Evaluation of the European Side Impact Dummy in rigid wall and padded wall sled tests

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Abstract

A series of rigid wall and padded wall sled tests has been performed based on the test set-up described in document ISO/DTR 9790. The sled impact velocities were 16, 24 and 32 km/h. The responses of the production prototype European Side Impact Dummy - EUROSID - have been analyzed in detail. Special emphasis has been given to the thoracic and pelvic protection criteria. The dummy results have been compared with cadaver responses and injuries in similar tests. The test data have been normalized and the results compared with the response requirements described in the ISO documents. It appears that the response of the EUROSID thorax is in good agreement with the cadaver responses, while the EUROSID pelvic response appears to be satisfactory in padded tests. The pelvis seems to be too stiff in rigid impacts.

Introduction

The European Side Impact Dummy - EUROSID - has been designed and constructed by a group of European research laboratories working together under the auspices of the European Experimental Vehicle Committee. Four prototypes of EUROSID were built and evaluated in 1986 in the framework of an EEC Evaluation Programme [1]*. The repeatability, reproducibility, sensitivity and durability of the four dummies have been evaluated by impactor tests, sled tests and full-scale car crashes. The dummy design was improved afterwards and production prototypes are now being evaluated in Europe, the United States of America, Canada and Japan.

In addition to requirements like sensitivity, repeatability and durability, a side impact dummy should also load the structural components of a car in a realistic way. Furthermore it should show a human-like response to this loading. Working Group 5 of ISO/TC22/SC12 has defined a series of impact tests to assess this dummy's performance. The impact test set-up and proposed dummy responses are based on cadaver impact tests and are described in documents ISO/DTR 9790-1 to 9790-6. The TNO Road-Vehicles Research Institute has conducted a large number of the proposed tests to study the biofidelity of EUROSID. The results of that study are summarized in ref. [2]. Among other tests the biofidelity assessment of the thorax and pelvis is based on sled impact tests. An extended analysis of these rigid wall and padded wall sled tests is presented in the current paper. In addition to the test conditions prescribed in the ISO documents also a low speed rigid wall test (16 km/h) has been performed. Moreover the cadaver injuries observed in similar sled tests are compared directly with the EUROSID results. Emphasis is given to the thoracic protection criteria V.C, TTI, as well as rib deflection.

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* Numbers in parentheses designate references at end of paper.

Test set-up

Introduction - A series of sled tests has been performed based on the test set-up described in documents ISO/DTR 9790-3 [3] and 9790-6 [4]. The sled impact velocities were 16, 24 and 32 km/h. The dummy impact surface was either rigid or padded. Table 1 shows the test matrix. A brief summary of the test set-up is presented in this section.

Dummy - The 1987 version of the European Side Impact Dummy (see Figure 1) has been used in the study presented in this paper. This production prototype dummy is described in an EEVC publication [5], as well as in the EUROSID User's Manual [6].

The EUROSID represents a 50th percentile adult male (total body mass 75 ± 1 kg). The dummy is designed to accept accelerometers, displacement and force transducers, as well as level detecting switches (see Figure 2). Table 2 shows the location, type of transducer and filter class generally used. ISO [4] requires a CFC 1000 filter for the pelvic accelerations.

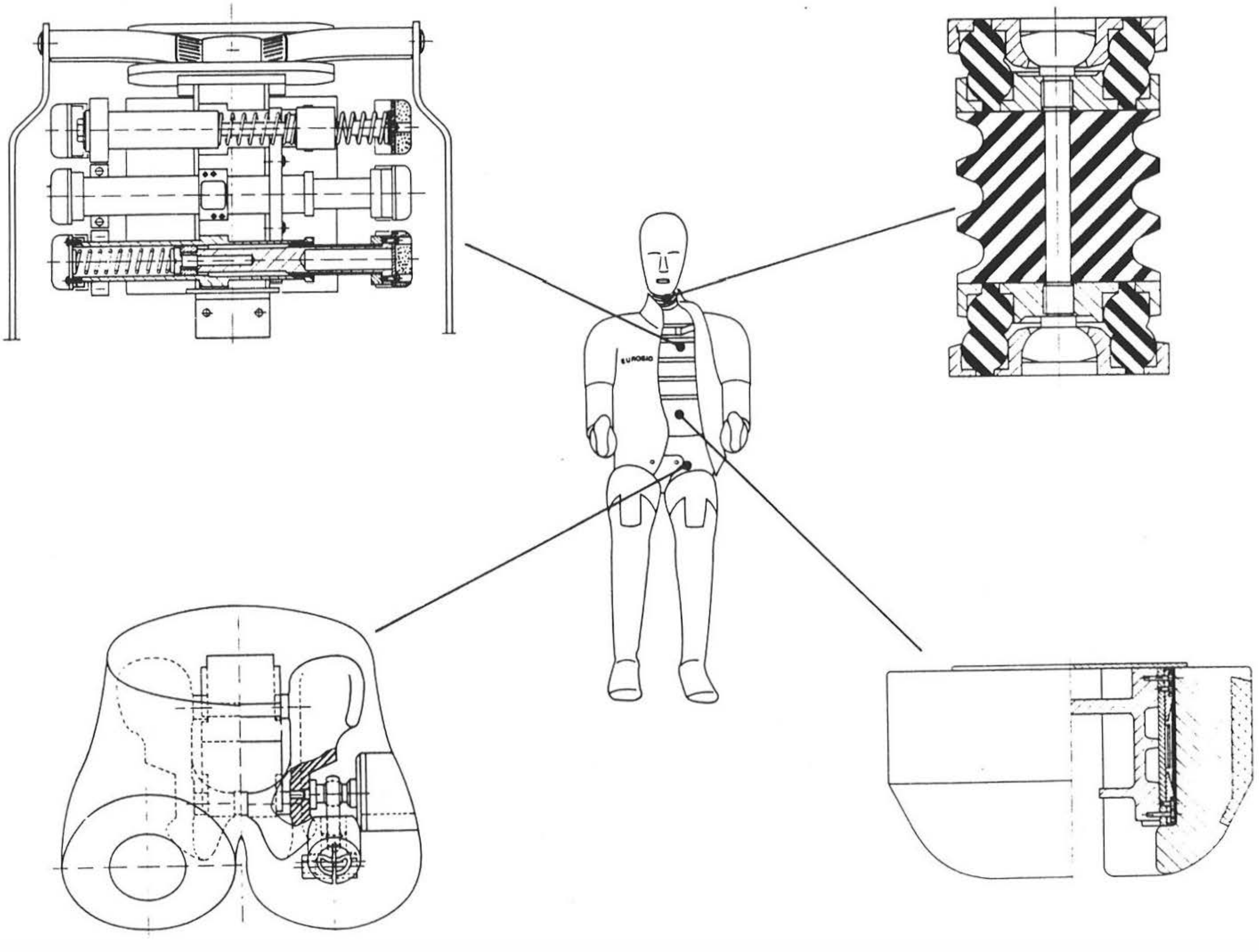


Figure 1. Overview of specially designed body parts of EUROSID; thorax (top left), neck (top right), pelvis (bottom left) and abdomen (bottom right).

