A MATHEMATICAL MODEL OF THE BIOSID DUMMY

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ABSTRACT

To evaluate the protective effects of airbags and interior padding in automobile side impacts, a two-dimensional lumped-mass model of the BIOSID dummy was developed. This two-dimensional dummy model was developed in the crash victim simulation program MADYMO2D. The model was intended for use together with mechanical tests. The mathematical BIOSID dummy consisted of five body parts; the head, neck, ribs, spine, and pelvis. The spine and ribs were connected by a number of springs and dampers. The pelvic plug on the side of the pelvic flesh was modelled by a separate mass.

To validate the model, the mechanical BIOSID dummy was impacted by a rigid 23.4 kg pendulum at various impact speeds. The cross-sectional diameter of the pendulum was 150 mm. In addition to the tests with the rigid pendulum, tests were conducted with padding and pre-inflated airbags on the pendulum. Sled tests at impact velocities of 9 m/s and 6 m/s were also used to validate the model.

Padding of various thicknesses and force/deformation properties as well as airbags with various internal pressures were tested with the model. The tested padding in the sled tests was 50 mm compliant polyethylene padding at the thorax level and 75 mm of the same padding at the pelvis level. The airbag tested was an 8 l bag at the thorax level with an internal pressure of approximately 1 bar. The airbag was used with the 75 mm polyethylene padding at the pelvis level. Good agreement was generally obtained between predictions of the model and the mechanical sled tests.

INTRODUCTION

The speed of the intruding door when contacting the occupant in a 48 km/h car-to-car side impact is 8 - 12 m/s (Mellander et al., 1989). At this speed the chest has visco-elastic properties (Lau and Viano, 1986). The viscous criterion (VC) takes this into account. The VC is the instantaneous product of chest deformation speed and compression. The proposed injury criterion is $VC \leq 1 m/s$. This is included in the European side impact requirements. The American requirements use a chest injury criterion called the thoracic trauma index (TTI), which is the average of the maximum spine acceleration and the impacted rib acceleration expressed in g's. The TTI must be below 85 g for four-door cars and below 90 g for two door cars (NHTSA, 1990).

There are three side impact dummies available at present; The US-SID, EUROSID-1 and BIOSID. Both the EUROSID-1 and the BIOSID are distinctly different from the US-SID in their design features.

The US-SID is prescribed in the new US regulation and the EUROSID-1 in the European version. However, the BIOSID, which is the latest of the three dummies, has the best biofidelity according to a comparative evaluation performed in 1990 (ISO, 1990).

A number of mathematical models have been developed for the existing side impact dummies US-SID and EUROSID-1 (Wismans and Malta, 1981; Hasewaga et al., 1989; Low and Prasad 1990; deCoo, 1990; deCoo, 1991; Midoun et al., 1991). Also, mathematical models have been developed to match side impact data from cadaver tests (Langdon, 1985; King et al., 1991). Up until now, no mathematical models of the BIOSID dummy have been published.

Lobdell et al. (1972), developed a lumped-mass model of the anteroposterior thoracic impact response of the human thorax consisting of a mechanical analogue of the human chest composed of two masses, connecting springs and dashpots. He matched the model's force deflection response to blunt impact data from human cadaver tests. The mechanical elements in the simulation (Fig. 1) were adjusted until the model response fell within the low and high velocity force-thoracic deflection corridors recommended by Kroell (1971) as representative of the human biomechanical response. This model provided guidance for the development of a mechanical analogue which culminated in the Hybrid III chest (Foster et al., 1977). A modification of the original model was made by Viano (1987a and b) so that the benefits of padding could be assessed for in side impact protection.

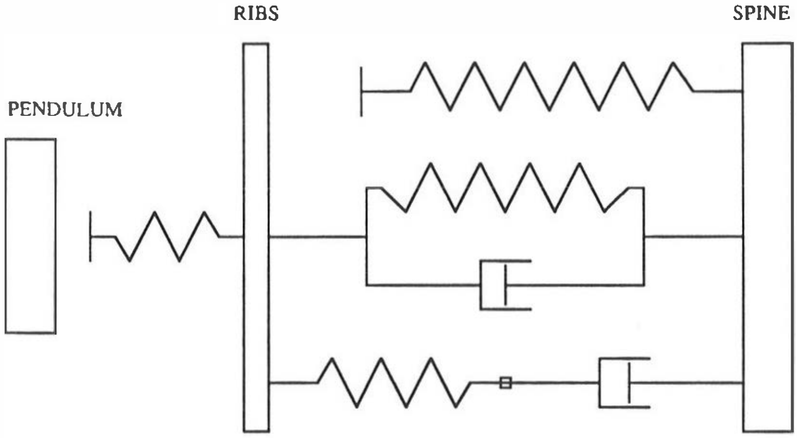


Figure 1. Lobdell lumped-mass model

The objective of this paper was to describe the development and experimental validation of a MADYMO 2D mathematical model of the BIOSID dummy. Special attention was paid to the development of the thorax and pelvis. This model was intended to be used in parallel with mechanical simulations to get a better understanding of the process of side impacts.

