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SIMULATION OF AUTOMOTIVE SEAT FOR REDUCING NECK INJURY IN LOW-SPEED REAR IMPACT

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ABSTRACT–Neck injuries sustained during low speed rear impact are the most commonly sustained traffic injury. Therefore, the analysis of neck injury mechanisms and methods for mitigating and reducing neck injuries during low speed rear impact are a very important issue in the vehicle safety field. In order to find a method to absorb the shock that is transmitted to the occupant, the response of frontal and rear dummy due to the motion of the struck vehicle and the rotational angular displacements of dummies' necks during rear impact at 12km/h speed were investigated using a Working Model 2D. The results suggest that the shock absorption system should be equipped in the bottom of the seat of the vehicle to reduce shock and mitigate neck injury to the occupants.

KEY WORDS : Neck injury, Automotive seat, Shock absorption system, Low-speed rear impact

1. INTRODUCTION

Having a vehicle is a modern necessity. The number of vehicles on the road and their use are increasing continuously. As a result, the number of vehicle accidents is increasing. According to data obtained from the Japan Traffic Safety Association, the greatest number of fatalities occurred from frontal impacts. Side impacts accounted for the second largest percentages of fatalities. Rear impacts were accounted for the least number of fatalities. However, rear impacts accounted for approximately 50% of all injuries. Approximately 90% of injuries in rear impacts were neck injuries (Watanabe *et al.*, 2000).

According to data compiled in Germany, more than 90% of neck injuries occur at speed of 25 km/h or less (Eichberger *et al.*, 1996). Thus, the occupants have a high probability of neck injury in spite of the low-speed impact. This finding along with the fact that approximately 90% of injuries resulting from rear impact are neck injuries, means that the neck injuries are a particular chracteristic of low speed rear impacts and are one of certainly considering matters in traffic accidents.

Several studies have examined the influence of seat properties, seatback and head restraint on neck injuries. In addtion, other studies have focused on designing and improving devices for mitigating whiplash injuries that occur during rear impact collisions. Vehicle design changes to the bumper, seat and belt restraint systems and so on, were suggested to improve occupant safety after investigations into low speed rear impacts (Thomson, 1990). Thomson *et al.* (1993) found that the rear of the vehicle may deflect downwards during an impact if the vehicle's center of gravity is higher than the position of the applied impact force, drawing the seat down from the occupant. This is the source of occupant ramping. Ramping may allow the occupant's head to extend beyond the head restraint, reducing its effectiveness. Occupant ramping tends to increase with seatback deflection. A close fit between the head and the head restraint in combination with well-chosen stiffness of the different seatback components minimize the risk of neck injury (Svensson *et al.*, 1996). The relationships among the physical parameters such as head rotational acceleration, neck bending moment, shearing and axial forces apply to the occupant's head and neck system, and the effect of the headrest height and seatback inclination angle, were analyzed by Ono (1996). The relationship between the seat back strength and neck injury were discussed by J. W. Lee *et al.* (2000). The relative rotation angle of an occupant's head to chest decreased with an increase in the initial seatback angle at a constant impact velocity (Huang *et al.*, 2000). An intelligent headrest that operated automatically to decrease the gap between occupant's head and headrest was designed by K. H. Park *et al.* (2000). A seat system that moved the head restraint forward and upward by using the occupant's initial force at the time of impact suppressed cervical vertebral

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motions (Watanabe *et al.*, 2000). Calibration and refinement of the seat and head restraints could possibly be used to minimize the displacement between the head and neck system, and thus reduce neck loads (Maher, 2000). Seat parameters, such as geometry relative to the occupant's head, dynamic and static stiffness and energy absorption, that may have an effect on head-neck kinematics was evaluated by Welcher *et al.* (2001). They found that vertical and horizontal head to head restraint distances have the most influence on occupant head-neck kinematics and the seat constitutive properties, such as stiffness and energy absorption, did not significantly influence the neck injury. Thus, in order to decrease and mitigate whiplash injuries, two general methods have mainly been researched. One is to minimize the shock energy that is transmitted to the occupant and the other method is to minimize the relative motion of occupant's body and head.

