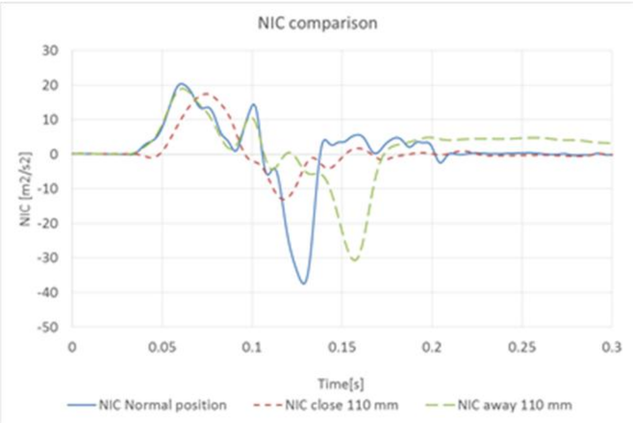

Fig. 20. NIC calculation for away distances

The lowest value is where the headrest is the closest to the head, although the away position and normal position have almost the same values. This would indicate that having the headrest in the normal is similar to having it away from the head and will not reduce the acceleration value of the head. The only parameter it will reduce is the angular displacement of the neck and head and thus reduce the whiplash effect in some degree.

For this study, a MADYMO occupant model was also used to compare results with the multibody model used. The head acceleration and angular displacement could be obtained and presented. In figure 21, the head acceleration in just 3 cases is presented, when the headrest is in a normal position, when it is close to the head and when it is missing.

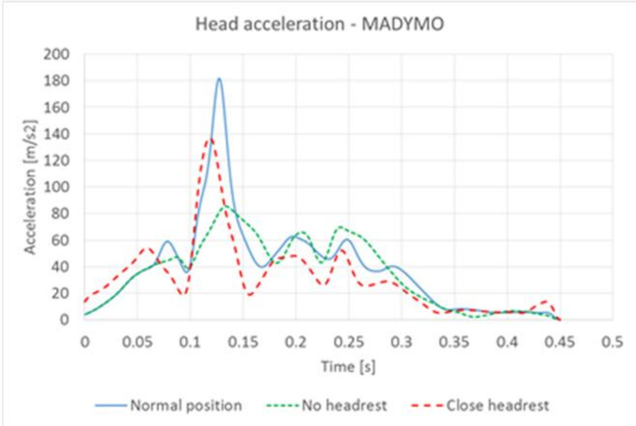

Fig. 21. Madymo head acceleration in all cases

In a similar manor to previous simulations it was observed that closing the distance between the head and headrest of the occupant will decrease the head acceleration. Not using the headrest will result in low acceleration due to the fact that the head does not hit the headrest.

The angular displacement of the head and neck could also be obtained, it is presented in figure 22.

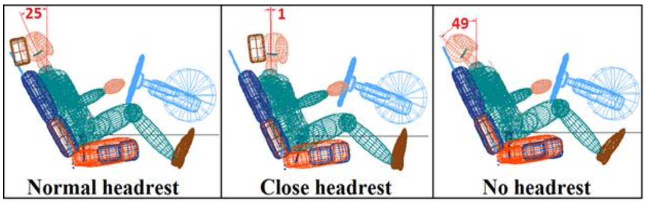

Fig. 22. Angular displacement of the head of neck of Madymo occupant

In the normal position of the headrest, the maximum angular displacement is 25 degrees and it's fairly acceptable, however, when the headrest is close to the head, there is virtually no displacement at all. This would be the ideal situation in case or rear impact. If the headrest is missing, whiplash effect would be present and increase the change of neck injury. However, compared to the previous study, the angle in this case is only 49 degrees which is acceptable, although it is not comforting, whiplash injury could occur and the occupant can get neck muscle strain. The difference in angular displacement between the 2 models is due to the fact that the Madymo model takes into account the neck muscles and limitations of the joints when the muscles are present. Based on NHTSA graph, the probability of whiplash could be obtained and presented in figure 23.

