EUROPEAN COMMISSION
DG RESEARCH

SIXTH FRAMEWORK PROGRAMME

MARIE CURIE RESEARCH TRAINING NETWORKS

MYMOSA

Motorcycle and motorcyclist safety

Deliverable no.	e.g. 3.1
Dissemination level	Public
Work Package	WP 3: Personal protective equipment
Author(s)	Mazdak Ghajari, Gaetano D. Caserta, Ugo Galvanetto, Imperial College London
Title	Comparison of safety helmet testing standards
Status (Final, Draft)	Final
File Name	WP31_310308.doc
Project Start Date and Duration	01 October 2006 - 30 September 2010

COMPARISON OF SAFETY HELMET TESTING STANDARDS ECE 22.05 – Snell M2005 – AS/NZS 1698 - BS 6658 – FMVSS 218

By:
Mazdak Ghajari, Davide G. Caserta and Ugo Galvanetto
Department of Aeronautics
Imperial College London

Abstract: The present document compares several safety helmet standards in force in different parts of the world with the EU standards ECE 22_05. Initially the parts of the ECE 22_05 concerning mechanical testing are summarised, then BS 6658:1985 (UK), FMVSS 218 (USA), Snell M2005 and AS/NZS 1698 are examined and the main differences with respect to the ECE 22_05 are highlighted. Numerical simulations are used to present the example of a helmet satisfying the ECE 22_05, but failing the tests required by other standards.

TABLE OF CONTENTS

1 Introduction 5

1.1 Brief overview of a few results of the COST action 5

1.2 Definition of helmet components 8

2 Main aspects of the European standards ECE 22.05 9

2.1 Definitions 10

2.2 Impact Absorption tests 11

2.2.1 Positioning of the helmet 11
2.2.2 Impact Speed 11
2.2.3 Output parameters 11
2.2.4 Headforms 11
2.2.5 Test apparatus 12
2.2.6 Impact points 13
2.2.7 Combination of conditioning and anvils 13
2.2.8 Approval Limits 14

2.3 Tests for projections and surface friction 14

2.3.1 Method A 14
2.3.2 Method B 16

2.4 Rigidity Test 17

2.5 Retention System Assessing Test 19

2.6 Retention Detaching Test (Roll-off test) 19

3 Comparison between ECE 22.05 and other helmet testing standards 20

3.1 Definitions 20

3.2 Conditioning 22

3.3 Impact Absorption Tests 23

3.3.1 Test apparatus 23
3.3.2 Headforms 24
3.3.3 Impact Initial Conditions 24
3.3.4 Output Parameter(s) and Approval Limit(s) 25
3.3.5 Impact points 25

3.4 External Projections and Surface Friction 27

3.5 Penetration test 28

3.6 Retention System Assessing Tests 29

3.7 Roll off Test 30

3.8 Chin Bar Impact Test 30

4 Conclusions 31

5 APPENDIX: SIMULATION OF IMPACT ABSORPTION TESTS 32

6 References 36

TABLES

Table 2.1: Mechanical tests required by ECE 22.05. 9
Table 2.2: General characteristics of the test headforms. 11
Table 2.3: Combination of conditioning and anvils. 13
Table 3.1: Extent of protection in Snell M2005 and AS/NZS 1698. 20
Table 3.2: Conditionings required by different standards. 22
Table 3.3: Anvils for impact absorption test of different standards. 24
Table 3.4: Impact initial conditions for different standards. 25
Table 3.5: Output parameters and relevant limits for five helmet testing standards. 25
Table 3.6: Sequence of testing for BS 6658. 26
Table 3.7: Specifications of penetration resistance test in Snell M2005, AS/NZS 1698, BS 6658, FMVSS 218. 28
Table 3.8: Specification of retention system assessing tests. 29
Table A1: results of finite element simulation of impact test according to three standards. 34

FIGURES

Figure 1.1: Collision types in relation to the head injury severity. 6
Figure 1.2: Statistical data on damage caused by motorbike accidents. 7
Figure 1.3: Main parts of a protective helmet (ECE 22.05). 8
Figure 2.1: Minimum extent of protection in ECE 22.05 standard. 10
Figure 2.2: Impact absorption test machine. 12
Figure 2.3: Identification of impact points. 13
Figure 2.4: Example of a suitable apparatus for projections and surface friction (method A). 15
Figure 2.5: Example of a suitable apparatus for projections and surface friction (method B). 17
Figure 2.6: Longitudinal and transverse loading directions for rigidity test. 17
Figure 2.7: Example of a suitable test apparatus for dynamic test of retention system. 18
Figure 2.8: Example of a suitable test apparatus for retention system detaching test. 19
Figure 3.1: Definition of test line and extent of protection in Snell M2005 and AS/NZS 1698. 21
Figure 3.2: Definition of extent of protection in BS 6658. 21
Figure 3.3: Definition of test line and extent of protection in FMVSS 218 where all appendices mentioned in the figure can be found. 22
Figure 3.4: definition of impact points for BS 665. 27
Figure 3.5: setup of chin bar test in Snell M2005 and BS 6658 standards, (b) setup of the proposed chin bar test (Chang et. al. (2000)). 31
Figure A1: helmet-headform finite element model (a) full helmet, (b) model for symmetric cases. 32
Figure A2: resultant linear acceleration at the center of gravity of the headfrom “O” for impacts against flat anvils and at (a) point B, (b) point P, (c) point R, and (d) point X. 33
Figure A3: resultant linear acceleration at the center of gravity of the headfrom “O” for impacts at points B, P, R and X according to (a) ECE 22.05, kerbstone anvil, (b) Snell M2005, hemispherical anvil, and (c) AS/NZS 1698, hemispherical anvil. 34
Figure A4: AIS head versus head impact speed (COST 327 (2001)). 35

1 Introduction

According to COST 327 [7] in total there are some 8.6 million motorcycles (not counting mopeds) in the 15 European countries, and approximately 5 thousand fatalities annually, accounting for a substantial proportion (16%) of total road fatalities. Although the number of fatalities in motorcyclists' accidents is high in comparison with motorcycle use, the almost only equipment that prevents motorcyclists from fatal injuries is the helmet. Results of a statistical investigation about motorcycle accidents in US from 2000 to 2002 revealed that about 51% of the unhelmeted riders suffered head injury as compared to 35% of the helmeted riders. This report concluded that "slightly more than half of the unhelmeted motorcyclists had one or more injuries to their head as compared to slightly more than a third of the helmeted motorcyclists" [14].

In order to assess performance of helmets in accidents, they are tested according to one of the accepted helmet testing standards. Almost all the standards follow the same concepts in evaluation of effectiveness of the helmets during accidents, which are:

- the helmet shall be able to absorb impact energy
- it shall remain on the head during accident phenomenon
- it shall resist penetration.

However, details of procedures in force in various countries are different. Hence, it is probable that a helmet satisfying the requirements of a standard will not comply with all requirements of another standard.

In this report the main procedures of five standards for testing of motorcycle helmets will be compared: ECE 22.05 (EU-2000), BS 6658 (UK-1985), FMVSS 218 (USA-2003), Snell M2005 (USA-2005) and AS/NZS 1698 (2006).

A brief summary of the main information collected from accident data (COST 327 [7]) will be given first, in the present section, in order to provide a framework in which testing of safety helmet should be included. Then a detailed description of the main testing procedures required by the European standards ECE 22.05 will be given in section 2. It should be mentioned that the emphasis of this report is on mechanical testing of motorcyclist's helmet, therefore several issues concerning other aspects of the helmets will not be treated in any detail. Section 3 will present the comparison among the five different regulations previously mentioned with a few comments by the authors. The report will be concluded by a conclusion section and the list of references. The interested reader might find interesting the appendix on virtual simulations of impact tests prescribed by different standards.

1.1 Brief overview of a few results of the COST action

The EU COST action 327 has carried out a study about impact configurations and severity injuries related to them, on the basis of the accident data reported on National Statistics of UK, Germany and Finland. In figure 1.1, taken from the final report of the COST action 327, the correlation between collision types and body injuries is reported:

Table 3.9 Collision types in relation to the maximum injury severity

Collision types		Total	Maximum Injury Severity of motorcyclists			
		n=140	Uninjured	MAIS 1	MAIS 2-4	MAIS 5/6
		100%	---------------------------- 100% --------------------------			
type 1		1.5%	-	50.0%	50.0%	-
			100.0%	-	-	-
type 2		9.2%	-	8.3%	33.3%	58.3%
			16.7%	8.3%	16.7%	58.3%
type 3		14.6%	5.3%	42.1%	31.6%	21.1%
			52.6%	10.5%	21.1%	15.8%
type 4		28.5%	-	51.4%	29.7%	18.9%
			51.4%	18.9%	24.3%	5.4%
type 5		4.6%	-	50.0%	50.0%	-
			50.0%	50.0%	-	-
type 6		-	-	-	-	-
type 7		41.5%	1.9%	25.9%	29.6%	42.6%
			20.4%	24.1%	31.5%	24.1%

Source: COST database;
Shadowed fields: Collision types in relation to the maximum head injury severity. n=271 total of which 131 were unknown.

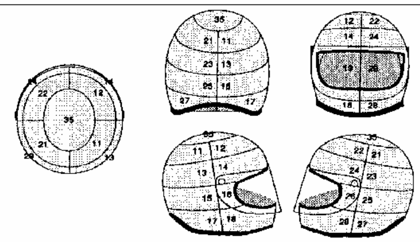
Figure 1.1: Collision types in relation to the head injury severity.

As it can be seen, a part from the collision type 7, which in reality corresponds to several different types of accident, the most dangerous impact configurations are the frontal collisions (types 2) in which severe injuries are the most likely to occur (high percentage of MAIS 5/6), whereas the most frequent collision types are the lateral impacts (types 3 and 4). The following figure 1.2 shows impact location on the helmet and head injuries related to the shape of the impacted object.

The data of the figure below show that impacts on the crown are rare, whereas other locations are impacted with similar frequencies. Unfortunately it is not clear what the words 'round' and 'flat' mean in this figure since, if the radius of curvature of the impacted object is significantly bigger than that of the helmet, then the object could be considered flat for most purposes concerning helmet testing. It is interesting to observe that the authors did not consider the opportunity to classify impacts against sharp objects, those which could penetrate in the shell. That is probably an indication of the fact that such a case is particularly rare.

Chapter 3

Table 3.5 Location of the external damage to the helmet



	Total		Type of damage							
			deformation		laceration		crack		other	
Location on helmet	n	%	N	%	n	%	n	%	n	%
Crown Section 35	17	2.2	3	17.6	12	70.6	2	11.8	-	-
Lateral right Sections 11 to 19	212	26.9	39	18.4	151	71.2	20	9.4	2	0.9
Lateral left Sections 21 to 29	207	26.3	44	21.3	123	59.4	40	19.3	0	0.0
Frontal Even sections 12 to 28 (excluding 20) plus 19 and 39	186	23.6	28	15.1	115	61.8	41	22.0	2	1.1
Rear Odd sections from 11 to 27 (excluding 17 and 19) plus 16	166	21.0	24	14.5	129	77.7	11	6.6	2	1.2
Total	788	100	138	17.5	530	67.3	114	14.5	6	0.8

Source: COST database; (100%= all damages of each sector)

**Table3.6 Head injury severity related to impact target shape.
(100%=all head injuries)**

	shape of impact objects									
	total		round		edge		flat		no information	
AIS Head	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
uninjured	80	32.0	61	30.5	2	20.0	9	39.1	8	47.1
AIS 1	47	18.8	37	18.5	1	10.0	6	26.1	3	17.6
AIS 2	27	10.8	25	12.5	-	-	1	4.3	1	5.9
AIS 3	20	8.0	13	6.5	1	10.0	2	8.7	4	23.5
AIS 4	18	7.2	14	7.0	2	20.0	2	8.7	-	-
AIS 5	30	12.0	25	12.5	4	40.0	1	4.3	-	-
AIS 6	28	11.2	25	12.5	-	-	2	8.7	1	5.9
Total	**250**	**100**	**200**	**100**	**10**	**100**	**23**	**100**	**17**	**100**

25

Figure 1.2: statistical data on damage caused by motorbike accidents.

In order to guarantee an acceptable level of safety, helmets have to meet specific requirements, in terms of mechanical (and chemical) properties, impact resistance, energy absorption and efficiency of retention system, specified by the currently available standards. (Impact resistance is intended as the protection of the head from penetrating objects during an accident, while energy absorption is a way to reduce the load transmitted to the head).

The various available standards establish minimum performance requirements for motorbike helmets, prescribing particular tests. In general Standards provide directions about

1) the choice of the points of the helmets where impacts have to be performed;
2) the shape of struck objects;

3) the velocity or energy of the impacts
4) the temperature at which the impacts take place

1.2 Definition of helmet components

A standard motorcyclist's helmet is made of four main parts as shown in figure 1:

- The shell of the helmet is the external component which directly experiences the impacts. Its duties are: prevention from penetration of very localized loads, distribution of external load on a larger area of the underlying component which is the liner and contribution to impact energy absorption. Shells are usually made of thermoplastic materials or composites.
- The protective padding, or liner, is composed of crushable foam which provides the main contribution to absorb impact energy.
- Comfort padding, or comfort foam, is made of easily deformable foam, and provides the best fit to the wearer's head.
- Retention system, or chin strap, should retain the helmet on the head during an impact or a series of impacts.

