AN EXTENDABLE AND RETRACTABLE KNEE BOLSTER

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ABSTRACT

Knee bolsters are integral parts of the occupant protection system for frontal impact in modern passenger vehicles. The knee bolster is the lower portion of the instrument panel of a passenger vehicle. It is generally made of padded structures, which structures are capable of absorbing the impact energy imposed by the knees during a frontal impact. In this paper we present an active knee bolster called the extendable and retractable (E/R) knee bolster. The E/R knee bolster is intended to automatically extend in situations in which there is a high risk of frontal impact to help prepare the vehicle for crash and retract when the risk subsides. Its key enabling technologies, implementation options and intended benefits are discussed in detail. A prototype vehicle is presented to demonstrate the unique styling, designs and utilities enabled by the E/R knee bolster.

INTRODUCTION

Knee bolsters are integral parts of the occupant protection system for frontal impact in modern passenger vehicles. The knee bolster is the lower portion of the instrument panel of a passenger vehicle. It is generally made of padded structures, which structures are capable of absorbing the impact energy imposed by the knees during a frontal impact. A knee bolster must be positioned close enough to the knees so that it can provide restraint forces in a timely manner. On the other hand, it should also be positioned as far away from the knees as possible for more legroom and interior spaciousness.

Recently, there has been a growing interest in using an inflatable device, such as a knee bag [1], a knee bladder [2], etc., to replace the stationary knee bolster. Depending on the needs of each program, these inflatable devices may be positioned either in the conventional stationary knee bolster location to enhance safety performance or in a farther away location to increase legroom and interior spaciousness with no compromise in occupant safety. However, special care must be taken in order to minimize the risk of inflation-induced-injury to out-of-position occupants.

In this paper we propose an active knee bolster called the extendable and retractable knee bolster or the E/R knee bolster in short. It applies the concept of crash preparation both to free up the position constraint that exists for a stationary knee bolster and to avoid the risk of inflation-induced-injury that can exist with inflatable devices. That is, the proposed E/R knee bolster provides advantages similar to both stationary and inflatable knee bolsters, but without the corresponding limitations. Its key enabling technologies, implementation options and intended benefits are discussed in general. A prototype vehicle is also presented to demonstrate the function of the E/R knee bolster.

BASIC CONCEPT

Conventional safety features of passenger vehicles, such as seat belts, airbags, knee bolsters, etc., are all pre-configured and packaged at their intended operation locations as they come off the assembly line. A passenger vehicle is therefore prepared and configured at all times for a crash even though crashes are relatively rare events. Full time readiness for a crash imposes stringent constraints on the styling, design, and utility of a vehicle.

To avoid such constraints, a new crash safety concept, called crash preparation, is proposed here. It is based on the idea that if a safety feature can reconfigure itself into the intended configuration in a non-intrusive and timely manner just before an imminent crash, it can then offer the desired occupant protection while allowing new styling, design and utility previously not possible in current fixed designs due to the need for full time readiness for crash protection. Moreover, if the safety feature can revert to its original configuration when the crash threat subsides, the high reliability requirement of not falsely detecting an imminent crash can also be relaxed. We define such a reversible and non-intrusive crash safety concept as “crash preparation.” Those pre-crash sensing assisted braking systems such as the Brake Assist and the Automatic Emergency Braking System proposed in Ref. [3] are not crash preparation features. They are rather crash avoidance features. In contrast, the extendable and retractable knee bolster proposed here is a crash preparation feature.

Figure 1 illustrates a conceptual interior design with a knee bag for the driver and an E/R knee bolster for the right front passenger. As shown, the passenger knee bolster is to be positioned in its stowed location, which could be either in its conventional location or in a location farther away from the knees. In either case an E/R knee bolster’s activation system, comprising sensors, control logic and actuators, would be designed to timely move the knee bolster closer to the occupants in a non-intrusive fashion when a need appears. The extended knee bolster would automatically retract to its stowed position when the need disappears. Clearly, the E/R knee bolster satisfies the definition of a crash preparation feature. Figure 2 shows a conceptual design illustrating passenger side interior changes that could be enabled by the farther away case.