DEVELOPMENT OF THE MATHEMATICAL BIOSID DUMMY

The developed mathematical BIOSID dummy consisted of five body parts: the head, neck, thorax, abdomen, and pelvis (Fig. 2). The body parts were modelled as rigid elements connected by joints. The joint characteristics from the MADYMO Hybrid III dummy were used in the the head-neck joint, the neck-thorax joint, the thorax-abdomen joint and the abdomen-pelvis joint of the BIOSID model.

In a driving position the upper arm will have approximately a 45^0 angle with respect to the body of the occupant. In a side impact the intruding structure will for the major part pass under the upper arm. If the arm is impacted by the intruding structure it will be pushed in front of the thorax and not impact the ribs. The arm will in that case have a minor effect on thorax impact response of the occupant. Therefore, The mechanical BIOSID dummy's arm and shoulder were not included in the model.

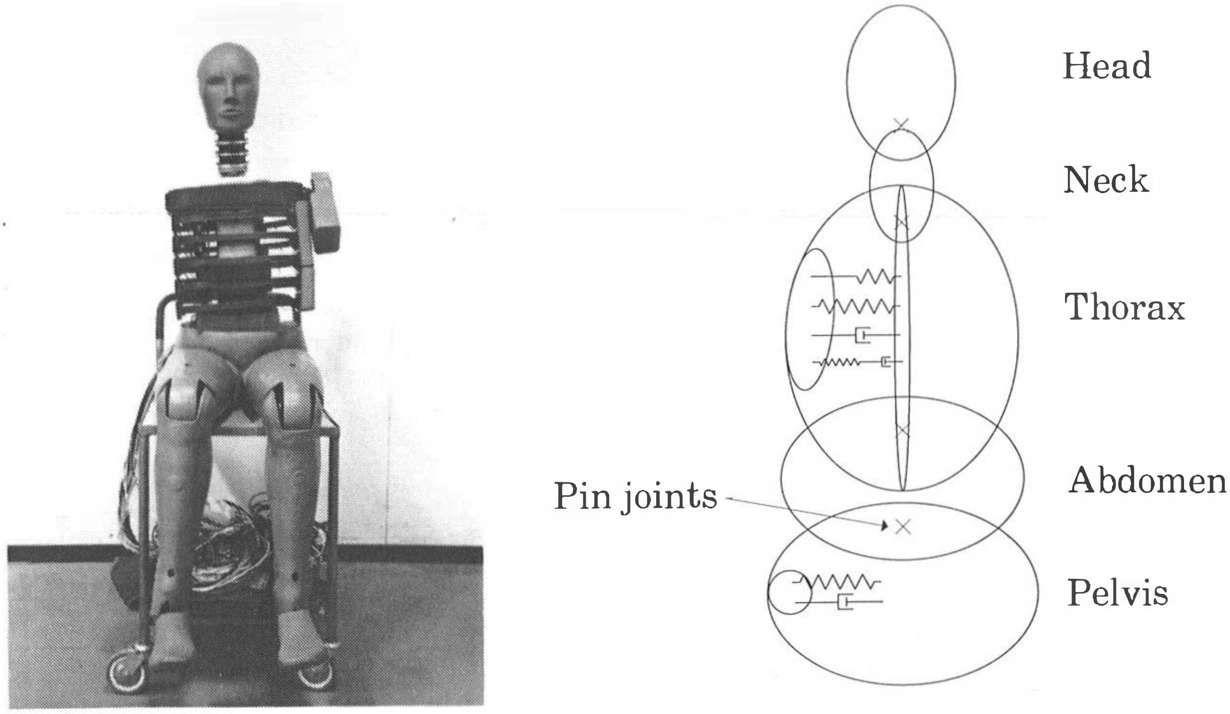


Figure 2. BIOSID dummy

Head

The mechanical BIOSID has the same head as the Hybrid III dummy. The head data was obtained from the MADYMO Hybrid III database. The head mass used in the model was 4.5 kg.

Neck

The BIOSID and the Hybrid III dummy has the same type of neck. When comparing results from pendulum tests for the neck it was noted that the performance, moment and rotation of the neck were almost identical in lateral pendulum tests as in anteroposterior pendulum tests. The neck mass, moment of inertia and joint data were therefore obtained from the MADYMO Hybrid III database. Mass of neck was 1.5 kg.

Thorax

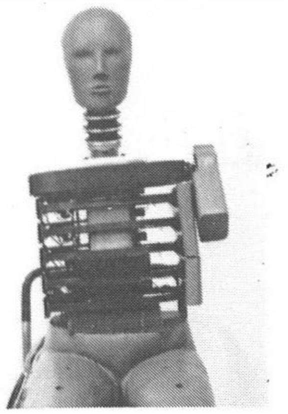
In the mechanical BIOSID dummy, the thorax consists of three ribs. These ribs are covered by 25 mm thick padding (ensolite pad). To make the model simple, the three ribs were modelled by only one mass in the shape of an ellipsoid (Fig. 3). The model thorax was therefore composed of two masses, ribs and spine. The ensolite pad was modelled by a stiff spring. The mass of one mechanical rib, the damping material and stiffener included, was 0.7 kg. The size and mass of the rib ellipsoid represented the size and mass of the three mechanical ribs. In order to keep the chest compression one-dimensional, a high moment of inertia was given to the rib ellipsoid. The mass of the thorax without ribs was 20.4 kg.