Table 1. Test matrix sled tests.

Test no.	88101	88111	88112	88113	88114	88115	88116	88117
Impact speed [km/h]	16	16	24	24	32	32	32	32
Impact surface	rigid	rigid	rigid	rigid	rigid	rigid	APR-pad	APR-pad

Table 2. EUROSID instrumentation.

Location	Transducer	SAE Channel Filter Class
Head	triax. accel.	1000
Upper spine T_1	triax. accel.	180
Upper rib	uniax. accel. displ. transd.	180 180
Middle rib	uniax. accel. displ. transd.	180 180
Lower rib	uniax. accel. displ. transd.	180 180
Lower spine T_{12}	uniax. accel.	180
Abdomen	3 switches	1000
Pelvis	triax. accel.	180*
- pubic symphysis	force transd.	600
- iliac wings	strain gauges	600

* CFC 1000 for ISO/DTR 9790-6 [4].

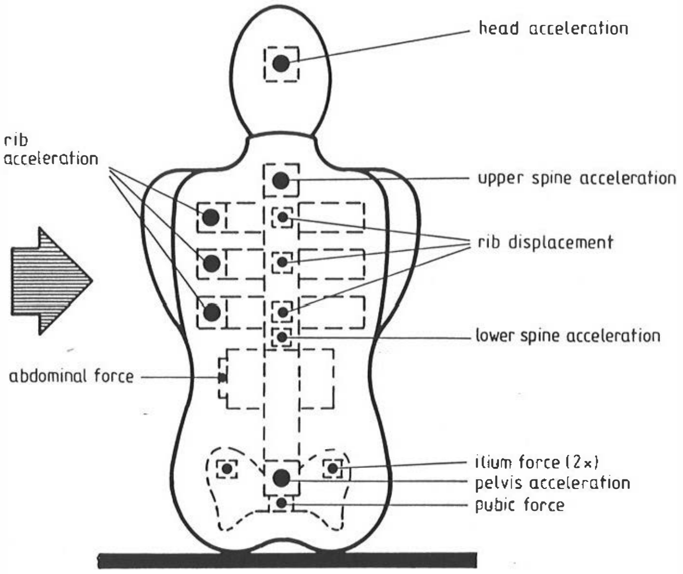
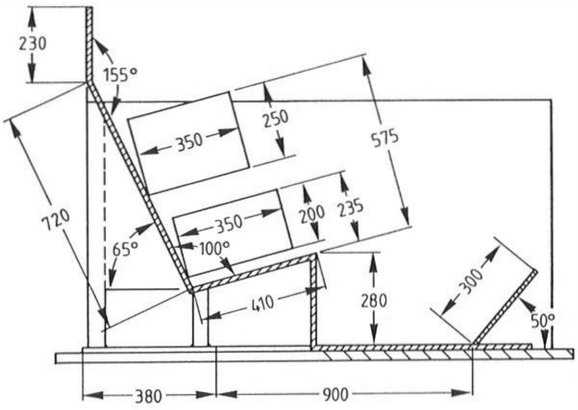


Figure 2. Overview of EUROSID's instrumentation.

Sled - A seat with an instrumented side panel was mounted onto an impact sled, sideways to the direction of travel. The side panel had two instrumented impact surfaces, one for the thorax and the other for the pelvis (see Figure 3). Each impact surface was attached to two load cells (responses filtered using SAE CFC 1000 and using a 100 Hz FIR filter). The dummy was retained at the end of the seat opposite the side panel while the sled was accelerated until it reached the prescribed impact velocity. The sled was then brought rapidly to a halt and the dummy slided towards the side panel, impacting it at almost the sled impact velocity. A low friction between seat and dummy ensured a translation of the dummy relative to the sled without rotating. The initial gap between the dummy and the side panel ensured that the sled was stationary and the inertial forces from the force plates had died down before the dummy contacted the plates. Both upper arms of the dummy were positioned along the thorax, rotated approximately 5 degrees forward (see Figure 4). The right hand was placed on the lap, while the left hand (impact side) was taped onto the right lower arm. In this position the left lower arm was horizontal and did not contact the pelvic load surface. The position of the arms is not prescribed in ISO-ref. [3] and was therefore based on the original cadaver tests [7]. Rigid surface impact tests were conducted with impact velocities of 16 km/h, 24 km/h and 32 km/h. In the 32 km/h padded impacts, the thoracic and pelvic impact surfaces were covered by 140 x 140 x 420 mm blocks of open cell urethane foam (APR padding). APR padding was also used to cover the panel opposite the lower leg in order to create a flat impact surface for the lower body. A protruding pelvic impact surface would induce rotation of the pelvis around a vertical axis. High speed movies from various directions have been made during all tests.

Figure 3. Dimensions of seat and side panel with the two impact surfaces.