In this paper, a method for mitigating and reducing neck injury is found through an understanding of the response of the occupant's body during low speed rear impact. Extension, which is the most easily sustainable neck injury during low speed rear impact, was investigated through a two-dimensional simulation. Particularly, the responses of frontal and rear occupant, the motion of struck vehicle and the rotational angular displacement of occupant's neck during rear impact of 12 km/h speed were analyzed by Working Model 2D. That is a shock absorption system to be equipped in an automotive seat bottom.

The unrealistic conditions of anthropomorphic structures must be considered before the results of simulations are projected into real life situations.

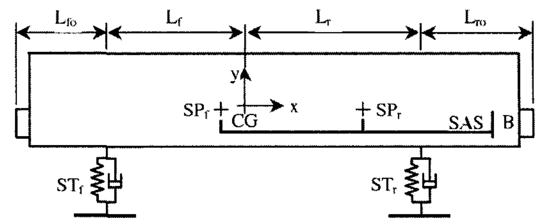
2. MODELLING

The vehicle model is simplified into a half vehicle model to consider only pitching, and the dummy is divided into 4 main parts. It was considered that the displacements of each part of the dummy are only rotational movements and that each jointing point is a rotational axis. Although the characteristic of the seat, head restraint and seatbelt had significant influence on the occupant's neck response, they are not considered in this simulation. The center of gravity of the vehicle was taken as the origin of the coordinate axes in this simulation.

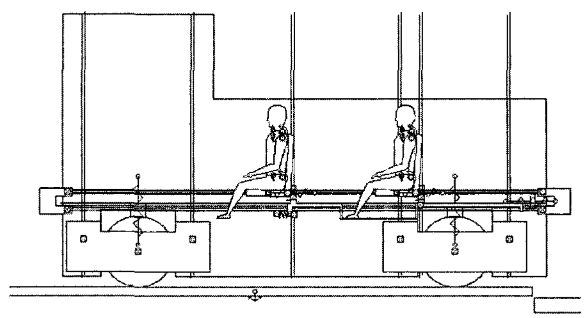
2.1. Vehicle Model Description

The half model of the vehicle used in this paper has been constructed by Maurice Olley's criteria as follows (Gillespie, 1992):

(1) The front suspension should have a 30% lower ride rate than the rear suspension, or the spring center should be at least 6.5% of the wheelbase behind the center of gravity.
(2) The pitch and bounce frequencies should be less than 1.2 times the pitch frequency. The dynamic index is almost equal to one.
(3) Neither frequency should be greater than 1.3 Hz., which means that the effective static deflection of the vehicle should not exceed 6 inches.
(4) The roll frequency should be approximately equal to the pitch and bounce frequencies.



(a) Schematic representation



(b) Simulation model

Figure 1. Simplified half vehicle model.

The simplified half vehicle model is represented in Figure 1 and its system parameters are listed in Table 1. The rigid seat with no head restraint was designed for investigating angular displacement of the occupant's head during low speed rear impact. The positions of the frontal and the rear seat pans were located at (–0.12m, –0.17m) and (1m, –0.17m) respectively from the center of gravity of the vehicle. The position of the bumper was 0.224m lower in the vertical direction than the center of gravity of the vehicle.

The tire shown in Figure 1(b) is represented as a simple spring in Figure 1(a), although its damper is included to represent the small amount of damping inherent to the viscous-elastic nature of the tire. The ride rate (RR) of suspension can be expressed as in equation (1).

$$RR = \frac{k_s k_t}{k_s + k_t} \tag{1}$$

where k_s and k_t are linear spring constants of the suspension and tire, respectively (Gillespie, 1992). The circular frequency ω_n can be computed as in equation (2).

$$\omega_n = \sqrt{\frac{k}{m}} \quad (2)$$

where k is the spring constant and m is the mass. The damping constant c can be defined as

$$c = 2m\zeta\omega_n \quad (3)$$

where ζ is the damping factor.

