DEVELOPMENT OF FUTURE PEDESTRIAN PROTECTION TECHNOLOGIES

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ABSTRACT

Because many pedestrians suffer fatal head injuries in traffic accidents with vehicles in Japan, methods of evaluating pedestrian head protection are being investigated along with various technologies for improving the energy-absorbing characteristics of the vehicle body. One approach to improving energy-absorbing characteristics is to expand available energy-absorbing space. However, this approach has a large influence on vehicle design, which is directly related to fuel economy. Accordingly, future technologies for increasing energy-absorbing space through the use of devices or for reducing the head impact velocity itself are also regarded as important approaches. This paper describes two future pedestrian protection technologies that have less influence on vehicle design. One is a "rear-rising hood" that increases the energy-absorbing space at the time of a vehicle-pedestrian collision. The other is an "airbag system for controlling pedestrian collision kinematics" that can help reduce the head impact velocity against the vehicle by helping to control the kinematics of a pedestrian following a collision with a vehicle.

The "rear-rising hood" is designed to raise the rear part of the hood upon estimating or detecting an imminent collision between a pedestrian's head and the host vehicle. It uses an electric motor to drive an actuator that raises the rear part of the hood by 100 mm and can also lower the hood again. In collision tests conducted with a pedestrian dummy and an experimental vehicle fitted with the system, it was found that head injury values were reduced by 50% under certain controlled conditions.

The "airbag system for controlling pedestrian collision kinematics" features an airbag mounted at the front of the vehicle to control the collision kinematics of a pedestrian. This system can help serve to control the collision kinematics of a pedestrian's lumbar region such that it moves upward over the hood leading edge instead of rotating around the hood edge. In collision tests conducted with an experimental vehicle fitted with this system, it was found that the impact velocity of the pedestrian dummy's head against the vehicle was reduced by one-half under certain controlled conditions.

INTRODUCTION

Approximately 9,000 people are killed in traffic accidents every year in Japan. Because pedestrians account for about 30% of the victims, pedestrian protection has become a major issue of concern to society. The principal methods considered so far for protecting pedestrians have included better traffic safety education for them and improvement of the road infrastructure. A great deal of research has also been done on automotive design and engineering approaches for improving pedestrian protection. For example, Ishikawa et al.(1) analyzed actual vehicle-pedestrian accidents and reported that the impact of the head against the vehicle is the principal cause of pedestrian fatalities.

Test procedures for evaluating the pedestrian head protection performance of the vehicle hood have been discussed at international meetings such as those organized by the International Organization for Standardization (ISO)[2] and the International Harmonized Research Activity (IHRA).[3] Additionally, in research based on numerical simulations, Mathematical Dynamic Models (MADYMO) software has been used to perform various safety analyses. Ishikawa et al.[4] reported that in a vehicle-pedestrian collision the head ultimately strikes the vehicle, and Mizuno et al.[5] noted that the collision behavior of pedestrians differs depending on the front-end geometry of the striking vehicle. Hayamizu and Sakuma[6] also reported that pedestrian collision behavior varies depending on the position of the legs just prior to the impact with the vehicle. Moreover, Higuchi and Akiyama[7] used crash test dummies in conducting experiments to evaluate pedestrian collision behavior. However, Begeman et al.[8] compared the lumbar spine stiffness of the commercial Hybrid III seated test dummy and Post Mortem Human Subject (PMHS) test results and reported that the dummy pelvis is stiffer than that of the human body. Akiyama et al.[9] subsequently developed a new pedestrian dummy by modifying the stiffness of all the dummy's joints on the basis of a bioengineering approach. Those modifications were intended to make the collision behavior of the pedestrian dummy coincide better with cadaver behavior in order to improve the reliability of pedestrian collision tests. Research studies have also been conducted to improve the pedestrian head protection performance of the vehicle hood. Okamoto et al.[10] conducted a basic study focused on changes in the head deceleration waveform due to the use of different materials, for the purpose of optimizing the energy-absorbing characteristics of the hood. They reported that the energy-absorbing characteristic associated with the buckling of metal materials is an important factor. They further noted that improving energy-absorbing characteristics requires not only the optimization of material properties, but also the provision of sufficient clearance between the hood and the engine.

One method of securing greater clearance would be to increase the height of the hood by redesigning the vehicle front-end. However, that approach would also entail a number of drawbacks, including reduced visibility and deterioration of fuel economy due to a substantial weight increase and greater aerodynamic resistance. This suggests that several technological hurdles will have to be overcome in developing pedestrian protection performance that also takes into account other safety considerations and global environmental concerns.