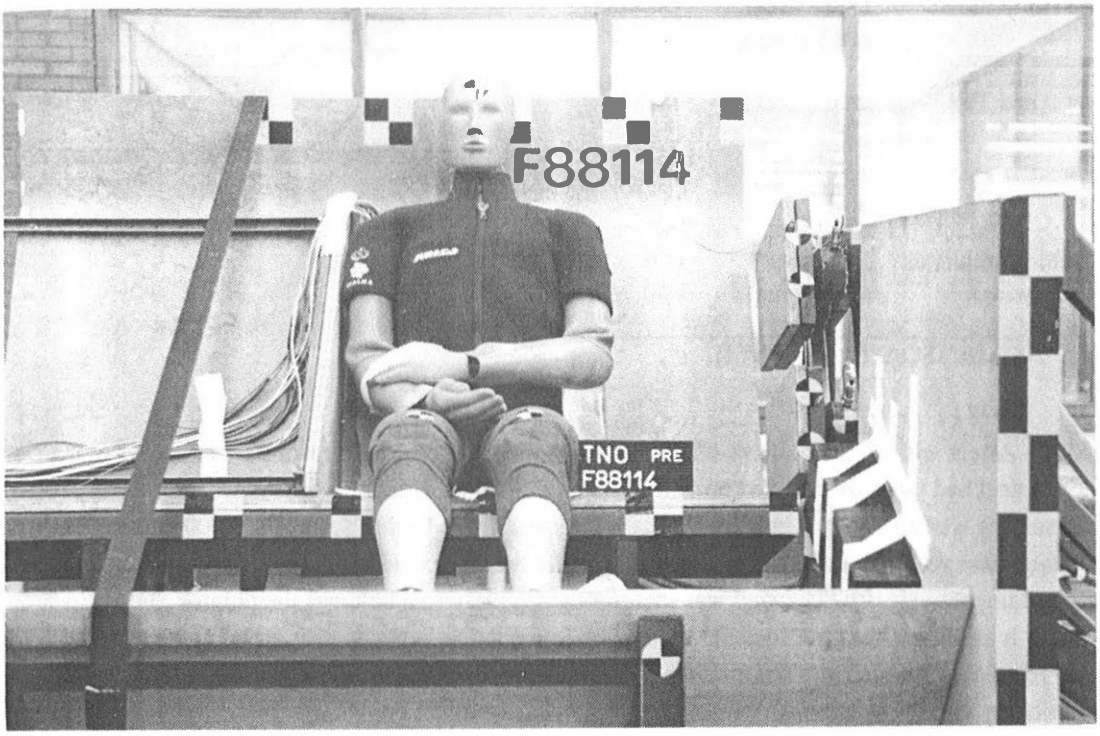


Figure 4. Initial dummy position.

Test results

Introduction - No mechanical failures have been observed in these tests. However, failures of the lower rib deflection transducer were observed in all 24 km/h and 32 km/h tests. These responses have been successfully corrected according to a specially developed method as specified in ref. [8].

Analysis of the high speed movies of the first 16 km/h test (no. 88101) showed that the impact surfaces were vibrating heavily due to the sled impact. Therefore the stiffness of the side panel structure has been improved after this test. The responses of EUROSID in the first test are probably influenced by these vibrations.

Table 3 summarizes the test results. The influence of impact speed and padding are analyzed more in detail in this section. Emphasis is given to the dummy protection criteria.

Influence of impact speed - Table 3 shows that all dummy responses (except rib deflection) increase with an increasing impact speed. This is also illustrated in Figures 5-8. Figure 5 shows an increasing maximum force on both impact surfaces. The force on the pelvic impact surface appears to be much higher than that on the thoracic impact surface. The influence of the impact speed is also clearly illustrated in Figure 6; the maximum thoracic spine and pelvic accelerations show a more or less linear relation with the impact speed.

Figure 7 shows the maximum rib deflection, maximum V.C and maximum TTI (dummy) observed in these tests. The influence of the impact speed is clearly reflected by V.C and TTI (d). The maximum rib deflection can not differentiate between a 24 km/h and a 32 km/h rigid impact, because the bump stop at 50 mm has (almost) been reached. The maximum pubic symphysis force and maximum iliac wing force obviously show the differences in impact speed (see Figure 8).

Since the abdomen is not directly impacted in these sled tests, no abdominal switch contact has been observed.

Influence of padding - Table 3 shows that the padding does not reduce all maximum response values. The elastic performance of the APR-padding caused high dummy rebound velocities and therefore a high velocity change (see also Table 4 and 5). Figure 5 illustrates that the maximum thoracic impact force was hardly affected by the APR-padding. The impulse ($\int Fdt$) was even 25% higher in the padded tests (see also Table 4). The thoracic velocity change in the padded tests was also considerably higher than that in the rigid 32 km/h tests (approx. 22%). The maximum upper spine acceleration appears not to be influenced by the padding (see Figure 6). The bump stop at 50 mm of one (or more) rib(s) has also been reached in the padded tests (see Figure 7). However the slope of the rib deflection versus time response appears to be much less in the padded tests and therefore V.C was also lower (see Figure 7). TTI is based on the maximum rib acceleration and the maximum T_{12} spine acceleration. Since both values, filtered through a 100 Hz FIR filter, decreased in a padded impact, TTI also decreased (see Figure 7). Filtered through SAE CFC 180 the maximum rib acceleration even increased in a padded impact. This is caused by the impact of the rib against the bump stop, illustrated as peak 2 in Figure 9. Peak 3 in this Figure is caused by the rebound of the rib. In a rigid impact the first peak in most cases shows the highest value and therefore this peak (see Figure 9) is also presented in Table 3 as result for the padded tests. This first peak is considered to be the only realistic peak acceleration.

The maximum pelvic impact force appears to be considerably lower in the padded tests (see Figure 5). This was also observed by the maximum pelvic acceleration (see Figure 6) and the maximum pubic symphysis and iliac wing forces (see Figure 8). The pelvic impulse and pelvic velocity change were respectively 16% and 22% higher in the padded tests (see also Table 5).

Table 3. Test results.