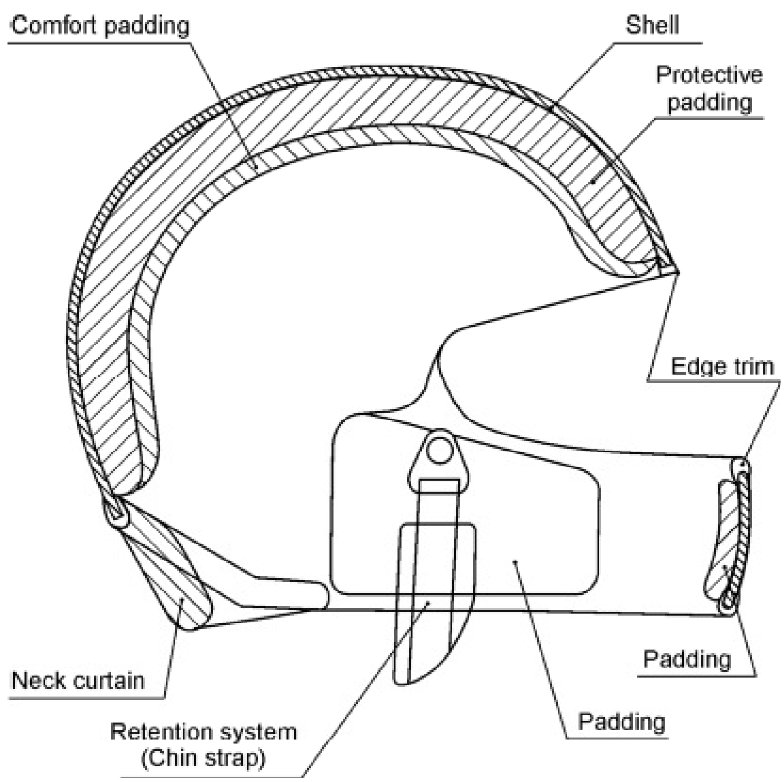


Figure 1.3: Main parts of a protective helmet (ECE 22.05).

2 Main aspects of the European standards ECE 22.05

The European standards ECE 22.05 are probably the most commonly used in the world. They are adopted by over 50 countries worldwide (webBikeWorld). Table 2.1 summarizes the mechanical tests required by ECE 22.05. In addition to these tests, ECE 22.05 require that any projection or irregularity greater than 2mm located at the outer surface of the shell be subjected to shear assessment, and outer surface of the shell be subjected to the same test for friction assessment. The following sections are a brief overview of the mechanical tests consisting of the test configuration, initial conditions and approval limit(s).

Table 2.1 Mechanical tests required by ECE 22.05.

Test	Number of Helmets to be conditioned				Total
for the largest size of each helmet type					
	solvent plus ambient-temperature and hygrometry conditioning	Solvent plus heat conditioning	Solvent plus low-temperature conditioning	Solvent plus ultra-violent radiation conditioning and moisture conditioning	
Impact absorption	2	1	1	1	5
Rigidity	2	-	-	-	2
Retention system	1	-	-	-	1
for each smaller headform size within the size range of the helmet type					
Impact absorption	-	1	1	-	2

The types of conditioning cited in Table 2.1 are defined as following:

- Solvent conditioning: the outer surface of the helmet shall become wet by a piece of cotton cloth soaked in a specific solvent 30 minutes before any conditioning or tests.

- Ambient-temperature and hygrometry conditioning: the helmet shall be exposed to a temperature of 25±5ºC and a relative humidity of 65±5% for at least 4 hours.

- Heat conditioning: the helmet shall be exposed to a temperature of 50±2ºC for not less than 4 hours and not more than 6 hours.

- Low-temperature conditioning: the helmet shall be exposed to a temperature of -20±2º C for not less than 4 hours and not more than 6 hours.

- Ultraviolet-radiation conditioning and moisture conditioning: the outer surface of the protective helmet shall be exposed successively to ultraviolet irradiation by a 125-watt xenon-filled quartz lamp for 48 hours at a range of 25 cm and spraying for 4 to 6 hours with water at ambient temperature at the rate of 1 litre per minute.

2.1 Definitions

All standards define reference planes, lines and points in order to clearly specify positions on the helmets to be tested. The following definitions are adopted in ECE 22.05.

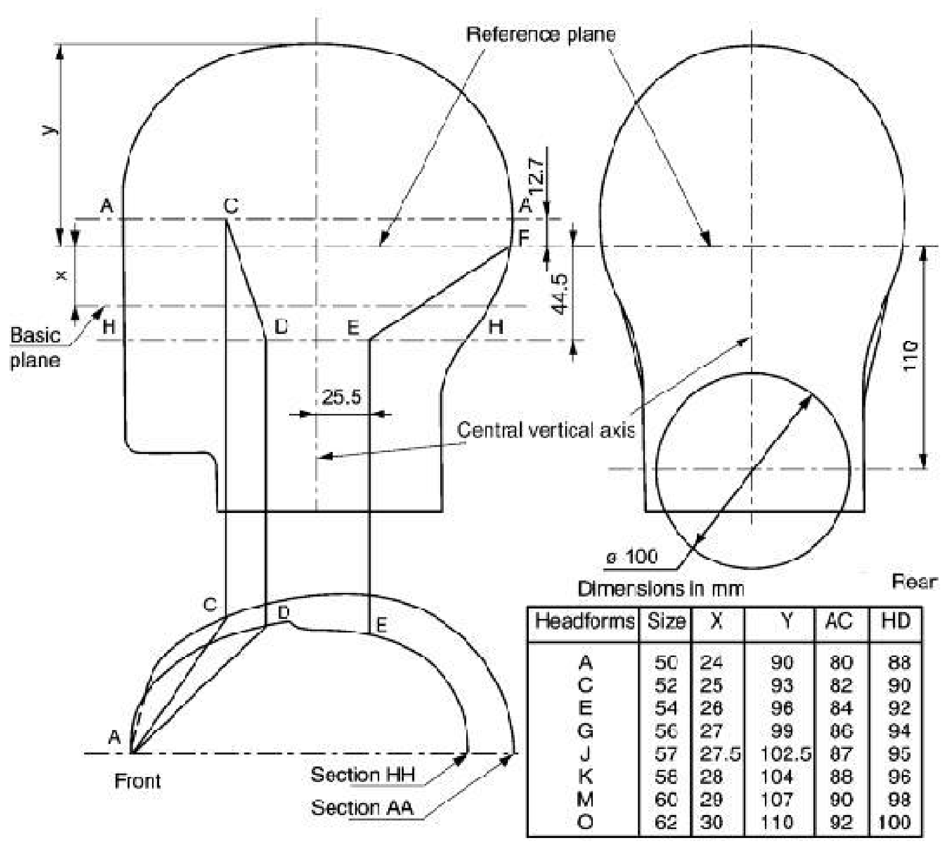
- Basic plane of the human head: means a plane at the level of the opening of the external auditory meatus (external ear opening) and the lower edge of the orbits (lower edge of the eye sockets);

- Basic plane of the headform: means a plane which corresponds to the basic plane of the human head;

- Reference plane: means a construction plane parallel to the basic plane of the headform at a distance from it which is a function of the size of the headform;

- The extent of the protection: The shell shall cover all areas above plane AA' and shall extend downwards at least as far as the lines CDEF on both sides of the headform (Figure 2.1).

At the rear, the rigid parts and, in particular, the shell shall not be within a cylinder in diameter and its axis situated at the intersection of the medium plane of symmetry of the headform and of a plane parallel to and below the reference plane.



Headforms	Size	X	Y	AC	HD
A	50	24	90	80	88
C	52	25	93	82	90
E	54	26	96	84	92
G	56	27	99	86	94
J	57	27.5	102.5	87	95
K	58	28	104	88	96
M	60	29	107	90	98
O	62	30	110	92	100

Figure 2.1: Minimum extent of protection in ECE 22.05 standard.

2.2 Impact Absorption tests

In ECE 22.05, the impact absorption capacity of the helmet is determined by recording against time the acceleration imparted to a headform fitted with the helmet, when dropped in guided free fall at a specific impact velocity upon a fixed steel anvil.

2.2.1 Positioning of the helmet

After conditioning, the helmet shall be positioned on a headform of appropriate size. When testing impact points B, X, P and R (section 2.2.6), helmet shall be tipped towards rear so that the front edge of the helmet in longitudinal vertical plane is displaced about 25 mm. If testing impact point S, the helmeted headform shall be rotated forward until the angle between lateral plane of the headform and vertical line is 65±3º.

2.2.2 Impact Speed

The drop height shall provide an impact speed of 7.5 (+ 0.15/- 0.0) m/s for both flat and kerbstone anvils and 5.5 (+ 0.15/ -0.0) m/s for tests at point S. The sequence of impact points is B, X, P and R. If necessary, impact at point S is after all other impact tests.

2.2.3 Output parameters

During impact the linear acceleration of the headform at its center of gravity is recorded against time. From resultant linear acceleration-time data, the head injury criterion (HIC) is calculated with the following equation:

$$HIC = (t_2 - t_1)(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt)^{2.5} \qquad (1)$$

where $a(t)$ is the resultant acceleration, expressed in multiples of *g*, versus time, in seconds, and t_2 and t_1 are respectively any starting and ending time in impact pulse duration.

2.2.4 Headforms

In ECE 22.05, headforms shall be made from metal and their resonance frequency shall not be less than 3000 Hz. The general characteristics of the test headforms to be used shall be as indicated in Table 2.2. The shape of the test headforms are defined in annexes 6 and 7 of ECE 22.05. The centre of gravity of the headform shall be near the point G on the central vertical axis at "*l*" mm below the reference plane, as shown in figure 2.3. The headform shall contain, near its centre of gravity, housing for a tri-directional accelerometer.

Table 2.2 General characteristics of the test headforms.

Symbols	Circumference (in cm)	Mass (in kg)
A	50	3.1 ± 0.1
E	54	4.1 ± 0.1
J	57	4.7 ± 0.1
M	60	5.6 ± 0.1
O	62	6.1 ± 0.1

2.2.5 Test apparatus

The test apparatus shall comprise of the following tools (Figure 2.2):

- Base: it shall be made of steel, concrete or both and will be at least 500 kg in weight. Natural frequencies of the base or its parts shall not influence the impact results.
- Anvils: two anvils are used in impact tests, which are flat and kerbstone. Flat steel anvil shall have a circular impact area 130±3*mm* in diameter. The kerbstone anvil shall have two sides forming an angle of 105°±3°, each of them with a slope of 52.5°±2.5° towards the vertical and meeting along a striking edge with a radius of 15±0.5*mm*. The height must be at least 50 *mm* and the length not less than 125 *mm*. The orientation is 45° to the longitudinal vertical plane at points B, P, and R, and 45° to the base plane at point X (front low, back up).
- Mobile system and the guides: the mobile system shall provide a free fall for helmeted headform and the guides shall be such that the impact velocity is not less than 95% of the theoretical velocity.
- Accelerometer: its mass shall be less than 50 grams.

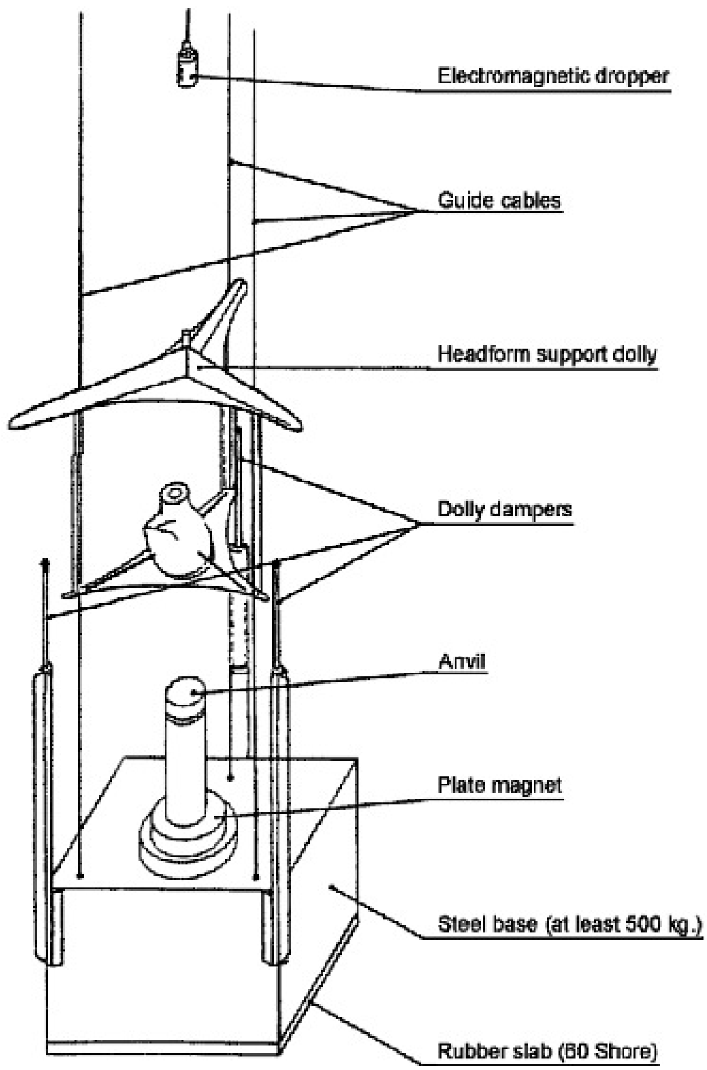


Figure 2.2: Impact absorption test machine.

