THORACIC IMPACT AND INJURY IN SIDE IMPACT ACCIDENTS

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ABSTRACT

The Transport and Road Research Laboratory has carried out a large number of side impact tests in order to gain a better understanding of side impact injury mechanisms and as part of a programme to develop the European test procedure. Some comparison tests have also been made using the barrier proposed for the US test procedure. In parallel with these tests, a series of quasi-static crush tests has been carried out using one of the types of car studied in the full scale test series. A suite of computer simulation programs has also been developed which is being upgraded in the light of the test results.

In the analysis of the experimental data, the effects of vehicle size, structural characteristics and door padding have been studied, along with the effects of different bullet vehicle characteristics. Some of the results have revealed misconceptions in some commonly held ideas, demonstrating the complexity of the side impact problem. In particular, it appears that the overall probability of injury is directly related neither to overall structural stiffness nor to the final extent of intrusion. Much more important is the way in which the stiffnesses of different parts of the side structure relate to one another.

In both the experimental tests and the computer simulations a number of different injury criteria have been compared. The results suggest that multiple performance criteria may well give a better prediction of injury to the thorax. The analyses indicate that thoracic loading may be influenced by pelvic motion but the extent of this has not yet been quantified sufficiently to relate to human performance.

1.INTRODUCTION

For some years, TRRL has been carrying out research on side impact accidents in order to gain a better understanding of the mechanisms of injury and so be able to draw up guidelines for improvements to car design. Such research is an essential part of formulating an effective side impact test procedure. The programme of research has also involved the joint development of the EUROSID anthropometric dummy along with its instrumentation (1) and the EEVC Mobile Deformable Barrier (MDB) face (2). Much of the research has to be based on full scale impact tests.

In parallel with these tests, a suite of computer simulation programs have been written (3,4) which attempt to model the thorax and pelvis of a EUROSID dummy seated in a car which is impacted by such objects as the EEVC MDB face or a typical car front. In conjunction with the impact testing these programs have helped to provide understanding of the dynamic interactions which occur in accidents. However, comparison of the simulation output with test data has revealed some deficiencies due to the programs being based on oversimplified concepts. More sophisticated programs are currently under development which use data obtained from quasi-static crush tests on a small car.

Because of their frequency in side impacts, injuries to the thorax are emphasised in this paper. In the research programme, other parts of the human body are also being studied.

Analysis of the output from this research has cast doubt on a number of the currently accepted ideas about the behaviour of cars and how their occupants are injured in side impacts. It is important that the factors influencing injury are understood and taken into account to ensure that the test procedure leads to the design of safer cars, rather than cars which simply pass the test.

This paper outlines the present state of the TRRL test programme, and describes some of the factors which appear to be important. It concludes by describing our current understanding of the vehicle design problem and relates it to the more sophisticated computer model being developed. Although qualitative in nature, the discussion in this paper is based on data obtained from full scale crash tests and accident investigation as well as computer simulation.

2. TRRL TEST PROGRAMME

2.1 Full Scale Impact Tests

Over the past two years, TRRL has carried out about thirty full scale impact tests on a range of standard and modified cars. The majority of the tests were carried out to the proposed European side impact test procedure (2), using the EUROSID dummy and the EEVC MDB face. Other tests have used either the NHTSA MDB face (5) or a production car as the bullet vehicle. These tests have been used to check the repeatability of EUROSID and the EEVC MDB face and the ability of the test procedure to detect cars with improved protection. They also contributed to the development of the TRRL Experimental Safety Car ESV87 (4) and have provided much information about the influence of car design on reduction of injuries as indicated by measurements taken from the EUROSID dummy.

A number of current production cars of different sizes and mass have been tested along with cars modified in a number of ways. In some cases the modifications have taken quite extreme forms to study the effect of a major reduction in intrusion or filling the entire space between the dummy and the door with padding.

By fitting a thick steel sheet on the outside of the car it was possible virtually to eliminate intrusion (Fig 1). However, this alone was insufficient to produce acceptable results. Likewise, thick padding alone had little protective effect. It was only when both the car was reinforced and the inside was padded that satisfactory results were obtained.