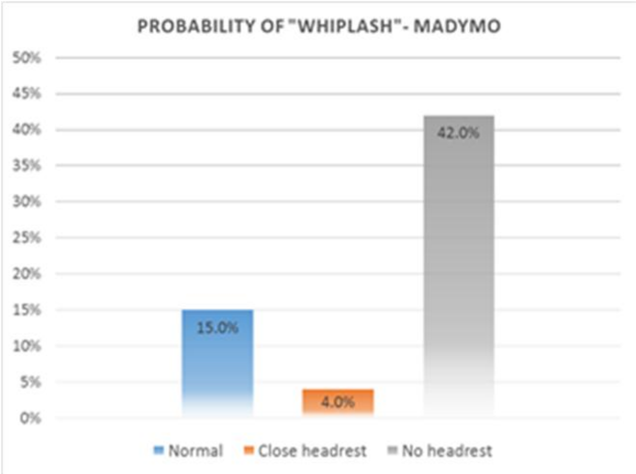

Fig. 23. Probability of "whiplash" for MADYMO model

In the normal position, the probability of whiplash was 15% witch is acceptable compared to the previous model. For the close headrest, the probability is very low, of only 4% and when the headrest is missing, the probability increases up to 42%. This would suggest moderate whiplash injuries.

To assess the injury risk, the Abbreviated Injury Scale (AIS) can be used to classify and describe the severity of injuries. Abbreviated Injury Score-Code is on a scale of one to six, one being a minor injury and six being maximal. An AIS-Code of six is not the described code for a deceased patient or fatal injury, but the code for injuries specifically assigned an AIS 6 severity. [17] In the next table, an AIS code is described for this specific case of study:

TABLE I. AIS CODE [18]

AIS-Code	Injury	Injury type	NICmax [m2/s2]
1	Minor	Muscle strain injury	< 15
2	Moderate	Disc herniation	> 15
3	Serious	Dislocation without fracture	-
4	Severe	Radiculopathy disc herniation	-

IV. LIMITATIONS

The major limitations of this study is that it was conducted using mathematical models of human occupants and not real volunteers. In real case accidents there are various factors to take into account such as muscles tightness, the position of the head, and if the human occupant would react or move in anyway during the collision.

V. OPTIMIZATION

For modern day cars there is a solution, active headrests, to counteract the whiplash effect, but only a few automotive manufacturers, such as SAAB and Mercedes use it. The active headrest involves a pelvis activated mechanism that extends and closes the headrest to the occupant head to decrease the distance between the head and headrest. [19].

VI. CONCLUSION

This study demonstrates that the distance between the headrest and the head represent an important factor in the case of rear end collisions, and it influences the whiplash effect. By using 2 mathematical multibody models, the conclusions were similar in which the closer the distance, the lower the whiplash effect, and head acceleration, and in result a lower risk of injury. Even in the normal position, the headrest can be dangerous, just by the impact of the head and headrest could have minor injury risk. The head acceleration reduction between the normal and close position of the headrest was 35%. Also the angular displacement reduction was about 60% which will eliminate the whiplash effect. In the normal position, even though the head acceleration show a possibility of injury, on the AIS scale it would be minor, AIS 1 that would indicate muscle strain injury.

Theoretically, if the headrest would be position away from the head, it would not make any difference from the normal position, other than the increased whiplash effect by increasing the angular displacement by 50% from the normal position. Even though in the case of not using a headrest at all, the head acceleration is lower than the normal position situation, it does increase the whiplash effect to the point of serious neck injury. The angular displacement in this situation is 52% increase compared to the normal position, and the angle in which the neck bends is 75 degrees, and will generate neck muscle strain or rupture and also neck vertebra displacement. The AIS scale in this case would be AIS 3, AIS 4 that would indicate a serious or severe injury situation. For the situation where the distance from the head is at 50-110 mm, based on the angular displacement and acceleration, an injury risk on the AIS scale would be AIS 2 or AIS 3 which would prove a moderate to serious neck injury.

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