The best performance of an isolator having a linear spring and viscous damping can be obtained at the fraction of critical damping factor $\zeta = 0.4$ (Harris *et al.*, 1961). Then, a dimensionless representation of energy absorption capability can be expressed as in equation (6).

$$\frac{\ddot{x}_m \delta_m}{\dot{u}_m^2} = 0.52 \quad (4)$$

where $\ddot{x}_m$ is the maximum transmitted deceleration, δ_m is the maximum deflection and $\dot{u}_m$ is the velocity step. A dimensionless representation of the maximum transmitted deceleration is

$$\frac{\ddot{x}_m}{\dot{u}_m \omega_n} = 0.86 \quad (5)$$

If the static deflection of a vehicle is 0.25m and the damping factor ζ is 0.4 for a good ride, then the linear spring constants and damping constants of the suspension will be the same as those calculated using equations (1)~(3) as in Table 2.

The approximate maximum tolerance limits for rapid decelerations applied to a sitting occupant supported with a seatbelt are summarized in Table 3. The experienceable extent of deceleration in automobile collisions is between 20g and 100g for durations of less than 0.1 seconds. The magnitude of the maximum deceleration of the vehicle with a conventional bumper was found to be 43g (Cheon *et al.*, 1995). If the maximum deflection of the bumper δ_m and the maximum transmitted deceleration $\ddot{x}_m$ are 0.13m and 43g, respectively, the linear spring constant and damping constant of the bumper will be the same as those calculated using equations (4) and (5) as in Table 2.

The shock absorption system (SAS) in the seat bottom for absorbing shock energy during rear impact is considered. The spring and damping constants of two types of isolators with linear springs used in this system are shown in Table 4. The linear damping constant was calculated from equations (2) and (3) when damping ratio

Table 2. Parameters of the isolators used in the suspensions and the bumper.

	Ride rate or spring constant (N/m)	Damping constant (N·s/m)
Front	18450	2134
Rear	25320	2275
Bumper	127400	2134

Table 1. Parameters of the half vehicle model.

Description	Symbol	Value
Center of gravity	CG	The origin of the coordinate axes
Bumper	B	
Frontal seat pan	SP_f	
Rear seat pan	SP_r	
Shock absorption system	SAS	
Ride rate and damper of frontal suspension and tire	ST_f	
Ride rate and damper of rear suspension and tire	ST_r	
Frontal moment arm from center of gravity to frontal axle	L_f	1.25 m
Frontal moment arm from center of gravity to rear axle	L_r	1.51 m
Wheel base	L_f+L_r	2.76 m
Frontal overhang	L_{fo}	0.656 m
Rear overhang	L_{ro}	0.801 m
Vehicle length	$L_{fo}+L_f+L_r+L_{ro}$	4.217 m
Mass of vehicle body		705 kg
Initial moment of vehicle		1269.652 kg-m^2
Dynamic index		0.97
Static frictional coefficient between tire and road		0.8
Dynamic frictional coefficient between tire and road		0.6

Table 3. Approximate duration and magnitude of some short-duration acceleration loads in the vehicle (Harris *et al.*, 1961).

Acceleration loads (g)	Duration (sec.)	Description
0.7	3	Maximum obtainable
0.25	5–8	Comfortable stop
0.45	3–5	Very undesirable
20–100	< 0.1	Crash

Table 4. Parameters of the isolators used in the shock absorption system.

	Spring constant (N/m)	Damping constant (N·s/m)
A type	2410	340
B type	1205	240.4

ζ was 0.4 and the mass was the sum of the dummy and seat masses. The linear spring constants and the damping constants are the same as in Table 4. The striking vehicle has been modeled such that the mass is the same as the struck vehicle and there is no bumper.