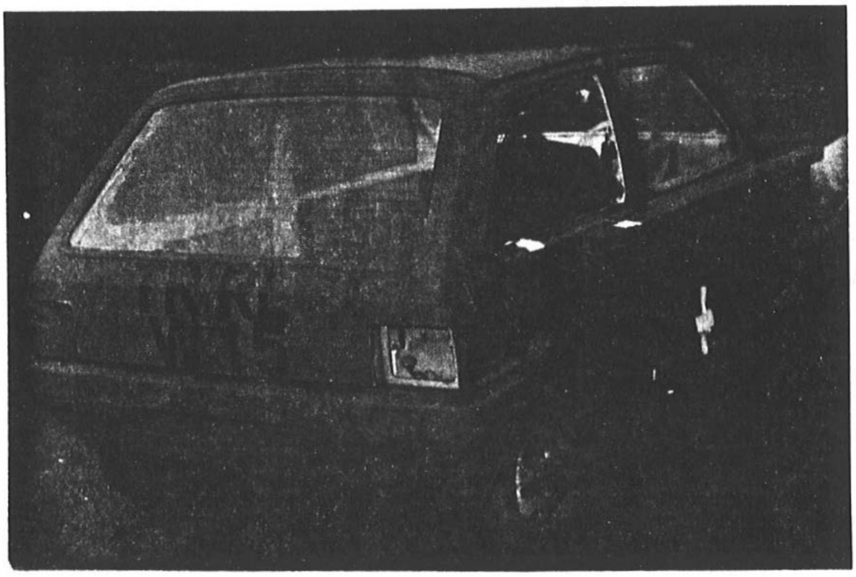

Figure 1. Car fitted with an external steel plate to study the effects of reducing intrusion

After testing more realistic modifications, it became clear that the shape of the intruding side was important. In most cases where the side structure was reinforced, there was more intrusion at the door's waistline than lower down. This comes as no surprise, as it is more difficult to support the structure at this level. The most obvious way of providing such support is by reinforcement of the B post. Tests showed that substantial reinforcement could be necessary to produce the required improvement.

From the tests, it became clear that injury parameters measured by the instrumentation within the dummy thorax could be reduced if loads could be applied to the pelvis early in the impact. Such loading would be transmitted up the spine to the thorax. If this happened, the thorax could be accelerated earlier so reducing rib compression and consequently the thorax injury parameter measurements.

The importance of the shape of the side intrusion was highlighted in a test on one small car. The sill on this particular car provided little support for the bottom of the door and the bottom part of the B post was comparatively weak (Fig 2). As a consequence, intrusion at the bottom of the door was greater than had been seen with other cars (Fig 3). This had the effect of allowing the door to intrude with a vertical flat profile. Although inspection of the car would lead one to expect it to have offered relatively poorer protection, the results from EUROSID indicated that the car had performed rather well. With the one exception of pelvic load, the car had performed better than most of the modified cars. This tends to confirm that residual intrusion is a poor indicator of injury. However, there is concern over the effects of pelvic loading and this is discussed later in the paper.

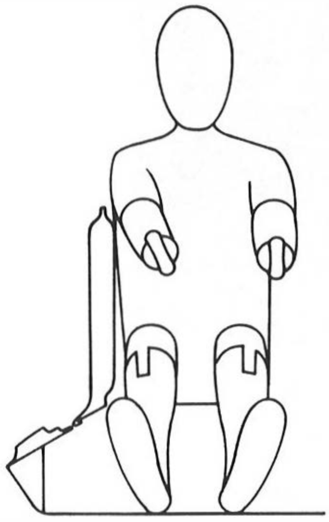

Figure 2. Car with little door to sill interaction. Door intrusion profile is vertical.

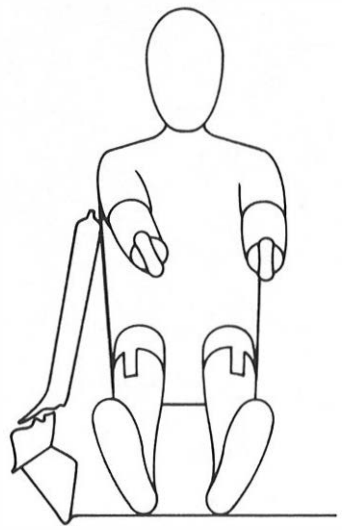

Figure 3. Car with significant door to sill interaction. Door tilts in at the waistline.

2.2 Tests using the NHTSA Mobile Deformable Barrier Face.

The Mobile Deformable Barrier (MDB) face proposed for the US side impact test procedure differs from the EEVC MDB face in a number of ways. It has greater stiffness, which is uniform across its width, it is wider, it has a slightly lower ground clearance and is used on a trolley of higher mass. The wheels of the trolley are crabbed at an angle of 27 degrees to simulate forward motion of the target car. The general expectation has been that the US test would be more severe than the European test.