The rib- and spine masses were connected, at the center of gravity, by springs, maxwell elements, and dashpots. The springs and dampers were adjusted until the model contact force, rib, and spine accelerations matched the mechanical tests. The upper spring was used to give the thorax added stiffness after 17 mm of compression (fig 3).

The average response of the three ribs was used when comparing predictions of the model with the results of the pendulum and sled tests.

The relative motion between the two segments was used to compute the rib deformation (C), the deformation rate (V), and the viscous criterion (VC). The average of the acceleration of the two masses was used to compute the thoracic trauma index (TTI).

The mechanical dummy has deformation stops for the ribs. No attempt was made to model these stops as the ribs did not hit these stops neither in the pendulum nor in the sled tests.



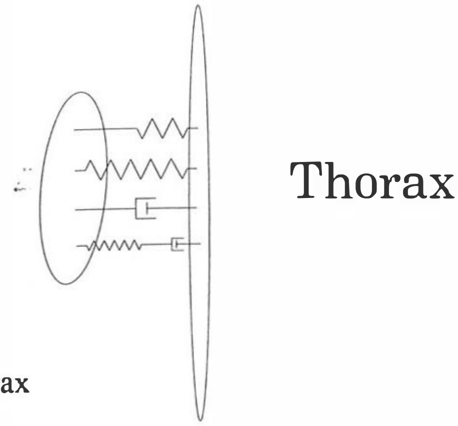


Figure 3. BIOSID thorax

Abdomen

The mechanical BIOSID has two abdominal ribs which the Hybrid III dummy does not have. The mechanical BIOSID uses the same lumbar spine as the mechanical 5% female dummy. This lumbar spine is smaller and lighter than that of the Hybrid III. It was considered that the abdominal mass had a minor effect on the pelvis and thoracic impact responses of the dummy. The mass of the BIOSID abdomen was therefore not measured. The same abdominal mass and joint properties were used in the model as in the MADYMO Hybrid III dummy. The mass of the model abdomen was 2.7 kg.

No attempt was made to model the two abdominal ribs.

Pelvis

On eather side of the pelvis flesh, the mechanical BIOSID dummy has a deformable styrofoam plug (794 kN/m^2, 115 psi foam) (Fig. 4) to give the pelvis impact response greater biofidelity. This plug was modelled by a small separate mass which was connected to the pelvis by a spring and damper. The mass of the upper legs was added to the pelvis mass. The effect of the lower legs on the dummy response was believed to be negligible; This mass was thus ignored. The mass of the pelvis, upper legs included was 32.7 kg.

The plug was included make the pelvis model a correct physical representation of the mechanical pelvis. The inertia effects of the plug can be neglected. The pelvic plug had a mass of 0.015 kg. To avoid model instabilities some of the pelvis mass was added to the model pelvic plug which had a mass of 0.3 kg. The effect of the heavier pelvic plug was considered to be negligible.

Joints

The joints are all pin joints where the data is given as torque as a function of angle.

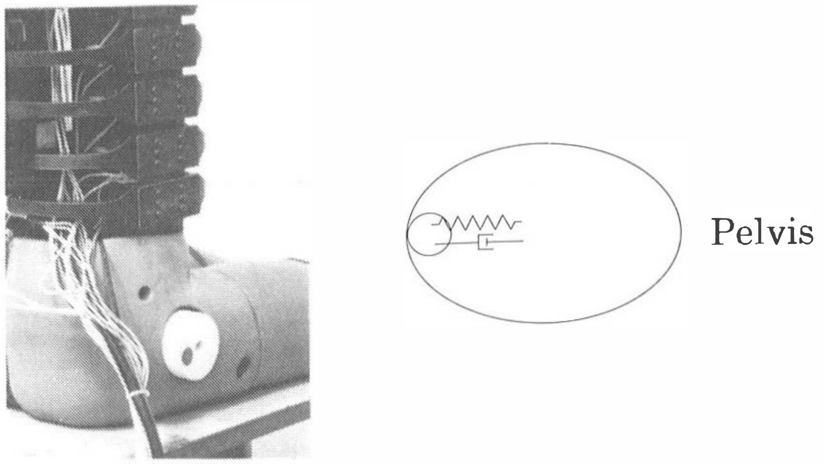


Figure 4. BIOSID pelvis

MODEL VALIDATION

Padding

Improved protection in side impacts can be achieved with padding or an airbag on the inside of the passenger vehicle door. An airbag may be considered as soft thick padding. The force/deformation properties of the padding materials and airbags to be used in the simulations were measured both statically and dynamically.