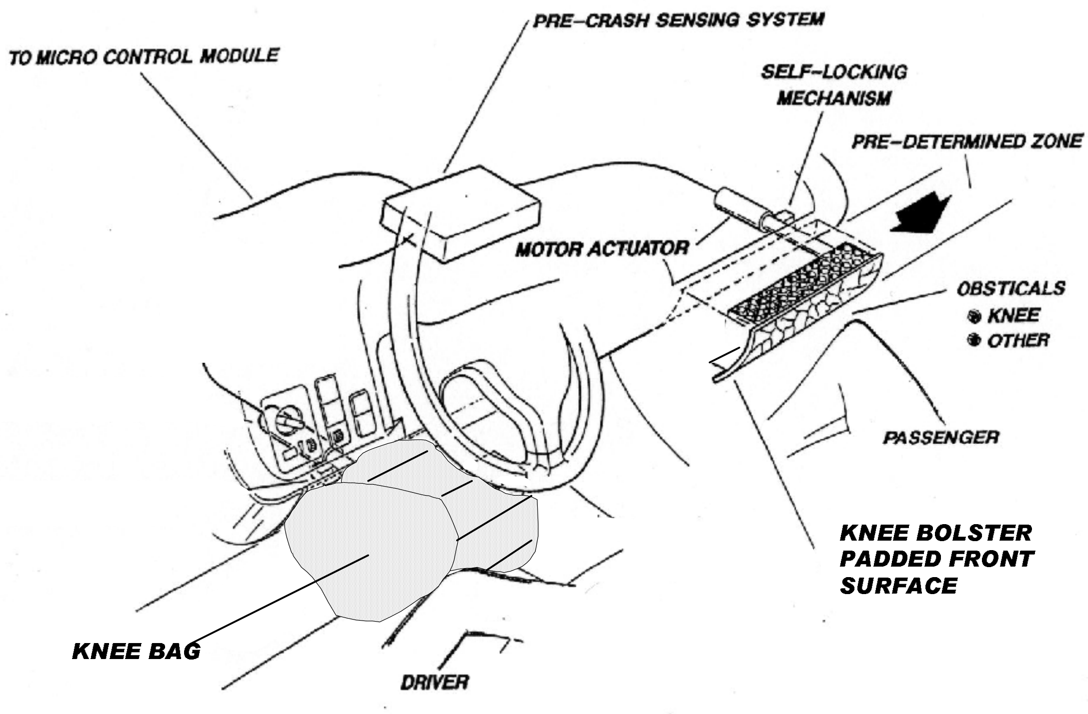
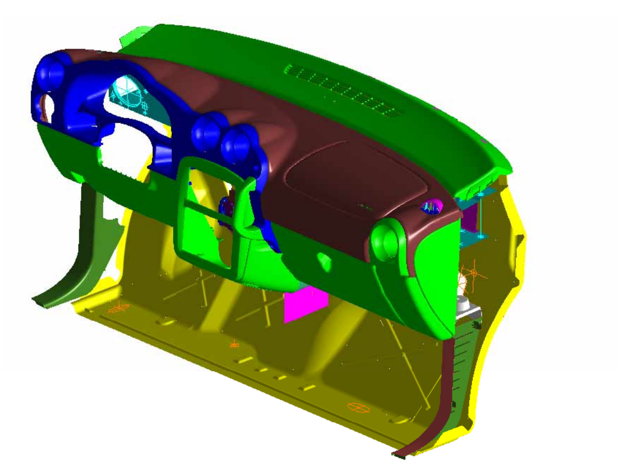
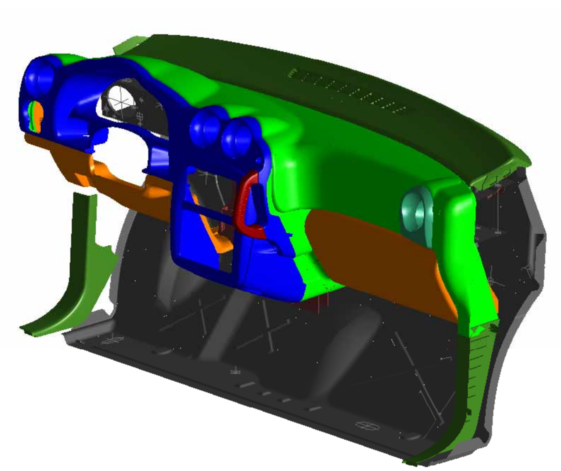


Figure 1. Conceptual design of a passenger side E/R knee bolster.



(a) Current interior



(b) Modified interior with the E/R knee bolster

Figure 2. Conceptual design of interior changes enabled by the E/R knee bolster.

ENABLING TECHNOLOGIES

There are two crucial enabling technologies for a crash preparation feature like the E/R knee bolster. One is a sensing and control means to determine the correct situations and timing for extending and retracting the knee bolster. The other is a combined actuator and crash energy management means to timely extend and retract the knee bolster and to provide the required restraint force and crash energy absorption capability when a collision actually occurs. We have been working on the development of these enablers. In what follows we will review the technologies that have been identified and implemented in our demonstration vehicle.

Sensing and Control Means

The E/R knee bolster could be tailored and used to meet the specific goals of different implementation options. Among those considered implementation options, our focus eventually narrowed to the following three options. Note that these are not mutually exclusive options and can be employed either individually or in any combination as deemed desirable or necessary for a particular vehicle application.

Pre-Crash Sensor Activated Option - This option represents the ultimate implementation goal of the E/R knee bolster. In this option, the extension of the E/R knee bolster would be automatically triggered by a detect signal from a robust pre-crash sensing system.

The long-range radar sensor with a 100 m plus range has been ruled out for this option, since its narrow radar beam has limitations when an object is closer than 7 m. A short-range sensor with a 3 m range has been ruled out for a rather different reason. While the short-range radar can work reliably when the object is close, it provides a very short actuation time budget for the E/R knee bolster. Figure 3 depicts the theoretical relationship among the range, closing rate and actuation time budget of a pre-crash sensing system. Note that a constant closing rate between the striking and the struck objects is assumed here to represent the worse case scenarios. We see that for a collision event with a 3 m range and 144 kph closing rate the actuation time budget is only about 80 msec. This presents a problem since this would require the E/R knee bolster to deploy aggressively, which is obviously in conflict with the non-intrusive requirement of the crash preparation concept.

To meet the crash preparation requirement, a sensor system with a range between the short and long ranges is required. From Fig. 3, we see that a sensor with a range of 20 m could provide an E/R knee bolster with a more than 500 msec actuation time budget before a collision, if the closing rate is equal to or lower than 144 kph. With such a long actuation time budget, the actuator of the E/R knee bolster could now move its knee bolster at a relatively slow rate.