2.2.6 Impact points

The points of impact are defined for each helmet in Figure 2.3:

B: in the frontal area, situated in the vertical longitudinal plane of symmetry of the helmet and at an angle of 20° measured from Z above the AA' plane.

X: in either the left or right lateral area, situated in the central transverse vertical plane and 12.7 mm below the AA' plane.

R: in the rear area, situated in the vertical longitudinal plane of symmetry of the helmet and at an angle of 20° measured from Z above the AA' plane.

P: in the area with a radius of 50 *mm* and a centre at the intersection of the central vertical axis and the outer surface of the helmet shell.

S: in the lower face cover area, situated within an area bounded by a sector of 20° divided symmetrically by the vertical longitudinal plane of symmetry of the helmet.

Impacts at points B, X and R should be within 10 mm radius of the defined point.

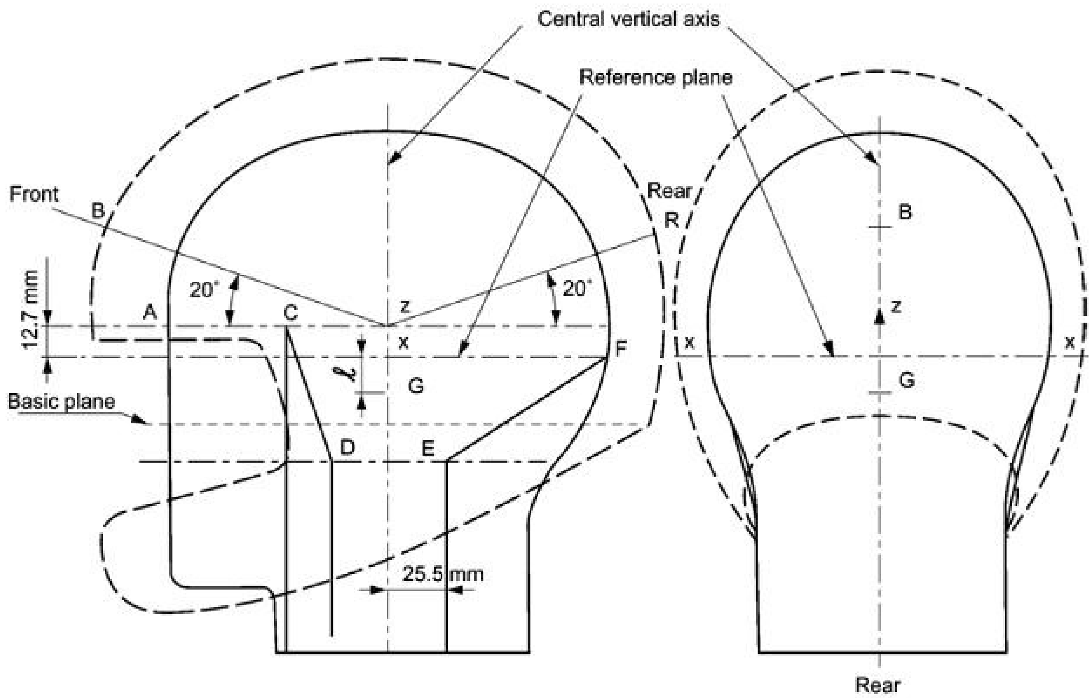


Figure 2.3: Identification of impact points.

2.2.7 Combination of conditioning and anvils

For impact absorption tests, combination of different conditionings and anvils are presented through table 2.3.

Table 2.3 Combination of conditioning and anvils.

	solvent plus ambient-temperature and hygrometry conditioning	Solvent plus heat conditioning	Solvent plus low-temperature conditioning (c)	Solvent plus ultra-violet radiation conditioning and moisture conditioning
(a)	flat and kerbstone	kerbstone	flat	flat or kerbstone

(b)	-	flat or kerbstone	flat or kerbstone	-
a) For the largest size of each helmet type b) For each smaller headform size within the size range of the helmet type c) Only helmets subjected to low temperature conditioning shall be impact tested at point S against only flat anvil.				

2.2.8 Approval Limits

The absorption efficiency shall be considered sufficient where the resultant acceleration measured at the centre of gravity of the headform at no time exceeds 275 g, and HIC does not exceed 2400.

2.3 Tests for projections and surface friction

In ECE 22.05, there are two test methods for testing of projections and surface friction of helmet. Each of them can be used for testing.

2.3.1 Method A

The principle of this method is: “The rotation-inducing forces caused by projections on the helmet and friction against the outer surface of the helmet which occur when a helmeted headform is dropped vertically on to an inclined anvil are measured in the longitudinal axis of the anvil. The peak force and its integral with respect to time over the duration of the positive impulse are used as performance criteria.” The drop height of the helmeted headform shall be such that its velocity, immediately before impact, is equal to 8.5(-0.0/+0.15) m/s. A schematic drawing of the test apparatus is shown in figure 2.4. Its components are the same for impact absorption test with the exception of anvil. The anvil is a minimum 200mm wide surface inclined 15° with respect to the vertical. It is adaptable to carry either of two different impact surfaces as follows:

- The bar anvil consists of a series of at least 5 horizontal bars at 40 mm centres. Each bar is made from a steel strip of height 6 mm and width 25 mm with its uppermost edge machined to a 1 mm radius and the lower 15 mm of its face chamfered at an angle of 15°. The bar anvil should be used to assess the tangential forces and their integrals with time caused by projections on the helmet, e.g. visor fittings, screws, press studs and steps in the shell surface, etc.

- The abrasive anvil is a sheet of grade 80 closed-coat aluminium oxide abrasive paper with a minimum supported length of 225 mm and is securely clamped to the base of the anvil to prevent slippage. The abrasive anvil should be used to assess the tangential forces and their integrals with time caused by friction against the outer surface of the helmet. This is particularly applicable to selected areas of helmets, the outer surface of which either have significant variations of curvature or are made of more than one material.

The headform for these tests is headform characterized by symbol J in table 2.2. Impact points are chosen in a way that all areas that are susceptible to produce greatest tangential force or impulse are tested. Examples of such areas are those having the greatest radius of curvature (i.e. the flattest surface) or areas having more than one type of surface.

Approval limitations depend on the type of anvil used in testing.

a) When tested against the bar anvil, the peak longitudinal force measured on the anvil shall not exceed 2,500 N, nor shall its integral with respect to time over the duration of the impact exceed 12.5 Ns for any of the selected impact points.

b) When tested against the abrasive anvil, the peak longitudinal force measured on the anvil shall not exceed 3,500 N, nor shall its integral with respect to time over the duration of the impact exceed 25 Ns for any of the selected impact points.

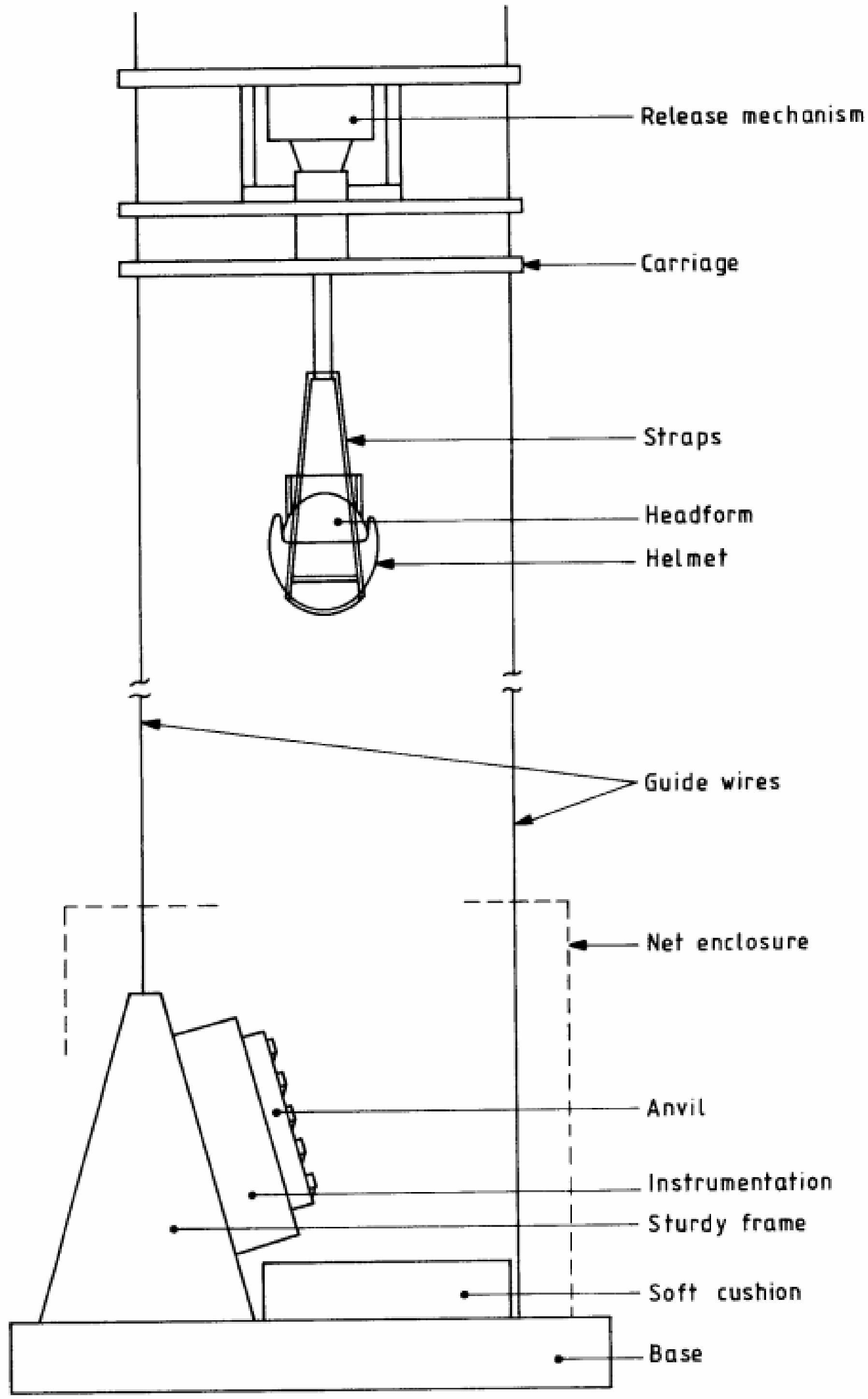


Figure 2.4: Example of a suitable apparatus for projections and surface friction (method A).

2.3.2 Method B

The principle of method B is: “The rotation-inducing forces caused by projections on the helmets and friction against the outer surface of the helmets are assessed firstly by a shear impact on the projections using a shear edge against which the projections shall shear away, be detached, or permit the shear edge to slide past the projections. The friction is assessed by the displacement of a carriage abrading the outer surface of the helmet. The shear impact and abrading carriage displacement are generated by a drop weight device.” The helmet is placed on a headform of appropriate size. Then, it is tipped towards the rear so that the front edge of the helmet in the median plane is displaced by 25 mm.

For testing of projections, the headform is adjusted in order to have the chosen projection on the carriage so that the shear edge is positioned 50 mm from the projection and makes lateral contact with the projection after the drop weight is released from its upper position. For testing outer surface, the abrasive paper is mounted on the carriage. The chosen outer surface of the helmet is lowered on to the abrading carriage at the centre of the flat surface without abrasive paper. For both tests, a loading mass is applied on the helmet.

For friction assessment, the carriage bears a sheet of grade 80 closed-coat aluminium oxide abrasive paper with a supported length of 300.0 (- 0.0/+ 3.0) mm and securely clamped to the carriage to prevent slippage. At its end towards the drop weight and in this direction the carriage has a 80 mm long smooth steel area not being covered by the abrasive paper and higher than the rest of the carriage by the thickness of the abrasive paper plus . For shear assessment, the carriage is provided in the middle, with a bar made from a steel strip of height 6 mm and width 25 mm with its uppermost edges machined to a 1 mm radius. The carriage and either attachment shall have a total mass of 5.0 (- 0.2/+ 0.0) kg.