Statically, the force/deformation characteristics of the padding materials were obtained by hydraulically compressing the material with a cylinder. This cylinder had a face area of 0.0175 m^2, an edge radius of 12.7 mm and a mass of 23.4 kg (Figs. 5 and 6). It was estimated that this is approximately the area of the chest that the door will strike in a side impact. The dynamic force/deformation measurements were performed with the same pendulum by putting the padding or airbag on the pendulum head and making the pendulum impact a rigid wall at various speeds. The impact speeds were chosen so it could be noted that the padding material was close to bottom out. The force was obtained by multiplying the acceleration signal, from the accelerometer on the pendulum, with the mass of the pendulum.

Two types of polyethylene (PE) padding (Ethafoam220 and Termolon30) were measured at pendulum speeds of 2.0, 4.0 and 5.0 m/s. The thickness of the padding material was 50 mm and 75 mm respectivley (Figs. 5 and 6). Pre-inflated airbags at three different pressures were also measured but, only at a pendulum speed of 4.0 m/s (Fig. 7). Two measurements were performed at each foam thickness and pendulum impact velocity (Table 1).

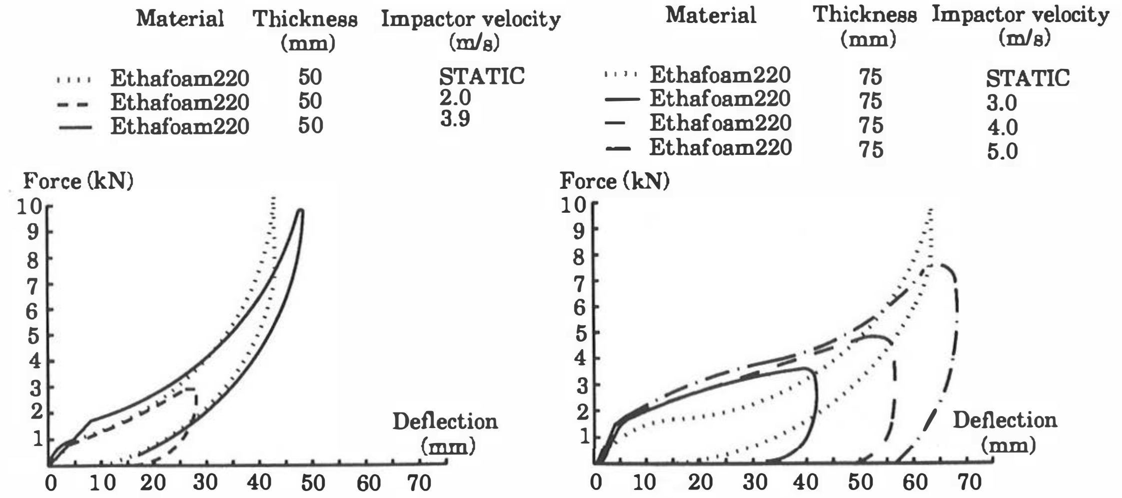


Figure 5. Ethafoam220 characteristics at different impact velocities
(Typical measurements)

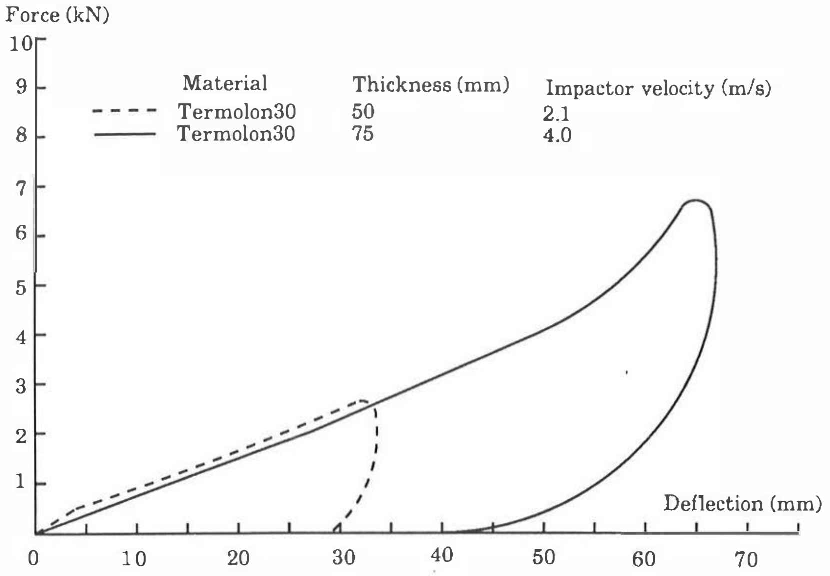


Figure 6. Termolon30 characteristics at different impact velocities (Typical measurements)