In the event of a false detect or a crash that was not sufficiently severe so as to damage the knee bolster system, retraction of the E/R knee bolster could be programmed for an even slower rate. Figure 4 shows our demonstration vehicle with a prototype mid-range pre-crash sensing system. Note that these sensors are packaged behind the front fascia of the vehicle, and that we have removed the fascia just for viewing purposes.

If the pre-crash sensing system is sufficiently precise, performance could be enhanced with this option by having the knee bolster extend all of the way to knee contact prior to the impact. This would allow the lower torso to be restrained by the knee bolster throughout the duration of the impact event.

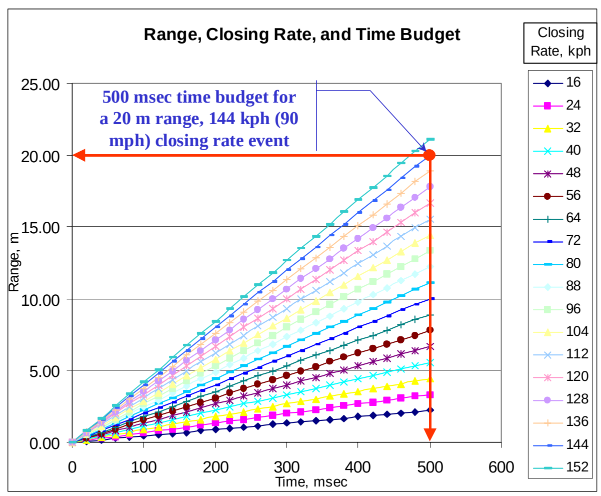


Figure 3. Relationship of range, closing rate and actuation time budget.

Intended benefits of this option are: (1.) it would obviate the need to have an occupant detection system and a seatbelt buckling sensor prior to E/R knee bolster implementation; (2.) it could provide enhanced safety performance if sufficient packaging room existed along with sufficient reliability of sensor detects to permit extension to the point of knee contact; and (3.) it could serve as a visual indicator that the vehicle is actively trying to enhance safety in higher risk operation modes.

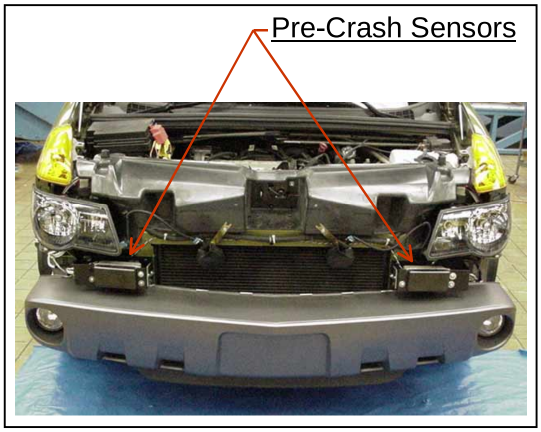


Figure 4. A mid-range pre-crash sensing system.

In this option output from other vehicle sensors could be used to extend the E/R knee bolster in select high collision risk scenarios in which detects may not yet have been registered by the pre-crash sensor. Among these could be the indication of the initiation of rollover or vehicle spin-out based on sensor input, the activation of the ABS braking system, operation at a speed in excess of a preset limit such as 128 kph, and the manual selection of an optional high-performance mode by the vehicle operator.

<u>Seatbelt Interlock Option</u> - The goal of this option is to provide knee restraints for unbelted occupants only, assuming that the lap belt could sufficiently restrain the lower torso of a belted occupant. The E/R knee bolster would be automatically extended in the case of an unbelted occupant, when the passenger door was closed and the vehicle was placed in gear. Since a collision is not imminent, the E/R knee bolster could extend at a rate even slower than the pre-crash sensor activated option. Opening of the passenger door, buckling of the seatbelt, or shifting the vehicle gear into park would cause the E/R knee bolster to automatically retract, again at a slow rate. If a passenger is not present, the knee bolster would remain stowed in its far forward (toward the front of the vehicle) location.

A visual sign could be exposed on the upper surface of the knee bolster (see Fig. 5), or either a chime or an oral reminder could also be provided when the knee bolster is extending, instructing the passenger to buckle up in order to retract the knee bolster. Accordingly, this option could also be viewed as a seatbelt use reminder. Belted occupants will be rewarded with more legroom and a spacious interior; those who choose not to use their seatbelts will not.

Output from other vehicle sensors could also be used to extend the E/R knee bolster in select scenarios even for a belted occupant. Among these would be the detection of the possibility of an impending collision event by a non-robust pre-crash sensing system, the indication of the initiation of roll-over or vehicle spin-out based on sensor input, the activation of the ABS braking system, operation at a speed in excess of a preset limit such as 128 kph, and the manual selection of an optional high-performance mode by the vehicle operator.

Intended benefits of this option are: (1.) it would allow more rapid implementation of E/R knee bolster technology since it does not require pre-crash sensing; (2.) it could serve as a seatbelt use reminder; and (3.) it would serve as a visual indicator that the vehicle is actively trying to enhance safety in higher risk operation modes. However, in order to avoid unnecessary activations, occupant presence sensors are desired for this option.

