AN EXTENDABLE AND RETRACTABLE BUMPER

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ABSTRACT

An extendable and retractable bumper (E/R bumper) is presented in this paper. The E/R bumper is intended to automatically extend in situations in which there is a high risk of frontal impact to prepare the vehicle for crash and retract when the risk subsides. A functional demonstration vehicle and two experimental vehicles were built with the E/R bumper. Analytical and nonlinear finite element models were used to aid in the design of these vehicles, and to predict their crash performance in full, offset and oblique impact tests. While the functional demonstration vehicle was used to study its control and operation sequences, the experimental vehicles were crashed in a 56*kph* rigid barrier impact test and a 64*kph* 40% Offset Deformable Barrier impact test. These crash tests, together with nonlinear finite element analysis, showed that the additional crush space realized by extending the bumper could reduce the severity of the crash pulse and the amount of structural intrusion to the vehicle compartment.

INTRODUCTION

The structures and interiors of modern motor vehicles are designed to prepare for a crash full time although crashes are relatively rare events. Full time readiness for a crash has imposed stringent restrictions on the styling, design and utility of motor vehicles. With the advancement in sensing technologies, a new class of safety features, called crash preparation features, has shown great potential in relieving the design restrictions. “Crash preparation” is the timely reconfiguration of a vehicle’s structure and interior to the crash-ready state before an imminent crash. If the threat of a crash subsides, the vehicle reverts to its normal driving state, i.e., a “less” crash-ready state. Crash preparation can offer the needed crash protection while allowing new styling, design and utility previously not possible due to the needs for crash protection.

A conceptual crash preparation feature, called the extendable and retractable knee bolster (E/R knee bolster), was previously presented in [1]. 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.

In this paper, another conceptual crash preparation feature, called extendable and retractable bumper (E/R bumper)[2], is presented. The E/R bumper is normally in the stowed position. When a high-risk of frontal impact crash is detected, the bumper extends to provide additional crush space. Recall that in a frontal impact crash accident, the kinetic energy of a motor vehicle is rapidly converted into work by plastic deformation of vehicle structures. During this energy conversion process, the vehicle is decelerated in a relatively short time and distance. The stopping distance, which is a function of the available crush space and the crush efficiency of the front-end of a vehicle, is a good crash severity indicator. For vehicles involved in similar crash impact conditions, elementary physics ensures that those with less crush space and lower crush efficiency will have shorter stopping distances, higher average deceleration, and hence, more severe crash outcomes.

As motor vehicles have become more compact to meet the ever-stringent fuel efficiency requirements, the available crush space of motor vehicles has been involuntarily reduced. The E/R bumper is the only known safety feature that could provide the desired crush space only when a need appears. The additional crush space would allow the extended bumper structure to absorb additional crash energy to reduce the severity of the crash. The bumper automatically retracts when the risk subsides. In this paper the proof of concept of the E/R bumper and its potential benefits are discussed in detail.

MAIN ENABLING COMPONENTS

The E/R Bumper consists of a pre-crash sensing system, a pair of actuator, self-locking mechanism and energy absorption element assemblies, and a bumper and its fascia. Of these, the main enabling components are presented in what follows.

Pre-Crash Sensing System

The extension of the E/R bumper is designed to be automatically triggered by a detect signal from a 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 bumper. Figure 1 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 impractical high power actuators and energy sources.

To provide a reasonable actuation time budget, we selected a sensor system with a range between the short and long ranges. Specifically, from Fig. 1, we selected a sensor with a range of 20*m*, which could provide more than 500*msec* for an actuation time budget before a collision, if the closing rate is equal to or lower than 144*kph*, for the E/R bumper. In the event of a false detect or a crash that was not sufficiently severe so as to damage the bumper system, retraction of the E/R bumper could be programmed for an even slower rate.