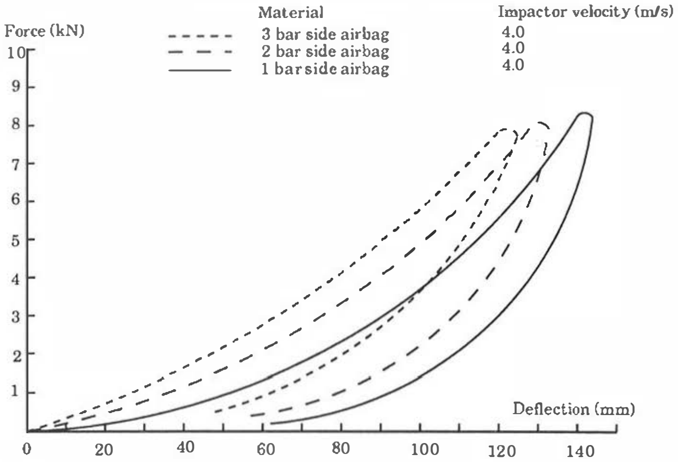


Figure 7. Preinflated airbag characteristics at different internal pressures (Typical measurements)

Table 1. Padding measurements

Material	Thickness (mm)	Impact vel. (m/s)	Max def. (mm)
Ethafoam220	75	3	42
Ethafoam220	75	3	38
Ethafoam220	75	4	56
Ethafoam220	75	4	51
Ethafoam220	75	5	73
Ethafoam220	75	5	68
Termolon30	50	2	34
Termolon30	50	2	35
Termolon30	75	4	63
Termolon30	75	4	67

Model validation with pendulum

Tests were performed, in which the mechanical BIOSID's three thoracic ribs were impacted with the same pendulum as that used for the padding measurements. The tests were performed with and without padding on the face of the pendulum. The padded impactor tests were performed to obtain additional data for further validation of the model. The padding used was 75 mm Ethafoam220. The pendulum speed was 4.5 and 6.7 m/s respectively. The 23.4 kg pendulum and the 6.7 m/s pendulum speed was chosen as it was in accordance with the calibration procedure for the mechanical BIOSID. In addition, the dummy response at the 6.7 m/s pendulum speed was very well documented.

The 4.5 m/s pendulum speed was chosen as it was assumed that the side structure of cars will get stiffer. The velocity of the intruding structure when it hits the occupant will decrease. It was therefore considered necessary to validate the model against pendulum tests at lower impact velocities. All the tests were performed twice.

The pelvis tests were performed in accordance with the calibration procedure for the pelvis. That is, the pendulum was impacting the mechanical dummy at an impact speed of 6.7 m/s. The corresponding tests were simulated with the mathematical BIOSID dummy (fig 8 and 9). The pendulum was simulated by a separate system with one rigid element. The mass of the pendulum was 23.4 kg and it was modelled as an ellipsoid with the padding characteristics prescribed for the ellipsoid.

Pendulum results

The results from the simulations agreed well with the results from the corresponding pendulum tests at 6.7 m/s. All parameters were within the performance corridors specified by First Technologies Safety Systems for pendulum tests at 6.58 - 6.84 m/s pendulum speed (Table 2) (BIOSID user's manual, 1991). For all pendulum tests the model thorax deflection was not as great as the mechanical thorax deflection and the duration of the model thorax deflection was not as long as the mechanical thorax deflection. However, the point in time where the maximum mechanical thorax deflection occured was predicted well with the model thorax. For the 6.7 m/s mechanical dummy test with padding the compression of the padding began after about 20 mm of chest compression. For the corresponding 4.5 m/s test the compression of the padding began after about 15 mm of chest compression. The model BIOSID predicted at what level of chest deflection the compression of the padding occured satisfactorily.

Table 2. Results from the model pendulum impact test compared to the performance specifications for the mechanical BIOSID (Without arm) (BIOSID user's manual, 1991).

	Mech. BIOSID Specification (6.58 - 6.84 m/s)	**Math. BIOSID** Model (6.7 m/s)
Probe Force Thorax	5.2 - 6.3 kN	6.1 kN
Thoracic Rib Deflection	50 - 70 mm	52 mm
Thoracic Rib Acceleration	1305 - 1756 m/s ^{2}	1524 m/s^2
Lower Spine Acceleration	118 - 162 m/s ^{2}	131 m/s^2
Probe Force Pelvis	7.7 - 9.7 kN	9.0 kN
Pelvis Acceleration	412 - 647 m/s ^{2}	562 m/s^2