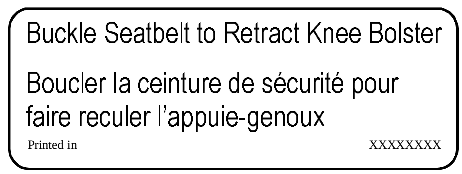


Figure 5. Information label to be displayed upon the extension of E/R knee bolster.

<u>Semi-Passive and Manual Option</u> - This option allows the powered manual extension and retraction of the knee bolster on demand through a push button. This would be a slow speed movement of the knee bolster on demand between the standard and far rearward locations. The former is defined as that required of current knee bolsters to comply with all motor vehicles safety standards and requirements on unbelted occupant crash performance.

Intended benefits of this option are: (1.) it could provide powered glove box extension/retraction; (2.) it could expose a work surface laptop docking station; and (3.) most importantly it could meet the individual needs of styling and/or safety conscious customers. As previously indicated this option can be readily incorporated with either seatbelt interlock or pre-crash sensor activated options.

Actuator and Crash Energy Management Means

<u>Reversible Actuator</u> - To extend and retract the knee bolster, reversible actuators are required for the E/R knee bolster. A wide range of reversible actuators, including electrical motors, solenoids, pneumatic cylinders, etc., could be used for the E/R knee bolster. However, linear actuators using rotary electric motors are attractive candidates for this application because of their flexibility of packaging and operation, their ready availability as off-the-shelf technologies, and the considerable experience with them in power seat and sunroof applications. Two specific types were considered for the prototypes to be developed, those involving motor driven ball screws and those involving motor driven lead screws. Motor driven lead screws were selected as the drive units for the E/R knee bolster, because of their low cost.

Self-Locking and Energy Absorption Mechanism - A special mechanism providing self-locking and energy absorption functions is required for the E/R knee bolster. This mechanism needs to be responsive only to impacts on the front surface of the knee bolster, and not to the normal operation of the extension and retraction actions of its actuator. An impact on the front surface of the knee bolster must activate the self-locking function of the mechanism and then allow the unit to stroke to absorb crash energy when the load exceeds a predetermined limit. Another necessary function of the mechanism is that it must be able to self-lock the knee bolster at any position and at any time to provide energy absorption in instances in which there is an incomplete actuation before an impact. A patented self-locking telescoping mechanism [4, 5], which possesses all these functions, is presented below.

The patented self-locking telescoping mechanism is composed of a stationary outer tube, an inner tube telescoped into the outer tube having a cone-shaped ramp at the inboard end and a bracket for attaching the knee bolster at the outboard end, and a plurality of metal balls between the cone-shaped ramp and the outer tube. Figure 6 shows the complete assembly of the self-locking telescoping mechanism with a motor drive and lead screw.

The self-locking telescoping mechanism can have three different modes of operation, namely extension, retraction and self-locking/energy absorption. To facilitate the extension and retraction modes, the self-locking telescoping mechanism further includes an actuator rod, a driver which translates the actuator in the collapse direction and in an opposite expansion direction corresponding to an increase in the length of the telescoping mechanism, and a tubular retainer on the actuator rod having a plurality of closed-ended slots around respective ones of the metal balls. During the extension action, all of the metal balls will stay in the ends of the slots due to their inertia. This essentially prevents the balls from becoming wedged between the cone-shaped ramp and the outer tube. During the retraction action, all of the metal balls will again stay in the ends of the slots. The only difference in this case is that they are confined by the tubular retainer but not by their inertia.

In the energy absorption mode, the metal balls become wedged between the cone-shaped ramp and the outer tube when the inner tube is thrust into the outer tube under a substantial load on the front surface of the knee bolster, such as the crash impact force, thereby locking the inner and outer tubes together and rendering the telescoping mechanism structurally rigid in the collapse direction (see Fig. 7). When the thrust is attributable to a severe impact on the inner tube, the balls plastically deform the outer tube by plowing tracks into it in so doing converting the kinetic energy of the impact into work. We see that the impact energy absorption mechanism is essentially a rolling torus energy absorber [6], which is known for producing a rather consistent uniform resistance force throughout the plowing event. This special characteristic is ideally suited for a knee bolster. An optimal resistance force can be chosen to ensure that the femur loads will be well below their injury threshold while the total amount of crash energy to be absorbed is maximized due to this uniform resistance force characteristic.