Test no. Sled impact speed [km/h] Impact surface		88101 16.4 rigid	88111 16.3 rigid	88112 24.5 rigid	88113 24.1 rigid	88114 32.3 rigid	88115 32.4 rigid	88116 32.2 padded	88117 32.4 padded
Head accel.									
- result. max.	[g]	25.5	18.8	35.3	31.4	100.8	143.4	57.6	63.0
- 3 ms max.	[g]	24.2	18.3	32.3	30.3	44.0	49.5	47.1	48.5
- HIC		41	36	107	100	296	374	281	284
Spine accel.									
- T_1 max.	[g]	20.3	21.7	41.8	40.5	61.2	63.8	60.2	53.8
- T_1 3 ms	[g]	19.8	20.5	39.2	37.1	58.1	56.7	48.1	49.3
- T_1 lat. max.	[g]	19.7	20.7	38.7	36.7	58.0	59.7	59.9	53.5
- T_{12} lat. max.	[g]	-	34.7	83.2	68.8	120.9	105.8	59.5	57.8
Lateral rib accel.									
- max. upper rib	[g]	38.4	63.6	104.9	99.2	132.7	136.9	71.1*	61.5*
- max. middle rib	[g]	55.9	47.4	129.0	146.6	191.8	194.9	59.1*	61.3*
- max. lower rib	[g]	51.2	48.1	121.9	139.3	234.7	246.4	62.3	60.4
Rib deflections**									
- max. upper rib	[mm]	39.6	37.0	47.6	50.1	51.6	51.5	53.1	53.1
- max. middle rib	[mm]	30.5	27.0	38.6	41.0	47.0	45.0	52.6	53.1
- max. lower rib	[mm]	27.0	20.6	33.5	37.3	-	41.0	48.2	48.4
V.C max.									
- upper rib	[m/s]	0.48	0.40	0.91	1.06	1.21	1.34	1.20	1.10
- middle rib	[m/s]	0.37	0.28	0.88	1.11	1.46	1.38	1.18	1.13
- lower rib	[m/s]	0.30	0.21	0.67	0.87	-	1.26	0.87	0.79
TTI (d) max.									
- upper rib	[g]	-	45.8	82.3	78.1	119.1	119.5	69.0	63.1
- middle rib	[g]	-	40.2	95.3	102.7	142.3	141.5	57.6	57.2
- lower rib	[g]	-	39.2	94.2	101.1	156.4	160.2	59.0	58.4
Abdomen									
- switch contact		no	no	no	no	no	no	no	no
Pelvic accel. (CFC 1000)									
- max.	[g]	66.2	54.9	135.9	145.2	227.5	239.7	66.7	69.0
- 3 ms	[g]	51.6	51.5	96.8	80.3	147.1	165.8	62.3	65.0
- lat. max.	[g]	66.2	54.7	134.9	144.4	224.2	238.9	65.9	67.9
Pelvic accel. (CFC 180)									
- max.	[g]	63.6	54.5	128.1	126.9	213.4	216.6	65.3	67.9
- 3 ms	[g]	51.8	51.2	98.7	101.6	144.7	160.8	63.1	65.1
- lat. max.	[g]	63.5	54.3	127.8	126.4	213.4	216.3	64.6	66.9
Pubic symphysis force									
- max.	[kN]	3.98	5.10	12.87	15.01	23.30	30.75	8.50	8.49
- 3 ms	[kN]	3.35	4.80	10.51	11.14	17.86	17.64	7.12	6.42
Iliac wing force									
- max.	[kN]	0.76	0.76	3.61	5.14	9.18	9.67	2.63	2.47
- 3 ms	[kN]	0.68	0.66	2.54	3.90	6.54	6.45	2.57	2.42
Thoracic impact force									
- max. CFC 1000	[kN]	5.74	6.10	12.08	11.01	15.23	16.32	14.41	14.86
- max. FIR 100	[kN]	5.51	5.48	9.44	10.14	14.70	15.16	13.74	14.13
Pelvic impact force									
- max. CFC 1000	[kN]	13.21	16.00	33.84	38.71	61.76	62.54	21.06	21.39

* peak before maximum deflection occurred
** rib deflection >50 mm means maximum deflection

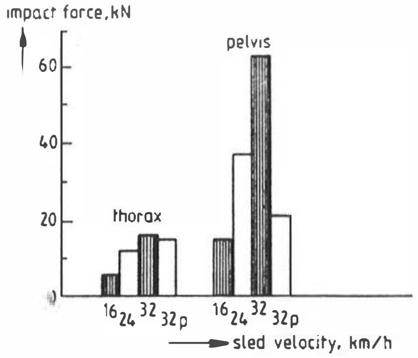


Figure 5. Influence of initial sled velocity and influence of padding on thoracic and pelvic impact forces.

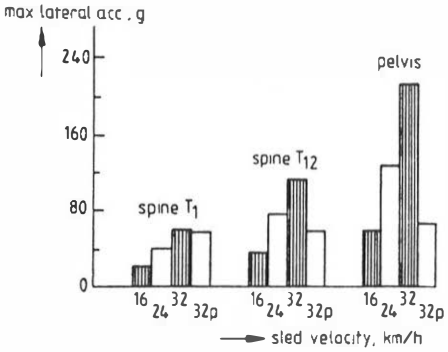


Figure 6. Influence of initial sled velocity and influence of padding on thoracic spine and pelvic accelerations.

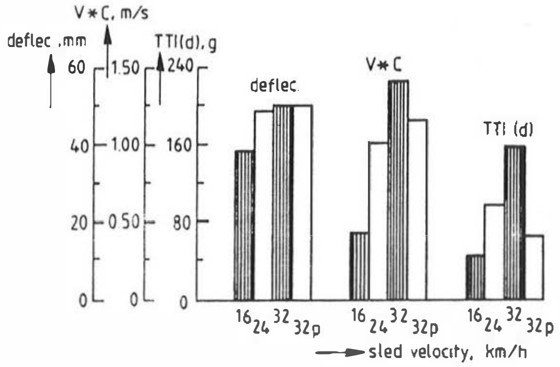


Figure 7. Influence of initial sled velocity and influence of padding on thoracic protection criteria.

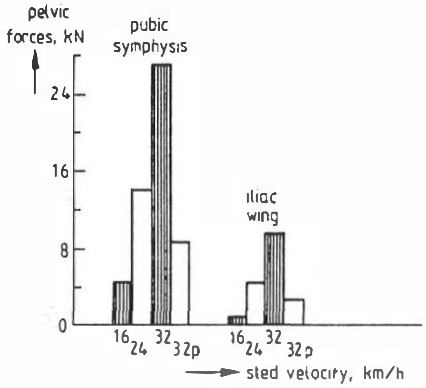


Figure 8. Influence of initial sled velocity and influence of padding on pelvic protection criteria.

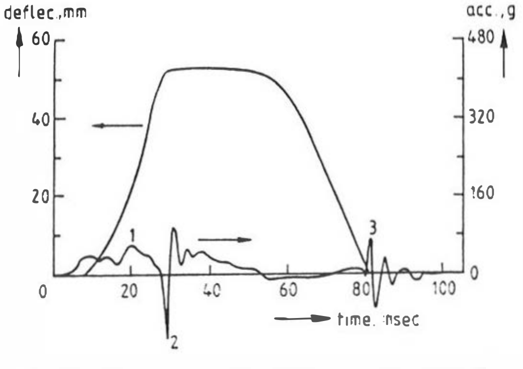


Figure 9. Relation between rib acceleration and rib deflection showing the initial impact (peak 1), the bump stop at 50 mm deflection (causing peak 2) and the rebound impact of the rib (peak 3).

Biofidelity of the EUROSID thorax and pelvis

Introduction - To assess the biofidelity of these body parts documents ISO/DTR 9790-3 [3] and 9790-6 [4] propose thoracic and pelvic responses for a 24 km/h and 32 km/h rigid sled test, as well as for a 32 km/h padded sled tests. In this section the results of the current EUROSID tests are compared with the proposed ISO requirements.