However, full scale impact tests show that this is an incorrect assumption and EUROSID dummy measurements indicating injury levels at the thorax tend to be lower with the NHTSA face than with the EEVC face. Furthermore, modifications that might be introduced to enable a car to pass the US test may not lead to safer cars. Modifications to increase the stiffness of a car's side are easier to incorporate if they can be restricted to the lower part of its structure. Because of its stiffness, it has been possible in crash tests to fend off the NHTSA barrier face with local reinforcement designed to react against part of the bumper area. This was achieved using a car which incorporated local reinforcement at the base of the A and B posts. Above the local reinforcement, the B post was weakened slightly. The only other modification was the provision of door padding. No structural improvements were made to the door or to the sill between the A and B posts (Fig 4).

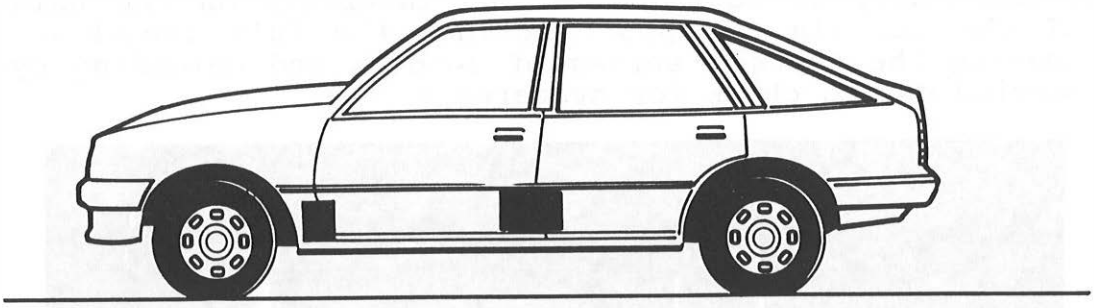

Figure 4. Positioning of local reinforcement sufficient to "fend off" the NHTSA MDB but not a current European car or the EEVC MDB.

Using target cars modified in this way, comparative tests were carried out with the NHTSA face, the EEVC face and a current production car. In each case, performance was assessed using the EUROSID dummy. The modified target car performed better using the NHTSA face, passing all the criteria, than it did using either the car or the EEVC face as bullet vehicle. This shows that the more massive and stiffer NHTSA face presents a less severe test than the EEVC face and at least one model of car. These results must throw some doubt on the validity of using the NHTSA face.

Localised low reinforcement is incapable of fending off the EEVC face. The face simply collapses at that point, allowing the rest of the face to load the side of the car. As a consequence, the door intrudes more at its waistline so concentrating loads on the thorax. Such a phenomenon could be expected in many of the types of side impacts observed in accident investigations. An extreme example of such an impact is where the bullet vehicle is a light goods or recreational vehicle. In these cases, the stiff bumper could completely override low structural reinforcement.

2.3 Quasi-Static Crush Tests

In order to obtain a better understanding of absolute and relative stiffnesses of the various parts of a car's side structure, a series of quasi-static crush tests have been carried out on one model of small car.

In the tests, a car body shell was crushed at low speed in a large hydraulic press (Fig 5). Loads were applied to the body shell through compliant blocks, in order to avoid local stress concentrations (Fig 6). Four different loading conditions were used; on the A and B posts at waist level, on the centre of the door, on the sill alone and with an EEVC MDB face in its test location. Deflection measurements were taken at a matrix of points on the loaded and unloaded sides of the car and loads were measured at each indentor. The bodyshell was constrained from moving vertically at each corner and laterally on the unloaded side of the car via a support against the full length of the sill. During the tests a series of loading and unloading cycles were carried out to check for hysteresis.