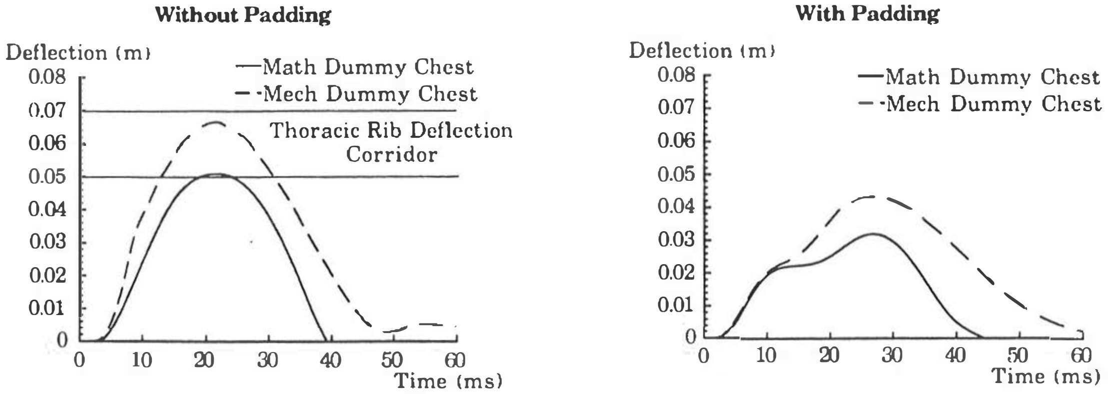


Figure 8. Typical chest deflection at a pendulum speed of 6.7 m/s

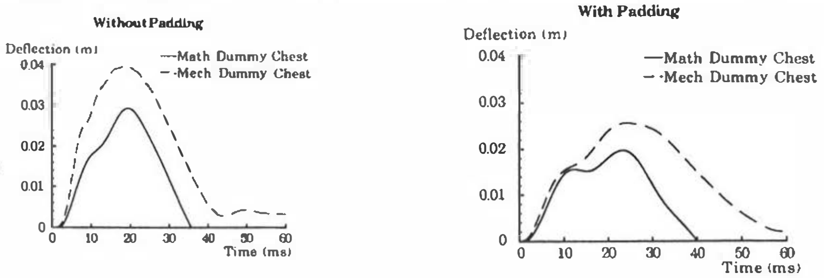


Figure 9. Typical chest deflection at a pendulum speed of 4.5 m/s

Model validation with velocity profile

In a car-to-car side impact the door inner panel will hit the occupant very early, after about 20 ms, with a speed that can be as high as the speed of the impacting car (Fig. 10) (Okamoto and Takahashi, 1991). The door will slow down relative to the impacted car and eventually the door and impacted car will end up at the same speed.

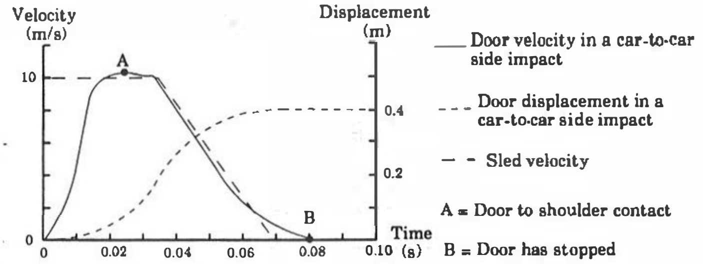


Figure 10. Door velocity and displacement relative to the car

Mechanical tests were conducted at the Electrolux Autoliv sled test facility in Vårgårda, Sweden (Håland and Pipkorn, 1991). A rigid passenger car door was mounted on a sled which impacted the BIOSID (Fig. 11). After the impact, the sled was braked down to 0 m/s. This test was supposed to be similar to a real world car-to-car side impact. Padding and airbags were mounted on the passenger car.

It has been found that the maximum padding thickness at the chest and at the pelvis area that car manufacturers can accept is 50 mm and 75 mm respectively (Håland and Pipkorn, 1991). The chest airbag normally hidden behind the door panel can be considered as thick soft padding, when inflated.

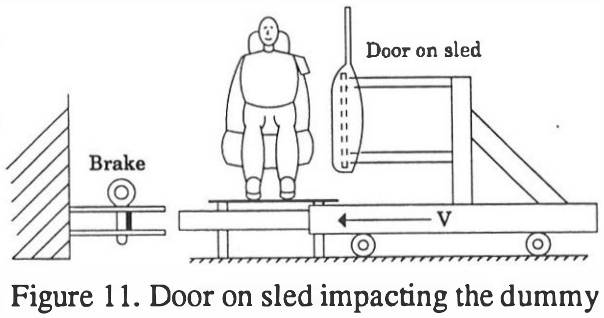


Figure 11. Door on sled impacting the dummy

Three basic configurations (A, B and C) were tested and the results from the mechanical tests were compared with the results from the model.

A: Reference door. Stiff polyethylene padding, 10 mm thick, (Termolon80), with a density of 80 kg/m^3, covered the flat rigid door's inner side and the B-pillar.

B: 50 mm chest and 75 mm pelvis padding. The chest padding was 50 mm thick and located at the upper part of the door to protect the chest. The pelvis padding was 75 mm thick and located beneath the chest padding to protect the lower part of abdomen, the pelvis and he thigh. The material was an open cell polyethylene foam with a density of 30 kg/m^3 (Termolon30).

C: Chest airbag and 75 mm pelvis padding. The airbag had an inflated volume of about 8 liters. The width was 120 mm. The same 75 mm thick pelvis padding as in configuration B was used (Fig. 12).

