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Side Impact Protection System—A Description of the Technical Solutions and the Statistical and Experimental Tools

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Abstract

It is a well-known fact that injuries in side impact collisions constitute a large percentage of the injuries suffered by occupants of passenger cars.

A substantial amount of research has been conducted at Volvo during the last ten years in order to understand the mechanisms behind injuries in side impacts and to be able to introduce effective countermeasures in our cars.

Different technical solutions used to upgrade the occupant protection of passenger cars in car-to-car side impacts are presented. Specific features were built into a conventional uni-bodied passenger car and as a second step, engineering principles of a Side Impact Protection System were integrated into a prototype vehicle. The rationale behind these changes is described.

In a recently developed methodology, data from Volvo's Traffic Accident Research Team was analysed with statistical methods in order to set requirement targets for the product development.

The method makes it possible to infer expected injury reduction in real accidents from dummy measurements in laboratory tests.

The concept cars were evaluated in tests with a moving deformable barrier. The SID-dummy was used as the anthropomorphic measuring device.

The results show that a reduction of measured injury criteria can be achieved by introducing body side structures with optimized energy absorbing characteristics in car-to-car impacts. With a tuning of the mechanical properties of the door, where occupant contact may occur, the results can be improved even further.

Introduction

Injuries in side impacts still constitute the second largest injury category in accident statistics after frontal impacts (1).* The evolutionary process of vehicle design, where priority has been given to low air resistance and low weight in combination with compartment roominess and comfort, has so far given us a car shape with deformation zones in the front and rear but with a rather limited amount of body structure to absorb energy in side impacts.

Numerous attempts have been made to reinforce the body or pad the interior of passenger cars in order to show experimentally that it is possible to mitigate the effects of a side impact. The conclusions from this research have been obtuse, partly because the injury mechanism has been complex and difficult to understand and partly because there has been a lack of good test methodology including dummy and injury criteria (2, 3, 4, 5).

Nevertheless, there is a common understanding today that structural reinforcement is needed to lower the velocity of the intruding side structure in car-to-car impacts, in order to create a basis on which an interior padding will work satisfactorily.

For side collisions with fixed, undeformable objects body stiffness and strength have less importance since the struck side will almost instantly be brought to a stop. Reasonable body characteristics are, however, required to ensure survival space after a collision. This is to some degree regulated in USA by FMVSS 214, where certain strength and stiffness requirements are imposed on the front doors.

However, interior padding is effective in smoothing out the contact phase between the occupant and the inside of the car.

This paper will give information on two successful research projects to improve the side impact crashworthiness of passenger cars.

The work has focused on the car-to-car crash configuration, since this is one of the most common injury producing types of accident and also a matter for a proposed legal requirement.

The authors of this paper are quite aware of the continuing controversy regarding the most suitable test methodology for side impacts. However, in order to bring forward feasible hardware solutions for consideration, and to expedite their incorporation in the ordinary passenger car, it has been necessary to choose one specific test method.

Technical Solutions

Improvements to a conventional uni-bodied car

Structure.—Neither the stiffness nor the strength of the side structure of uni-bodied cars have by tradition been optimized to take lateral forces under dynamic loading conditions. Door stiffness and strength were upgraded with the introduction of FMVSS 214 but this requirement only carries the deformation to a limited distance in a quasi-static test.

The objective was to come up with suggestions for required reinforcements or re-engineering of the body structure without causing severe penalties in terms of cost and increased weight.

A goal was set up to reduce the door intruding velocity at the time of dummy contact during dynamic loadings from a CCMC-barrier to <10 m/s in a 35 mph 90° side impact with the target car at rest. As a basis for the study, a midsize production car body was chosen.

The loading of a moving deformable barrier takes place over a large area of the impacted car and it is important to

*Numbers in parentheses designate references at end of paper.

find the weak spots of the body. Once a failure has developed, as the cross section in a box section is destroyed by buckling, the structure collapses and the door velocity will increase.

The main load paths in a side impact are through the rocker panel, the cross member under the seat, and bending of the B-pillar supported by the roof beams.

In order to enhance the stiffness and strength of the side structure, a mathematical analysis was carried out at Cranfield Impact Centre in accordance with their in-house methodology (6).

Different quasi-static deformation tests were made on important elements and joints in order to map the characteristics of the body and obtain in-put data for the model.

A number of model runs on different solutions were tried, in an iterative process. It is beyond the scope of this paper to describe this work in detail, but briefly the following elements and joints were studied:

- A-pillar with door-hinges.
- Rocker panel and joint to B-pillar.
- B-pillar and joint to roof frame.
- Roof panel and influence of sunroof.
- Cross-member in the floor under seat.