The horizontal guide which guides and supports the carriage may consist of two cylindrical bars on which the ball bearings of the carriage may freely travel. A wire rope or strap is fixed to the end of the carriage and led to the vertical direction through two rollers which shall have a diameter of at least 60 mm (Figure 2.5). The vertical end of the wire rope or strap is fixed to the drop weight. The drop weight shall have a mass of 15.0 (- 0.0/+ 0.5) kg. For both shear and friction assessments the free drop height shall be 500.0 (- 0.0/ + 5.0) mm with provision for further possible travel of at least 400 mm.

The system supporting the headform shall be such that any point on the helmet can be positioned in contact with the upper surface of the carriage. A rigid lever shall connect the headform support to the test apparatus with a hinge. The height of the hinge pivot above the upper surface of the carriage shall not be greater than 150 mm. A loading system is used to generate a force of 400.0 (- 0.0/+ 10.0) N on the helmet normal to the surface of the carriage.

Any point on the helmet may be selected for friction and/or shear assessment. A helmet shall be tested as many times as necessary to ensure that all notable features are evaluated with one test only per feature. For shear assessment, all different external projections greater than 2 mm above the outer surface of the shell shall be evaluated. For friction assessment, areas of the outer surface that are likely to produce the greatest friction shall be evaluated. The rim of the shell and the upper and lower edge of the visor situated within an area bounded by a sector of 120° divided symmetrically by the vertical longitudinal plane of symmetry of the helmet do not constitute a projection for the purpose of this test.

For shear assessment, the tested projection shall shear away, be detached or alternatively shall not prevent the assessment bar from sliding past the projection. In all cases the bar on the horizontal carriage shall travel past the projection. For friction assessment, the abrasive carriage shall not be brought to rest by the helmet.

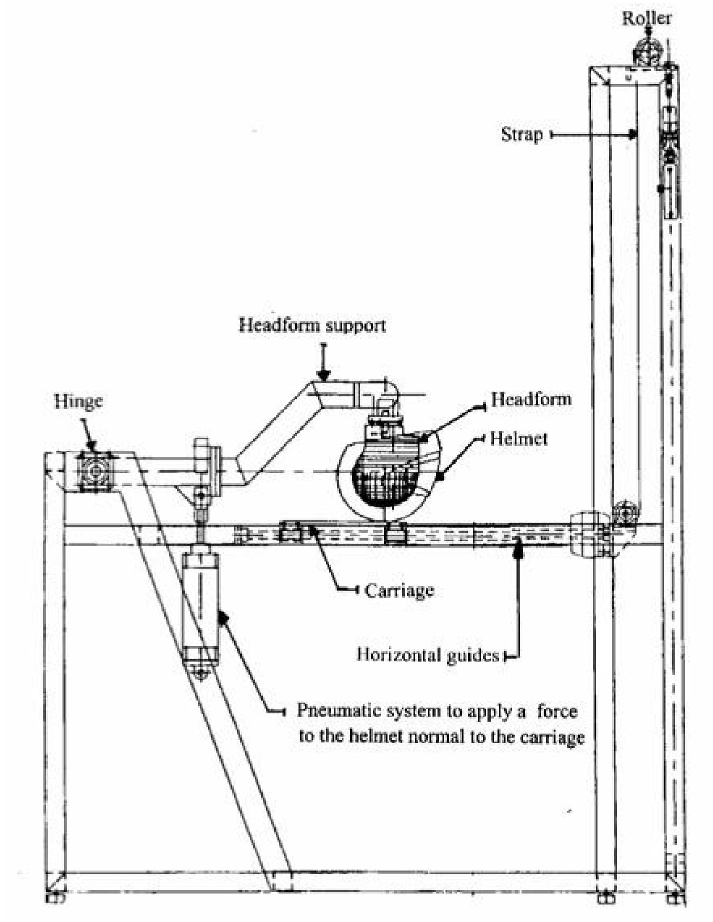


Figure 2.5: Example of a suitable apparatus for projections and surface friction (method B).

2.4 Rigidity Test

The helmet, after undergoing ambient-temperature and hygrometry conditioning, shall be placed between two parallel plates by means of which a known load can be applied along the longitudinal axis (line LL in figure 2.6) or the transverse axis (line TT in figure 2.6).

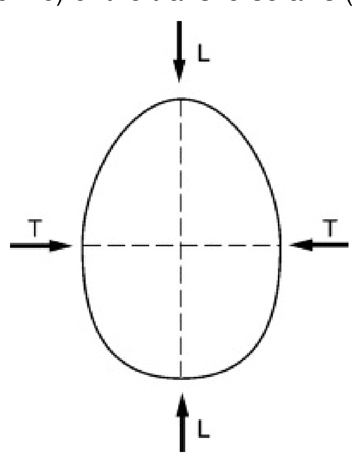


Figure 2.6: Longitudinal and transverse loading directions for rigidity test.

An initial load of 30 N shall be applied, at a minimum plate speed of 20 mm/min, and after two minutes the distance between the two plates shall be measured. Then the load shall then be increased by 100 N, at a minimum plate speed of 20 mm/min, and kept constant for two minutes. This procedure shall be repeated until the application of a load of 630 N. The load applied to the plates shall be reduced to 30 N, at a minimum plate speed of 20 mm/min; the distance between the plates shall then be measured. In the test along each axis, the deformation measured under the 630 N load shall not exceed that measured under the initial 30 N load by more than 40 mm. After restoration of the 30 N load, the deformation measured shall not exceed that measured under the initial 30 N load by more than 15 mm.

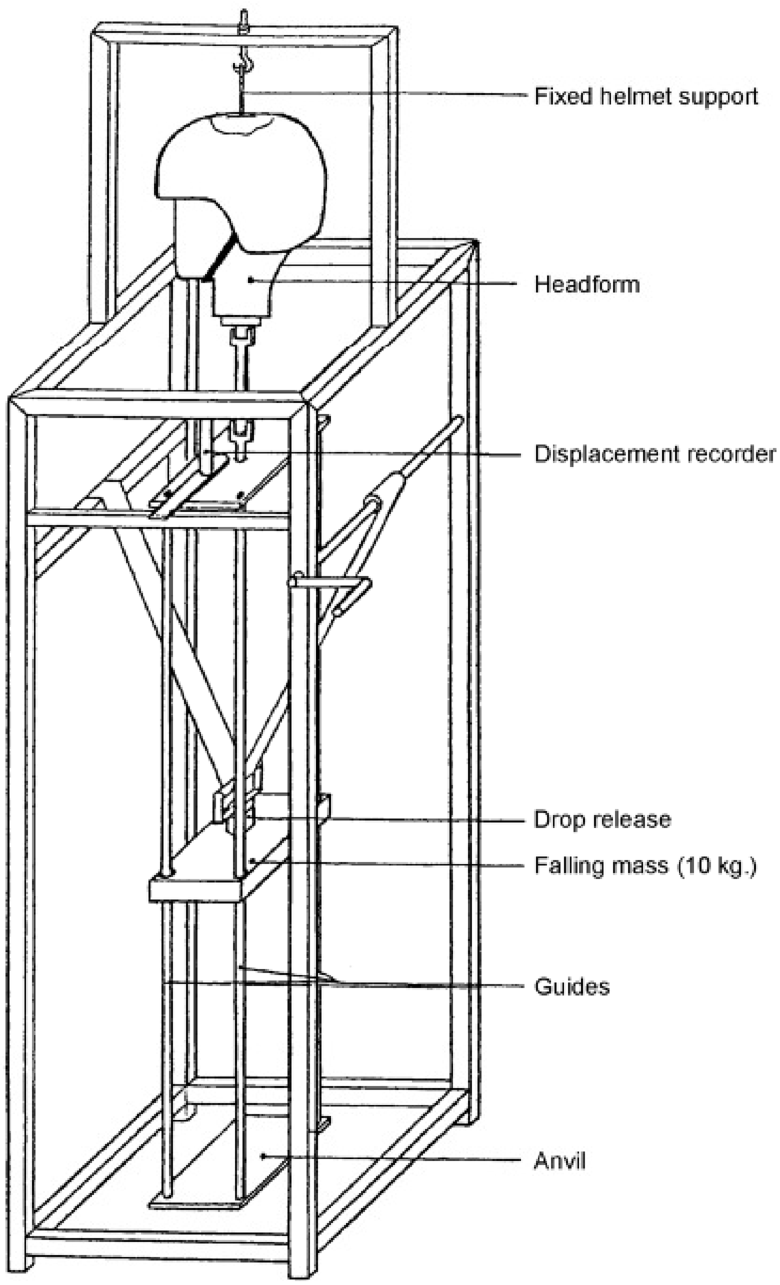


Figure 2.7: Example of a suitable test apparatus for dynamic test of retention system.

2.5 Retention System Assessing Test

The helmet shall be positioned as shown in figure 2.7. In this position the helmet is held by the shell at a point traversed by the vertical axis passing through the centre of gravity of the headform. The headform is equipped with a load-bearing device aligned with the vertical axis passing through the centre of gravity of the headform and with a device to measure the vertical displacement of the point of application of the force. A guide and arrest device for a falling mass shall then be attached below the headform. The mass of the headform so equipped shall be 15±0.5*kg*, which shall be the pre-loading on the retention system for determining the position from which the vertical displacement of the point of application of the force shall be measured. The falling mass of 10±0.1*kg* shall then be released and shall drop in a guided free fall from a height of 750±5*mm*. During the test, the dynamic displacement of the point of application of the force shall not exceed 35 mm. After two minutes, the residual displacement of the point of application of the force, as measured under a mass of 15±0.5*kg*, shall not exceed 25 mm. Damage to the retention system shall be accepted provided that it is still possible to remove the helmet easily from the headform.

2.6 Retention Detaching Test (Roll-off test)

The helmet, previously conditioned at ambient temperature and hygrometry, is attached to the appropriate headform. A device to guide and release a falling mass (the total mass being 3±0.1*kg*) is hooked on to the rear part of the shell in the median vertical plane of the helmet, as shown in figure 2.8. The falling mass of 10±0.1*kg* is then released and drops in a guided free fall from a height of 500±10*mm*. The guiding devices shall be such as to ensure that the impact speed is not less than 95 per cent of the theoretical speed. After the test the angle between the reference line situated on the shell of the helmet and the reference plane of the headform shall not exceed 30°.

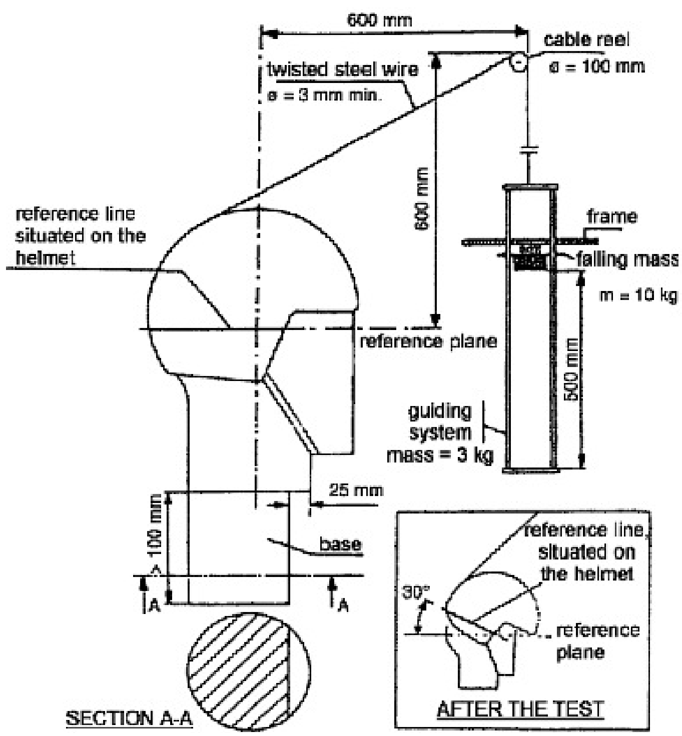


Figure 2.8: Example of a suitable test apparatus for retention system detaching test.

3 Comparison between ECE 22.05 and other helmet testing standards

In the present section a comparison between different standards will be carried out. Only the main aspects of the mechanical-structural testing of motorbike helmets will be considered. The document will compare ECE 22.05 to:

- the British standards BS 6658;
- the U.S. Department of Transportation's Federal Motor Vehicle Safety Standard No. 218 (FMVSS 218);
- another American standard, Snell M2005, which is issued by Snell Memorial Foundation;
- the Australian and New Zealand standards AS/NZS 1698.

The frame of all helmet testing standards is almost the same and similar to what presented in the previous chapter. Nonetheless, there are differences in details of tests such as conditioning, initial conditions, output parameters, approval limits, etc. Furthermore, some criticisms on the current helmet testing standards are added.

3.1 Definitions

- Extent of protection: figure 3.1 accompanied with table 3.1 define the extent of protection required by Snell M2005 and AS/NZS 1698 standards in gray colour.

Table 3.1 Extent of protection in Snell M2005 and AS/NZS 1698 (dimensions in mm).