Normalized data - The dummy response requirements described in documents ISO/DTR 9790-3 and 9790-6 (thorax and pelvis) are based on normalized cadaver responses. These cadaver data were normalized to represent the response characteristics of a 50th percentile adult male using the technique described by Mertz [9]. From this procedure a so-called 'effective mass' for the standard subject is selected for each type of impact test (see Appendix 1). ISO references [3] and [4] require that the dummy data is also normalized in order to adjust for changes in effective mass due to slight differences in dummy position at impact. However some uncertainties arise from the described procedures in the ISO documents:

- ISO/DTR 9790-3 refers to the paper of Mertz [9] for the normalization procedure of the thoracic response in the sled tests. In ref. [9] the impact velocity (V_o) has been used to normalize the thoracic response in a drop test, while normally the velocity change (ΔV) should be used (see Appendix 1). It is not clear if V_o or ΔV was used to normalize the cadaver thoracic responses obtained from sled tests. The velocity change (ΔV) is required by ISO/DTR 9790-6 to normalize the dummy pelvic responses, while the cadaver responses were normalized by ISO using the ratio between the 50th percentile adult male body mass and standing height, and the respective cadaver values. In the current tests, the EUROSID responses have been normalized using V_o as well as ΔV.
- The standard effective mass for normalizing the pelvic response in the sled tests prescribed in ISO/DTR 9790-6 is 14.5 kg. This value is based on other tests (impactor tests) using cadavers with other anthropomorphic characteristics, since the required data were not available from the cadavers used in the sled tests. This standard effective mass should represent the effective mass of a 76 kg subject in a similar impact test. However, the calculations from the responses in the current dummy tests show that this effective mass is 2 to 3 times higher. This leads to very large or very small normalizing factors, which are not only based on 'slight differences in impact position'. For the thoracic drop tests a standard effective mass of 50% of the body mass (76 kg) has been selected by Mertz [9]. Therefore a standard effective mass of 38 kg was also selected for normalizing the pelvic response in the current sled tests.

Thoracic response - Table 4 shows the normalized thoracic responses; it appears that the effective mass calculated from ΔV is quite constant and much lower than the effective mass calculated from V_o. Figures 10, 11 and 12 show the normalized impact force versus time responses of EUROSID in the three different test conditions. It appears that the dummy responses are in good agreement with the corridors proposed by ISO.

Pelvic response - Table 5 shows the normalized pelvic responses using the impact velocity as well as the pelvic velocity change. The difference in effective masses calculated from both methods is quite large. ISO ref. [4] requires maximum normalized impact forces which appear to be considerably lower than the values obtained from the current rigid impact tests; 6.4 to 7.8 kN for the 24 km/h rigid tests, and 22.4 to 26.4 kN for the 32 km/h rigid tests. Comparison with Table 5 shows that the results obtained from the current tests are 3 to 5 times higher. The results obtained from the 32 km/h padded tests appear to be 1.5 to 2 times higher than the required 11.6 to 13.6 kN (see also Figure 13). The required maximum normalized pelvic accelerations are 63 to 77 G for the 24 km/h rigid tests, 96 to 116 G for the 32 km/h rigid tests and 61 to 75 G for the 32 km/h padded tests. Comparison with Table 5 shows that the dummy responses in the rigid tests are twice too high, while the response in the padded test is just above (V_o-method) or within the requirements (ΔV-method). Figure 13 summarizes the requirements and dummy responses.

Table 4. Normalized thoracic responses (see Appendix 1).

Test no.		88112	88113	88114	88115	88116	88117
Impulse ∫Fdt	[Ns]	269.3	252.9	316.4	314.7	390.3	394.6
Veloc. change ΔV	[m/s]	8.72	8.63	10.86	10.70	13.10	13.26
Effective mass M_e*	[kg]	39.55	37.80	35.30	34.95	43.61	43.90
Mass ratio R_m		0.96	1.01	1.08	1.09	0.87	0.87
Stiffness ratio R_k		1.0	1.0	1.0	1.0	1.0	1.0
Normalizing factors							
- force R_f		0.98	1.00	1.04	1.04	0.93	0.93
- time R_t		0.98	1.00	1.04	1.04	0.93	0.93
Impact force							
- max. FIR 100	[kN]	9.25	10.17	15.25	15.81	12.81	13.13
Effective mass M_e**	[kg]	30.88	29.31	29.13	29.40	29.79	29.71
Mass ratio R_m		1.23	1.30	1.31	1.29	1.28	1.28
Stiffness ratio R_k		1.0	1.0	1.0	1.0	1.0	1.0
Normalizing factors							
- force R_f		1.11	1.14	1.14	1.14	1.13	1.13
- time R_t		1.11	1.14	1.14	1.14	1.13	1.13
Impact force							
- max. FIR 100	[kN]	10.47	11.55	16.78	17.23	15.50	15.97

* based on V_o
** based on ΔV

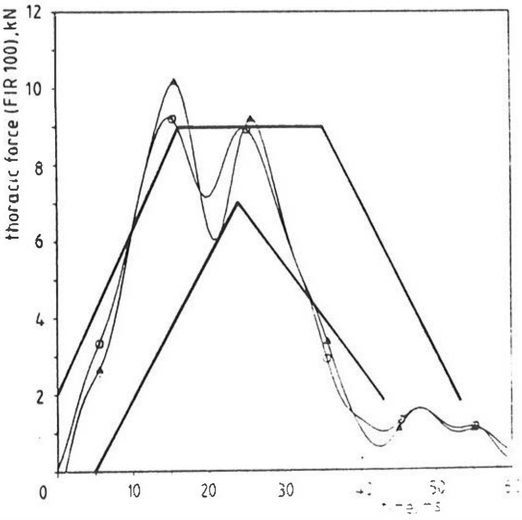


Figure 10. Normalized thoracic impact force vs. time obtained from 24 km/h rigid wall test; EUROSID responses (based on V_o normalization procedure) compared with ISO requirement corridor.

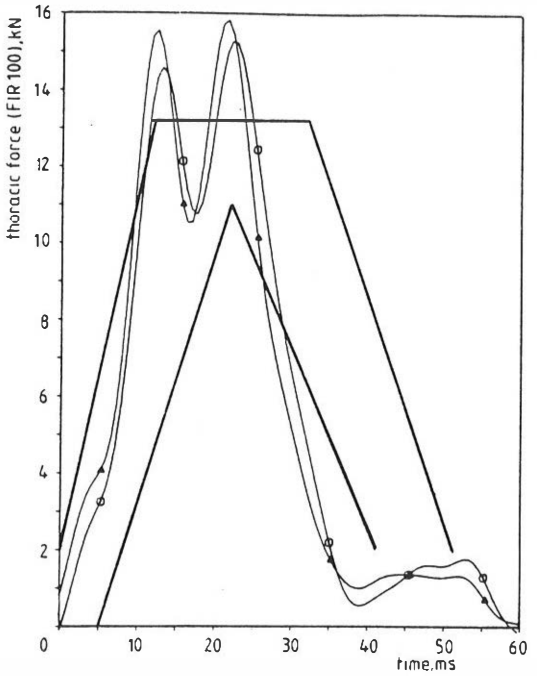


Figure 11. Normalized thoracic impact force vs. time obtained from 32 km/h rigid wall test; EUROSID responses (based on V_0 normalization procedure) compared with ISO-requirement corridor.