2.2. Dummy Model Description

The dummy model designed in this paper includes a head, torso, arm and leg parts, and each of the parts was joined by linear rotational springs and linear rotational dampers. It is very difficult to determine the linear rotational spring constants and linear rotational damping constants of the jointed parts of the dummy because each joint differs according to muscle strength, age and gender. The occupant's torso and legs were supported by the seat as can be seen, shown in Figure 1(b). The constants for the springs used in the waist and the shoulders were selected on the basis of their ability to endure the moments induced by the eccentricity between the center of gravity and the joint point in each parts. The eccentric distances of each parts are listed in Table 5. The spring constant used in the neck was decided by the assumed transmitted deceleration of 0.7g and the moment occurring due to the eccentricity between the center of gravity of the head and the joint point of the head and the torso. The linear rotational damping constants of each parts were calculated when the damping factor ζ was 0.4. The results are shown in Table 6.

Table 6. Parameters of the isolators used in the dummy model.

Position	Rotational spring constant (N·m/rad)	Rotational damping constant (N·m·s/rad)
Neck	23.364	1.568
Shoulder	28.104	3.140
Waist	130.691	18.449

The static frictional coefficient between the dummy model and the rigid seat was taken as 0.7.

3. SIMULATION

In the simulation, the vehicle was rear impacted by a vehicle moving at 12 km/h. The occupants of the struck vehicle were riding in the front and rear seats. The head restraint and seatbelt that restrain the occupant's responses were not considered in this study. This is why the rotational angular displacement of the occupants' heads was closely related to the physical quantity when expressing the extent of the extension.

The baseline of the seatback angle was defined as an upward vertical axis, and in this study positive movement from the baseline was in the positive direction. The inclinations of seatback were calculated as 0.07 radian, 0.14 radian, 0.21 radian, 0.28 radian and 0.35 radian. The inclined angles of the occupants' torsos were initially set to be same as those of seatback, while the angle of occupants' heads were taken as 0 radian regardless of the seatback angle.

This simulation focused on constructing a method to mitigate neck injury during low speed rear impact. In the first part of the simulation, the effect of type A and B isolators in the seat bottom were investigated and compared. Next, a shock absorption system (SAS) that minimizes the rotational angular displacement of the head was investigated by examining the effect of seat-back inclination on the rotational angular displacement of

Table 5. Conditions of the dummy model used in this simulation.

	Mass (kg)	The horizontal and vertical distance between the center of gravity and joint point in each parts (m)	Jointed part
Head	9.072	0.05, 0.125	Torso
Arm	15.876	0.075, 0.17	Torso
Torso	27.216	0.05, 0.2	Leg
Leg	22.691	0.23, 0.107	Torso

the head.

The simulation under these conditions and situations explained above was performed using the 2D Working Model. The time steps of all simulations were 0.01 second.

4. RESULTS AND DISCUSSION

The lapse time that the bumper of the struck vehicle was in contact with striking vehicle was 0.09 sec..

There were a clockwise moment and forward horizontal force on the struck vehicle during collision because the bumper of the struck vehicle was in the lower position than the center of gravity. The bumper of the struck vehicle absorbs a part of the impact energy. If the horizontal impact force due to the remainder of the impact energy is larger than the static frictional force due to contact with the tires of the struck vehicle and the road surface, the struck vehicle will move forward in an instant due to the forward horizontal force that subtracts the static frictional force from the horizontal impact force and its rear will deflect simultaneously downward due to the clockwise moment that subtracts the moment to be absorbed by the frontal and rear suspension from the moment to be created by the eccentric horizontal impact force. The forward horizontal force and the clockwise moment are the main factors that cause neck injury.

Because the position of the front seat is closer to the center of gravity of the vehicle than the rear seat, the vertical fluctuation of the front seat occupant is smaller than the rear occupant during rear impact. This is shown in Figure 2. The magnitude of the fluctuation relates to the clockwise moment and the distance between the center of gravity and the position of seat. This is an underlying cause that induceing ramping. Because ramping makes relatively low the height of head restraint, it increases the incidence of neck injury. Therefore, the position of bumper should be designed to be the same height as the center of gravity of the vehicle.