Other vehicle sensors could also be used to extend the E/R bumper in select high collision risk scenarios in which detection may have not yet been registered by the pre-crash sensor. Among these could be the activation of the ABS braking system, operation at a speed in excess of a preset limit such as 128*kph*, or the manual selection of a precautionary mode by the vehicle driver.

Actuators

To extend and retract the bumper, reversible actuators are required for the E/R bumper. A wide range of reversible actuators, including electrical motors, solenoids, pneumatic cylinders, etc., could be used. 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 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 bumper, because of their low cost.

Energy Absorption Elements

There are many different means[3] that can be used for energy absorption applications. Of these, the crushing structure tube was selected for the E/R bumper due to its high energy density. The required force to crush a tube can be estimated with the following empirical equation:

$$F_{tube} = 2\sigma_{ut}\left(\frac{4t}{d}\right)^{1.7}\left(\frac{\pi d^2}{4}\right) \quad (1).$$

where σ_{ut} is the ultimate strength of the tube material, t is the thickness of the tube wall, and d is the diameter of the tube.

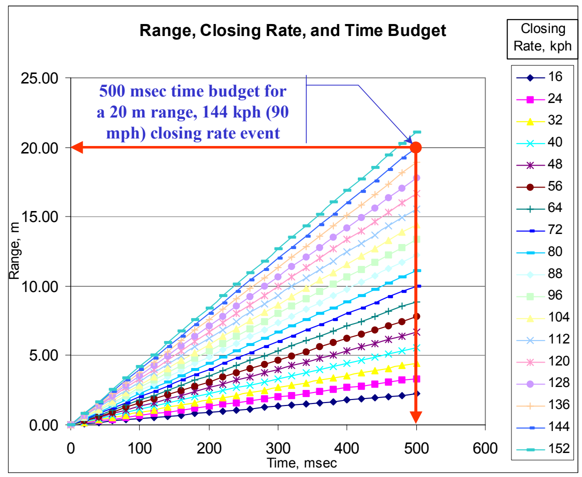
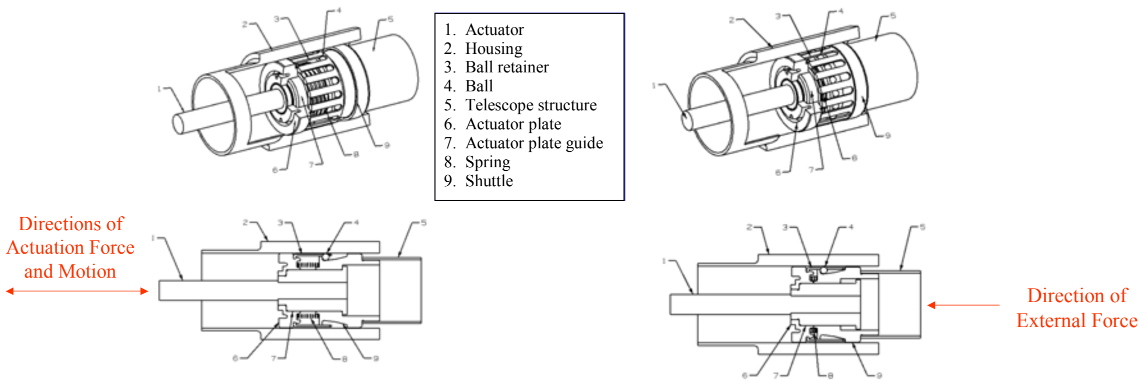


Figure 1. Relationship of range, closing rate and actuation time budget.

Self-Locking Mechanism

A mechanism that can provide self-locking functions is desired for the E/R bumper. This mechanism needs to be responsive only to impacts on the front surface of the bumper, and not to the normal operation of the extension and retraction actions of its actuator. An impact on the front surface of the bumper must activate the self-locking function of the mechanism and then allow the unit to withhold the violent impact force. Another desired function of the mechanism is that it must be able to self-lock the bumper at any position and at any time to provide resistant force in instances in which there is an incomplete actuation before an impact. A patented self-locking telescoping mechanism[2,4], which possesses all these functions, was chosen for the E/R bumper.