The analysis pointed out the importance of having a stable cross-section of the rocker panel while bending of the B-pillar occurred. Consequently, five bulkheads were designed which improve the crushing resistance of the box-sectioned rocker panel considerably (see figure 1). Although it would have been desirable to improve the joint between the rocker panel and the B-pillar, it was impossible to find a suitable solution for this specific body.

The B-pillar was reinforced with an additional inner part to improve its bending characteristics. The joint between the B-pillar and the roof frame was re-engineered to improve bending resistance.

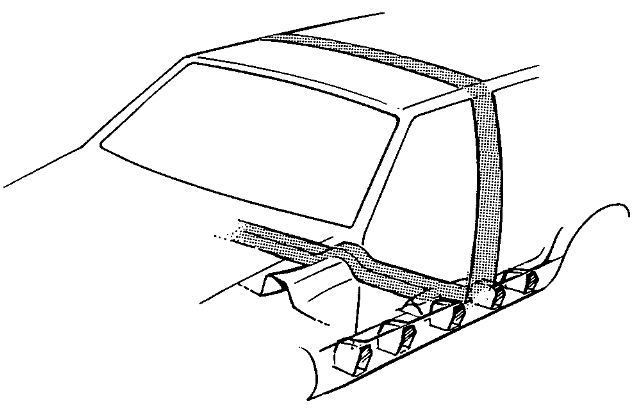

Figure 1. Improvements to a conventional uni-body. Shaded areas indicate reinforcements.

It was found that a roof with sun-roof had sufficient strength but that a specific roof strap (closed section, see figure 1) had to be fitted to cars without sun-roof. The cross-member between the rocker panel and the propeller shaft tunnel had a geometry which initiated a bending collapse, and by changing the shape and adding material the performance could be considerably improved.

The suggested changes resulted in a stiffer and stronger side structure with better possibilities to remain energy absorbing during deformation without creation of collapse joints. For more specific information see reference (6).

Interior.—The existing door panel made of formed wood fibre was not changed and no extra padding was used between the panel and the inner door skin. The panel will crush during impact and dummy loading.

Expanded and integrated improvements to a uni-bodied car

To further upgrade the side impact protection, a second project has been run. In this project, more extensive body changes were made and door panels with energy absorbing material was used.

The constraints were that the concept should be possible to apply on a modern 4/5-door midsize family car.

Overall system description.—In order to reduce the door intruding velocity the main principle has been to increase the lateral strength and stiffness of the car by using all the conventional elements such as the body, including the doors, the seats and the trim panels in a continuous load path.

In order to soften the occupant's contact with the door energy absorbing elements have been built into the doors between the inner door structure and the trim panel.

Structural elements.—In the very first phase of this project an in house lumped mass model was used to dimension the main load transferring structure.

The goal was to restrict the rate and depth of intrusion. As bullet vehicles, both a car and an MDB were analysed.

As a second step, a beam model was developed to enable a more detailed analysis. It was decided to try to avoid the initial peak and reduce the plateau of the velocity of the side frame and to keep the velocity at the time of occupant contact <10 m/s.

Important joints like B-pillar to upper roof rail have also been studied in finite element analysis.

In order to increase stiffness and strength at bumper height the body was equipped with a special concept which had been developed in several previous advanced engineering studies.

This concept consists of foam blocks inside the front doors and an enlarged lower joint of the B-pillar matching up with two thick-walled tubes in the front seats. Between the seats there is an energy absorbing box attached to the propeller shaft tunnel, (see figure 2).

The B-pillar has increased bending resistance and is supported at the lower level by substantial cross-members under the front and rear seat and also by the load transferring elements at bumper height.

At upper level the B-pillar is supported by an upgraded roof rail and a roof strap between the B-pillar (see figure 2).

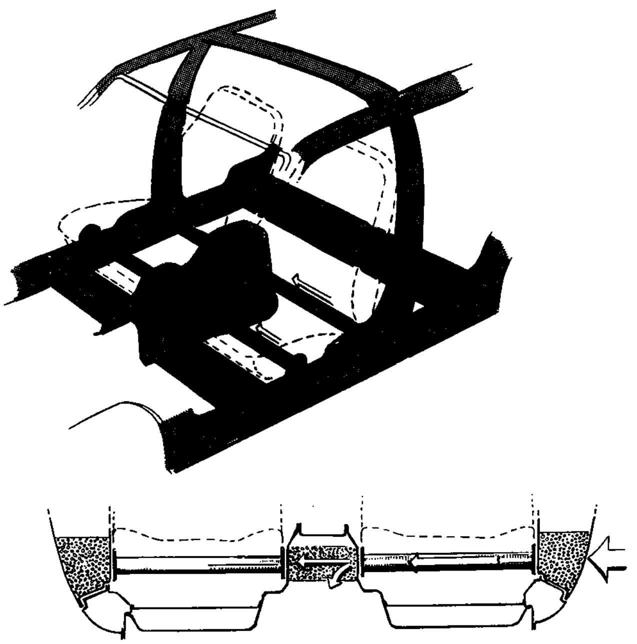

Figure 2. An integrated Side Impact Protection System. Shaded areas indicate load transferring elements. The arrows show major load paths.