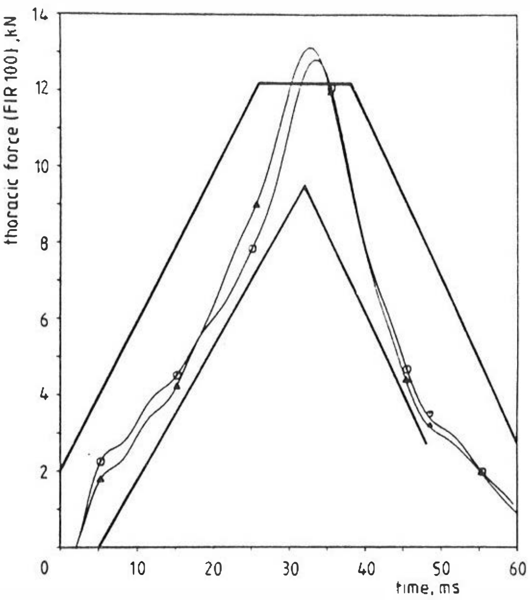


Figure 12. Normalized thoracic impact force vs. time obtained from 32 km/h padded wall test; EUROSID responses (based on V_0 normalization procedure) compared with ISO-requirement corridor.

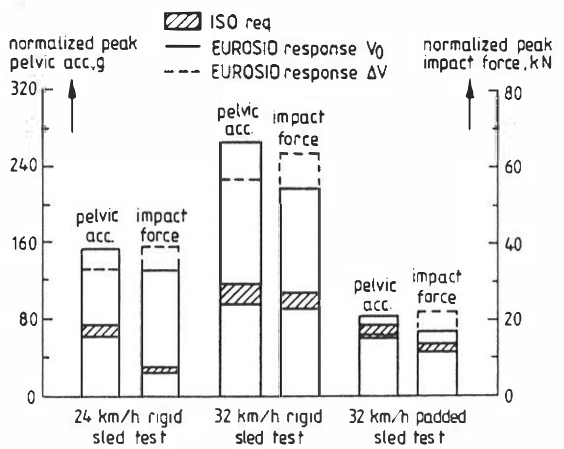


Figure 13. Normalized EUROSID peak pelvic acceleration and normalized EUROSID peak pelvic impact force (both based on V_0 and ΔV normalization procedure) compared with ISO requirements.

Table 5. Normalized pelvic responses (see Appendix 1).

Test no.		88112	88113	88114	88115	88116	88117
Impulse ∫Fdt	[Ns]	304.4	314.5	447.6	456.2	520.6	520.4
Veloc. change ΔV	[m/s]	9.32	9.37	12.57	12.46	15.21	15.11
Effective mass M_e*	[kg]	44.69	47.01	49.94	50.70	58.83	57.90
Mass ratio R_m		0.85	0.81	0.76	0.75	0.65	0.66
Stiffness ratio R_k		1.0	1.0	1.0	1.0	1.0	1.0
Normalizing factors							
- force R_f		0.92	0.90	0.87	0.87	0.80	0.81
- time R_t		0.92	0.90	0.87	0.87	0.80	0.81
- pelvic acc. R_a		1.09	1.11	1.15	1.16	1.24	1.24
Impact force (CFC 1000)							
- max.	[kN]	31.20	34.80	53.86	54.16	16.93	17.32
Lat. pelvic accel.							
- max. CFC 1000	[g]	146.3	160.6	257.1	175.9	82.0	83.8
- max. CFC 180	[g]	138.7	140.6	244.8	249.9	80.3	82.6
Effective mass M_e**	[kg]	32.65	33.58	35.61	36.61	34.22	34.44
Mass ratio R_m		1.16	1.13	1.07	1.04	1.11	1.10
Stiffness ratio R_k		1.0	1.0	1.0	1.0	1.0	1.0
Normalizing factors							
- force R_f		1.08	1.06	1.03	1.02	1.05	1.05
- force R_t		1.08	1.06	1.03	1.02	1.05	1.05
- pelvic acc. R_a		0.93	0.94	0.97	0.98	0.95	0.95
Impact force (CFC 1000)							
- max.	[kN]	36.51	41.19	63.80	63.72	22.20	22.46
Lat. pelvic accel.							
- max. CFC 1000	[g]	125.0	135.8	217.0	234.6	62.5	64.6
- max. CFC 180	[g]	118.5	118.8	206.6	212.4	61.3	63.3

* based on V_0

** based on ΔV

EUROSID injury assessment

Introduction - The ISO thoracic and pelvic response requirements are based on sled tests performed by the University of Heidelberg using human cadavers [7]. The injury severity of the cadavers used to define the requirements for the biofidelity of the thorax in document ISO/DTR 9790-3 are summarized in Table 6. The influence of impact speed and padding seems to be not obvious. Notable is the high number of fractured ribs in the padded tests. Only one pelvic fracture (test no. 82-014) has been observed. In this section the EUROSID protection criteria are also compared with injury severities obtained from other cadaver tests than those used for the ISO requirements.

Table 6. Thoracic injuries of cadavers used to define the ISO biofidelity requirements in ref. [3].

Test no.	Impact veloc. [km/h]	Impact surface	AIS thorax	Number fractured ribs
H-82-015	24	rigid	1	2
H-82-018	24	rigid	3	9
H-82-019	24	rigid	3	7
H-82-014	32	rigid	4	12
H-82-016	32	rigid	2	8
H-82-021	32	padded	4	13
H-82-022	32	padded	4	15

Thoracic protection criteria - Marcus et al. [10] analyzed 42 similar sled tests using human cadavers and calculated the mean thoracic injury severity for different test conditions; 15 mph rigid, 20 mph rigid, 25 mph rigid and 20 mph APR-padded impacts. The injuries have been normalized for cadavers of 45 years. Figure 14 shows the mean number of fractured ribs and the mean AIS relative to the sled impact speed. For a first comparison with the current EUROSID tests the curves have been linearly extrapolated to a 16 km/h rigid impact using the results of the 24 and 32 km/h rigid tests. The reduction in the number of fractured ribs due to the padding appears to be 38%. The AIS of the thorax and the AIS of the hard thorax (includes thoracic spine and abdominal organs) reduce by 28% and 22% respectively (see Table 7). If the injury severities of the 32 km/h padded tests are transferred to their respective curves for the rigid tests (shown in Figure 14), an equivalent rigid impact speed can be calculated resulting in the same injury severities as found in the padded tests. The equivalent rigid impact speed for NFR, AIS and AIS_H is approximately 25 km/h, 26 km/h and 28 km/h respectively (see also Table 7).