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

Figure 2. Three operation modes of the self-locking telescoping mechanism.

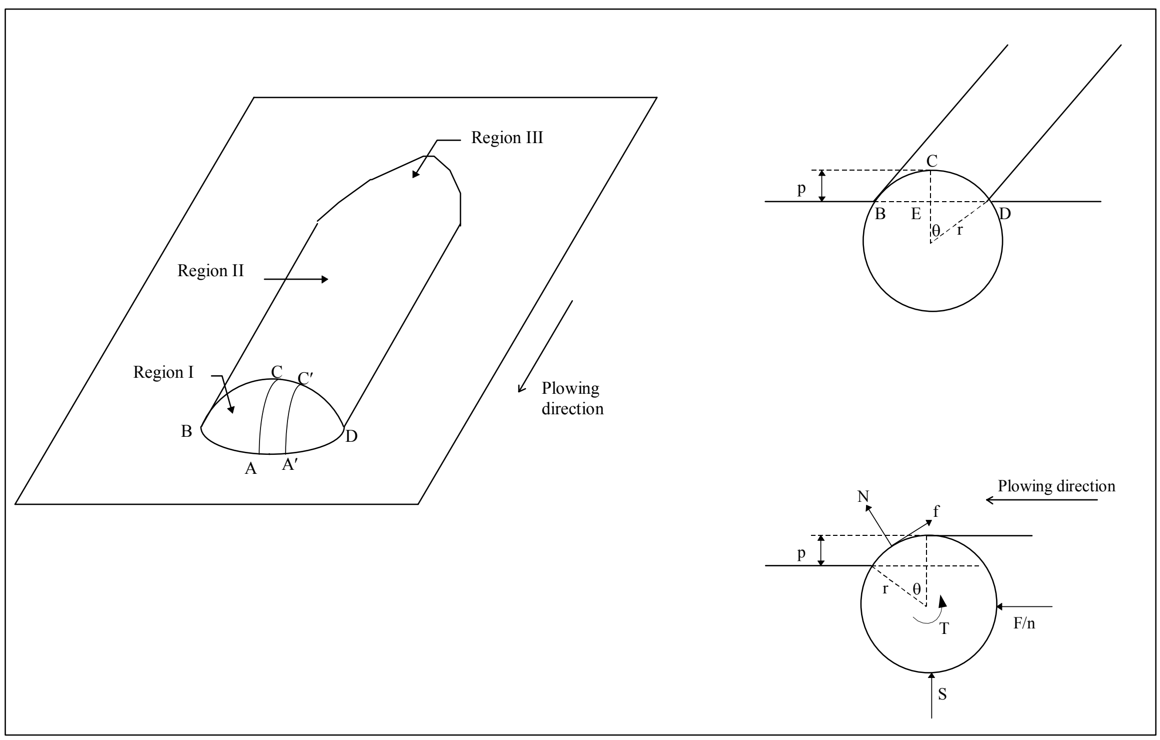


Figure 3. The mechanics model for estimating the locking force.

As shown in Fig. 2, the 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 bumper at the outboard end, and a plurality of metal balls between the cone-shaped ramp and the outer tube. 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 self-locking 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 bumper, 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. A previously developed mechanics model [1] could be used to analytically estimate the locking force. As shown in Fig. 3, a balance of internal work and external work of all the balls gives the following relationship for the plowing force, i.e., the locking force, *F*,

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

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

$$g(\theta,\mu) = 1 - \frac{1}{\cos\frac{\theta}{2} + \frac{1}{\mu}\sin\frac{\theta}{2}} \qquad (3).$$

Self-locking mechanisms could be designed and built using Eqs. (2), and (3).