All these elements have been carefully developed step by step both in mathematical analysis, component testing and full scale testing as mentioned above.

The guiding principle for crush energy management in this project has been the same as in the previous one. Special emphasis has been put on compatibility between structural elements and on prevention of failure buckling in the structure.

It is, for instance, critical that no bending collapse occurs in the B-pillar at chest height. The B-pillar, its upper and lower support and the door beams must therefore be carefully tuned in stiffness, strength and energy absorbing capacity.

The front doors have been specially engineered to carry an upper beam close to the outer panel enabling the inner panel to yield on occupant contact. The FMVSS 214 beam is placed at a low level where interaction with an occupant pelvis is avoided.

All hardware for operating windows and door locks has been omitted in the prototype. When incorporating these functions into a door it is essential that they are kept out of the way to avoid occupant contact.

Interior.—As mentioned earlier all clearances between doors, seats, and the tunnel box have been minimized, while still allowing space for seat adjustment.

The door panel has been designed to make room for a 100 mm thick layer of compliant tubes between the panel and the door at chest height. The doorpanel was flat with no armrest. At pelvic level the padding was 60 mm and consisted of thin-walled aluminum honeycomb.

The depth and characteristics of the padding have been developed in a mathematical model where the door and the padding interact with the US-SID dummy. The input door velocity profile has been taken from full-scale testing.

The critical points in such a simulation are the mechanical properties of the door during the dynamic crushing of the car.

In order to test a number of canditative materials and elements, quasi-static tests were performed. As the final step before full-scale testing, the chosen door padding was tested by impacting the dummy at rest with a moving barrier carrying the door panel with the underlying padding mounted on a support resembling the crushed door.

For the chest padding, a progressive (constant stiffness) characteristic was chosen to give protection in lower speeds and for the weaker portion of population. For the pelvis a square-wave characteristic was chosen.

Statistical and Experimental Methodologies

In order to test the two prototypes, and to try to assess the achieved level of safety, the following methodology has been used.

Procedure for evaluating occupant protection

As a first step in the research, a procedure for predicting the real-world effectiveness of different design approaches for side impact occupant protection was established (7). The method is summarized below.

The point of the procedure is the evaluation of real-world occupant protection over the whole range of crash severities where injuries occur, in contrast to the traditional single severity test.

By correlating real-world side impact accident data with laboratory test data for the same baseline design in equivalent crash configurations, it has been possible to develop chest and pelvis injury probability functions associated with dummy response amplitudes (see figure 3) where

$P(I|x)$ = injury risk (e.g. chest injuries AIS 3+) vs crash severity function obtained from real-world accident data,

$d(x)$ = dummy response vs crash severity function obtained from laboratory testing at different test speeds, and

$P(I|d)$ = injury risk vs dummy response function obtained by correlating $P(I|x)$ with $d(x)$.

The baseline car used for developing $P(I|d)$ was the Volvo 240. Provided that dummy response is measured by a parameter that fundamentally relates to the injury-producing mechanism, a given dummy response should correspond to the same injury risk, irrespective of in which car this response is measured. This means that the established injury risk vs dummy response function $P(I|d)$ can be generally used for predicting the real-world injury risks in any car design that is tested in the laboratory—provided that the test procedure is kept the same.

The injury risk vs dummy response function $P(I|d)$ can be employed in two ways: (1) for direct evaluation of a modified design, (2) for establishing a set of dummy re-

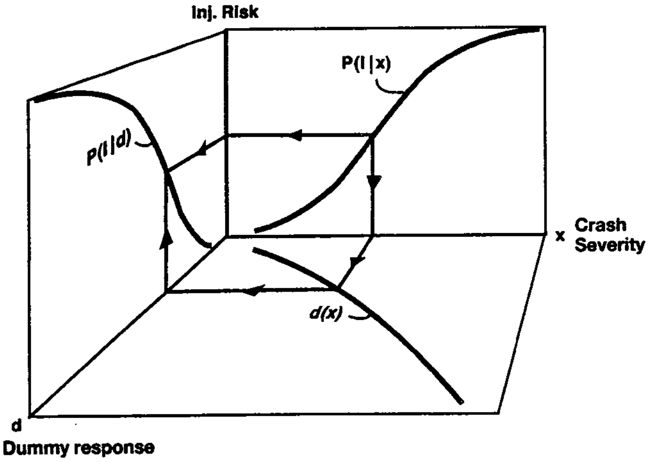

Figure 3. Converting injury risk versus crash severity P(I|x) into injury risk versus dummy response P(I | d).

sponse reference curves that can be used as a guide in the design and evaluation process.