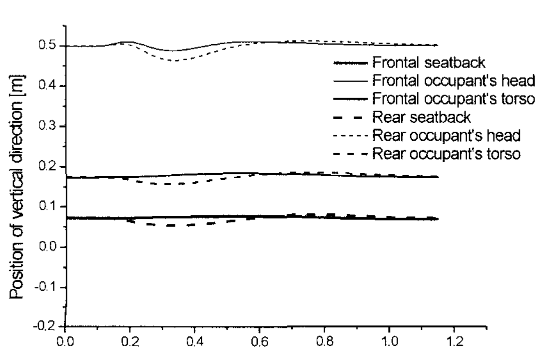


Figure 2. The vertical fluctuation of each position for a 0.07 radian inclined seatback.

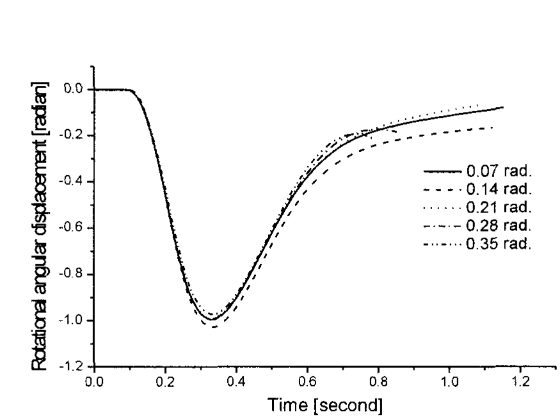


Figure 3. Rotational angular displacements of frontal occupant's head according to inclinations of seatback.

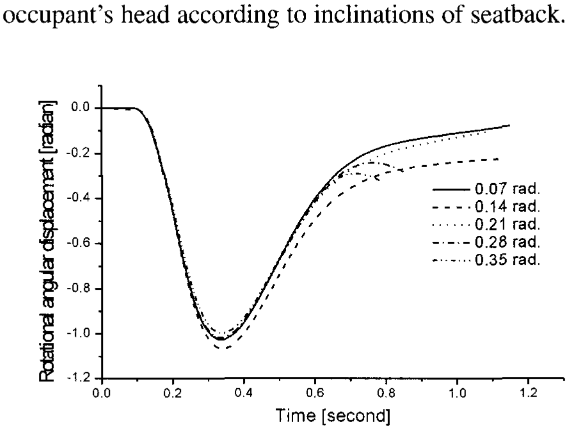


Figure 4. Rotational angular displacements of rear occupant's head according to inclinations of seatback.

The rotational angular displacements of the heads of the occupants in the front and rear seats as a function of seatback inclination are shown in Figures 3 and 4. In these figures it can be seen that the rotational angular displacements of the rear occupants' heads are somewhat larger than those of the frontal occupant's heads. The lapse times when the rotational angular displacements of the front and rear occupants' heads reached their maximum values were 0.33 sec. and 0.34 sec., respectively. The differences in the rotational angilar displacement and lapse times were closely related to the clockwise moment.

The rotational angular displacement of occupants' heads with and without the isolator under the seat are shown in Figure 5. Figure 5 shows that the maximum rotational angular displacement of the occupants' heads sitting on seats with a type A isolator were very similar to the maximum rotational angular displacement when no isolator was used. However, the lapse times when the rotational angular displacements of the front and rear occupants' head are at their maximums were 0.33 sec. and 0.46 sec., and the slope of the curve for the type A isolator is smaller than without an isolator. These means

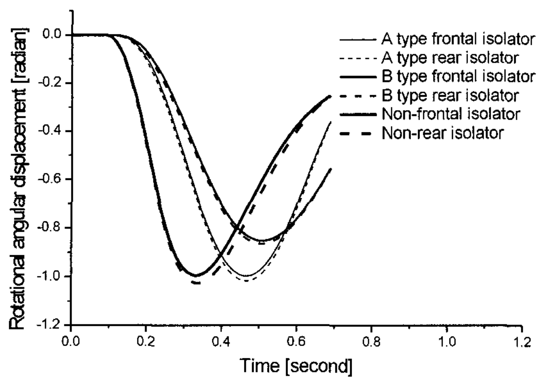


Figure 5. The rotational angular displacements of occupant's head with and without the isolator for a 0.07 radian inclined seatback.