Subassembly of actuator, self-locking and EA mechanism

Figure 4 shows an assembly drawing of the self-locking telescoping mechanism with a motor drive and lead screw, and a tubular energy absorption element. Observe its a rather compact design, which will allow it be fitted inside of a mid-rail structure to save packaging space.

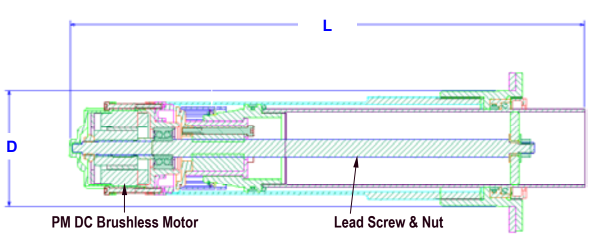


Figure 4. Assembly drawing of a self-locking telescoping mechanism with a motor and lead screw, and an EA element.

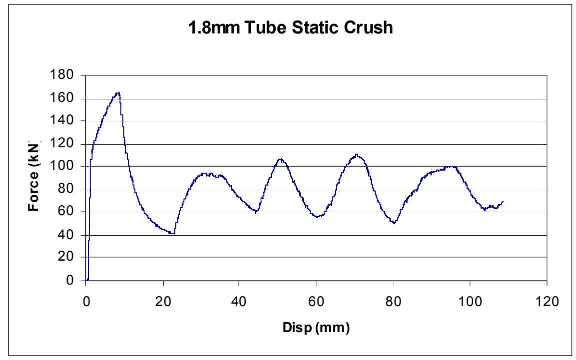


Figure 5. Drop tower test result of the energy absorption element.

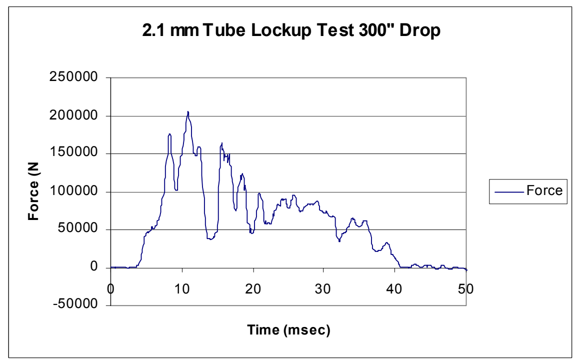


Figure 6. Drop tower test result of the self-locking telescoping mechanism.

DEMONSTRATION VEHICLE

Design Analysis

To demonstrate the extension, retraction and self-locking modes of the E/R bumper concept, a 2001 Aztek was chosen as the functional demonstration vehicle. An E/R bumper with two energy absorption elements, each with an 80*kN* crushing capacity and 100*mm* crushable length, was designed using Eq. (1) to provide a 10% additional energy absorption capacity to the 1800*kg* Aztek in a 48*kph* full barrier impact test.

A drop tower crush test was conducted to verify the design. Figure 5 shows that as intended the average crush force of the energy absorption element is indeed about 80*kN* each. The very same test also provided the minimal self-locking force requirement for the self-locking mechanism (observe the high peak force of 165*kN* required for initiating the crush).

Factoring in a safety margin, we have selected 250*kN* as the design locking force for the self-locking mechanism. Equations (2) and (3) were used in aiding the design of the self-locking mechanism. Another drop tower test was conducted to verify the design. The force versus time trace from the drop tower test is shown in Fig. 6. We see that the mechanism has successfully taken 200*kN* impact force punishment from the moving mass of the drop tower without any failure. Although the peak load of this test was 50*kN* lower than the self-locking mechanism's design load, 250*kN*, we chose not to repeat the test, since the result was within the safety margin of the design.

Figure 7. Main components of the E/R bumper assembly and their relative assembling relationship.

Figure 8. A partially assembled E/R bumper mounted at the end of the mid-rail.