(1) *Direct evaluation of a modified design:*

Obtain the dummy response vs crash severity function d′(x) for the modified design by running crash tests at several different test speeds and use d′(x) for converting P(I | d) into a predicted real-world injury risk vs crash severity function P′(I | x) for the modified design (see figure 4).

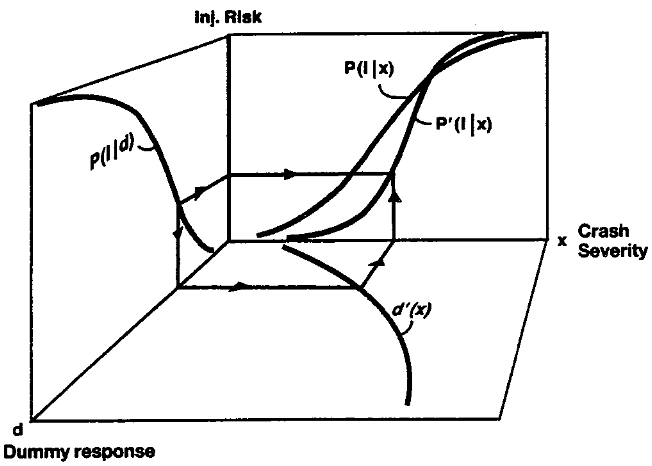

Figure 4. Converting injury risk versus dummy response P(I | d) into injury risk versus crash severity P′(I | x).

When the crash severity distribution for real-world side impacts is known, the overall injury risk P′(I), averaged over all crash severities, for the modified design can then be estimated by integrating the specific injury risk P′(I | x) over the range of crash severities and using the crash severity density at each crash severity level as a weight function.

The effectiveness of the modified design is the relative difference between the (known) overall injury risk P(I) for the baseline design and the predicted overall risk P′(I) for the modified design.

(2) *Establishing a set of dummy response reference curves:*

In this case, a set of conceivable injury probability vs crash severity functions P′(I | x) are obtained by shifting the baseline risk curve to the right. Corresponding overall injury risk reductions are calculated as above, using the known crash severity function as a weight function.

The established injury risk vs dummy response function P(I | d) is then used for converting the attempted set of real-world risk functions P′(I | x) into a set of dummy response reference curves d′(x), corresponding to different degrees of overall real-world injury risk reduction, as described in figure 5.

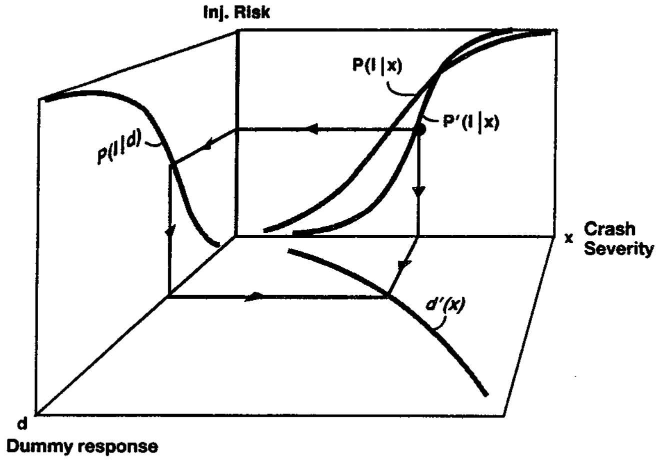

Figure 5. Converting a desired injury risk versus crash severity function. P′(I | x) into a desired maximum dummy response versus crash severity curve d′(x).

By comparing dummy response amplitudes for a modified design with the established set of response reference curves d′(x), the overall real-world injury risk reduction for the given modified design can be approximately estimated by running laboratory tests at only a few different test speeds, provided that the test data variability is known.

In the side impact testing and development work currently in progress at Volvo, the latter evaluation strategy is employed, i.e., a set of dummy response reference curves has been developed that can be used as a guide when estimating the overall effectiveness of a modified design.

To be able to evaluate the overall effectiveness of the specific side impact protection projects described in this paper, crash tests will need to be run at different test speeds over the range of crash severities where injuries occur. This is to ensure good occupant protection even at the relatively more frequent, and thus very important, low crash severities.

The final product of these elaborations will be a diagram as shown in figures 6 and 7. From this diagram it is possible to approximately assess the overall injury reducing effect of a countermeasure by plotting the test data at different speeds.