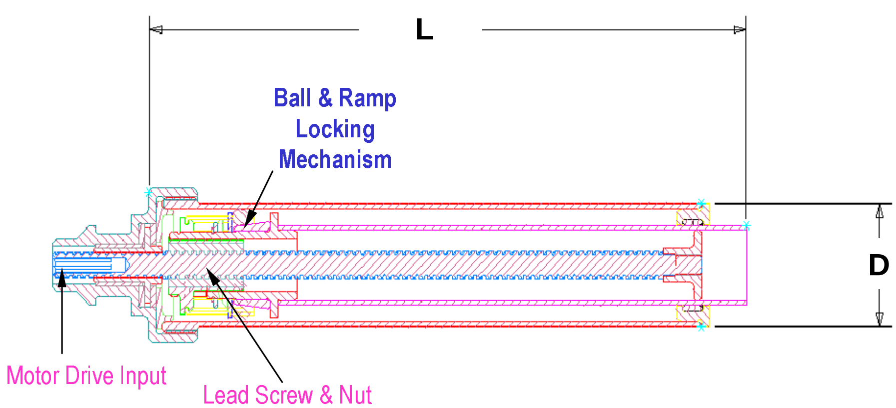
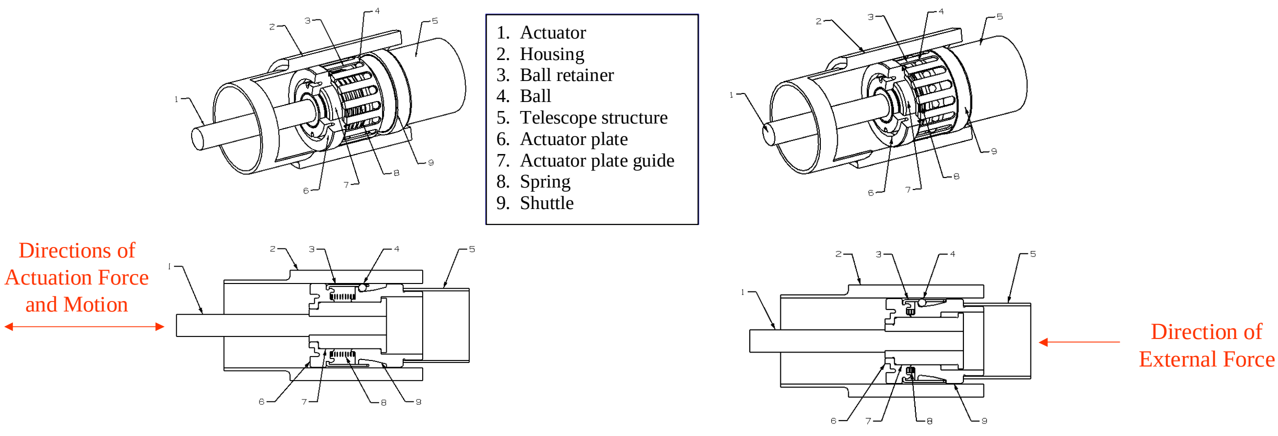


Figure 6. Assembly drawing of a self-locking telescoping mechanism with a motor and lead screw.



(a) Extension mode and retraction mode (b) Self-locking/energy absorption mode

Figure 7. Three operation modes of the self-locking telescoping mechanism.

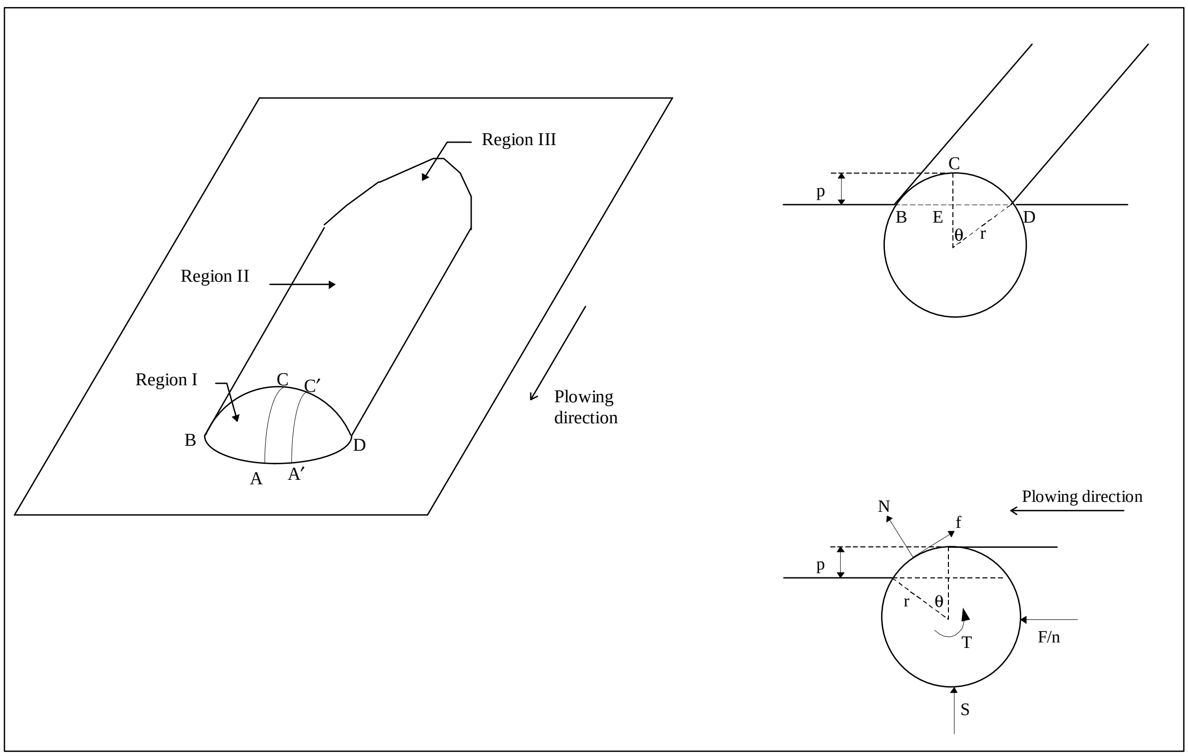


Figure 8. The plowing model.

This self-locking mechanism provides the combined function of actuation, locking and energy absorption in a simple, lightweight unit. Its rolling torus energy absorber is known for its almost ideal square wave shape stroking force time history and the mechanism also provides the required function of self-locking at any position and any time to cover situations in which there might be an incomplete actuation before an impact.