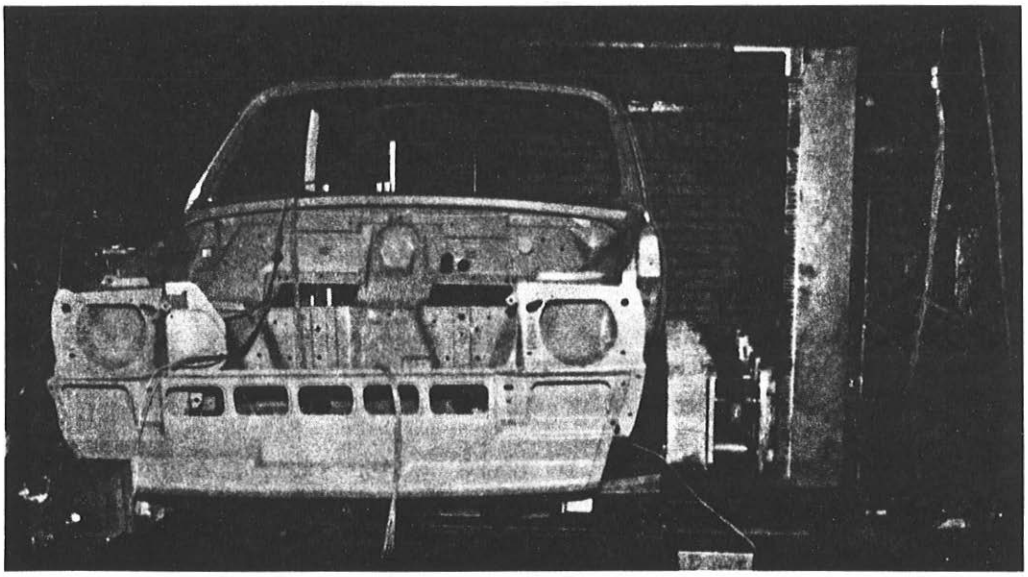

Figure 5. Quasi-static crush test of a car side structure.

The force / deflection data obtained from these tests is being used in the development of an improved computer simulation model.

3. PROBLEMS OF DUMMY BEHAVIOUR AND INJURY CRITERIA

3.1 Spine Acceleration Measurements

For research purposes, the lateral acceleration of the EUROSID spine is measured at two points, corresponding to vertebrae T1 and T12. These measurements provide useful information about the motion of the dummy's thorax. The T12 measurement is also used in the calculation of Thoracic Trauma index (TTI) (6), which is the criterion recommended by NHTSA for estimating the probability of injury to the thorax.

The EUROSID dummy records spinal accelerations which agree quite well with those seen with cadavers both in impactor tests against the thorax and in full scale car tests, though there are no directly comparable tests of EUROSID and cadavers using the same model of car.

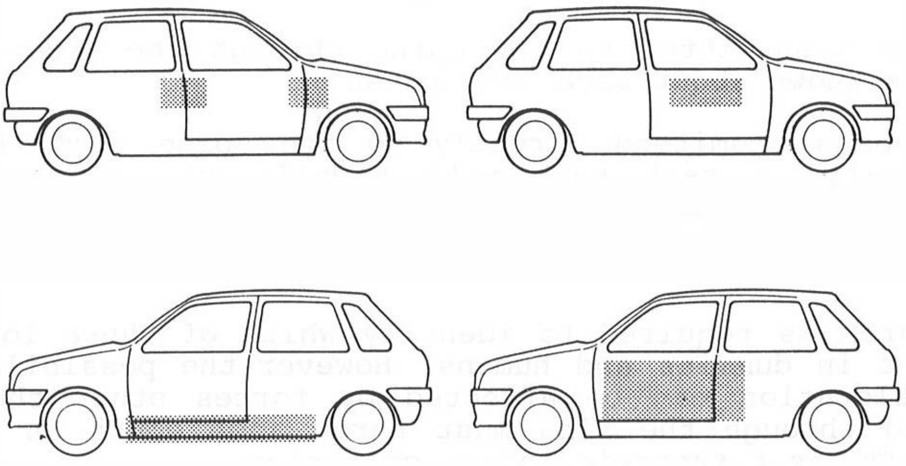

Figure 6. Location of loading points, using compliant indentors, in quasi-static crush tests.

However in the rigid and padded wall (Heidelberg) tests (7), spinal accelerations measured on EUROSID are low compared with those measured on cadavers. This may be because:

i) The cadaver spine is lighter than the EUROSID spine. In a cadaver, much of the thorax mass is in the soft tissues. These may not be accelerated until after the peak spine acceleration has occurred.

ii) There may be alternative load paths to the cadaver's spine, perhaps through the shoulder blades, in addition to that through the rib structure.