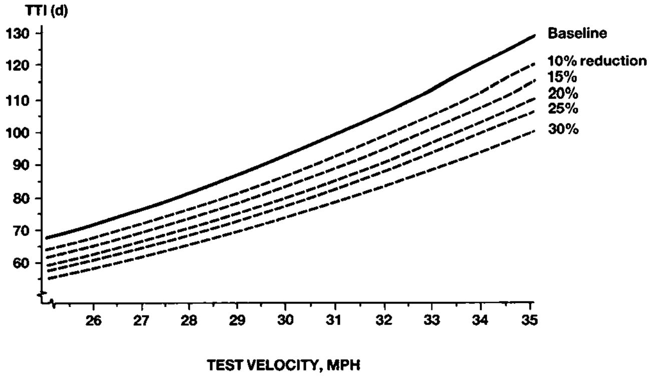

Figure 6. Baseline data TTI(d) and a set of curves for different injury reduction.

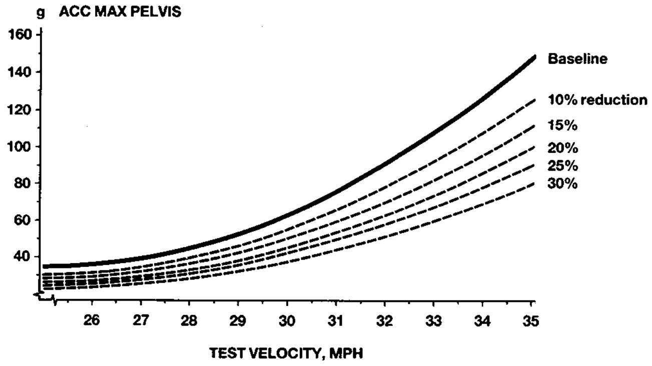

Figure 7. Baseline data for pelvis and a set of curves for different injury reduction.

To get an exact figure for the expected overall injury reducing effect the computations as described in (1) have to be performed.

Laboratory experiments

As mentioned earlier, in-depth studies of side-impact accidents have been conducted by our accident research team. This knowledge is used to develop a laboratory procedure for side-impact testing. In this study the car-to-car accidents have been focused, although other areas also need to be considered in the future, i.e. fixed objects and collisions with heavy vehicles.

The full-scale performance test using a moving deformable barrier, and a side impact ATD and corresponding injury criteria have been used to assess the level of crash safety.

Test configuration

Today, proposals from European and U.S. governments differ in terms of the approach for the barrier impact angle. The U.S. proposal (8) uses a "crabbed" configuration, 90/27 degrees, simulating an event where the struck and the striking vehicle are moving. The European configuration is a 90 degree impact with the target car at rest.

Although the crabbed configuration might be a more frequent situation in the real traffic environment, the differences in test results between the two methods are considered of minor significance. Because the "crabbed" impact is considered less repeatable, the 90 degree impact has been chosen in our test matrix.

Striking object barrier

Since the preference in this examination was to study the car-to-car impact, a moving deformable barrier (MDB) was used as the striking vehicle. This increases the repeatability compared with results obtained with a car as a bullet. Several barriers have been proposed over the years and the force-deflection characteristics differ significantly.

At present the CCMC and the EEVC MDBs are based on European cars. They present similar characteristics up to approximately 200 mm of deformation. For higher deformation, the EEVC barrier is softer while the CCMC barrier corresponds well with a Chevrolet Citation up to approximately 300 mm.

The aluminum honeycomb NHTSA barrier is much stiffer and does not represent the characteristics for most passenger cars.

Compared with the present car fleet, the CCMC barrier is the closest with respect to force characteristics, and it was chosen as the MDB in this study. The ground clearance was set to 250 mm.

Test speed

Our accident data shows that 90% of all side impacts (irrespective of injury outcome) occur at impact speeds below 35 mph. Because of this, and since approximately half of the severe to fatal injuries are incurred below this speed, 35 mph was chosen as an appropriate single severity test speed for preliminary testing.

It must be emphasized again, that in order to assure that the safety design gives the desired level of protection over the whole velocity span, the final development testing must also be made at other speeds, especially in speeds lower than 35 mph.

Anthropomorphic test device (ATD)

Today, there are basically two side impact dummies; the European Euro-SID and the American US-SID.

Both dummies have been subjected to various body and component testing to assess their biofidelity. This has been done by using the procedure recommended by ISO.

The results from these tests have shown that neither the Euro-SID nor the US-SID met these requirements. Although some projects have been undertaken to improve the biofidelity of these dummies, there is as yet no modified dummy that meets the ISO requirements.