Modeling of A Rolling Torus Energy Absorber - A previously developed mechanics model [7] as reviewed below can be used to analytically estimate the locking force. As shown in the plowing model, Fig. 8, the plowed groove is segmented into three regions: Region I is the leading spherical part and the ball is always underneath it during the plowing process; Region II is the middle cylindrical part which roughly covers the stable plowing distance; and Region III is the beginning part characterizing the penetration process associated with the initial load increase that occurs before reaching the full plowing force level. Since we are more interested in the stable plowing force, the beginning part (Region III) is not included in our analysis. A balance of internal work and external work of all the balls gives the following relationship for the plowing force, F [7].

$$F = \frac{2n\sigma_0 t\left[t\theta + r(\theta - \sin\theta)\right]}{g(\theta,\mu)} \quad (1).$$

where n is the number of balls, σ_0 is the yield stress of the tube material, t is the thickness of the outer tube wall, r is the common radius of the balls, μ is the coefficient of friction between ball and tube, and

$$g(\theta,\mu) = 1 - \frac{1}{\cos\frac{\theta}{2} + \frac{1}{\mu}\sin\frac{\theta}{2}} \quad (2).$$

A prototype of the self-locking mechanism was built using Eqs. (1) and (2). Drop tower dynamic crush tests were conducted to determine whether the locking mechanism would remain locked in an impact event as well as whether the device would collapse at the “designed-in” stroking force level, 4 kN. A mounted test specimen is shown in Fig. 9. The test started with the inner tube in the extended position, the distance between consecutive black marks on the extended inner tube corresponding to 25.4mm (1 inch). Drop energy was chosen such that the inner tube would stroke approximately 100 mm if it generated a stroking force of 4 kN as designed.

A stroked specimen appears on the left in Fig. 10 with one of the ridges created by plowing of one of the balls being highlighted by red marker so as to show up better in the photograph. Total stroke in this case was indeed 100 mm (four black marks). Filtered stroking force versus time traces from two drop tests conducted on “identical” self-locking mechanisms appears on the right in Fig. 10. Note the very repeatable and the almost ideal square wave nature of the traces, which is a known signature of a rolling torus energy absorber. Average force levels for both traces were quite close to the design force level of 4 kN. This validated the above mechanics model and formulas.

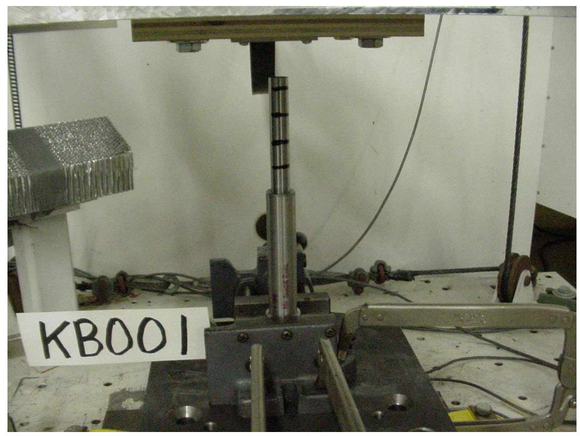


Figure 9. Drop tower setup for dynamic axial crush test of the self-locking mechanism.

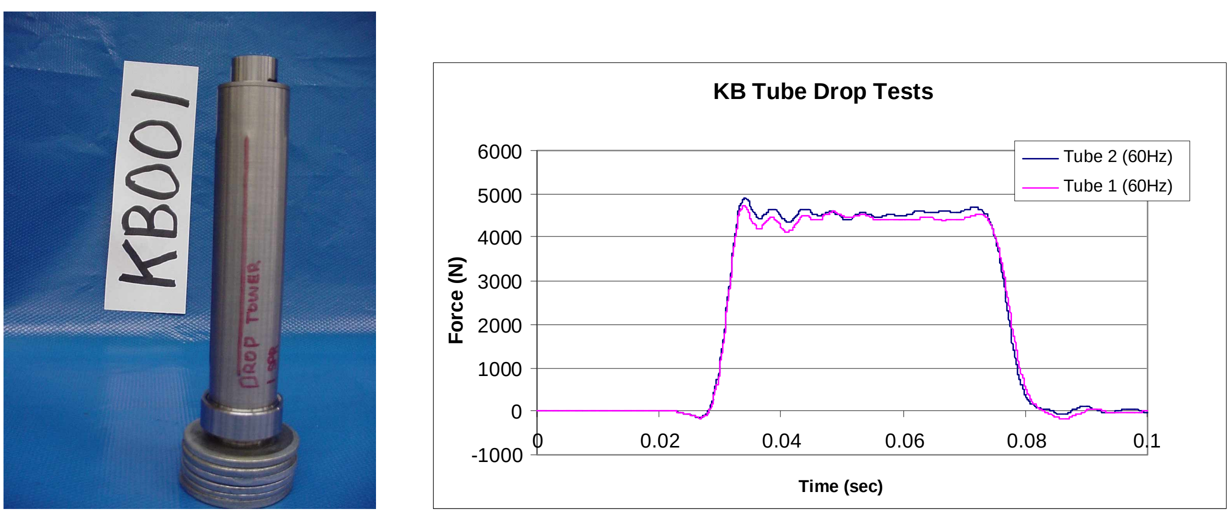


Figure 10. Stroked actuator and force vs. time traces from the drop tower test.