	Snell M2005					AS/NZS 1698				
Headform	a	b	c	d	e	a	b	c	d	e
A	39.0	128.6	26.1	46.8	52.2	65	153	24.5	59	32.5
E	42.2	139.0	28.2	50.0	56.4	65	159.5	25	64	31
J	45.2	148.4	30.0	53.0	60.0	65	166	25	66	30
M	47.4	155.8	31.5	55.2	63.0	65	171	25.5	67	30
O	49.2	161.5	32.2	57.2	64.5	65	173.5	26	68	30

- Test line: AS/NZS 1698 define the test line as a line denoting the extent of protection of a helmet coinciding with the dimensions given in table 3.1, as shown in figure 3.1 (the boundary of gray area). The test line in Snell M2005 is different from its extent of protection (shown figure 3.1).

According to the BS 6658 standards, the shell shall extend downwards on both sides of the headform at least as far as the lines CDEF here reported again in figure 3.2.

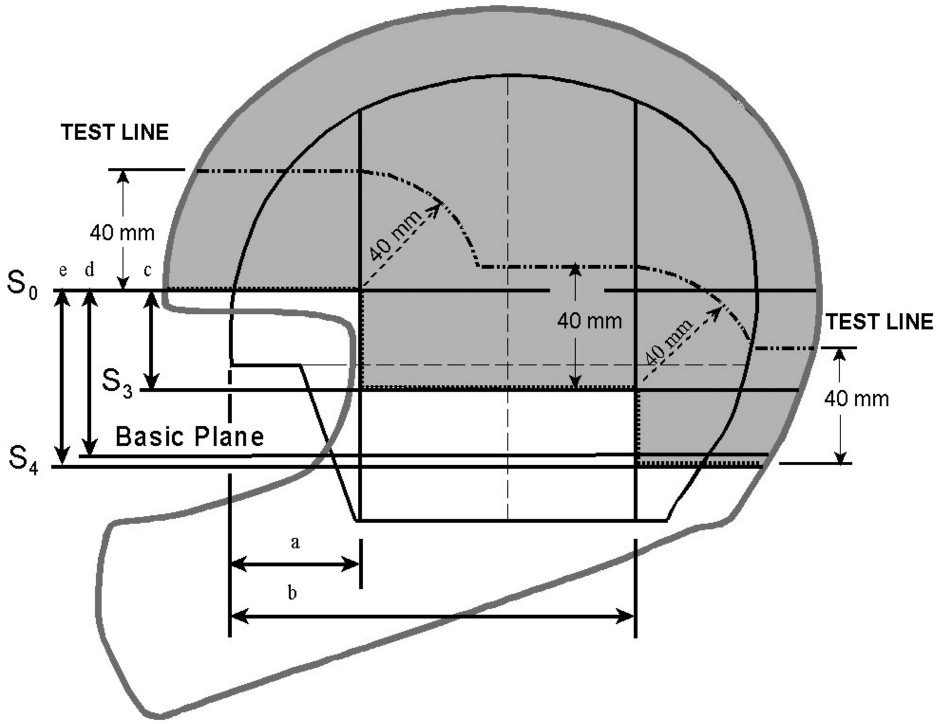


Figure 3.1: Definition of test line and extent of protection in Snell M2005 and AS/NZS 1698.

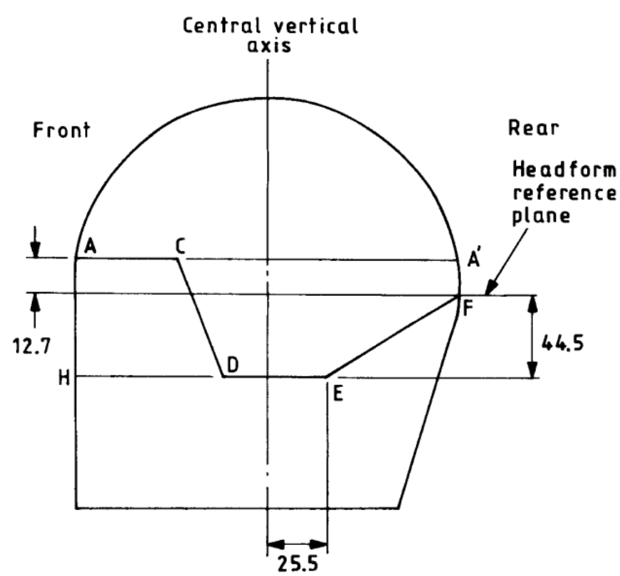


Figure 3.2: Definition of extent of protection in BS 6658.

Instead, according to the FMVSS 218 standards, shell extension shall cover all the points above a "test line" reported in the figure 3.3. The extent of protection is represented by the dotted area.

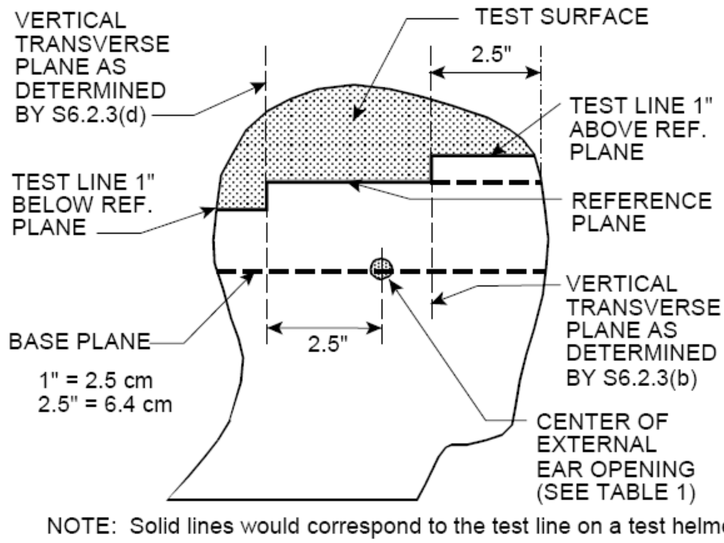


Figure 3.3: Definition of test line and extent of protection in FMVSS 218 where all appendices mentioned in the figure can be found.

It is apparent that the various standards define the extent of protection in a similar way; nonetheless it is apparent as well that differences are not always negligible. In particular it seems that the US standards require protecting an area of the head much smaller than that protected by the other regulations.

3.2 Conditioning

The conditioning requirements of the five standards are similar. Table 3.2 summarizes four applicable conditionings for the above mentioned standards. As mentioned before, solvent shall be applied before all conditioning in ECE 22.05 standard. In Snell M2005 standard, helmets may be exposed to solvents which have been found to attack or degrade some components of the helmet. The tester is who decides using solvent or not. AS/NZS 1698 standard states that solvent shall be used when it is mentioned in the manufacturer's standard.

Table 3.2 Conditionings required by different standards.

	ECE 22.05	Snell M2005	AS/NZS 1698	BS 6658	FMVSS 218
Ambient	$T = 25^\circ C$ $\phi = 65\%$	Laboratory temperature and humidity	$T = 18^\circ C - 25^\circ C$ $\Delta t = 4h - 30h$	Not required	$T = 21 \pm 6^\circ C$ $\phi = 40\%\ to\ 60\%$
Hot	$T = 50^\circ \pm 2^\circ C$ $\Delta t = 4h - 6h$	$T = 50^\circ C$ $\Delta t = 4h - 24h$	$T = 50 \pm 2^\circ C$ $\Delta t = 4h - 30h$	$T = 50 \pm 2^\circ C$ $\Delta t = 4h - 24h$	$T = 50^{+0^\circ}_{-4} C$ $\Delta t > 12h$
Cold	$T = -20^\circ \pm 2^\circ C$ $\Delta t = 4h - 6h$	$T = -20^\circ C$ $\Delta t = 4h - 24h$	$T = -10 \pm 2^\circ C$ $\Delta t = 4h - 30h$	$T = -20^\circ \pm 2^\circ C$ $\Delta t = 4h - 24h$	$T = -10^{+4^\circ}_{-0} C$ $\Delta t > 12h$
Wet	UV+ $4h - 6h$ water spray at ambient temperature	$4h - 24h$ water spray at a temperature of $25^\circ C$	$4h - 30h$ immerse in water at a temperature of $18^\circ C - 25^\circ C$	$T = 15 \pm 2^\circ C$ $\Delta t = 4h - 24h$	$T = 25 \pm 6^\circ C$ $\Delta t > 12h$

T : temperature, ϕ : relative humidity, Δt : duration, UV: ultraviolet.

As it can be seen, the common conditioning procedures (temperature, water immersion and/or hygrometry conditioning) are more or less prescribed by all the standards here compared. It is also evident that in the UK standard the maximum exposure duration during heat conditioning is up to four times the maximum duration prescribed in the ECE Regulation. Also, exclusively in the ECE Regulation a radiation exposure is prescribed (not present in any other standard here discussed). Differences are also present in the use of solvents when conditioning the helmets to be tested.

3.3 Impact Absorption Tests

The objective of impact absorption tests is the same in all standards, to guarantee that the energy applied to the head by impacts is below critical levels. However, there are several differences in the details of the testing.

3.3.1 Test apparatus

A drop tower is used by all regulations. The definition of the base of it varies from standards to standards but the principles are the same: it has to be massive and its natural frequencies of vibrations should not affect the test results. For all examined standards a headform equipped with a helmet will hit an anvil after a free guided fall. For testing in accordance with Snell M2005, AS/NZS 1698 and BS 6658, the headform shall be attached to the supporting assembly by ball joint. This joint allows rotation of headform and vertical translation, but prevents two other translations. However, the headform shall fall freely with no constraint according to ECE 22.05. In FMVSS 218 the drop system restricts side movement during the impact attenuation test so that the sum of the areas bounded by the acceleration-time response curves for both the x- and y-axes (horizontal axes) is less than five percent of the area bounded by the acceleration-time response curve for the vertical axis. Mass of the drop assembly, which comprises the supporting arm, ball socket stem and headform, differs in the standards. For Snell M2005 it is $5\pm0.1kg$, whereas for ECE 22.05 and AS/NZS 1698 it depends on the headform size (as indicated in table 2.2 of the previous chapter). Despite the wide range of headforms prescribed by BS Standards, only one mass value for the drop assembly is given by BS that explicitly state: "The total mass of the drop assembly without helmet is 5 kg (-0,+0.2kg) and the mass of the supporting assembly is not more than 20 % of the total mass of the drop assembly". In FMVSS 218 the combined weight of drop assembly + headform can have three values: Small $3.5kg$, Medium, $5.0kg$, Large $6.1kg$.

In the SHARP (2008) rating system, impact absorption test is similar to that used by British Standard BS 6658. Citing a publication by Mellor et. al. (2007), it is stated that the carriage supported drop test of the helmeted headform reduces dissipation of energy by excessive rotation of the helmet-headform and sliding of the helmet on the anvil. Thus, this method results in larger peak linear acceleration than the method of testing used by ECE 22.05. Furthermore, it is claimed that this method of testing provides better repeatability and accuracy of testing, especially when compared with the free motion prescribed by ECE 22.05. Through performing experimental tests, Thom and co-workers (1998) showed that when helmets were tested according to FMVSS 218 standard, which constraints the headform from horizontal motion, resultant accelerations were larger than when the same helmets were tested in accordance with ECE 22.05 standards. They argued that ECE 22.05 testing apparatus is more complex and still leads to less conservative results.

Anvils used by different standards are shown in table 3.3. All standards use flat anvil in impact absorption test.

Table 3.3 Anvils for impact absorption test of different standards.

Standard / Anvil	ECE 22.05	Snell M2005	AS/NZS 1698	BS 6658	FMVSS 218
Flat	$D = 130 + 3mm$	$D \geq 127mm$	$D \geq 127mm$	130 ± 3 mm	127 mm
Hemispherical	-	$R = 48 \pm 0.5mm$	$R = 48 \pm 0.5mm$	50 ± 2 mm	48 mm
Kerbstone	$\varphi = 105^\circ$, $H \geq 50mm$ $r = 12mm$	-	$\varphi = 90^\circ$, $H = 85$ $r \leq 0.5mm$		
Edge	-	$L = 180mm, W = 6.3mm$ $H = 35mm$	-		

D : diameter, R : radius, φ : vertex angle, H : height, r : fillet radius, L : length, W : width.

In the COST 327 database, the shape of the striking object and the relevant frequency were reported as mentioned in the introduction. It was concluded that the most serious injuries occurred for edge struck objects (40% of all collisions to edge objects was AIS 5). Using flat anvils in standards seems reasonable; however, there are some criticisms about using hemispherical anvils. For instance, Gilchrist et. al. (1994) stated that the objects struck are mainly flat and rigid (Vallee et. al. (1984)), whereas less are flat deformable, round rigid, round deformable and spike-shape rigid. The authors argued that the hemispherical anvil should be substituted with the kerbstone anvil, because statistics show that cases of accidents involving a hemispherical object are rare.