During the 1990s, an Advanced Safety Vehicle (ASV) project[11] was promoted in Japan. In the first phase of ASV research, a hood airbag[12] for pedestrian protection was reported, which was designed to deploy over the hood for better protection of pedestrians without changing the height of the hood. The results of the second-phase of ASV research[13] were announced in 2001, the same year that Fredriksson et al.[14] reported bench test results for a system designed to increase hood-engine clearance by using gas injectors to raise the hood pyrotechnically. Instead of using gas injectors, though, a motor-drive system for raising the hood may be effective in terms of reparability because it would allow the hood to be lowered again to its normal position in the event the system was mistakenly activated in a collision with an object other than a pedestrian. There are various reports in the literature about technologies for improving the energy-absorbing characteristics of the hood, but there appear to be very few reports concerning ways of controlling the impact velocity of a pedestrian's head.

The objective of the present research is to help improve pedestrian protection performance through the combined use of future devices that can help overcome the technological issues which have been difficult to resolve with existing pedestrian protection technologies. This paper describes an energy-absorbing hood structure with an optimized buckling characteristic, a rear-rising hood that has already been announced in Japan, and an A-pillar airbag system, all of which

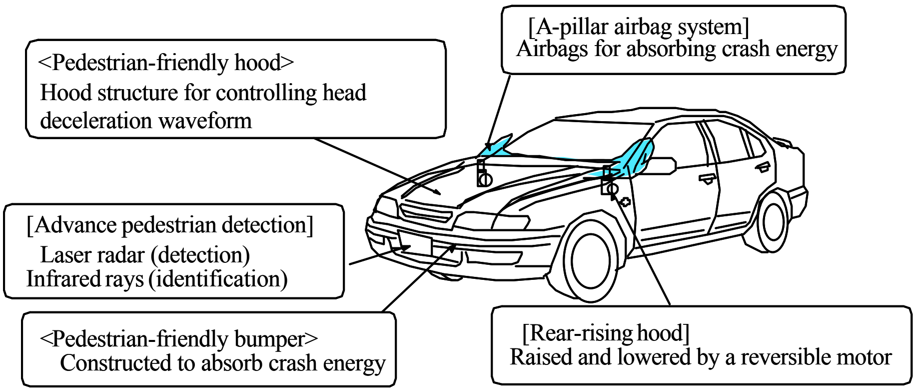

Figure 1. Pedestrian protection technologies incorporated in Nissan ASV II.

were incorporated in our second-phase ASV experimental vehicle (Nissan ASV II) as pedestrian protection technologies. It also describes an airbag system for to help control pedestrian collision kinematics. The system is mounted at the front of a vehicle and serves to help reduce the impact velocity of a pedestrian's head. The mechanism incorporated in this system for to help reduce the head impact velocity was obtained from an analysis of bicyclist collision kinematics in a head-on collision with the vehicle front-end.

VEHICLE BODY WITH IMPROVED ENERGY-ABSORBING CHARACTERISTICS

Pedestrian protection technologies for different impact velocities

The structure of the metal hood displays outstanding energy-absorbing characteristics. In impact tests conducted with the hood alone at a velocity of 40 km/h, HIC values below 1,000 were obtained. However, HIC values can exceed 1,000 when rigid structures such as the engine or front suspension are present below the hood and it is not possible to secure sufficient energy-absorbing space between them and the hood. Under that condition, it is markedly more difficult technologically to deal with higher head impact velocities, using only the energy-absorbing characteristics of the hood.

Therefore, the pedestrian-protecting vehicle body adopted for the Nissan ASV II included a structure for raising the hood under a condition of a high impact velocity so as to increase the clearance with the structures underneath the hood (Figure 1). Specifically, the pedestrian-friendly body structure with optimized energy-absorbing characteristics was designed to help mitigate impacts at velocities up to 30 km/h. In an impact velocity range of 30-40 km/h, an electronic device was used to raise the rear part of the hood so as to improve its energy-absorbing characteristics and thereby help provide better head protection at higher impact velocities. Additionally, there are also instances when a pedestrian's head strikes one of the A-pillars instead of the hood.[15] Therefore, airbags were adopted to cover the A-pillars as a protective measure in the event a pedestrian's head should collide with one of the pillars.

Pedestrian-friendly structure

One approach to minimizing the necessary clearance between the hood and the rigid structures underneath it is to control the deceleration waveform of the head. Head injury severity is generally evaluated according to the HIC formula. For the sake of simplicity, a comparison was made of the crumple distance needed with respect to three head deceleration waveforms, i.e., an initial-period triangular waveform, a latter-period triangular waveform and a rectangular waveform, in order to obtain the same HIC values (Figure 2).