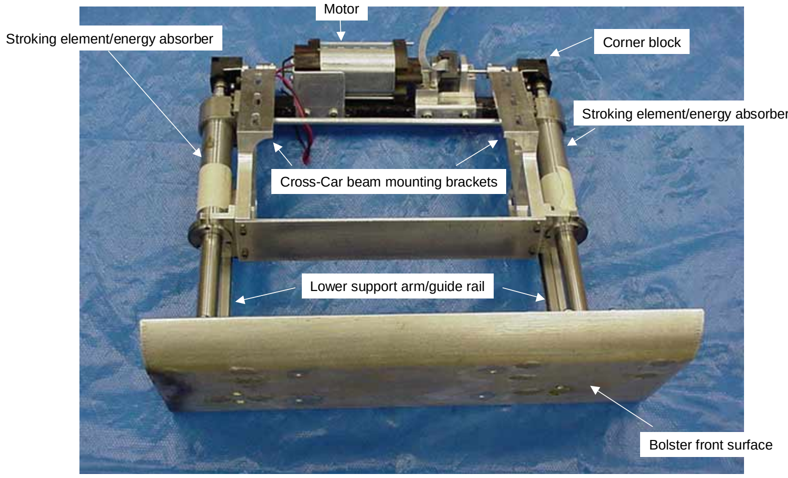


Figure 11. Demonstration E/R knee bolster subassembly.

DEMONSTRATION VEHICLE

Subsystem

An E/R knee bolster hardware unit was developed (see Fig. 11) and integrated into the demonstration vehicle. Key elements of the unit that are labeled include the brush motor used to drive the two stroking elements, the corner blocks, the two cylindrical actuator/stroking element/energy absorbers, the two brackets used to mount the unit to the cross car beam, the two lower support guide rails added to increase stiffness under off-axis loading, and the bolster front surface which, for purposes of this demonstration unit only, was an aluminum plate with bending stiffness matching that of the current glove box door.

Observe that a single motor rather than two was chosen to drive the stroking elements in order to minimize the unit cost and mass. A load limit of 8 kN, i.e. 4 kN per each stroking element, was selected for the bolster crushing/stroking force upon knee loading based on trying to provide a safety margin of 2 kN with respect to the FMVSS requirement of 10 kN for the worst case scenario, i.e. one knee only loading the knee bolster in a crash. The total mass of the unit is approximately 3.5 kg.

Functional Demonstration

The passenger side knee bolster and instrumentation panel of the demonstration vehicle were re-designed to incorporate a fully operational E/R knee bolster hardware unit mounted so as to provide 100 mm more interior space. Figure 12 shows the difference in interiors between the demonstration vehicle and an unmodified vehicle for a large adult in the mid-seating location. Figure 13 shows the difference in knee room provided by these two interiors. Note that in both vehicles the passenger seat has been located in the identical mid-seating position.

(a) Current interior

(b) Modified interior with the E/R knee bolster

Figure 12. Interior changes enabled by the E/R knee bolster.

(a) Current interior (b) Modified interior

Figure 13. Difference in knee room for a large adult in the mid-seating location.

(a) Retracted (b) Extended

Figure 14. The E/R knee bolster in retracted and extended positions.

(a) Retracted (b) Extended

Figure 15. The E/R knee bolster in fully retracted and extended locations for an adult in the mid-seating location.

Figure 14 contains photographs of the interior with the E/R knee bolster in its fully retracted and fully extended positions. Figure 15 shows the E/R knee bolster in its retracted and extended positions for an adult occupant in the mid-seating location. Given that the extended position corresponds to that required by the unbelted occupant protection requirements, this illustrates the significant gain in interior space enabled by the E/R knee bolster. We see that indeed, without preparing full time for crashes, an open cockpit design is possible for a vehicle with the E/R knee bolster.

Figure 16 demonstrates the seatbelt interlock option. Recall that under this option the E/R knee bolster would be automatically extended in the case of an unbelted occupant when the passenger door is closed and the vehicle is placed in gear. Since a collision is not imminent, the E/R knee bolster could extend at a rate slower than in the pre-crash sensor activated option. Opening of the passenger door, buckling of the seatbelt, or shifting the vehicle gear into park would cause the E/R knee bolster to automatically retract. If a passenger is not present, the knee bolster would remain stowed in its far forward location. A visual sign is exposed on the upper surface of the knee bolster instructing the occupant to buckle up in order to retract the knee bolster (see Figs. 16 and 17). This demonstrates that the seatbelt interlock option could also be implemented as a seatbelt use reminder, as suggested previously, through rewarding a belted occupant with more legroom and a more spacious interior.

Another important characteristic of the E/R knee bolster is demonstrated in Fig. 18 in which the extending motion of the knee bolster was stopped by an out-of-position occupant. To achieve the “non-intrusiveness” requirement demanded of a crash preparation feature like the E/R knee bolster, a relatively low emergency stop load-limit of 70 N was built into the motor control logic. With this low load limit, the deployment of the E/R knee bolster is benign to an out-of-position occupant. It is also worth mentioning that although in this scenario of knee contact during deployment the knee bolster can fail to deploy to its design position, its patented self-locking mechanism will still be fully operative. Should an impact event actually occur, it can then lock and stroke to absorb the crash energy, and eventually stop the knee motion relative to the vehicle to ride down the remaining kinetic energy of the occupant.