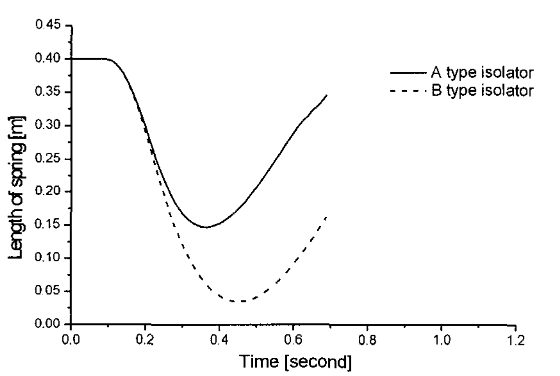


Figure 6. The deformations of the type A and B isolators used in the seat bottom.

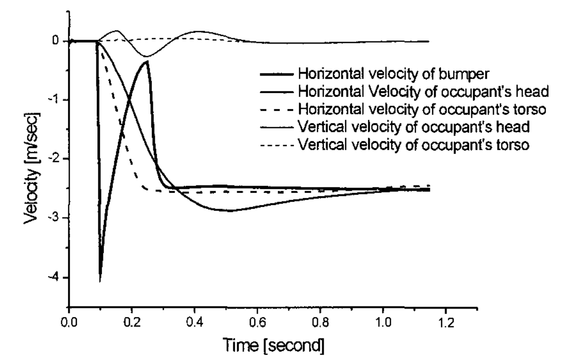


Figure 7. The horizontal and vertical velocities of the bumper and the frontal occupant.

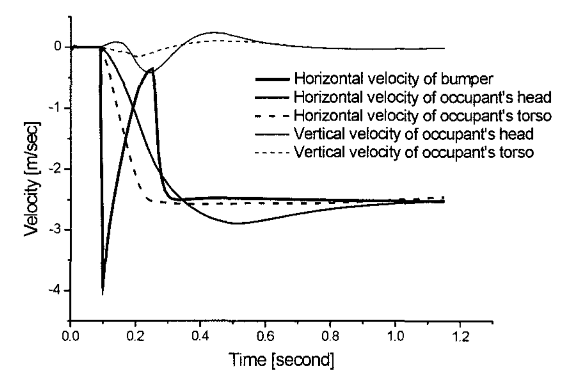


Figure 8. The horizontal and vertical velocities of the bumper and the rear occupant.

the type A isolator does little to reduce shock from rear impact. For the type B isolator, the maximum rotational angular displacements of frontal and rear occupant' head decreased to 14.3% and 15.7% respectively, and the lapse time to reach the maximum rotational angular displacements was 0.51 sec.. This means the type B isolator mitigates shock more than the type A isolator. Generally, an isolator with a small spring constant mitigates more shock energy than an isolator with a large spring constant. On the other hand, as shown in Figure 6, the deformation of the type B isolator to keep the small spring constant is larger than the type A isolator to keep the large spring constant. Using an isolator with a small spring constant is an efficient means for reducing neck injury in small energy collisions, but not all vehicle accidents are small energy collisions. During a high energy rear impact collision of a vehicle with an isolator with a small constant, the movement of the seat to the rear would be very dangerous to the occupant. Therefore, an isolator with a the small spring constant cannot be relied on to reduce neck injury. The deformation of the spring must be small during impact.

As mentioned above, it was an insufficient method that both the bumper and the isolator worked simultaneously for mitigating shock in rear impact. The horizontal velocity of the bumper, and the horizontal and vertical velocities of the frontal and rear occupants' heads and torsos during low speed rear impact are shown in Figures 7 and 8. When the displacement of the bumper due to impact reaches its maximum value, or when the relative velocity of the bumper on the vehicle is zero, the bumper does not continue function adequately as an isolator. In Figures 7 and 8, the horizontal velocities of the vehicle and occupant's torso are the same immediately after collision. The isolator has to operate before the rotational angular displacement and velocity of the occupant's head reaches the maximum value. The operational time of the isolator was found in this simulation. The point in time when the bumper ceases to work adequately as an isolator is the point where the horizontal velocity curves of the bumper and occupant's torso cross intersect. In this simulation this was at 0.17 sec.. Therefore, it is necessary to consider the shock absorption system at this time. The spring used in the shock absorption system is the A type. When the bumper ceases to work adequately as an

Table 7. The maximum rotational angular displacements of the frontal and rear occupants' heads with and without the shock absorption system.