Rectangular waveform - The maximum G level is assumed to be a constant G_0, and the basic equation for calculating HIC in the time interval of t_1 and t_2 is expressed as

$$HIC = \left| G_0^{2.5} \left(t_1 - t_2 \right) \right|_{max}$$

where the maximum values at t_1 and t_2 are $t_1 = 0$ and $t_2 = t_0$, so HIC can be given by

$$HIC = G_0^{2.5} t_0$$

Triangular waveforms - In the case of the triangular waveforms, the peak G is assumed to be G_0, and the timing for the occurrence of the peak G is assumed to be t_a. Then, it can be considered that the HIC value will occur in the interval defined by t_1 and t_2 and centering around t_a. Accordingly, letting

$$\Delta t = t_2 - t_1$$

we obtain

$$HIC = 2\left(t_a - t_1\right) \left| \left\{ \frac{1}{2}\left(\frac{G_0}{t_a} t_1 - G_0 \right) \right\}^{2.5} \right|_{max}$$

The maximum value of this expression is found with

$$t_1 = \frac{3}{7} t_a \text{ and } t_2 = \frac{11}{7} t_a$$

hence,

$$HIC = \frac{8}{7} t_a \left(\frac{5}{7} G_0 \right)^{2.5}$$

Accordingly, at a duration of 8/7, the HIC value becomes the same as that of a rectangular wave having a G_0 level of (5/7). Since the timing for the occurrence of t_a is arbitrary, both the initial-period triangular waveform with a deceleration peak in the initial period of a collision and the latter-period triangular waveform with a deceleration peak due to bottoming out display the same HIC value.

The results of the crumple distance comparison indicated that the head deceleration waveform should be controlled to the shape of the initial-period triangular waveform, in order to minimize the necessary energy-absorbing space without increasing this HIC value (Figure 3). Because the stiffness of the hood differs from one area of the panel to another, the hood structure would have to be extremely complex in order to control the head deceleration waveform to the pattern of the initial-period triangular waveform. Figure 4 shows one example of a pedestrian-friendly hood structure for con-

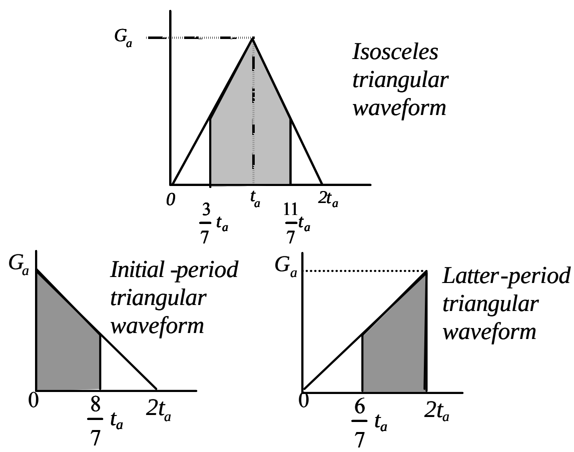

Figure 2. Triangular waveforms of head deceleration.

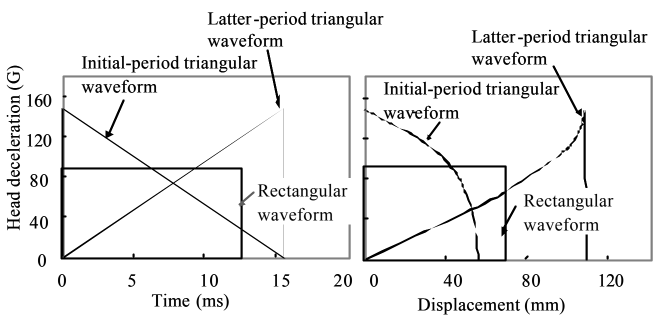

Figure 3. Comparison of energy-absorbing distance needed for head deceleration waveform control.

trolling the head deceleration waveform. Because of low local stiffness near the head impact point, this hood incorporates a reinforcement, or buckling structure, to increase head deceleration in the initial period of the collision.

Rear-rising hood system

As mentioned earlier, the energy-absorbing characteristics of the hood alone present certain practical issues

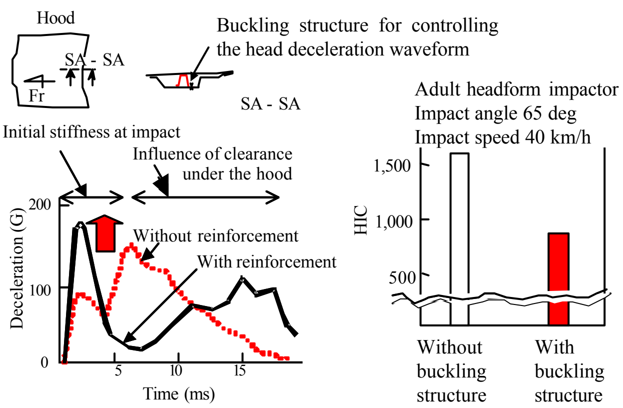

Figure 4. Effect of buckling structure.