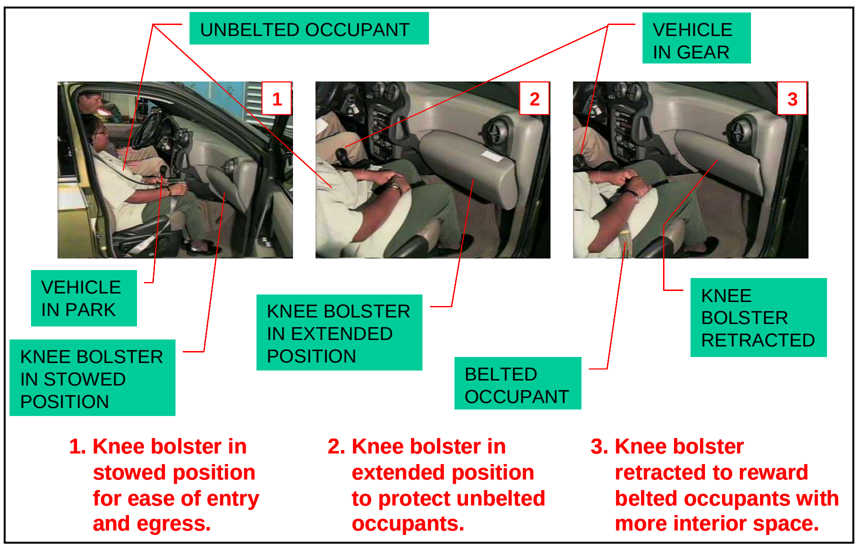


Figure 16. Demonstration of the seatbelt interlock option.

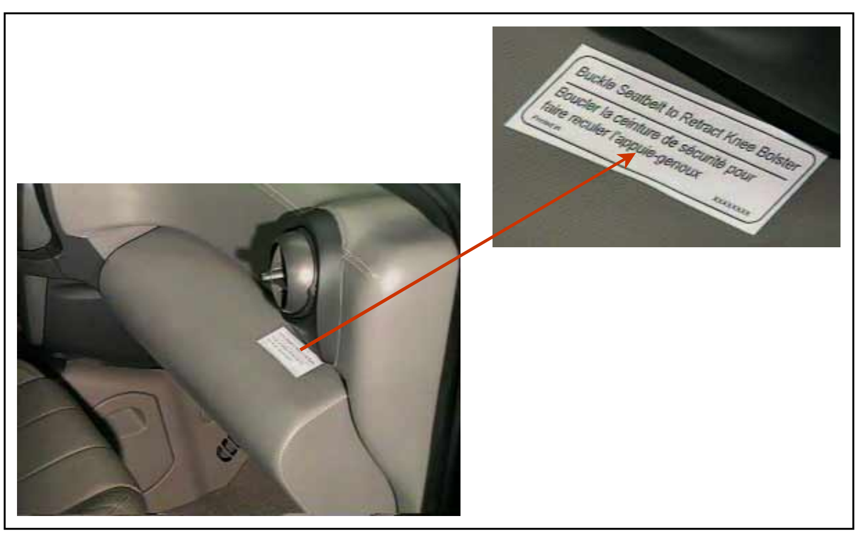


Figure 17. Instruction label displayed upon the extension of E/R knee bolster.

Figure 18. Demonstration of knee bolster stopped by an out-of-position occupant.

SUMMARY

The concept of an extendable and retractable knee bolster is presented. The E/R knee bolster is powered by an electrical motor drive. It is intended to automatically extend in an at-risk situation of frontal impact to help prepare the vehicle for a subsequent crash and retract when risk subsides. A key enabling technology of the E/R knee bolster is a patented self-locking and energy absorption mechanism. This mechanism is only responsive to impacts on the front surface of the knee bolster and not to the normal operation of the extension and retraction actions of its electrical motor drive. An impact on the front surface of the knee bolster will activate the self-locking function, independent of the position of the knee bolster, and then the device will stroke to absorb crash energy when the load exceeds a predetermined limit. A mechanics model was used to analytically estimate the locking force. There are many ways to implement the E/R knee bolster to enable different interior styling designs and additional utilities in passenger vehicles. For demonstration purposes we have narrowed down the list to three implementation options: (1.) if the E/R knee bolster is activated by a mid-range pre-crash sensing system, it could be implemented as either an occupant protection enhancer or an open cockpit enabler, depending upon the installation position of the E/R knee bolster; (2.) when it is activated by seatbelt usage signals, it could be implemented as an open cockpit design enabler and/or a seat belt use reminder; and (3.) when it is activated by a push button on demand, it could be implemented to meet the individual needs of styling and/or safety conscious customers. These implementation options are not mutually exclusive and could be employed either individually or in any combination for a particular vehicle application. A prototype has been built and integrated into a vehicle to demonstrate the unique interior styling designs and additional utilities enabled by the E/R knee bolster.

CONCLUSIONS

A prototype extendable and retractable knee bolster has been successfully developed and demonstrated in a passenger vehicle. The demonstration shows that this technology could provide many benefits, including enhanced occupant protection, enhanced ease of entry and egress, greater interior spaciousness, and in general more flexibility in the design of the vehicle interior. It also demonstrates that the E/R knee bolster could be implemented as a seatbelt use reminder to increase the seatbelt utilization rate. However, the reader should recognize that further developments to address all safety requirements, including real-world crash events, are necessary before implementing this feature in a production vehicle. No attempt was made to assess manufacturability, mass implications, market interest, or the availability of reliable mid-range pre-crash sensors.

ACKNOWLEDGMENTS

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