Seatback (rad.)	Non-shock absorption system		Shock absorption system		Average reducing rate (%)	
	Front (rad.)	Rear (rad.)	Front (rad.)	Rear (rad.)	Front	Rear
0.07	0.995	1.026	0.832	0.909	16.4	11.4
0.14	1.027	1.064	0.863	0.884	16.0	16.9
0.21	0.991	1.021	0.823	0.846	17.0	17.1
0.28	0.993	1.017	0.826	0.847	16.8	16.7
0.35	0.971	0.996	0.822	0.842	15.3	15.5

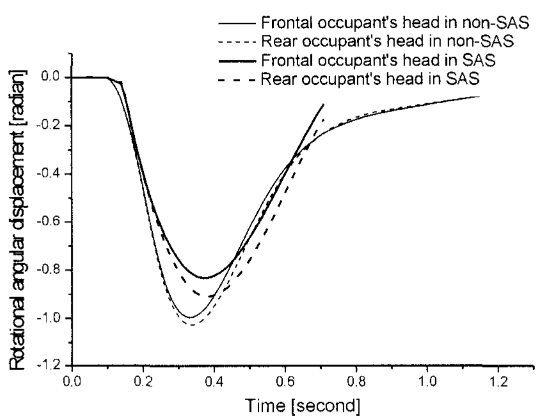


Figure 9. Comparison of the rotational angular displacements with and without the shock absorption system (SAS) for a 0.07 radian inclined seatback.

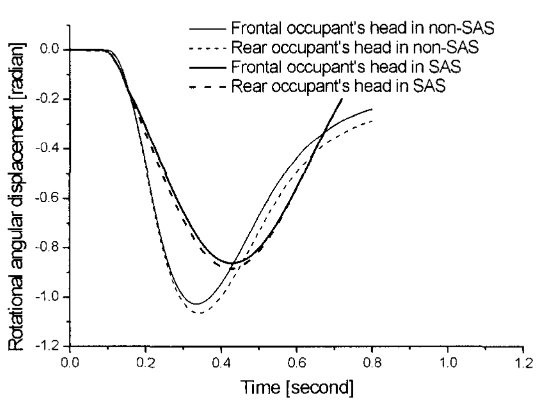


Figure 10. Comparison of the rotational angular displacements with and without the shock absorption system (SAS) for a 0.14 radian inclined seatback.

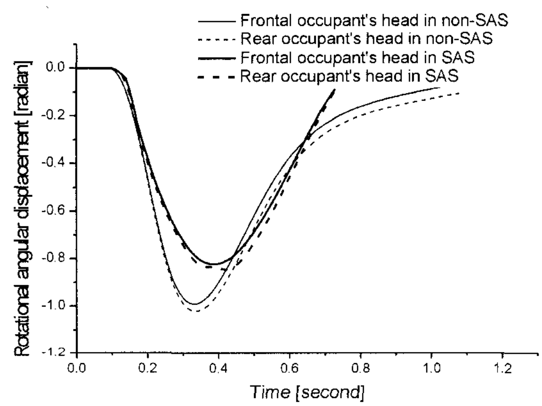


Figure 11. Comparison of the rotational angular displacements with and without the shock absorption system (SAS) for a 0.21 radian inclined seatback.