in trying to provide better head protection at higher impact velocities. Accordingly, the Nissan ASV II adopted a rear-rising hood system to help protect pedestrians by increasing the energy-absorbing space at the time of the collision with the vehicle. This rear-rising hood system mainly consists of sensors for advance detection of a collision with a pedestrian, a control unit that judges an impending collision with a pedestrian and issues a signal to raise the rear edge of the hood and a drive unit that makes use of an electric motor. The operational sequence from the moment the hood begins to rise until the impact of the pedestrian's head is illustrated in Figure 5. The system predicts a collision with a pedestrian 400 ms before the pedestrian's head strikes the vehicle and immediately begins to raise the rear part of the hood. The rear portion is lifted by 100 mm in that 400 ms interval in preparation for the collision with the pedestrian. Moreover, the direction of hood movement is also reversible. If no vehicle deceleration indicative of a collision with a pedestrian is detected after the hood has been raised, the system judges that the sensors for advance pedestrian detection did not detect a pedestrian impact and it lowers the hood to its normal position again.

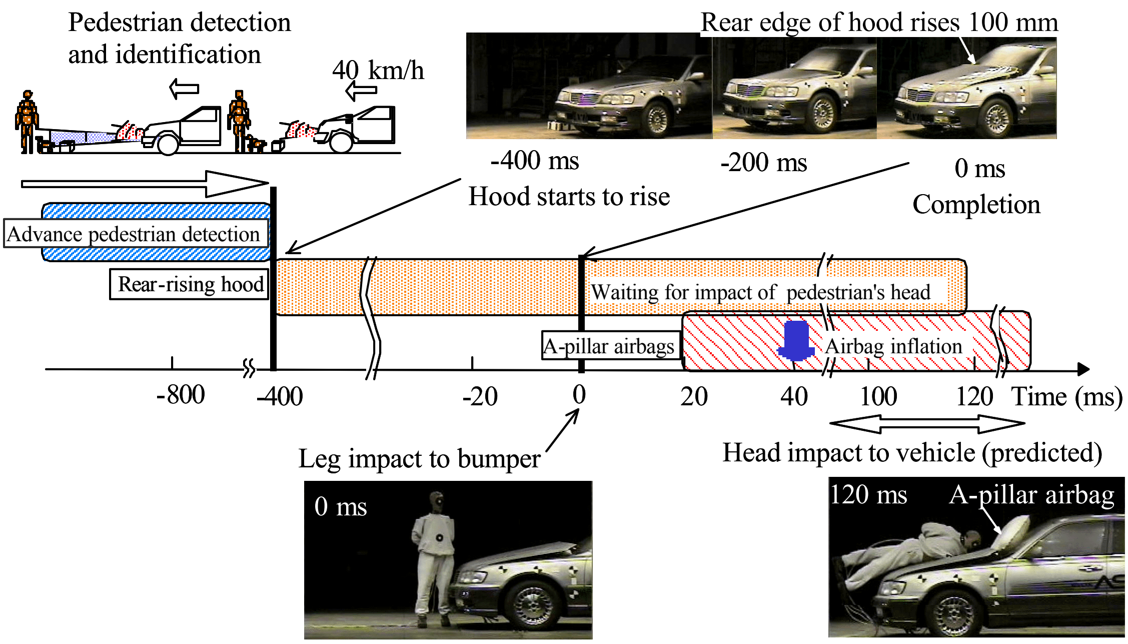

Figure 5. Operational sequence of rear-rising hood and A-pillar airbag system from time of pedestrian-vehicle impact.

A-pillar airbag system for pedestrian head protection

It has been found on the basis of an accident analysis [3] that a pedestrian's head can strike the A-pillars. The A-pillars, however, require a slender shape to ensure good outward visibility for the driver and also high stiffness to help secure occupant survival space in frontal offset crashes and in rollover accidents. Consequently, the A-pillars are one area of the vehicle body where it has been very difficult technologically to improve energy-absorbing characteristics with the conventional pillar structure.

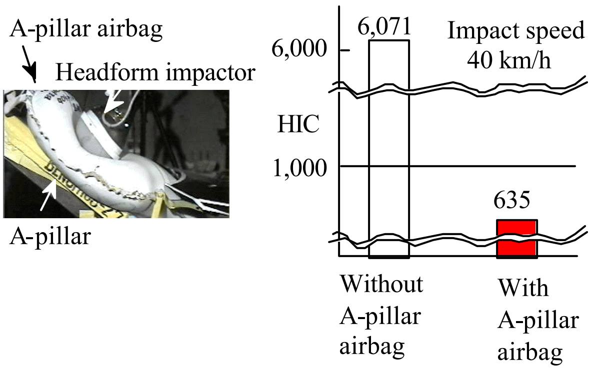

Figure 6. Comparison of test results with/without A-pillar airbag system.