Figure 15 shows the thoracic protection criteria obtained from the current dummy tests relative to the sled impact speed. As a first approximation for comparison with the cadaver tests the curves have been linearly extrapolated to a 40 km/h rigid impact using the results of the 24 and 32 km/h rigid tests. The mean deflection shown in Figure 15 is defined as the mean value of the maximum upper rib deflection, the maximum middle rib deflection and the maximum lower rib deflection. Table 7 shows the reduction in maximum rib deflection, in mean rib deflection, in maximum V.C and in maximum TTI (d) for the 32 km/h padded tests compared with the 32 km/h rigid tests. The equivalent rigid impact speed is also presented in Table 7. It appears that V.C. follows the cadaver responses quite good, while the rib deflection overestimates and TTI underestimates the severity of the padded impact.

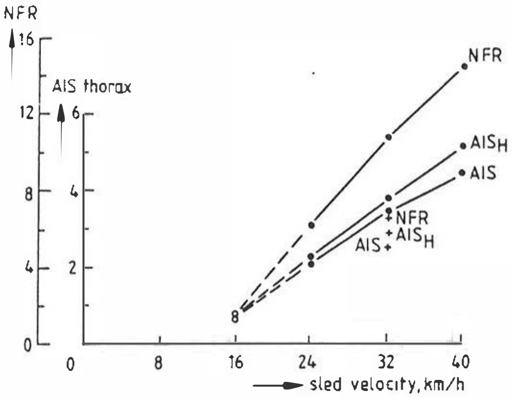


Figure 14. Mean number of fractured ribs and mean thoracic AIS of cadavers in rigid wall (•) and padded wall (+) sled tests based on ref. [10] (AIS_H = hard thorax injuries). Results are linearly extrapolated to 16 km/h rigid wall test (o).

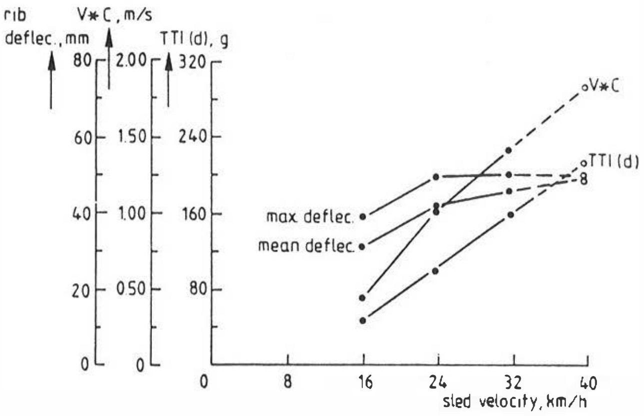


Figure 15. Thoracic protection criteria obtained from EUROSID in rigid wall tests (•) and linear extrapolation to a 40 km/h rigid impact (o).

Table 7. Influence of APR-padding on cadaver injury severity and dummy thoracic protection criteria.

Injury severity/ protection criteria	Reduction due to padding*	Equivalent rigid impact speed* [km/h]
Cadavers:		
- number fractured ribs	38%	25
- AIS thorax	28%	26
- AIS hard thorax	22%	28
Dummy:		
- max. rib deflection	0%	32
- mean rib deflection	-7%	37
- V.C max.	18%	27
- TTI max.	58%	19

* see text

Figure 16 shows a cross-plot of the cadaver injuries (obtained from Figure 14) and the maximum dummy V.C (obtained from Figure 15). The correlation between NFR or AIS and V.C appears to be good (partly caused by the linear extrapolations). The results of the padded tests are also shown, however they were not used for the regression curve. In these test conditions a thoracic AIS 2 would correspond with a maximum EUROSID thoracic V.C of 0.93 m/s, while AIS 3 corresponds with 1.29 m/s.

A similar analysis has been performed for the (hard) thoracic AIS and TTI (d). Figure 17 shows the results. As mentioned before TTI underestimates the severity of the padded impacts; for instance the results of the padded tests presented in Figure 17 are located too much to the left side of the figure.

The maximum rib deflection and the mean value of all ribs are plotted against AIS and NFR in Figure 18 and Figure 19 respectively. It appears that a thoracic AIS 2 or 6 fractured ribs correspond to a mean rib deflection of 41 mm and a maximum rib deflection of 48 mm. The results of the padded tests are also presented in Figure 18 and 19; as mentioned before the severity of the padded impact appears to be overestimated by the rib deflection.

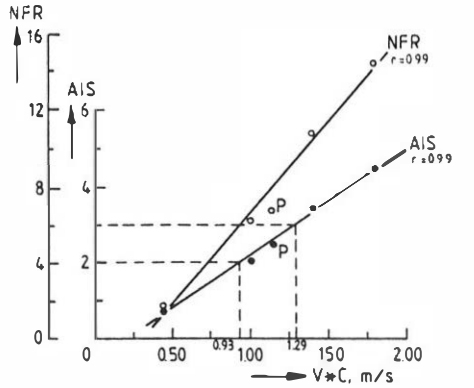


Figure 16. Cross-plot of thoracic cadaver injuries (see Figure 14) and maximum V.C obtained from similar EUROSID tests (see Figure 15). P = padded tests.

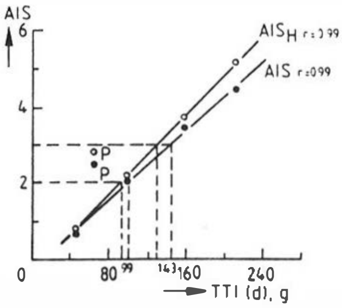


Figure 17. Cross-plot of (hard) thoracic AIS obtained from cadaver tests (see Figure 14) and maximum TTI obtained from similar EUROSID tests (see Figure 15). P = padded tests.

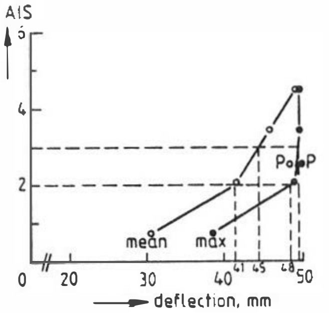


Figure 18. Cross-plot of thoracic AIS obtained from cadaver tests (see Figure 14) and the maximum (•) and mean (o) rib deflection obtained from EUROSID tests (see Figure 15). P = padded tests.