3.3.2 Headforms

The definitions of the headforms is confusing and of limited interest. ECE 22.05, AS/NZS 1698 and Snell M2005 adopt same mass and geometry. FMVSS218 adopt three sizes (small, medium and large); BS6658 gives a detailed description of its headforms. Usually standards provide the shape of the sections of the headform along the plain of symmetry and the plans parallel to the reference plane. Standards also provide internal dimensions of the headforms, in order to ensure their best fit with the test devices such as accelerometers. Finally regarding materials to be used, the headforms shall be constructed of a metal or metallic alloy and should have natural frequencies above given limit values.

3.3.3 Impact Initial Conditions

Prescribed initial conditions are different for all considered standards. ECE 22.05, BS 6658 and FMVSS 218 define impact velocity, Snell M2005 define impact energy and AS/NZS 1698 define drop height, as shown in Table 3.4. Snell M2005 and BS6658 require a second impact at the same site, but with lower impact energy or impact velocity. AS/NZS 1698 require as well a second impact at the same site; however, the input energy is the same. According to FMVSS 218, each helmet is impacted at four sites with two successive identical impacts at each site. Two of these sites are impacted upon a flat steel anvil and two upon a hemispherical steel anvil.

Gilchrist et. al. (1994 a) argued that the second impact test required by some standards prevents the optimisation of the liner foam density for the first impact and leads to higher yield stress and stiffer foams. They have explained that the major impact damages about 100mm area of the helmet which it is about 5% of the whole protecting area of the helmet. It was concluded that the second impact test is unnecessary and possibly detrimental.

Referring to Table 3.4, first impact velocity is calculated 7.7 m/s and 6 m/s for Snell M2005 and AS/NZS 1698 standards, respectively. Comparing all standards, Snell M2005 has the highest impact velocity. Impact velocity of ECE 22.05 is very near to the largest velocity.

Table 3.4 Impact initial conditions for different standards.

Standard / Anvil	ECE 22.05	Snell M2005	AS/NZS 1698	BS 6658		FMVSS 218
				Type A	Type B	
Flat	Initial velocity: 7.5 m/s	Impact energy: 150 J (for the second impact 110 J)	drop height: 1830+30, -5 mm	7.5 (1st) 5.3 (2nd)	6.5 (1st) 4.6 (2nd)	6.0 m/s
Hemispherical	-	Impact energy: 150 J (for the second impact 110 J)	drop height: 1385+30, -5 mm	7 (1st) 5 (2nd)	6 (1st) 4.3 (2nd)	5.2 m/s
Kerbstone /Edge	Initial velocity: 7.5 m/s	Impact energy: 150 J	-	-		-

3.3.4 Output Parameter(s) and Approval Limit(s)

The output parameter for impact absorption test is the same for the standards, which is resultant linear acceleration of the center of mass of the headform or support assembly versus time. However, each standard extracts different data from this curve and enforces different limits, which are shown in table 3.5.

Table 3.5 Output parameters and relevant limits for five helmet testing standards.

Standard	ECE 22.05	Snell M2005	AS/NZS 1698	BS6658	FMVSS 218
Condition 1	$PLA \le 275g$	$PLA \le 300g$	$PLA \le 300g$	$PLA \le 300g$	$PLA \le 400g$
Condition 2	$HIC \le 2400$	-	$LA > 200g$ for not more than $3ms$	-	$LA > 200g$ for not more than $2ms$
Condition 3	-	-	$LA > 150g$ for not more than $6ms$	-	$LA > 150g$ for not more than $4ms$

PLA : Peak Linear Acceleration, *LA*: Linear Acceleration.

3.3.5 Impact points

In contrast to ECE 22.05, which define the points of impact exactly, the other four standards do not define specific points. In Snell M2005 test impact sites shall be on or above the test line. Each impact site shall be subjected to a group of one or two impacts according to the anvil selected for that site (table 3.4). The impact site for the first impact within a group is the target for the successive impacts in the same group. In addition, impact groups shall be 120 mm distant or more. There is no restriction regarding test anvil selection. Indeed, the impact test procedures of Snell M2005 standard leave considerable discretion to the helmet tester regarding site and anvil selection. It is expected that the tester will organise each standard test series in order to investigate potential weaknesses and to exercise each likely failure mode and will conduct deviation level testing to exercise the failure modes identified previously. From the definition of the test line in AS/NZS 1698, it can be concluded that the test sites shall be on or above this line. This standard requires that the helmet be subjected to impacts at four sites with two successive impacts at each site. Two pairs of impacts shall be on a flat anvil and two pairs shall be on hemispherical anvil. BS 6658 state about the impact points: “Test two sets each consisting of three helmets in the sequence given in Table 3.6. Test each helmet by the procedure described in an appendix at three separate impact sites, separated on the helmet by a distance not less than one-fifth of the maximum circumference of the helmet and located as follows:

a) at the rear or side, on or above the line AA′ as described in an appendix;

b) at any other site above the line AA′;

c) at the front on the perimeter BB′ as described in an appendix.”

The following figure is representative of the lines described in the appendix.

Table 3.6 Sequence of testing for BS 6658.

Set number	Helmet number	Conditioning	Anvil face
Set 1	1	High temperature	Hemispherical
	2	Low temperature	Hemispherical
	3	High temperature or water immersion	Hemispherical or flat
Set 2	4	High temperature	Flat
	5	Low temperature	Flat
	6	Low temperature or water immersion	Hemispherical or flat

USA standards prescriptions about impact points are quoted as follows: “The impact sites are at any point on the area above the test line, and separated by a distance not less than one-sixth of the maximum circumference of the helmet in the test area.”

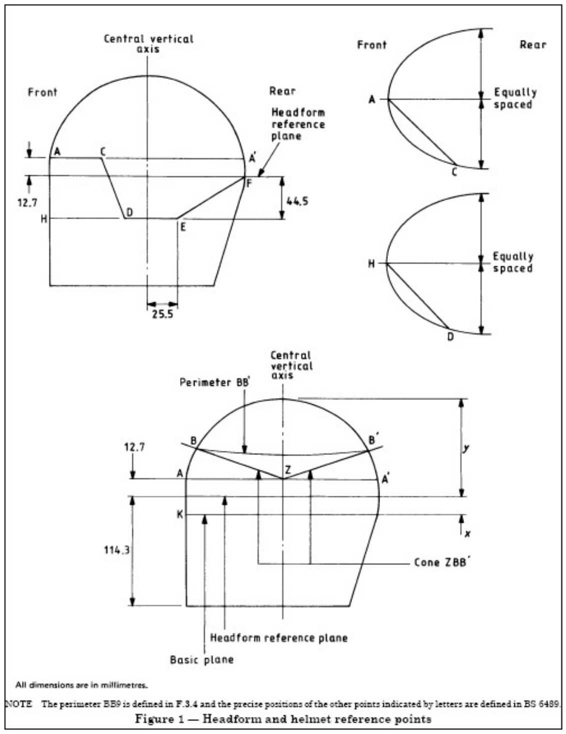


Figure 3.4: definition of impact points for BS 665.

3.4 External Projections and Surface Friction

External projections on the surface of the shell shall not prevent the helmet from rotating in accidents. Snell M2005 standard requires that all projections higher than 7mm beyond the surface of the helmet must readily break away. However, this standard does not include a specific test for external projections and surface friction. According to AS/NZS 1698 standard, some unavoidable projections such as those necessary for retention system shall not have a height more than 5 mm. Nonetheless, non-rigid projections higher than 5 mm are permissible when they have complied with the requirements of Oblique Impact Test in BS 6658, using the bar anvil.

The above mentioned test is the same as method A of ECE 22.05 for testing projections, when bar anvils are used, except for the initial velocity. The initial velocity for external projections and surface friction test is 10 *m/s* in BS 6658, while it is 8.5 *m/s* in ECE 22.05. When abrasive anvil is used, the limits for longitudinal force and its impulse (integral of force with respect to time) are a bit higher in BS 6658, 4*KN* and 28*Ns*. In ECE 22.05, limits of these parameters are 3.5*KN* and 25*Ns*, respectively.

Halldin et. al. (2001) and Aare et. al. (2004) described that oblique impact test in BS 6658 standard is to ensure that:

a) visor mounts and other projections shear off easily when there is an impact with a series of parallel bars,

b) the tangential force on the helmet shell, when it impacts a rough flat surface, is not larger than that for typical shell materials used in 1985 (the year of introduction of the test).

The Projection test is not contemplated in the USA standards.

3.5 Penetration test

The penetration test is to measure the resistance of the shell of the helmet to impacts to sharp objects.

In testing procedures, a penetration test striker is dropped onto the outer surface of a helmet positioned on a rigidly mounted headform. Table 3.7 summarizes characteristics of penetration test in the five examined standards. In Snell M2005 the helmet tester decides how many sites shall be tested. Furthermore, the headform can be a non-standard one which means it can deviate from standard headform geometry, but it should provide enough stability for the helmet during testing.

Table 3.7 Specifications of penetration resistance test in Snell M2005, AS/NZS 1698, BS 6658, and FMVSS 218.

	ECE 22.05	Snell M2005	AS/NZS 1698	BS 6658	FMVSS 218
Mass of Striker (kg)	There is NO penetration resistance test required by this standard.	3 ± 0.05	$3^{+0.045}_{-0.000}$	3	3
Drop height (mm)		3000 ± 15	3000 ± 15	Type A 3000; Type B 2000	3000
Shape of Striker		Conical: $\alpha = 60^\circ \pm 0.5^\circ$, $h = 38 \pm 0.38$, $r = 0.5 \pm 0.1$	Conical: $\alpha = 60^\circ \pm 0.5^\circ$, $h \geq 38$, $r = 0.5 \pm 0.1$	Conical: $\alpha = 60^\circ \pm 0.5^\circ$, $h \geq 40$, $r = 0.5 \pm 0.1$	Conical: $\alpha = 60^\circ \pm 0.5^\circ$, $h \geq 38$, $r = 0.5 \pm 0.1$
Penetration Site(s)		site(s) shall be at least 75mm away from centers of previous impacts	at least 2 sites 75mm away from centers of previous impacts	two sites at least 75 mm from each other and from the centres of previous impacts.	Two penetration blows are applied at least 7.6 cm apart, and at least 7.6 cm from the centers of any impacts applied during the impact attenuation test.
Criteria		No contact between striker and surface of headform	No contact between striker and surface of headform	No contact between striker and surface of headform	No contact between striker and surface of headform

The penetration test is not prescribed in the European Standards, since statistical analysis has shown that impact with penetrating objects are very unlikely (COST 327) as discussed in the introduction. Indeed, there are some criticisms about requiring penetration test by some standards. Gilchrist et. al. (1994 a, 1996) stated that the thickness of the helmet shell is largely determined by the penetration test which is felt as irrelevant since it corresponds to a very rare phenomenon in real accidents. Penetration tests lead to thick composite helmet *shells that behave in a very stiff way when striking rigid flat surfaces. Shuaeib et.al. (2002) stated that the penetration test is the main criterion for determining the thickness of the helmet shell, and it leads to thick shells whose weight is 6-8 times the liner weight. As a consequence stiff shells designed to pass penetration tests provide a worse protection than more flexible shells in the much more common cases of impacts with flat or curved surfaces. The requirement of the penetration test forces all standards to accept higher accelerations than those accepted by ECE 22.05 in the energy absorbing test, see table 3.5.*

3.6 Retention System Assessing Tests

Efficiency of retention system is assessed in different standards by dynamic or static loading, as summarised in table 3.8. For instance, ECE 22.05, Snell M2005 and BS 6658 require dynamic loading (refer to section 2.5), while AS/NZS 1698 and FMVSS218 require static loading. In these standards, two parallel rollers simulate the wearer chin and are used to apply primary and secondary static loads to the retention system of a helmet positioned on a fixed headform. The loads shall be applied normal to the basic plane and symmetrical with respect to the mid-sagittal plane. In AS/NZS 1698 the primary load of 225±5*N* shall be applied for 30*s*, and the secondary load of 1110±25*N* shall be added to it and sustained for 120*s*. Under this final condition, the retention system and its attachments shall not separate, and elongation between pre-loading and test loading shall not exceed 25*mm*. A similar procedure is used in FMVSS218.

The retention system assessing test in Snell M2005 standard is done using dynamic loading. In this standard, the helmet is positioned on a device whose upper end approximates headform. The load is applied through two rollers each 12.7±0.5*mm* in diameter, separated by 76±0.5*mm*, simulating jaw of the headform. A preload of 23±0.5*kg*, including simulated jaw, shall be applied for at least 60*s*. Then, a 38±0.5*kg* mass shall be dropped in a guided fall a height of 120*mm* in order to load the retention system abruptly. The retention system shall sustain this load and its dynamic vertical deflection shall not exceed 30*mm*. A similar procedure is used in BS 6658.

Table 3.8 Specification of retention system assessing tests in ECE 22.05, Snell M2005 AS/NZS 1698, BS 6658 and FMVSS 218.