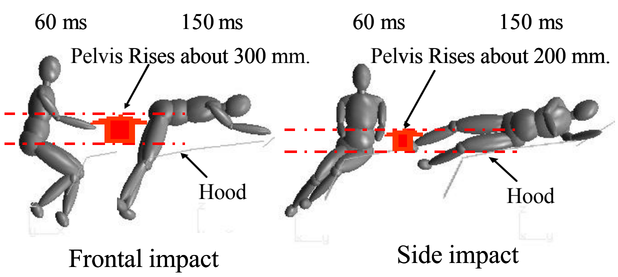

Figure 7. Upward movement of bicyclist dummy's pelvis.

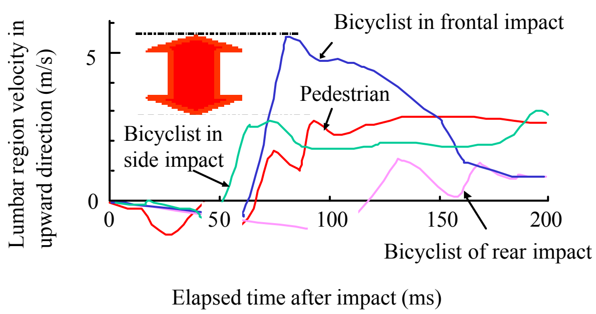

Figure 8. Comparison of pelvis velocities in the upward direction.

Therefore, the Nissan ASV II adopted an A-pillar airbag system that inflates airbags to cover the pillars when the system detects deceleration resulting from a collision between the vehicle and a pedestrian. The airbags are housed below the hood and are deployed through the clearance between the raised rear edge of the hood and the cowl. These A-pillar airbags are designed to deploy within 40 ms after the bumper collides with a pedestrian's legs. To determine the effectiveness of the A-pillar airbag system, a comparison was made of the HIC values that were recorded in bench tests when a headform impactor was crashed into an A-pillar with and without an airbag. The results showed that the HIC value was less than 1,000 when the A-pillar airbag system was used (Figure 6).

AIRBAG SYSTEM FOR CONTROLLING COLLISION KINEMATICS

Mechanism that helps reduce head impact velocity

An analysis of traffic accidents in Japan involving vulnerable road users shows that the fatality rate of bicyclists is lower than that of pedestrians. It is particularly noteworthy that the bicyclist fatality rate in frontal collisions, in which a rider collides head-on with a vehicle, is only about one-tenth of the pedestrian fatality rate.[16] Based on the results of numerical analyses[17, 18] conducted with MADYMO simulation models, the authors have shown that the head impact velocity of bicyclists is low in frontal collisions. One of the mechanisms involved in reducing the impact velocity is influenced by bicyclist collision kinematics, which is characterized by greater upward movement of the pelvis than that observed for a pedestrian (Figure 7). In a frontal collision in particular, the upward velocity of a bicyclist's pelvis is approximately double that seen in other bicyclist accident patterns and that of a pedestrian (Figure 8).

Collision kinematics with and without upward movement of the pelvis can be explained using a simple model that ignores the sliding of the body over the hood (Figure 9).[19] Using a pedestrian model that simulates only the upper body, it is seen that after the initial collision with the vehicle the upper body rotates around the lumbar region toward the vehicle and the head strikes the vehicle at a velocity corresponding to the initial impact velocity, which can result in serious head injury. In this case, the radius of rotation from the lumbar region to the head does not increase. However, with the bicyclist model in which the thighs act as a linkage mechanism, the lumbar region moves upward around the knees that strike the vehicle. In addition, the radius of rotation between the knees at the center of rotation and the head increases on account of the larger lumbar region angle between the thighs and the upper body. As a result, it is inferred from the law of conservation of angular momentum that the rotational velocity of the bicyclist model with the increased radius of rotation is less than that of the pedestrian model.

LUVI for collision kinematics control

A study was conducted to try to reduce the head impact velocity of a pedestrian in a collision with a vehicle by increasing the head's radius of rotation as a result of rotating the lumbar region by means of an airbag that was deployed from the radiator grille. The movement of the lumbar region was regarded as being a key factor, inasmuch as it was observed that the bicyclist dummy's lumbar region separated from the hood after the initial impact and moved upward toward the vehicle. Accordingly, a Lumbar Velocity Index (LUVI) for the upward and forward velocity components was defined, and an analysis was made of the relationship between LUVI and the head impact velocity.

The first step was to make clear the lumbar region behavior of bicyclists in frontal collisions and that of bicyclists and pedestrians in side collisions. To do that, frontal and side collision experiments were conducted using dummies with a modified lumbar region stiffness[19] and the experimental results were then compared. In the frontal collision, the upper body of the bicyclist dummy became horizontal by 160 ms after the impact and the lumbar region was displaced upward by at least 200 mm compared with its position at the time the knees collided with the vehicle. In the side collision, however, the lumbar region of the bicyclist dummy and that of the pedestrian dummy came in contact with the vehicle, and there was no upward displacement of the lumbar region like that observed in the frontal collision. The lumbar region's upward velocity and the relative forward velocity of the lumbar region and the vehicle in the latter's direction of travel were then determined from high-speed video images (Figures 10 and 11).