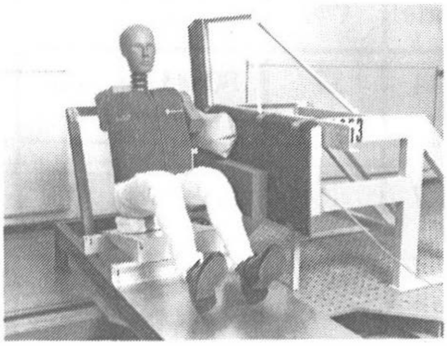


Figure 12. Conf C, Chest airbag and pelvis padding

Two series of tests were conducted with the different configurations. The door velocity in the first series of tests was 9 m/s (Fig. 13), corresponding to a 48 km/h (30 mph) car-to-car side impact. This represents a car with a good reinforcement of the body and door structure (Mellander et al., 1989). The door velocity in the second series of tests was chosen to be 6 m/s (Fig. 13) corresponding to a 32 km/h (20 mph) side impact.

The velocity profile of the sled was integrated and the displacement profile obtained was used in the validation simulations with the BIOSID, as MADYMO requires displacement as a function of time as input. In the 9 m/s and 6 m/s test with conf A, the door impacted the dummy after 180 mm displacement. This corresponds to a car body lateral deformation of about 500 mm for the 9 m/s test and 300 mm for the 6 m/s test (integration of the velocity profile).

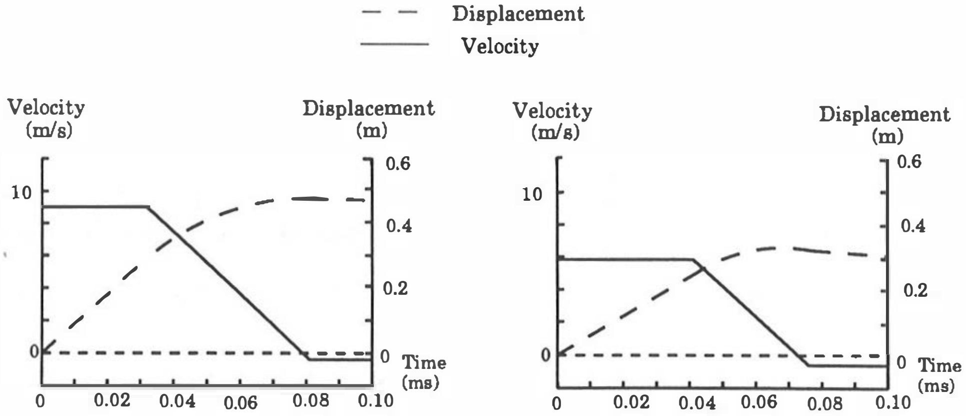


Figure 13. Door velocity and displacement at 9 m/s and 6 m/s side impacts, respectively.

Velocity profile results

The test and simulation results of the three configurations at 9 m/s are summarized in Table 3. The mean of the maximum values from each test configuration and the 95% confidence limit of the mean value for each parameter are shown. The number of tests conducted are indicated in Tables 3 and 4.

Table 3. Results from sled tests (mean ± 95% confidence limit) and math model with corresponding relative differences with configurations A, B and C at a door speed of 9 m/s.

Parameter	Configuration A Reference door			Configuration B Chest + pelvis padding			Configuration C Chest airbag + pelvis padding		
	Mech Test (N=5)	Math Model	Rel diff (%)	Mech Test (N=3)	Math Model	Rel diff (%)	Mech Test (N=5)	Math Model	Rel diff (%)
TTI (g)	123(±7)	144	17	80(±11)	108	35	75(±6)	105	40
Chest VC (m/s)	1.5(±0.2)	1.7	13	1.1(±0.1)	1.2	9	0.78(±0.14)	0.86	10
Pelvis acc (g)	233(±7)	218	7	128(±13)	119	7	125(±0.3)	107	14

Table 4. Results from sled tests (mean ± 95% confidence limit) and math model with corresponding relative differences with configurations A and C at a door speed of 6 m/s.

Parameter	Configuration A Reference door			Configuration C Chest airbag + pelvis padding		
	Mech Test (N=3)	Math Model	Rel diff (%)	Mech Test (N=3)	Math Model	Rel diff (%)
TTI (g)	79(±30)	127	60	47(±15)	46	2
Chest VC (m/s)	0.45(±0.09)	0.68	51	0.16(±0.03)	0.11	31
Pelvis acc (g)	75(±16)	89	19	73(±4)	50	32

The differences in mean values between the parameters of configurations A and B and between A and C, respectively, are all statistically significant; $P<0.05$ or better (comparison of two means, independent samples, t-distribution).

50 mm of chest padding gave the same TTI reduction as the airbag but there was a significant difference in chest VC. For the reference door, the chest VC was 1.5 and for

configuration B and configuration C the chest VC was 1.1 and 0.8, respectively. The reduction in pelvis acceleration was the same for configurations B and C, down to about 125 m/s^2 from 235 m/s^2 for the reference door (conf.A). The same type of 75 mm padding was used for both configurations.

DISCUSSION

The spring that modelled the ensolite pad covering the thorax ribs, could not model the bottoming-out effect of the pad very well. The spring was softer than the pad after bottoming out.