Further examination of the full scale car tests, and comparison with simulation models, show that the recorded spine acceleration cannot be produced solely by forces transmitted through the rib system. Even at full dynamic compression of the rib springs there is insufficient force from the ribs to provide an acceleration of more than about 40g, whereas in side impact tests over 100g has been recorded. In many of these, there is no direct loading on the shoulder. There must be additional load paths to the spine but it is not clear what they are. Possibilities include:

i) A shear force transmitted up the spinal column from the pelvis. However, the acceleration at T12 is frequently greater than the peak acceleration at the pelvis. So this could not be a complete explanation. Interestingly, the peak acceleration at

T12 is almost always greater than that at T1, usually by about thirty to forty percent.

The force available at the pelvis is probably much larger than that which could be transmitted up the human spine.

ii) Loads transmitted to the spine through the abdomen. Very little is known about such load paths.

iii) Loads transmitted directly to the spine from the seat. Theoretically a seat back with significant curvature could transmit quite high loads, but this possibility has not yet been demonstrated.

More research is required to identify which of these load paths are present in dummies and humans. However,the possibility that spine acceleration can be affected by forces other than those transmitted through the ribs must throw some doubt on reliance solely on TTI as a thoracic injury criterion.

3.2 Spinal Interconnection Between Pelvis and Thorax

There is evidence, from both full scale impact tests and computer simulation, that early loading on the pelvis can reduce loading to the thorax. Such early pelvic loading, giving rapid sideways movement of the pelvis, can be used to move the upper part of the torso before or during contact with the incoming door structure, so reducing thoracic loading. The amount of such thoracic movement is clearly dependent on the shear stiffness of the spine.

Tests on volunteers have established the range of fore and aft spinal stiffness between relaxed and tensed conditions (8). The Hybrid II spine, used for the EUROSID dummy, has a stiffness within this range. However, no lateral stiffness data under impact conditions is available. If the human spine were to be more flexible than that of the dummy, early pelvic loading would have less effect and deliberate attempts to move the pelvis early may not produce real benefits. It is also possible that vehicle modifications which increase the shear stress in the lower spine could increase the risk of spinal injuries. This highlights the importance of measuring pelvic loads and accelerations, when studying side impact mechanisms, as can be done with the EUROSID dummy.

4. COMMENTS ON VEHICLE DESIGN

4.1 Padding

Simulation suggests that padding the side of the car in the areas adjacent to the chest and pelvis can reduce injury under almost all circumstances. So far, full scale impact tests confirm this. It is likely that padding adjacent to abdomen would also be advantageous. However, the simulation models do not yet include an abdominal section and EUROSID has only "event" switches to detect excessive loading of the abdomen. These have seldom been triggered even in tests on unpadded cars, though none of the cars tested had rigid protruding arm rests. Consequently, improvements due to abdominal padding are not certain.

The optimum stiffness of padding for protecting the thorax is dependent upon the dynamic response of the chest wall. Because of its stiff, massive ribs, the US SID dummy will optimise with stiffer thoracic padding than the EUROSID dummy. The human rib system may require even softer padding.

The choice of padding is also influenced by the choice of injury criterion. Viscous Criterion and Peak Rib Compression would appear to be optimised with different padding from that which optimises TTI. This emphasises the importance of using a dummy which is dynamically as similar as possible to a live human, and of using injury criteria which relate closely to the probability of injury for live humans.

Impact tests using the EUROSID dummy suggest that there has been a tendency to select padding which is too stiff. However, if low stiffness padding is used it is important to provide adequate thickness. If the padding is too thin it may "bottom out," producing a sudden increase in stiffness and putting dangerously high loads on the thorax.

The computer simulation indicates that if the padding is much too stiff, or if "bottoming out " occurs, injury levels could actually be increased above those seen with no padding. In practice an increase in risk is unlikely, but its theoretical possibility demonstrates the importance of correct padding design. Variations in size and strength of humans also requires consideration.

4.2 Structural Modifications

It has generally been accepted that structural modifications to reduce side impact injuries involve an overall stiffening of the side structure. Simulation using the simple model showed that increasing stiffness would not always be beneficial. Beyond a certain point, further stiffening could increase injury. However, the optimal stiffness indicated was well above that of current vehicles.

The explanation of this apparent anomaly requires an examination of the fundamental requirements for side impact protection of the vehicle occupant. Prior to impact, the vehicle and its occupant have no lateral velocity. Within about 70 msec of the impact, the target vehicle is moving at a relatively constant velocity, which is the same or slightly greater than that of the bullet vehicle. By this time, the various parts of the car structure have more or less reached their final, relative, post-impact positions. To remain inside the car, the occupant must also have reached the car's velocity and must have moved sufficiently to be ahead of, or in contact with, the intruded side of the car. To achieve this situation with minimum applied acceleration, it is necessary to spread the acceleration over as long a time as possible.