Subassembly and Packaging

The preferred approach is to design the E/R bumper during the initial vehicle design so that they could be seamlessly integrated for aesthetics and optimal performance. For the modified Aztek, we took a less desirable add-on design approach due to obvious reasons. Figure 7 depicts the main components of the E/R bumper assembly and their relative assembling relationship. Notice that the energy absorption elements are in the extended position for viewing purposes. Figure 8 shows a partially assembled E/R bumper mounted at the end of the mid-rail (again the energy absorption elements are in their extended position for easy viewing). The actuator and self-locking mechanism units are not visible because they are packaged inside the mid-rail. Note that this mounting arrangement is only one of many possible mounting arrangements[5].

Figures 9 and 10 show the Aztek with a fully installed E/R bumper without and with the pre-crash sensing system, respectively. The sensing system consists of two 24-GHz radar sensors, which are packaged behind the front fascia of the vehicle. Note that the bumper fascia was removed for visual purpose.

Figure 9. The modified Aztek with a fully installed E/R bumper, but without the pre-crash sensing system.

Figure 10. The modified Aztek with a fully installed E/R bumper and the pre-crash sensing system.

Figure 11. The modified and unmodified Aztek.

(a) Retracted **(b) Extended**

Figure 12. Front-end changes enabled by the E/R bumper.

In Figure 11, observe the similarities between the unmodified Aztek on the right and a second Aztek on the left equipped with an E/R bumper. That is, when the E/R bumper is fully retracted, it appears identical to the bumper on the unmodified Aztek. Figure 12 contains photographs of the modified vehicle with the bumper in its fully retracted and fully extended positions.

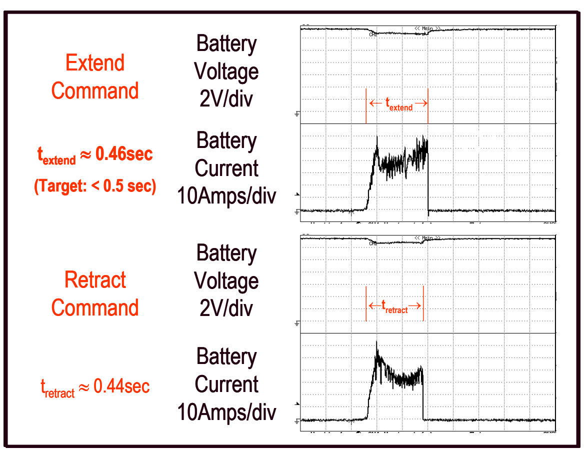


Figure 13. Measured voltages and currents of the E/R bumper.

Actuation Time Verification

Recall that the energy absorption elements of the E/R bumper for the Aztek demonstration were designed to provide 100*mm* extra crush, and that the actuation time budget is 500*msec*. To meet the 100*mm* crush requirement, the E/R bumper was actually designed with a 160*mm* extendable and retractable stroke. The additional stroke is required to accommodate the stacking of the crushed materials. The extension and retraction operations of the E/R bumper were verified using the demonstration Aztek. Figure 13 verifies that the E/R bumper can extend and retract within the 500*msec* actuation time budget.

EXPERIMENTALVEHICLES

To further study the feasibility and potential benefits of the E/R bumper, another E/R bumper prototype was designed and built using the same methods described in the above. It was designed for two identical experimental vehicles, namely A and B. Since these vehicles are lighter than the Aztek, their E/R bumper consists of two smaller energy absorption elements with 60*kN* crush capacity energy absorption elements with 120*mm* crushable length. These experimental vehicles were crashed in a 56*kph* rigid barrier NCAP test and a 64*kph* 40%, Offset Deformable Barrier (ODB) impact test, individually. Figures 14 and 15 show these vehicles with their bumper extended in the test cell before the tests.

Figure 14. NCAP test setup for the experimental vehicle A.

Figure 15. 64*kph* 40% ODB test setup for the experimental vehicle B.