	ECE 22.05, dynamic	Snell M2005 dynamic	AS/NZS 1698 stat.	UK, dynamic	USA static
Pre-Load	$15 \pm 0.5kg$ for $120s$	$22.5 \pm 0.5kg$ for $30s$	$23 \pm 0.5kg$ for $60s$	7+0-0.25 kg	22.7kg+ 4.5kg,-0kg for $30s$
Test Load	$10 \pm 0.5kg$	$38 \pm 0.5kg$	$111 \pm 0.5kg$ for $120s$	$10 \pm 0.5kg$	131.5kg+ 0.0kg,- 2.3kg for 120*s*
Drop Height	$750 \pm 5mm$	$120mm$	-	$750 \pm 5mm$	
Maximum allowed Deflection under pre-load	$25mm$	-	-		-
Maximum allowed Deflection after application of the test load	$35mm$	$30mm$	$25mm$	$32mm$ (1st drop) $25mm$ (2nd drop).	25 mm
Residual Extension	-	-	-	$16mm$ (1st drop) $8mm$ (2nd drop)	

3.7 Roll off Test

Roll off test is also called helmet stability test or retention detaching test. In Snell M2005 the full face standard headform shall be used for testing the stability of the helmet. The vertical axis of the headform shall be oriented with respect to the direction of gravity and its face shall be downward for forward testing or upward for rearward testing. Headform shall be fixed and helmet positioned on it. An elastic strap shall be hooked to the center of either rear or front edge of the helmet, and its end hung downward across the top of the helmet. A dynamic load is applied by an inertial hammer which facilitates dropping of a 4±0.5*kg* mass for a height of 600*mm*. The criterion is that the helmet should remain on the headform albeit shifting. Roll off test required by AS/NZS 1698 is similar to retention detaching test of ECE 22.05 that was explained in section 2.5. The only difference is the drop height of the mass which is 300*mm* in AS/NZS 1698.

When comparing the energy of the dropped mass released to the helmet in roll off test in different standards, it is found that ECE 22.05 requires the most imparted energy. In the BS the test is called 'Test for effectiveness of retention system'. The concept is similar to that of ECE 22.05 with several differences in the apparatus and the procedure.

In the USA standards such a test is not required.

3.8 Chin Bar Impact Test

Some standards require testing of the chin bar for full face helmets. For instance, in ECE 22.05 standard, this test is equivalent to impact absorption test at point S. There is no requirement for testing chin bar in AS/NZS 1698 and FMVSS 218 standards. The chin bar impact test of Snell M2005 requires that the helmet be firmly mounted on a rigid base so that the chin bar faces up and the reference plane is at 65 ±5° from horizontal. A mass of 5 ± 0.2 kg with a flat striking face of 0.01 m^2 minimum area shall be dropped in a guided fall so as to strike the central portion of the chin bar with an impact velocity of 3.5 ±0.2 m/sec. The maximum downward deflection of the chin bar must not exceed 60 mm nor does any component fail so as to cause a potential injury to the wearer.

BS carefully prescribe a chin-guard test which requires that 'When any chin guard is tested by the method described in Appendix R, the maximum deceleration of the striker shall not exceed 300 g. The chin guard shall not develop or generate any additional hazard for the wearer and any internal padding shall remain in place.' Appendix R describes a test similar to that of Snell M2005 of figure 3.5(a).

Chang et. al. (2000) raised some concerns about the test procedure of Snell M2005 and BS6658 for evaluating the protective performance of the chin bar of motorcycle helmets. They believe that hitting a striker on the chin bar of a fixed helmet is in contrast to real accidents. The authors proposed a new test procedure (Figure 3.5(b)), by which, the helmet was dropped on a fixed anvil (Chang et. al. (1999)); maximum acceleration and HIC of the headform were the evaluating outputs. They concluded that the new test procedure provided a more realistic way for assessing the protective capability of the chin bar in facial impacts. The configuration of the proposed test and output parameters are similar to the procedure adopted in ECE 22.05.

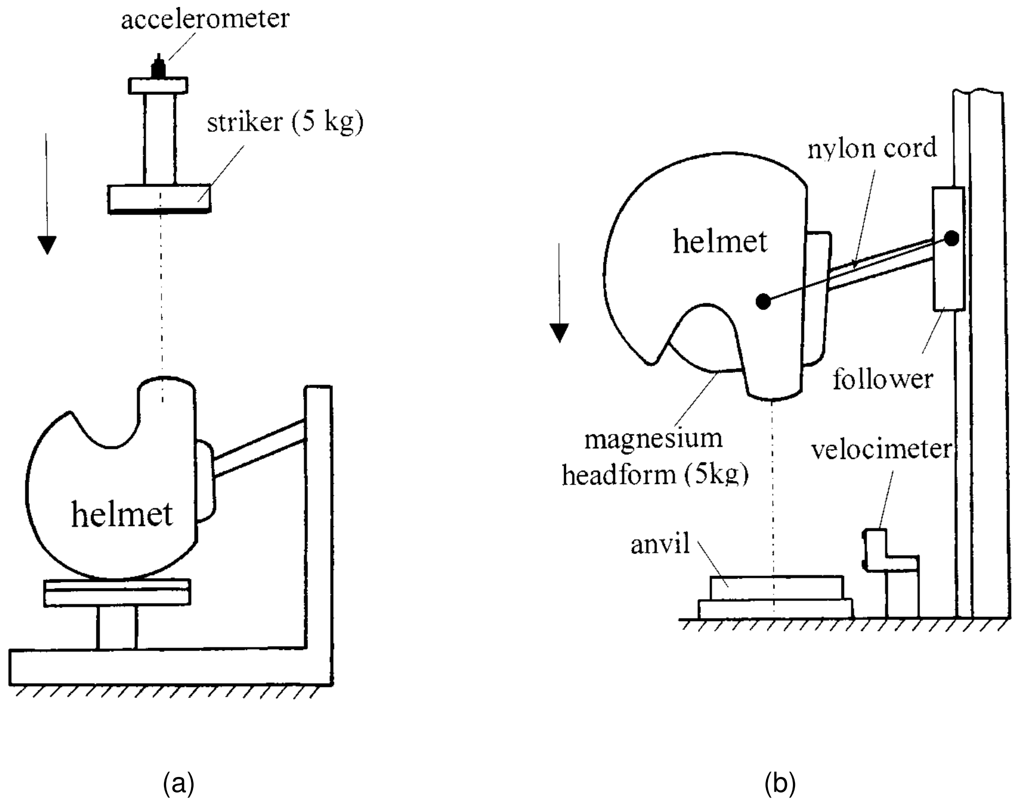


Figure 3.5: (a) setup of chin bar test in Snell M2005 and BS 6658 standards, (b) setup of the proposed chin bar test (Chang et. al. (2000)).

4 Conclusions

The substantial differences among the five examined regulations seem to be three:

- ECE 22.05 is the only regulation not to require penetration tests;
- Snell M2005, AS/NZS 1698, BS 6658 and FMVSS 218 require a double impact on the same site for the energy absorbing tests whereas ECE 22.05 requires one impact only;
- ECE 22.05 is the only regulation not to adopt a ball-joint in the energy absorbing impact tests.

As we said in the previous comments ‘stiff shells designed to pass penetration tests provide a worse protection than more flexible shells in the much more common cases of impacts with flat or curved surfaces.’ For that reason the authors believe that in the most frequent road impact cases, helmets designed according to the ECE 22.05 standards would provide a better protection than other helmets designed to pass penetration requirements.

Moreover in practice also the case of a double impact on the same location appears rather rare and therefore it seems more important to optimise the choice of the energy absorbing foam for the single impact case.

The prevention of the rotational motion of the headform-helmet assembly, provided by the ball joint is a discussed issue. According to some authors, that makes the tests required by

Snell M2005, AS/NZS 1698, BS 6658 and FMVSS 218 more reliable than those imposed by ECE 22.05.

Finally the regulations FMVSS 218 do not prescribe a few of the tests which are instead required by other standards (external projections and surface friction test, roll off test, chin bar impact test) and seem, for that reason, to accept a lower level of safety.

5 APPENDIX: SIMULATION OF IMPACT ABSORPTION TESTS

In order to have a preliminary comparison between impact absorption tests of ECE 22.05, Snell M2005 and AS/NZS 1698 standards, the finite element model of a commercial helmet (Cernicchi et. al., 2007)) was used to simulate drop tests at hot temperature conditioning (figure A.1). The largest size of the helmet was fitted with headform size "O". For this headform impact energy is the highest for ECE 22.05 and the lowest for AS/NZS 1698 standard.

In comparison to Cernicchi's model, the current helmet model has some minor differences. The chinstrap, which was simulated by linear springs, is replaced by seat belt element of the LS-Dyna971 software. Contact is defined between chinstrap and headform. Furthermore, this helmet is full face and is equipped with chin-guard. Since the finite element model for simulating impacts at points B, P and R against flat and spherical anvils is symmetric with respect to the longitudinal mid-plane (mid-sagittal plane), only half of the helmet is used and symmetric boundary conditions are defined on the relevant section (figure A1(b)).

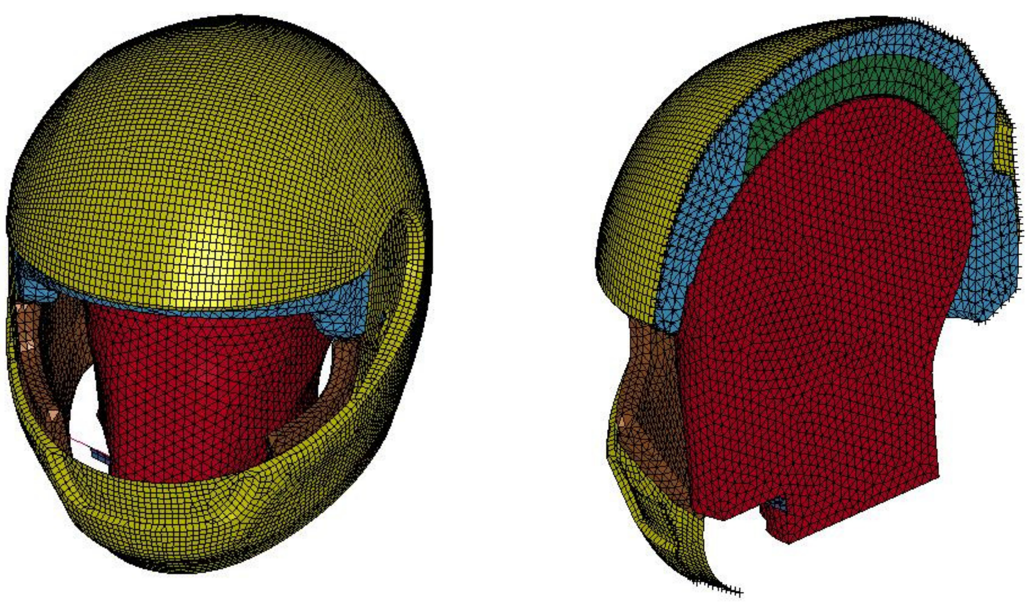


Figure A.1: helmet-headform finite element model (a) full helmet, (b) model for symmetric cases.

The output parameter for the standards is resultant linear acceleration versus time, which is plotted in figure A2, for impact against flat anvil, and in figure A3 for impacts against kerbstone and hemispherical anvils. The resultant acceleration curves of figure A2 indicate that the helmet would pass maximum acceleration requirements of all three standards, except the requirement of AS/NZS 1698 for the acceleration not to be above 100m/s2 for more than 6 milliseconds for the impact at point B (table A1). When the kerbstone anvil was used the maximum acceleration was lower than when flat anvil was used according to ECE 22.05 test procedure (figure A3(a)). However, the helmet failed the impact tests against hemispherical anvil required by Snell M2005 (figure A3(b)).