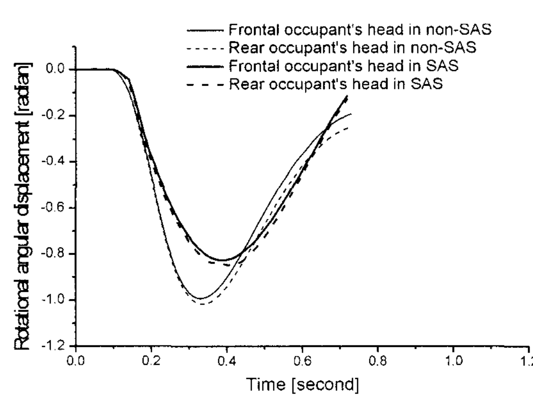


Figure 12. Comparison of the rotational angular displacements with and without the shock absorption system (SAS) for a 0.28 radian inclined seatback.

isolator, the shock absorption system must be capable of mitigating neck injury works at this time. Table 7 and Figures 9~13 show, the rotational angular displacements of frontal and rear occupants' heads due to the inclined seatback angles with and without the shock absorption system during low speed rear impact.

The rotational angular displacements of front and rear occupant's heads could be decreased remarkably by using the shock absorbing system shown Figures 9 to 13. From Table 7, the average rate of reduction of the rotational angular displacement of frontal and rear

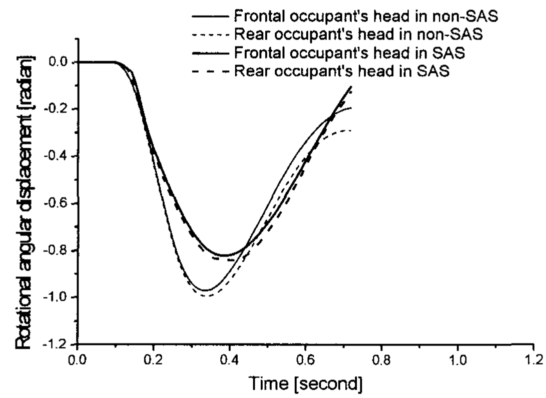


Figure 13. Comparison of the rotational angular displacements with and without the shock absorption system (SAS) for a 0.35 radian inclined seatback.

Table 8. Spring deformation of the isolators for reducing neck injury.

A type isolator		Shock absorption system		Reducing rate (%)	
Front	Rear	Front	Rear	Front	Rear
0.253	0.253	0.109	0.114	56.9	54.9

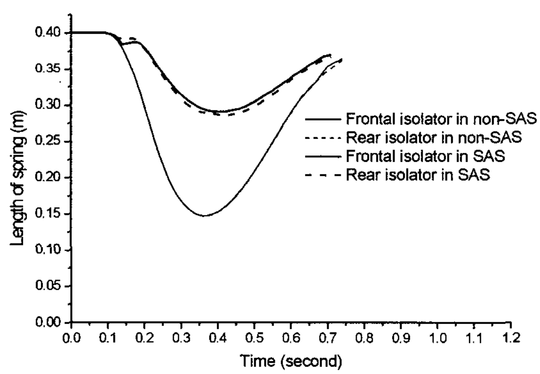


Figure 14. The comparison of deformations of the springs used in the isolators and the shock absorption systems.

occupants' heads are 16.3% and 15.5%, respectively.

The deformation of the spring is also decreased remarkably. The rate of reduction of the deformation of the springs used in the front and rear shock absorption system are 56.9% and 54.9%, respectively. The results are listed in Table 8 and shown in Figure 14.

5. CONCLUSIONS

Because the bumper of the struck vehicle is in a lower position than the center of gravity and the position of the front seat is closer to the center of gravity of the vehicle than the rear seat, the ramping motion of the rear occupant is greater than the passenger in the front seat. The angular displacement of rear occupant's head was larger than that of frontal occupant's head due to the ramping phenomenon.

The change of the angular displacement of an occupant's head according to an increase of the seatback angle was not observed in this simulation.

The shock absorption system for mitigating and reducing neck injury in low-speed rear impact was considered. This systems operates at the point in time when the bumper ceases to work adequately as an isolator. The rotational angular displacements of frontal and rear occupant's heads could be decreased remarkably using the shock absorption system. Further study on these factors is needed for the application to cars.

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