NCAP Test Performance

Nonlinear finite element models were created to predict the crash performance of these experimental vehicles. Figures 16 and 17 depict the predicted crash sequence of the experimental vehicle A with the E/R bumper and its energy absorption elements during the first 30*msec* of the NCAP test event. The simulation predicts that the E/R bumper will be axially crushed as intended. The parts later extracted from the actual test, shown in Fig. 18, verified this prediction. The simulations further predict that adding the E/R bumper to experimental vehicle A has reduced the average deceleration of the vehicle by 9% (from 20.3*G* to 18.6*G*) and the toe-pan intrusion by 40*mm*. Figure 19 shows the comparison of the simulated vehicle velocity time history plots for the vehicle with and without the E/R bumper. Indeed, we see that the vehicle with the E/R bumper rendered a much softer crash pulse than without it.

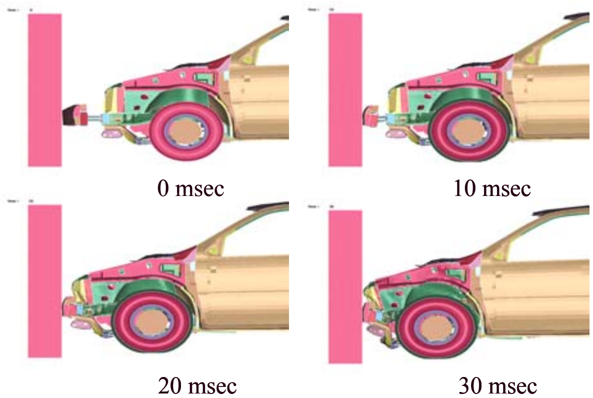


Figure 16. Simulation of the NCAP Test.

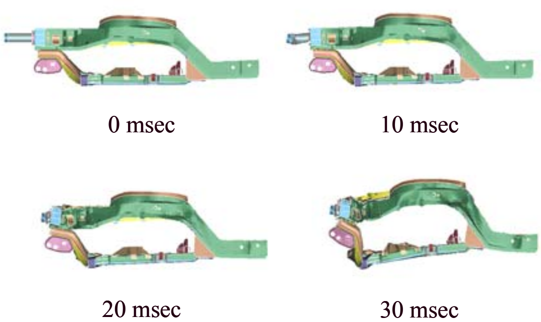


Figure 17. Simulated NCAP test: crush sequence of the energy absorption elements.

Figure 18. NCAP test: Axially crushed energy absorption elements.

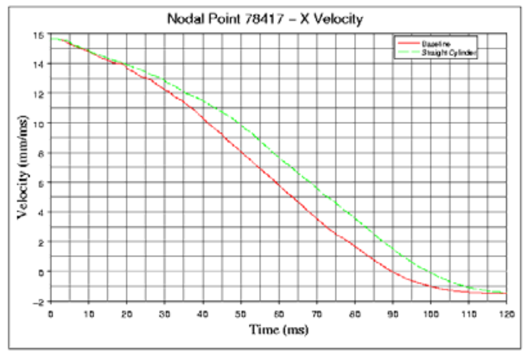


Figure 19. Comparison of the simulated vehicle velocity time history plots with and without the E/R bumper.

64*kph*, 40% ODB Test Performance

The simulation of the experimental vehicle B in a 64*kph* 40% Offset Deformable Barrier test is shown in Fig. 20. The simulation predicts that the offset barrier load will bend the bumper beam at near its 40% offset mark. This, in turn, causes the impact-side energy absorption element of the E/R bumper to buckle prematurely and the non-impact side energy absorption element to be pulled inward by the bending motion of the bumper beam. The parts extracted from the actual test, shown in Fig. 21, verified this prediction. Observe the similarity of the buckled energy absorption element from the test and simulation (see Fig. 22). The simulation also identified the main benefit of the E/R bumper for the ODB tests - the reduction in vehicle compartment intrusion. As shown in Fig. 23, toe-pan intrusion decreased by as much as 100*mm* for the vehicle with the E/R bumper.