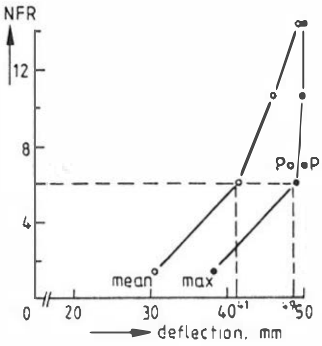


Figure 19. Cross-plot of number of fractured ribs obtained from cadaver tests (see Figure 14) and the maximum (•) and mean (o) rib deflection obtained from EUROSID tests (see Figure 15). P = padded tests.

Pelvic protection criteria - Only 5 pelvic fractures have been observed in 44 rigid and padded wall sled tests performed by the University of Heidelberg and HSRI [11]. They were found in 32 km/h and 40 km/h rigid impacts, as well as in a 36 km/h impact against a vehicle door. No injuries were found in the 24 km/h rigid or 32 km/h padded tests. The 3 ms maximum pelvic acceleration of EUROSID in a 24 km/h rigid test is approximately 100 g, while the 3 ms maximum pubic symphysis force and iliac wing force appear to be 10.8 kN and 3.2 kN respectively. The values obtained from a 32 km/h padded tests appear to be much lower, so the above mentioned values could be considered as non-injury producing limits.

Discussion and conclusions

A series of rigid and padded wall sled tests has been performed to assess the biofidelity of the European Side Impact Dummy. The test set-up was based on ISO proposals. The dummy responses have been normalized as required by ISO/DTR 9790-3 and 9790-6, however with some modifications. A standard effective mass of 38 kg rather than 14.5 kg has been used to normalize the pelvic responses. This was done to obtain more realistic normalization factors. Furthermore the dummy responses have been normalized using the impact velocity as well as the velocity change.

The normalized thoracic impact force versus time responses in the rigid as well as padded impacts appear to be in good agreement with the ISO requirements. The normalized pelvic impact force and acceleration appear too high in the rigid impacts, while they are more in agreement with the cadaver responses in the padded impacts. It should be noted that a padded impact will be more typical of the occupant-to-door impacts experienced in side crashes than rigid impacts. The biofidelity of the production prototype EUROSID seems to be satisfactory in this respect (see also ref. [2]).

The influence of the sled impact speed is clearly demonstrated by most EUROSID responses; a more or less linear relation with the impact speed has been observed. The ribs bottom out after a deflection of 50 mm, causing a non-linear relation above an impact speed of approximately 25 km/h. All dummy responses, except the rib deflection, show a lower maximum in the 32 km/h padded test than in the 32 km/h rigid test. TTI assesses the severity of the padded test even lower than the 24 km/h rigid test; the equivalent rigid impact speed appears to be 19 km/h. Maximum V.C assesses the padded test as a 27 km/h rigid impact, which appears to be quite similar to the results of cadaver sled tests. The maximum rib deflection was also reached in the padded tests. The cadaver injuries found in similar tests were sometimes very severe (AIS = 4), so it seems reasonable that the maximum rib deflection indicates an overload condition.

Comparison of cadaver injury severities and dummy protection criteria shows the injury assessment capabilities of EUROSID. It seems that the mean value of the three maximum rib deflections is quite well able to differentiate between AIS 2 and AIS 3 thoracic injuries; corresponding values (in this test condition !) are 41 and 45 mm deflection respectively. The values for V.C max. and TTI max. corresponding with an AIS 2 to AIS 3 thoracic injury are 0.93 m/s to 1.29 m/s and 99 g to 143 g respectively.

It seems that due to the nature of the pelvic force responses a 3 ms maximum criterion is preferable to a single maximum. Since only a few pelvic injuries were found in all cadaver tests, no obvious relation with the EUROSID protection criteria could be seen. However, a limit of 100 g for the 3 ms maximum pelvic acceleration and of 10 kN for the 3 ms maximum pubic symphysis force seems suitable for this test condition.

Acknowledgements

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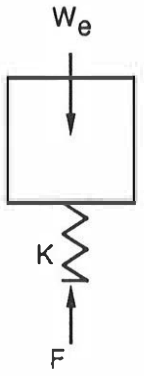
APPENDIX 1

Mertz [9] showed that for normalizing purposes a cadaver subject during impact with an impact surface can be replaced by a simple spring-mass system (see Figure below). A mass, known as the "effective mass" M_e, can be determined that produces the same interaction impulse and velocity change as that experienced by the cadaver. Reference to impulse-momentum consideration gives,



$$\int_0^T F\,dt = W_e V_o / g + W_e T$$

$$\rightarrow \quad W_e / g = \left[\int_0^T F\,dt \right] / (V_o + Tg) = M_e$$

where F - load on subject due to interaction with impact surface

T - impact duration

g - acceleration of gravity

V_o - initial velocity

K - stiffness of subject

W_e - effective weight of subject

M_e - effective mass

Mertz selected an effective mass for a standard subject M_s. The average percentage body weight involved in the cadaver tests has been calculated and this percentage applied to the 50th percentile adult male's body mass (76 kg). The result is known as the standard effective mass M_s. The mass ratio used to normalize the cadaver data is,

$$R_m = M_s / M_e$$

The stiffness ratio is defined as:

$$R_k = K_s / K_i$$

where K_s is the stiffness of a standard subject and K_i of the i-th cadaver.

Mertz [9] calculated normalizing factors based on this procedure for force, acceleration, displacement and time:

$$R_f = (R_m)^{1/2} (R_k)^{1/2}$$

$$R_a = (R_k)^{1/2} (R_m)^{-1/2}$$

$$R_x = (R_m)^{1/2} (R_k)^{-1/2}$$

$$R_t = (R_m)^{1/2} (R_k)^{-1/2}$$

Documents ISO/DTR 9790-3 to 9790-6 require that the dummy data be normalized in order to adjust for changes in effective mass due to slight differences in dummy position at impact. The velocity change ΔV for the calculation of M_e should be obtained from integration of the dummy acceleration-time curve:

$$M_e = \left[\int_0^T F\,dt \right] / (Tg + \Delta V)$$

where $\Delta V = \int_0^T a \, dt$ (if the acceleration time response is not available, ISO uses V_0 as an estimate of ΔV).

For non-drop tests, e.g. impactor and sled tests, the equation reduces to:

$$M_e = \left[\int_0^T F dt \right] / (\Delta V)$$

It is assumed that the stiffness ratio R_k for dummies is equal to 1, so the normalizing factors are based on R_m only.