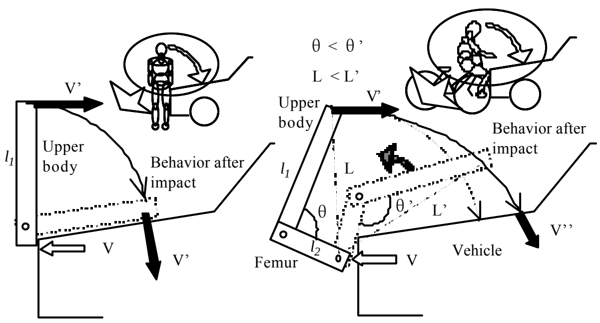

Figure 9. Simple mechanism reducing bicyclist head impact velocity in frontal collisions.

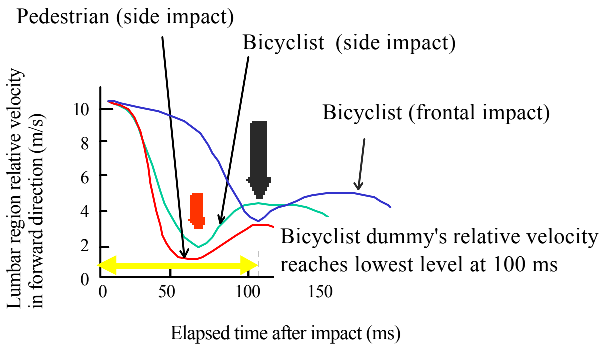

Figure 10. Lumbar region relative velocity in forward direction in frontal and side impacts using the modified dummy.

In the side collision, it was observed that both the bicyclist dummy and the pedestrian dummy were accelerated in the vehicle's direction of travel during the first 50 ms and that the relative forward velocity of the lumbar region with respect to the vehicle reached its

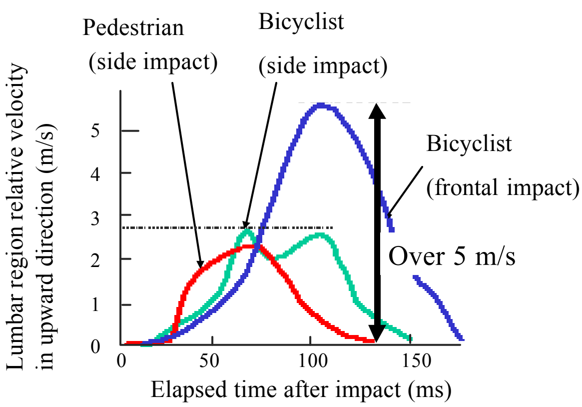

Figure 11. Lumbar region relative velocity in vertical direction in frontal and side impacts using the modified dummy.

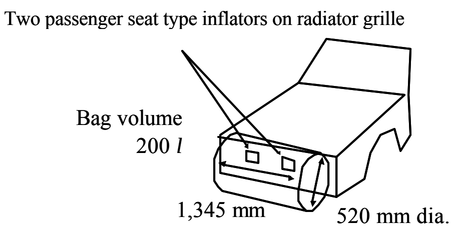

Figure 12. Basic airbag specifications for controlling bicyclist behavior in side collisions.

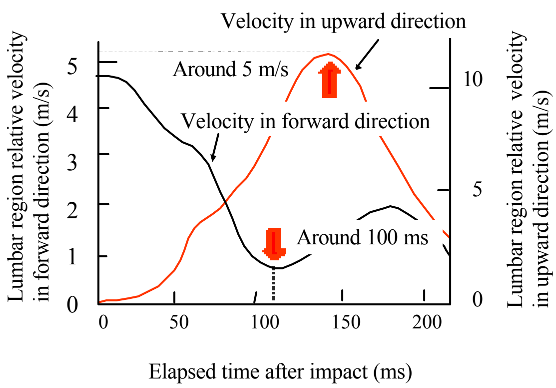

Figure 13. Comparison of bicyclist lumbar region velocities in upward and forward directions in side collision using airbag system.

lowest level at that point. On the other hand, one characteristic of the bicyclist dummy in the frontal collision was that its relative forward velocity reached its lowest level at 100 ms after the impact, i.e., at about double the elapsed time as in the side collision. Furthermore, at approximately the same elapsed time of 100 ms after the impact, the lumbar region's upward velocity was more than double (5 m/s) the velocity seen in the side collision.