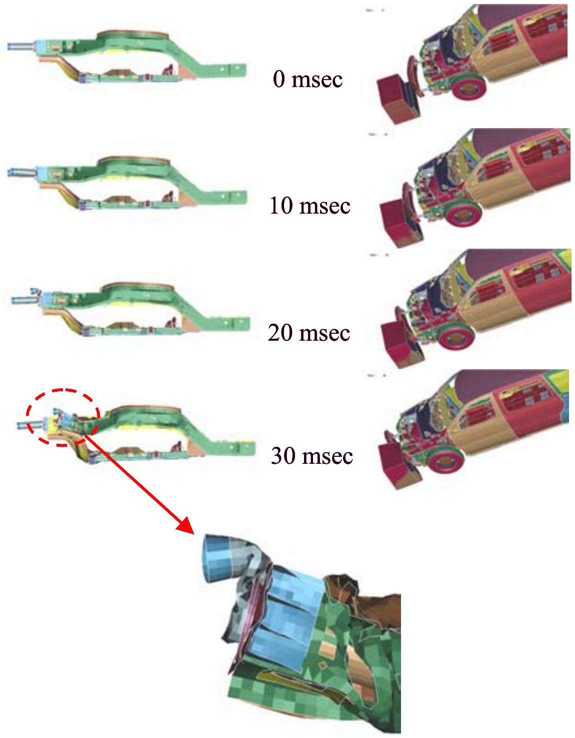


Figure 20. Simulation of the 64*kph* 40% ODB test.

Figure 21. 64*kph* 40% ODB test: Prematurely bent bumper beam and buckled/pulled energy absorption elements.

(a) Simulated **(b) Tested**

Figure 22. 64*kph* 40% ODB test: Comparison of buckled energy absorption element from the test and simulation.

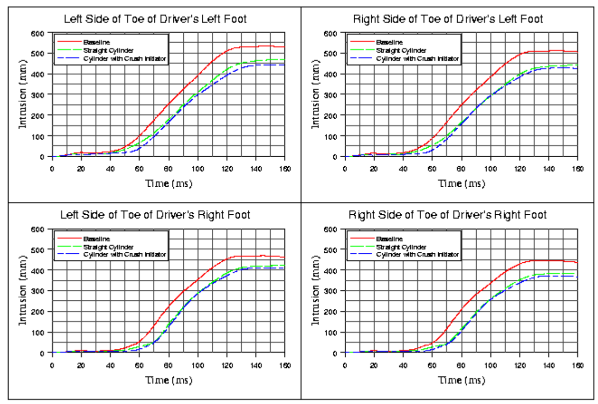


Figure 23. Simulated results of the 64*kph* 40% ODB test: Toe-pan intrusions.

48*kph* Oblique Rigid Barrier Impact Test

No physical test was planned for the 48*kph* 30^0 rigid barrier impact test. However, we used the experimental vehicle model to simulate this load case. The benefits identified from the simulation include: reduction of toe-pan intrusion by 50*mm*, yawing reduction of 145*mm*, and pitching reduction of 62*mm*.

CONCLUSIONS

A crash preparation feature, the extendable and retractable bumper, has been studied with analytical methods, nonlinear finite element analysis, experiments and demonstration vehicles. The study shows that the E/R bumper can provide additional crush space in an at-risk situation of frontal impact to prepare the vehicle for a subsequent crash and retract when that risk subsides. The study further shows that the additional crush space realized by extending the bumper can reduce the severity of the crash pulse and the amount of structural intrusion to the vehicle compartment. Other potential benefits of the E/R bumper include improving compatibility in car-to-truck crashes and enabling short, front overhang styling. However, no attempt was made to assess manufacturability, mass implications, market interest, or the reliability of the pre-crash sensing technology in this study. Further developments to address all safety requirements, including real-world crash events, are necessary before implementing this feature in a production vehicle.

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