One way of achieving this is to start the acceleration as soon as possible. Stiffening the side structure increases the collapse of the bullet car's front, so reducing door intrusion velocity. However, it also delays the time of first contact with the occupant, leaving less time for the acceleration to take place.

The concept of an "overall" stiffness of the side is now seen to be a misconception, arising from early experiments using a rigid barrier in which the whole side of the car was constrained to intrude in step with the barrier movement. This does not happen in impacts between cars.

It was found that the simple simulation model could not provide an adequate explanation of the data obtained from impact tests using deformable barriers. This is because the relative motion of the various parts of the side structure is important. The new simulation model will treat the sill, the A and B pillars and the door as separate entities, which can move relative to one another. The resulting dynamic system is complex and its properties have not yet been analysed in detail. However, some indication of the structural design requirements has been provided by the full scale impact tests.

It is clearly desirable to provide a stiff sill, which is high enough to engage with stiff points on the bullet vehicle, to "fend off" the bullet vehicle in the early stages of the impact and initiate collapse of its front. This can be aided by strong A and B posts.

However, care must be taken to ensure that the B post remains relatively upright so that it does not intrude at a higher velocity at the car's waistline than at sill level. On many current cars, the B post tends to bend at the waistline resulting in a high side intrusion velocity adjacent to the thorax. This may concentrate loads on particular ribs as well as on the thorax as a whole.

The requirements for the door are less clear. Excessive stiffness early in the impact will delay impact with the occupant, so reducing the time available to accelerate him. However, this delay could be reduced by the provision of padding to decrease the gap between the door and the occupant. Constraining the door from overriding the sill may also cause problems. Excessive stiffness at the bottom of the door is likely to emphasise the way doors tend to lean in at the waistline. Impact tests have indicated the desirability of keeping the door vertical to spread the load evenly over the torso.

A door which behaves like a tensioned membrane may provide a solution. It would deform easily in the early stages of the impact, quickly closing the gap. It would then rapidly stiffen so reducing its velocity during impact with the occupant.

In the impact tests at TRRL, motion of the inner and outer door skins is measured. Currently, for practical reasons, these measurements have to be made at points forward of the thorax and, although they have produced much valuable information, it is clear that the measured velocities differ from those adjacent to the thorax. At the moment, attention is being paid to obtaining better information on the details of door motion adjacent to the occupant. This should then give a better indication of how doors might be designed to improve occupant protection.

4.3 The Influence of Intrusion on Occupant Injury

In the past, it has been assumed that minimising intrusion is desirable. A direct relationship between intrusion and injury may hold good in accidents involving broadly similar designs of car, but this may be because both intrusion and injury are independently related to impact severity. Full scale tests, of the same severity, suggest strongly that there is no clear correlation between extent of intrusion and injury in different models of car. In some cases, lower levels of injury parameters have been recorded with higher levels of intrusion (4).

Because injuries are related to the velocity of intrusion, an initial high intrusion velocity continuing through the period of initial contact with the occupant will give a higher probability of injury than a lower velocity which continues for a longer time, even though it may result in greater final intrusion.

5 COMPUTER MODELLING OF SIDE IMPACT

5.1 Basic Model

The original side impact simulation model (Fig 7) was based on data from rigid impactor tests, where the whole barrier front and the whole side of the car were constrained to move together. When the model was modified to represent a deformable barrier, the solid front of the mobile barrier was replaced by a spring and light mass. This represented the contact plate at the front of the deformable element which impacted a massless outer door skin. The outer door skin was connected to the inner skin by a further spring. This inner skin included a major part of the mass of the sill, and was connected to the main mass of the car through a spring representing the structure supporting the sill. The occupant was loaded through a spring representing the door padding, once an initial gap had been closed. All the springs were non-linear and were represented in the simulation by tabulated functions. Special routines allow for hysteresis effects as the springs unload during the impact. The occupant is represented by a mass/spring/damper system which models the thorax of the EUROSID dummy.