The model was validated against filtered data from the mechanical tests. In the model the chest deflection was obtained by integrating the acceleration of the spine and ribs twice and subtracting the two. In the mechanical BIOSID the chest deflection was measured by string potentiometers. The filtered acceleration signal affects the model thorax deflection while the mechanical thorax deflection is not affected by filtering the acceleration signal.

The soft ensolite pad spring and the fact that the model was validated against filtered data resulted in that model thorax deflection was somewhat less than mechanical thorax deflection in the pendulum tests.
The model response could be improved if it was matched against unfiltered data. However, this could introduce numerical instabilities.

The force/deformation properties of the Ethafoam220 padding were dependent on the rate of deformation and the thickness (Fig. 5). It could be observed that the properties of the Termolon30 padding were neither dependent on the rate of deformation, nor on the thickness of the material. The variations in the padding material force/deformation properties could introduce some variation in the pendulum and sled test results.

All model parameters were within the performance corridors specified by First Technology Safety Systems for pendulum tests at 6.58 - 6.84 m/s pendulum velocity. The 6.7 m/s thoracic pendulum test was approximately as violent for the thorax as the test with the reference door mounted on the sled impacting the dummy with an initial velocity of 9 m/s. Approximately the same amount of energy was transferred to the dummy. In the sled test, the dummy was hit at the pelvis level and at the thorax level.

The pelvis padding was impacted both by the upper leg and the pelvis of the mechanical BIOSID. The force/deformation characteristics of the padding were obtained by the pendulum test. The area of the pendulum face was much smaller than the area of the pelvis and upper leg. The pelvis padding used in the model may therefore be too soft. In the 6 m/s test with Conf.C, the pelvis acceleration was much lower in the simulation compared to the mechanical tests resulting from that the padding material used in the model was too compliant. In the 9 m/s tests the pelvis padding was bottoming out so that the fact that the padding was too compliant did not have any effect on pelvis acceleration.

There are two readily observed features associated with the pendulum impact which differentiate it from the door/thorax impact in a car-to-car side collision. First, since the pendulum is moving at a constant speed before impact, the initial spacing between the pendulum and the thorax has no effect on the thorax response. Secondly, the pendulum velocity is reduced during its contact with the thorax.

The use of padding on the door and on the face of the pendulum reduced both the spine and the rib acceleration at all impact speeds. Best reduction of both spine and rib acceleration was obtained with configuration C, chest airbag and 75 mm pelvis padding.

The results from the simulations agreed well with the results from the sled tests. For the impact velocities and configurations used, the VC showed a very good agreement between tests and simulations. For configurations B and C, the relative improvement, compared with configuration A, for the 9 m/s sled simulation was consistent with the relative improvements in the sled tests (Table 3). The TTI and pelvis accelerations indicated the correct trend for the different configurations. The 6 m/s sled test results show great variations in test values. The pelvis acceleration showed a very small variation for the 6 m/s test compared to the variations of the other parameters.

In the 9 m/s sled test, the 50 mm chest padding in configuration B and the pelvis padding in configurations B and C bottomed out. There are difficulties in modelling the bottoming-out stiffness of a material, as the materials could not be modelled infinitely stiff. The airbag in configuration C was not fully compressed. In future simulations softer airbags and stiffer pelvis padding will be tested.

At pendulum impact velocities of 4.5 - 6.7 m/s and sled tests at velocities 6 - 9 m/s, the model predicted the mechanical dummy response very well. Simulations with pendulum impact velocities and sled test initial velocities of 12 m/s have been found to provide realistic predictions of dummy behaviour.

The three thoracic ribs of the mechanical BIOSID were modelled by only one mass. Impacts where only one or two thoracic ribs were hit can not be evaluated with the model. However, in the tests conducted all three ribs have been impacted by the door. If there is a need to study impact of only on or two ribs the model can be modified to model the three ribs by separate masses.

When padding was placed on the inside of the door, contact between the occupant and the door will take place earlier in a side impact with an intruding door. More energy will be transferred to the occupant. The padding will reduce the rib and spine accelerations. The TTI will therefore be lowered. However, there is a risk that the rib deformation and the viscous response, the VC, will increase (Deng, 1987). It must be pointed out that the TTI and VC showed a tendency towards a decrease, both with padding and with the airbag.

The 10 mm thick stiff padding (Termolon80) used on the reference door was considered to have very little influence on the dummy response, compared with the stiff door in the configuration A sled tests. No attempt was therefore made to measure or model this padding.

CONCLUSION

The lumped-mass model of the BIOSID dummy is a very valuable tool for evaluating the protective effect of padding and airbags in the side door. The model has proven to produce reliable results for both pendulum and sled tests at impact velocities from 4.5 - 12 m/s.

Different intrusions of the door at the chest and pelvis levels could be accounted for with the model.

Head impact in the side structure could be studied with the model.

An arm rest intruding at the abdominal level could not be evaluated with the present model. However, if needed, abdominal ribs could easily be added to the model.

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