It is thought that the rotational velocity of the upper body around the lumbar region will generally increase in cases where the lumbar region undergoes large forward acceleration. Therefore, with the aim of reducing that acceleration, attention was focused not only on the lumbar region's upward velocity that causes its upward displacement, but also on the elapsed time at which its relative forward velocity reaches its smallest value. A lumbar region upward velocity of 5 m/s and an elapsed time of 100 ms for the occurrence of its smallest relative forward velocity were set as the target LUVI values for the upward velocity and relative forward velocity of the lumbar region.

The upward velocity of a bicyclist's lumbar region is thought to increase in a frontal collision because the thighs rotate around the knees toward the vehicle, as was mentioned earlier. Accordingly, an airbag was positioned at the front-end of a test vehicle such that it would deploy at an upward angle of approximately 30° and rotate rearward toward the vehicle after colliding with the bicyclist dummy. The specification for the airbag inflation pressure was set at a lower level than that of a front passenger's airbag so as to make the upward velocity of the lumbar region and the elapsed time for the occurrence of its smallest relative forward velocity coincide with the LUVI values for controlling collision behavior (Figure 12).

Bench test using the airbag system for controlling collision kinematics

Figure 13 shows the lumbar region velocities found for the bicyclist dummy when the airbag system for controlling collision kinematics was used in a side collision. The airbag system was used to control the lumbar region's collision kinematics such that its smallest relative forward velocity occurred at approximately 100 ms and its upward velocity was approximately 5 m/s, based on the LUVI as the lumbar region index. As a result, the bicyclist dummy became horizontal at 140 ms after the impact and the lumbar region showed upward displacement of approximately 200 mm at that time (Figure 14). Without the collision-kinematics-controlling airbag system, the bicyclist dummy's head reached its maximum impact velocity in the vertical direction at the moment it struck the vehicle. With the airbag system for controlling collision kinematics, the dummy's head collided with the vehicle at the point of its lowest impact velocity in the longitudinal direction (Figure 15).

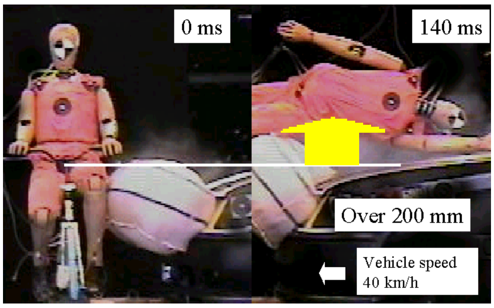

Figure 14. Experimental reproduction of a side impact using the modified bicyclist dummy and an airbag for controlling collision behavior.

In a bench test conducted under the same conditions as the bicyclist side collision experiment, it was confirmed that the collision-kinematics-controlling airbag system had the same effect on the collision kinematics of a pedestrian dummy (Figure 16). Because the deployed airbag covered the lumbar region of the pedestrian dummy in this bench test reproduction of a side collision with a pedestrian, the lumbar region velocities could not be determined inasmuch as images for analysis were not obtained. However, the pedestrian dummy's lumbar region was raised by at least 200 mm at 140 ms after the impact, so it is inferred that he upward velocity of the lumbar region was the same as that of the bicyclist dummy in the side collision experiment.

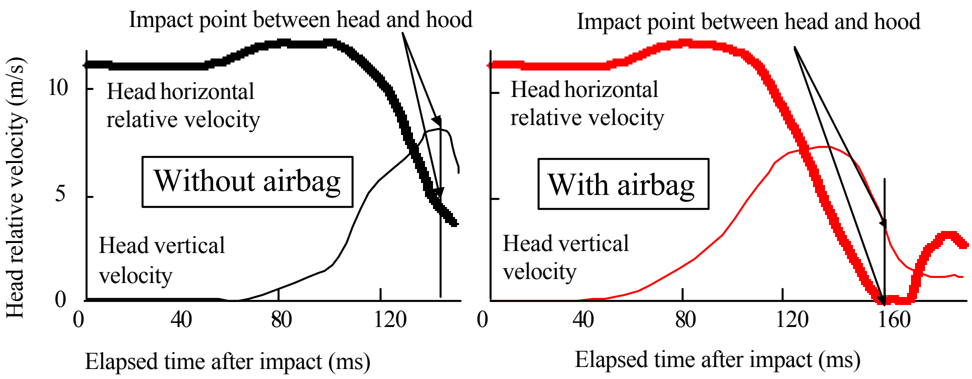

Figure 15. Comparison of experimental results for bicyclist dummy head velocities with/without airbag.

Figure 16. Experimental reproduction of side impact using the modified pedestrian dummy and an airbag for controlling collision behavior.