The US-SID has been used for several years, and therefore the experience with it is greater than with the Euro-SID. The US-SID has also proved to be repeatable and able to discriminate between different levels of violence. It was therefore chosen to be used in this project.

Injury criteria

Based on the frequencies and severity of injuries obtained from our accident files, two body areas were chosen to be specially monitored in this study. These are the chest and the pelvis.

For the chest, the Thoracic Trauma Index (TTI(d)) was chosen as the criterion for chest injury. The TTI(d), proposed by NHTSA as injury predictor, is calculated from accelerations measured on the spine and the ribs on the impact side (8).

For the pelvis, peak acceleration was chosen.

Test Results

Test results—reinforced uni-body

As mentioned earlier, a number of tests with a deformable barrier were made until a satisfactory result was achieved.

Structural results.—In terms of permanent deformation, the reinforced car proved to be less deformed, (see figure 8).

The difference between the reinforced and the standard car, measured at the B-pillar, was approximately 100 mm.

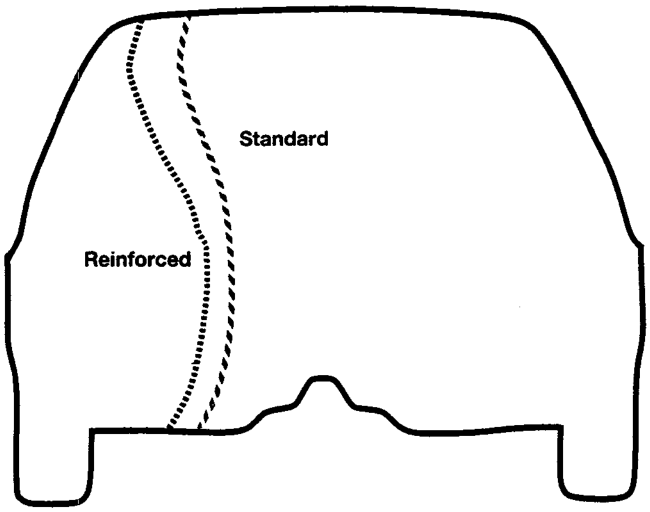

Figure 8. Permanent deformation at the B-pillar.

The door velocity profile was also lower than for the standard car (see figures 9 and 10). Somewhat disappointing, however, was the fact that the decrease in wall velocity at the moment of dummy contact was not as significant as first expected, but the velocity showed much more consistent behaviour during the first 25 msec when dummy contact is probable.

A positive effect of this is less sensitivity to the effect of distance between the occupant and the door.

Dummy results

Chest.—The TTI(d) at 35 mph was 98 compared to 115 for the standard car. It should be noted that crushing of the door panel occurred and although the padding characteristics of the panel were not optimized, it is understood that it contributes significantly to the results.

Pelvis.—The pelvis maximum acceleration was 100 g for both the standard and reinforced car. No effect was measurable at pelvic level.

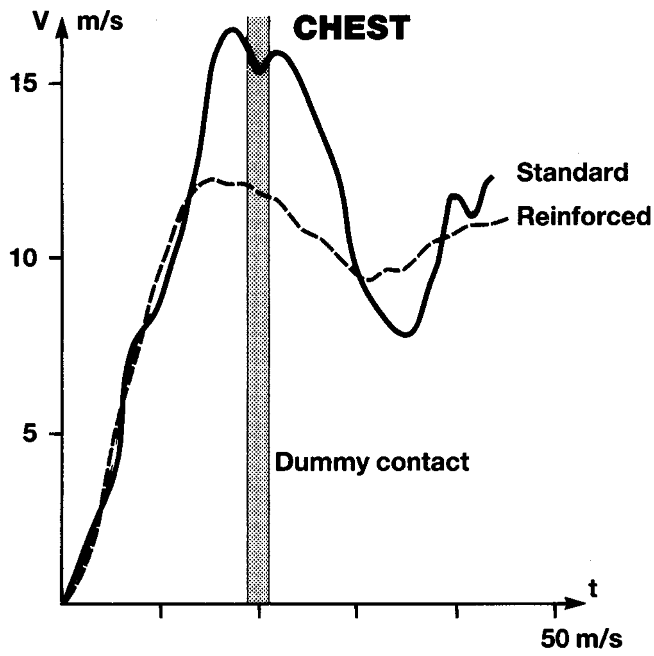

Figure 9. Door velocity time history at chest height.