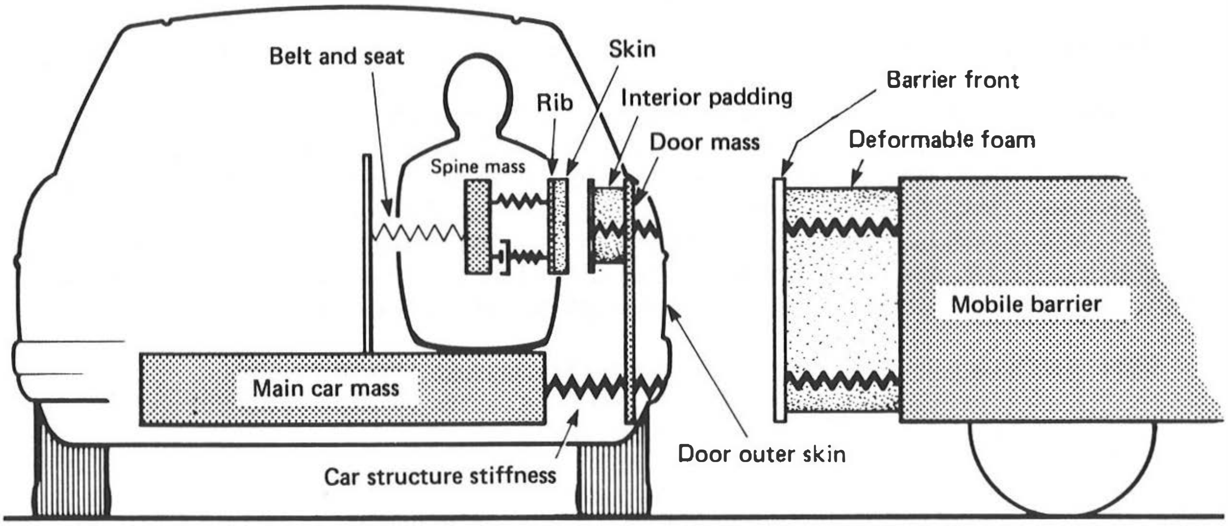

Figure 7. Simulation model of EUROSID dummy in side impact (basic)

5.2 Deficiencies in the Basic Model

This model has been useful for helping to explain the dynamics of side impact and for obtaining qualitative information about the effects of varying certain parameters. However, comparing the model with data from impact tests has shown that it is too simple to provide an adequate representation of the impact. Some significant deficiencies are:

i) Both the EEVC and NHTSA .mobile deformable barriers have different stiffnesses at the top and bottom. The stiff lower part of the barrier contacts the bottom of the door, with a fairly direct transmission of load into the sill and A and B post structures. The softer top of the barrier contacts the upper door and higher parts of the A and B posts.

ii) The sill, the A and B posts and the door are separate structures which can move relative to one another. This relative movement can be an important determinant of side impact injury.

iii) The door contacts the occupant on the abdomen and pelvis, as well as the thorax. The spine connecting the pelvis and thorax can bend, shear and rotate. The effect of pelvic loading on the motion of the thorax appears to be important in determining the severity of thoracic injury.

iv) The door is liable to rotate in the roll plane as it intrudes. A door which intrudes more at waist level than at the bottom appears to be more injurious to the thorax.

5.3 Development of a New Simulation Model

A new simulation model is being developed based on knowledge gained from impact tests and using numerical data obtained from quasi-static crush tests. The development is being carried out on a step by step basis, with a limited number of new features being introduced at each stage. This is in order that the effect of each change can be assessed and so that no unnecessary complication is introduced. The present stage of development is shown in Fig 8.