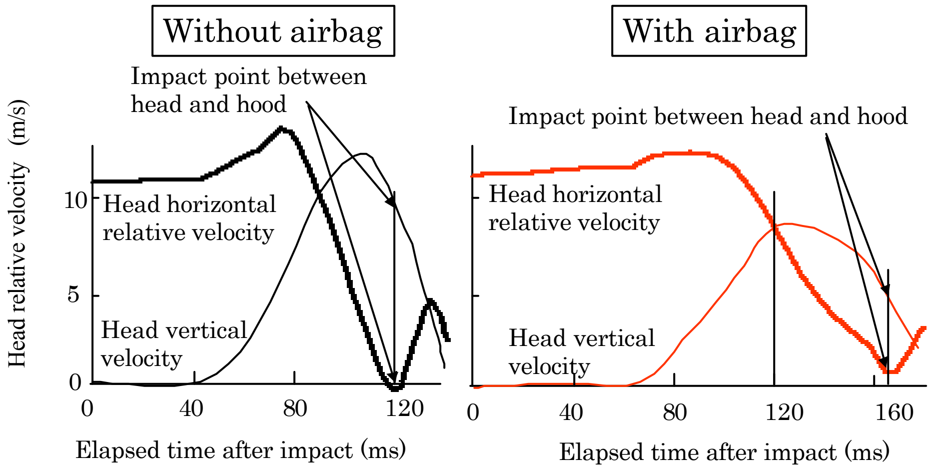

Figure 17. Comparison of experimental results for pedestrian head dummy velocities with/without airbag.

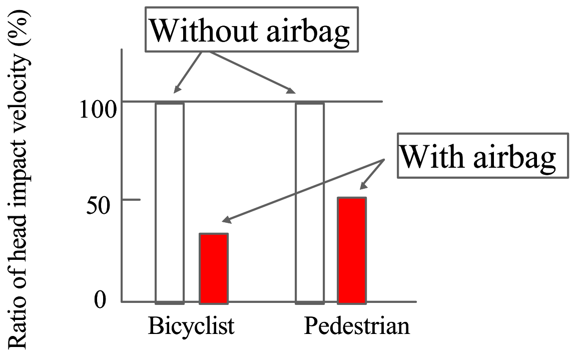

Figure 18. Comparison of head impact velocities against the hood (experimental).

Figure 17 compares the experimental results for the relative velocities of the pedestrian dummy's head in the horizontal and vertical directions until the head struck the vehicle. Like the bicyclist dummy, the impact time of the pedestrian dummy's head was delayed until approximately 160 ms and the relative velocity of the head in each direction following the impact was also lower, similar to the results seen for the bicyclist dummy. The use of the collision-kinematics-controlling airbag system reduced the triaxial composite impact velocity of the bicyclist dummy's head by approximately 70% and that of the pedestrian dummy's head by approximately 50% compared with the results obtained without the system (Figure 18).

SUMMARY

In the second-phase of ASV research, a hood structure, a rear-rising hood and an A-pillar airbag system, all designed for pedestrian head protection, were incorporated in an experimental vehicle and their effectiveness was confirmed under certain controlled conditions. Additionally, an airbag system for controlling pedestrian collision kinematics by means of an airbag housed in the radiator grille was also developed. This system reproduces the mechanism that reduces the impact velocity of a bicyclist's head in a head-on frontal collision with a vehicle under certain controlled conditions. It was shown that the Lumbar Velocity Index (LUVI) for the upward and forward velocity components of the lumbar region was an effective index for the development of this collision-kinematics-controlling airbag system.

CONCLUDING REMARKS

The effectiveness of several advanced pedestrian protection technologies has been confirmed in experiments conducted under certain specified conditions. The hinge structure of the rear-rising hood has been shown to achieve HIC values below 1,000. However, there are two issues related to this technology that need to be addressed in future work. One issue concerns assurance of the durability of the hinge structure. The second issue is to improve the strength of the hinges so that the hood does not intrude into the passenger compartment in a frontal impact.

Because pedestrians and bicyclists have more degrees of freedom in a collision than vehicle occupants who are restrained by seatbelts, their collision kinematics in real-world traffic accidents involves many diverse conditions. For instance, based on the results of numerical simulations, the authors have reported that the timing at which the head strikes the vehicle differs significantly between pedestrians and bicyclists.(18) Additionally, there are many situations in which advance detection of pedestrians by sensors is impossible, such as the detection of wet pedestrians or distinguishing them from other heat sources in rainy winter weather and the detection of pedestrians when the related sensors are covered with road grime. These and other circumstances make it extremely difficult to obtain accurate judgments in all types of collision situations. The second-phase ASV research activities also yielded sensing technologies that are reported to be still at the experimental stage.(20) It is hoped that the accuracy of advance detection will be further improved in the future as the levels of these technologies rise. Promoting better pedestrian protection requires not only vehicle-level measures, but also cooperation in a broad range of areas, such as the implementation of infrastructure facilities and traffic safety education, with an eye toward preventing people from dashing unexpectedly from narrow alleys or other hard areas where detection is difficult to accomplish.

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