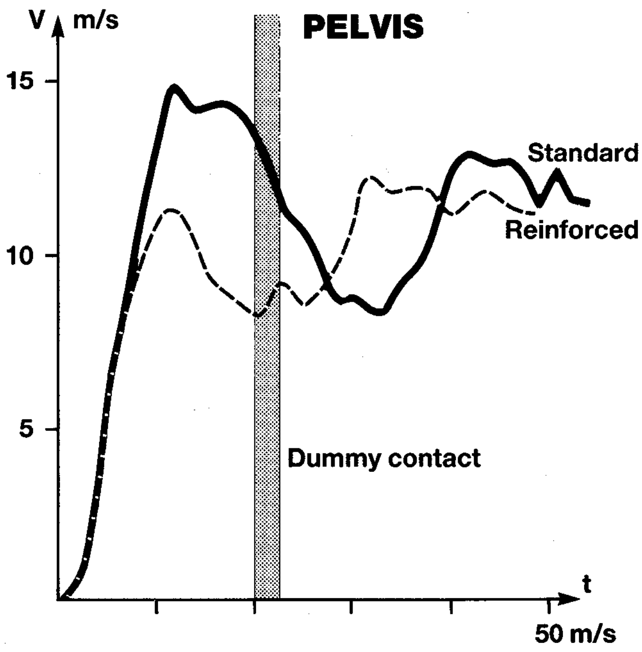

Figure 10. Door velocity time history at pelvis height.

Test results—body with integrated side impact protection system

Test with final prototype—structural results.—The permanent deformation of the body is depicted in figure 11 in comparison to the standard car.

The tubes in the front seats limit the deformation and ensure that sufficient survival space is available after the collision.

The door velocity time history is shown in figures 12 and 13 for the chest and the pelvis height.

It has been found from mathematical simulation of the interaction between the door and the dummy that the most

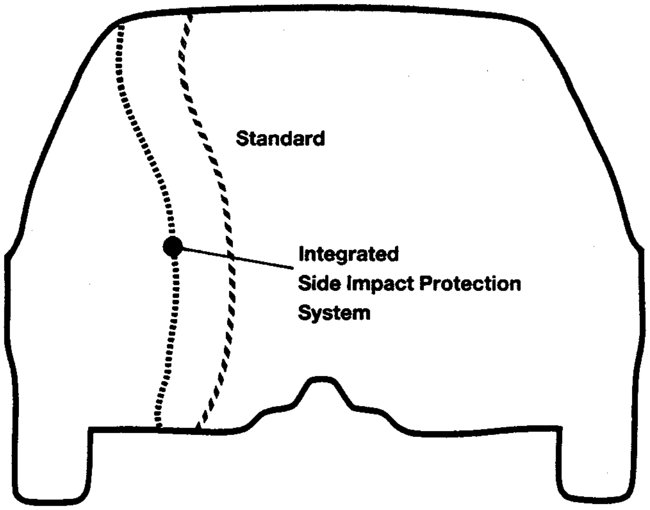

Figure 11. Permanent deformation at the B-pillar.

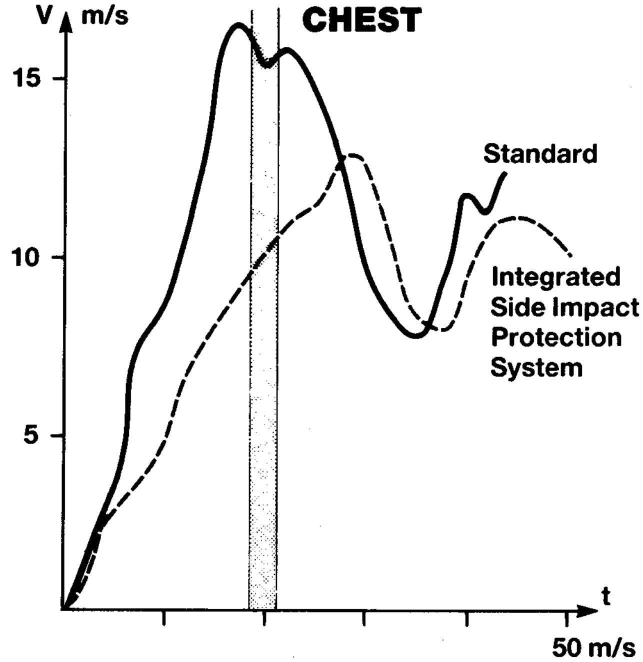

Figure 12. Wall velocity time history at chest height.

important parameter to reduce chest response is the door mean velocity during dummy contact. In the test with the prototype this mean velocity at chest height was 11 m/s.

Compared to tests with other cars this concept has shown a very repeatable door velocity time history throughout the project.

Dummy results

Chest.—The TTI(d) was 80 compared to 115 for the standard car. The constant stiffness characteristic of the panel generates a peak of 65 g on the ribs. The spinal acceleration reaches its maximum of 95 g later in the phase when the door and the padding is more or less bottomed out.