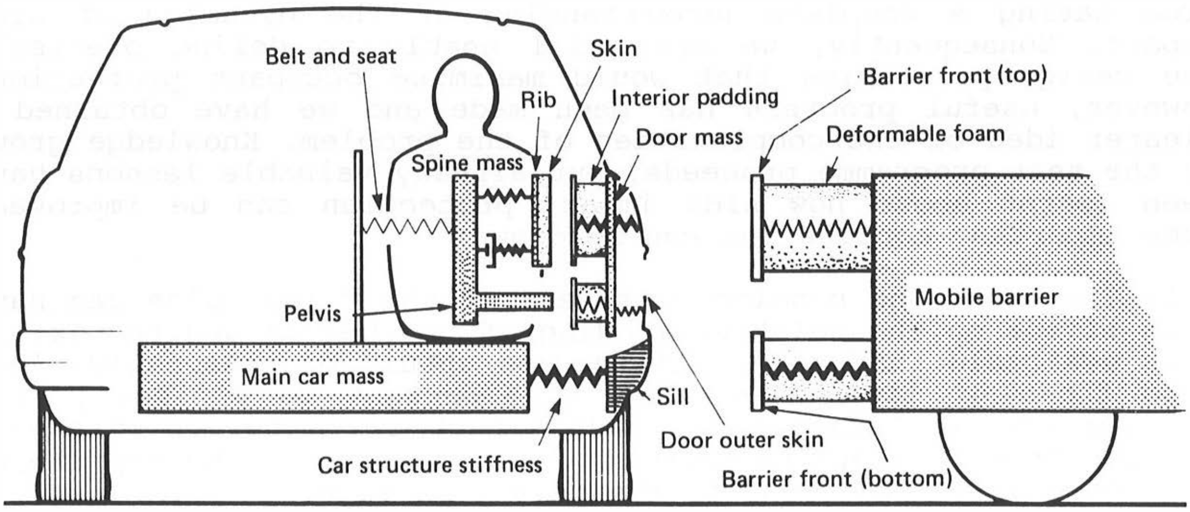

Figure 8. Simulation model of EUROSID dummy in side impact. (modified)

The deformable barrier face has been split, with the top half impacting the door and the bottom half contacting the sill. The sill is connected to the main mass of the car by a spring, and the door is connected to the sill by another spring. There is separate padding on the inside of the door to contact the thorax and the pelvis. The pelvis is attached rigidly to the bottom of the spine but the single rib, which currently represents all three of EUROSID's ribs, is connected through the same spring/damper system as used previously. The spine has a moment of inertia as well as mass. It can rotate freely but, at present, it does not bend or shear. Initial gaps can be set between each part of the barrier and the car and between each part of the padding and the dummy.

The next stage of development is to examine the connection of the door to the sill and the rest of the car structure, in the light of the results from the quasi-static crush tests. This will require an understanding of the way in which the B post and the door move when loaded by the barrier face and what influences rotation of the door. At this stage, it should be possible to ignore differential movement of the A and B posts. Subsequent development is likely to include a more realistic model of the dummy spine. This more complex model is still an extremely simplistic representation of the mechanisms involved and it cannot be expected to be a reliable predictor of the effects of side impact. It should, however, provide a better understanding of the processes observed in full-scale impact tests and allow some extrapolation of these results to indicate likely avenues for improved design.

6 CONCLUSIONS

The work described in this paper shows that we are still far from having a complete understanding of the dynamics of side impact. Consequently, we are still unable to define precisely the design principles that would maximise occupant protection. However, useful progress has been made and we have obtained a clearer idea of the complexities of the problem. Knowledge grows as the test programme proceeds, but already valuable lessons have been learnt about how side impact protection can be improved. Some important conclusions can be drawn:

i) The shear and bending stiffness of the dummy spine can have an effect on the relative loading of the pelvis and thorax. It is desirable that these stiffnesses should be reasonably close to those of live humans. It is important to monitor pelvic loads and accelerations in side impact crash tests, to ensure that thoracic injuries have not been reduced at the expense of unacceptably high risks to the pelvis or spine.

ii) There is some mystery about the load paths that transmit the forces necessary to produce the high spine accelerations seen in full scale impact tests using dummies and cadavers. This uncertainty throws doubt on the adequacy of the acceleration-based Thoracic Trauma Index as an indicator of thoracic injury and strongly supports the use of Viscous Criterion and peak rib compression as an alternative.

iii) The indicated optimum stiffness for padding can vary quite widely with different dummy designs, and with the injury criteria used.

iv) There are indications that the provision of a very stiff structure, to minimise intrusion, will not necessarily provide good protection. It is, however, important to optimise the relative stiffness of the various parts of the side structure, and it appears to be very important that the inside of the door remains vertical as it intrudes.

v) The complicated interactions between the various parts of the side structure must throw doubt on the validity of any simple computer model. At TRRL a more comprehensive model is under development and this will be used to investigate and extrapolate upon the results from impact testing. Present modelling ability is still a long way from reliable prediction, from first principles, of the results of side impact.

vi) A preliminary study of the proposed US MDB has shown that, in spite of its greater stiffness and mass, it appears to present a less severe and less realistic test of side impact protection than does the EEVC MDB. It may well be possible to design a car which will pass a test using the US MDB face, but which would be no safer in road accidents.

The EUROSID dummy has proved its value as a research tool and has shown that it is capable of meeting current requirements for use in regulatory testing.

7. ACKNOWLEDGEMENTS

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