Pelvis.—The maximum pelvis acceleration was 90 g compared with 100 g for the standard car. The constant strength characteristic of the padding limits the peak acceleration.

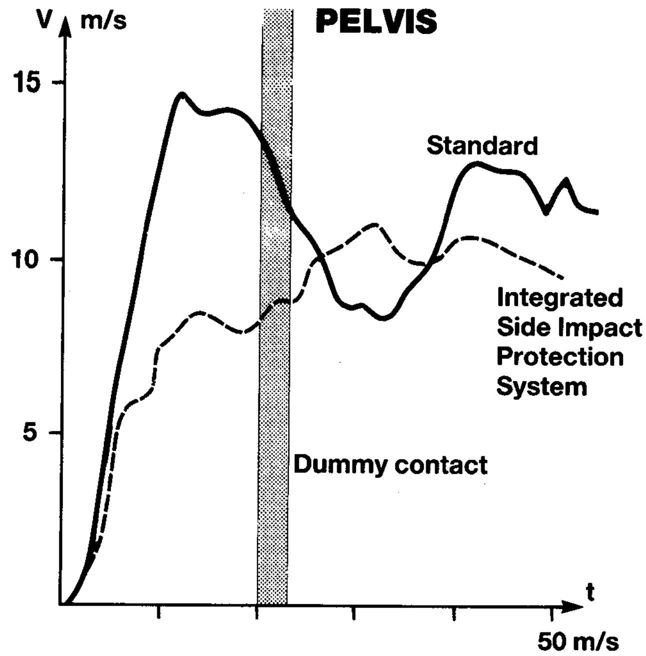

Figure 13. Wall velocity time history at pelvis height.

Discussion

Following the methodology described earlier in this paper, the single test speed results with the standard car and the two prototypes indicate the following reductions of severe to fatal injuries in chest and pelvis in car-to-car impacts (see figures 6 and 7). In relation to the baseline data, TTI(d) for the standard uni-bodied car suggests a ~15% reduction, the reinforced uni-bodied car a ~30% reduction and the uni-bodied car with the integrated side impact protection system a reduction in the region of 50%.

For the pelvis, the reduction was ~20% for the standard and the reinforced uni-bodied car. Consequently, no further improvement was seen in the pelvis region with the added reinforcements. In the car with the integrated side impact protection system the reduction was ~25% compared with baseline data.

However, it is necessary to continue the testing at other velocities and make repeated tests to assess the scatter before any final inference about the overall injury reduction can be made.

For the prototype with the integrated system, the detailed analysis of the test results from component and full-scale testing has given many important findings.

Interaction between the chassis of the seat and the metallic pelvis and spine skeleton may occur and create high peaks in accelerometer readings and by-pass the loading on the door padding. Stiff components in the door may cause localized loading on the dummy which may result in high injury criteria. The profile of the door panel will govern the deflection kinematics of the SID-chest. The existence of an armrest which catches the lower ribs will cause large variations in dummy readings, other parameters being held constant.

The conflict between roominess and the desire to use a deeper door padding became very obvious in this project. Unless future consumers are willing to sacrifice some of the interior space, the only solution seems to be to make the padding expand when an impact occurs. This could be made, for instance, with a side airbag (12, 13).

It is also possible that the introduction of a new side impact dummy with better biofidelity will make it necessary to re-tune the padding force deflection characteristics of the door panel.

Conclusions

In this project, it has been shown that a significant reduction of chest response [TTI(d)] can be achieved by careful engineering and reinforcement of a conventional uni-bodied car. Studies of the production feasibility of the changes are underway.

The prototype where structural and interior improvements are combined in an integrated, expanded solution improved the results even further and this suggests that a reduction of up to 50% for the chest and 25% for the pelvis of severe to fatal injuries in car-to-car impacts is a realistic goal. Further testing with an MDB at different impact velocities and with bullet cars with bumpers must be done before final conclusions can be made.

The conflict between compartment roominess and keeping the vehicle cross area small, and still being able to add sufficient depth of energy absorbing door padding, is obvious.

Ongoing research and innovations in this area, however, seem promising.

Redesign of the car door as a concept or the fitting of a side airbag could perhaps be solutions to this problem.

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Air Bag System for Side Impact Protection

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Abstract

It is difficult to install side impact padding of sufficient depth, due to the limited space inside conventional automobiles. A different approach is to use the air bag technique to provide sufficient energy absorption and softening of the occupant door impact.

Presented is an air bag system for side impact protection jointly developed by Volvo Car Corporation and Electrolux Autoliv AB.

The system uses pyrotechnical gasgenerators to deploy a side air bag hidden within the door structure.

A description of the function of the system is given to-