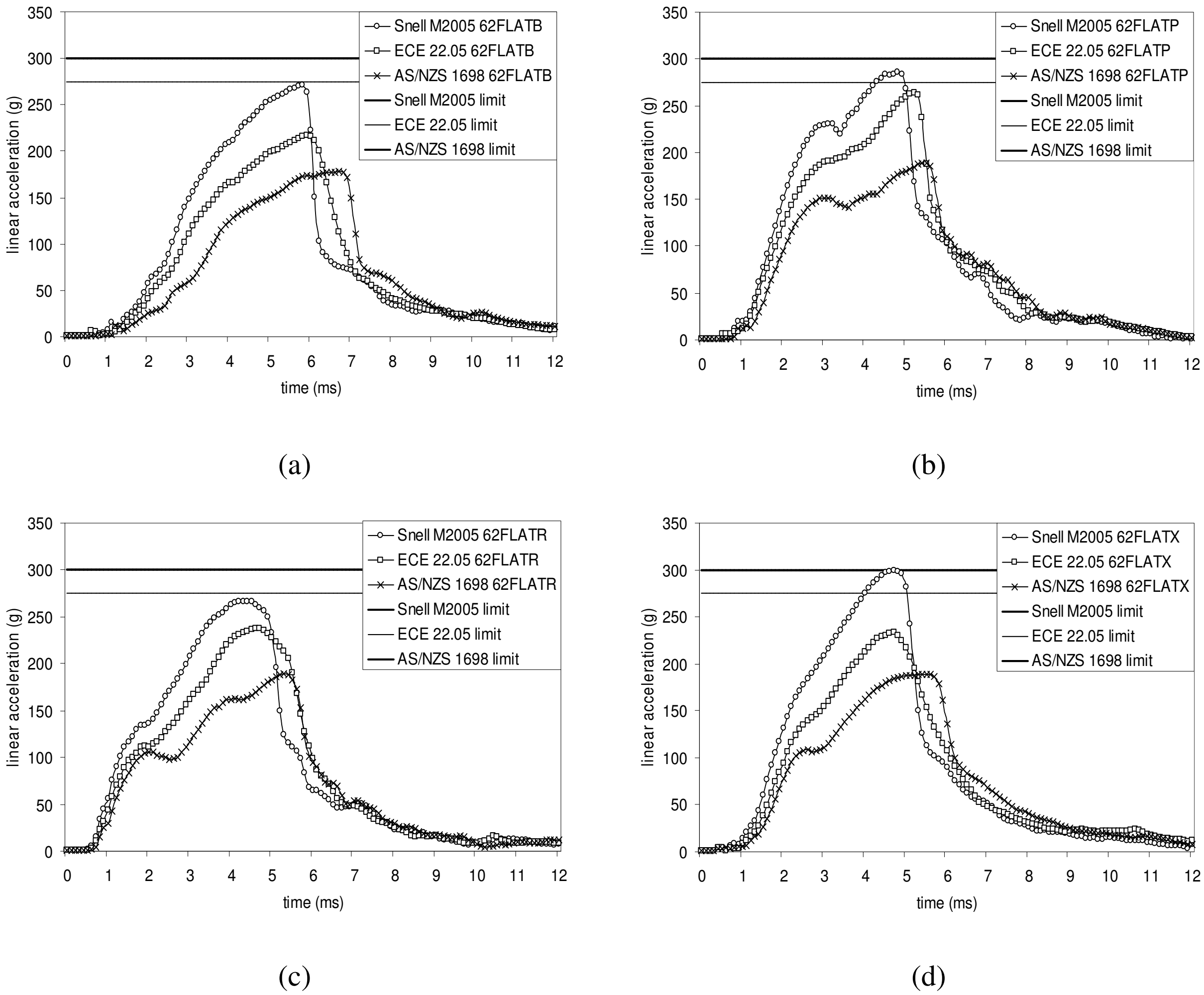
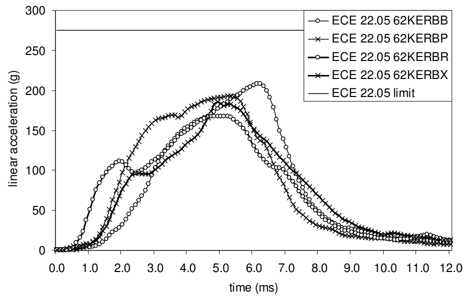


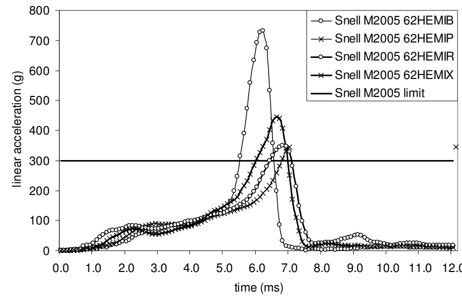
Figure A.2: resultant linear acceleration at the center of gravity of the headform "O" for impacts against flat anvils and at (a) point B, (b) point P, (c) point R, and (d) point X.

For impact at point P, the compression of the foam was so severe and localised that the software could not finish the analysis and the solution was terminated with an error message. The results of impact tests against hemispherical anvil of AS/NZS 1698 are shown in figure A3(c), and indicate that maximum acceleration is well below limits for all impact sites. All the results are summarized in table A1. It should be highlighted that both Snell M2005 and AS/NZS 1698 standards require two impacts at the same point.

The discussed finite element simulations were only for the first impact. As mentioned before, the second impact is unlikely to happen at the same point in reality so that the requirement of having two impacts seems to be unnecessary. However, Snell specialists believe that the main purpose of their second impact test at the same point is to simulate increased impact energy at that point (HIC workshop, 2005). Higher energy impacts would require a modified apparatus and therefore would be too expensive.



(a)



(b)

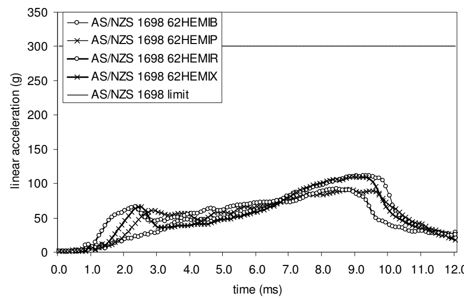


Figure A.3: resultant linear acceleration at the center of gravity of the headform "O" for impacts at points B, P, R and X according to (a) ECE 22.05, kerbstone anvil, (b) Snell M2005, hemispherical anvil, and (c) AS/NZS 1698, hemispherical anvil.

Table A1 Results of finite element simulation of impact test according to three standards.

Standard	Anvil	Impact	PLA (g)	LA(g)@ 3ms	LA(g)@ 6ms	HIC
ECE 22.05	Flat	B	216.70	111.19	216.03	1529
		P	263.60	189.75	103.56	2191
		R	237.88	161.90	98.56	1841
		X	233.46	154.79	107.27	1630
	Kerbstone	B	208.36	103.03	205.95	1496
		P	193.15	162.31	149.56	1565
		R	167.79	113.96	130.60	1098
		X	185.52	101.22	151.15	1099
Snell M2005	Flat	B	270.81	148.06	223.04	2358
		P	286.06	229.15	102.24	2785
		R	266.85	208.20	64.39	2365
		X	299.6	208.93	89.76	2791
	Hemispherical	B	731.46	68.29	692.93	7936

		P	343.7	88.79	169.55	-
		R	349.57	73.59	212.47	1934
		X	445.34	55.71	307.75	3106
AS/NZS 1698	Flat	B	177.99	59.33	172.80	1022
		P	188.76	151.09	110.18	1190
		R	189.34	116.38	94.41	1041
		X	189.21	111.27	136.00	1132
	Hemispherical	B	110.84	29.01	63.36	357
		P	91.74	58.85	66.11	325
		R	92.02	46.71	71.33	307
		X	109.68	36.79	58.58	320.9
PLA: peak linear acceleration, LA: linear acceleration Note: highlighted figures shows quantities exceeding the limits of table 3.5.						

Assuming that two impacts at the same point are almost equivalent to one impact at that point while keeping the impact energy equal to the sum of two impact energies, the equivalent velocity of the single impact is calculated about 10.2*m/s* for Snell M2005. This value is 8.5*m/s* and 7.4*m/s* for AS/NZS 1698 impact tests against flat and hemispherical anvils, respectively. The last figure is near the impact speed required by ECE 22.05. According to COST 327 (2001) database (figure A4), head impact speeds of 10.2*m/s*, 8.5*m/s* and 7.4*m/s* are respectively about 23% cumulative speed for AIS5/6, 18% cumulative speed for AIS5/6 and 20% cumulative speed for AIS2-4. Therefore, on one hand, it can be concluded that Snell M2005 aims to prevent from fatal injuries, whereas AS/NZS 1698 and ECE 22.05 standards tend to decrease the severity of head injuries. On the other hand, the above assumption seems reasonable for measuring merely energy absorption of the helmet and not peak acceleration of the headform; since, while all other conditions are the same, higher impact velocity induces higher peak linear acceleration at the center of gravity of the headform. As a conclusion, owing to the main duty of the helmet which is, from standards point of view, decreasing linear acceleration of the headform and spreading it over time, it is better to test the helmet at higher velocity rather than exposing it to two impacts at the same point.

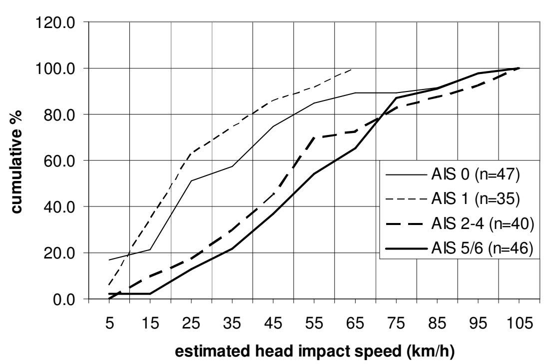


Figure A.4: AIS head versus head impact speed (COST 327 (2001)).

There are some suggestions by researchers about increasing the impact velocity of ECE 22.05 standard; for instance, COST 327 action has suggested increasing impact speed from 7.5*m/s* to 8.5*m/s*, which is believed to increase energy absorption capacity of the helmets by 24% and decrease AIS5/6 head injuries to AIS2-4 head injuries by 20%. It is almost accepted by researchers that both resultant linear acceleration and its distribution over time are important factors in head injury caused by accidents. The well known Wyne State tolerance curve (WSTC) and head injury criterion was based on the same fact (Versace (1971)). The Snell M2005 standard does not account for the duration of linear acceleration in contrast to the other two standards. A research program (HIC workshop) on comparing Snell M2005 certified and ECE 22.05 certified helmets has shown that former helmets could pass peak acceleration limit of ECE 22.05 standard but couldn't pass its HIC requirement. There are still doubts about using HIC in motorcycle helmet testing standards, but most of the researchers believe that duration of linear acceleration should be taken into account in standards. Although both ECE 22.05 and AS/NZS 1698 standards account for this duration, values of linear acceleration at 6 milliseconds for testing in accordance with ECE 22.05 standard (table 3.5) show that these two criteria are not compatible. It seems that more biomechanical research on head injury in motorcycle accidents is necessary to define a unique sophisticated head injury criterion for helmet testing standards.

The free fall and the restricted fall impact test procedures of ECE 22.05 and Snell and AS/NZS 1698 standards have been always controversial. Although kinetic energy of drop assembly in Snell standard is smaller than that of ECE 22.05 for testing the largest helmet size (fitted with headform "O"), figure A2 shows that the restricted fall of the former standard leads to higher linear acceleration at the center of gravity of the headform than latter standard. The main concept of helmeted headform fall is to mimic the real accident. It is obvious that using a headform for impact testing corresponds to neglecting the effect of the rest of the body on head acceleration. Comparing helmeted dummy drop test with helmeted headform drop test according to ECE 22.05, COST 327 concluded that in order to obtain the same results, the detached headform needed to be tested at slightly higher velocity. In particular, dummy impact test at 5.2*m/s* corresponded to headform test at 6*m/s*, and dummy impact test at 6*m/s* gave the results which were in accordance with helmet tests at speeds between 6*m/s* and 7.5*m/s*.

It can be deduced from figure A3 that the impact test of Snell M2005 against hemispherical anvil is very sever for the current helmet at all four points, whereas the helmet could pass impact test of ECE 22.05 against kerbstone anvil. The peak acceleration for drops to hemispherical anvil in accordance with AS/NZS 1698 standard is quit below the limit, which is mainly due to the low impact speed (5.2*m/s*). As mentioned before, statistical observations showed that hemispherical struck objects are rare in motorcycle accidents, and the kerbstone anvil is a good replacement for this anvil. Furthermore, in order to pass the strike on hemispherical anvil, the helmet shell should be made stiffer. Very stiff shells can not contribute in energy absorption. By finite element simulation, Kostopoulos et. al. (2002) showed that composite helmet shell can absorb up to 12% of the impact energy by delamination.

6 References

1) Aare, M., Kleiven, S., Halldin, P., Injury tolerances for oblique impact helmet testing, International Journal of Crashworthiness, 9:1, 15 - 23, 2004.

2) AS/NZS 1698, Protective Helmets for Vehicle Users, Austrailian/New Zealand Standard, 2006.

3) Cernicchi, A., Galvanetto, U., Iannucci, L., Virtual modeling of safety helmets: practical problems, Submitted to International Journal of CrashWorthiness, 2007.

4) Chang, C.H., Chang, L.T., Chang, G.L., Head Injury in Facial Impact—A Finite Element Analysis of Helmet Chin Bar Performance, Transactions of the ASME, 122, 2000.

5) Chang, L. T., Chang, C. H., and Chang, G. L., Experimental Evaluation of Chin Bar on Head Injury in Facial Impact, JSME International Journal, Ser. A, 42, 294–300, 1999.

6) ECE 22.05, Uniform Provisions Concerning the Approval of Protective Helmets and of Their Visors for Drivers ans Passengers, United Nations, 2002.

7) European Communities, COST 327, Motorcycle Safety Helmets, Final Report of the Action, Belgium, 2001.

8) FMVSS 218, Motorcycle Helmets, Federal Motor Vehicle Safety Standards, 1997.

9) Gilchrist, A., Mills, N.J., Modelling of the Impact Response of Motorcycle Helmets , International Journal of Impact Engineering, 15, 201-218, 1994.

10) Gilchrist, A., Mills, N.J., Protection of the side of the head, Accident Analysis and Prevention, 28, 525-535, 1996.

11) Halldin, P., Gilchrist, A. and Mills, N.J. , A new oblique impact test for motorcycle helmets, International Journal of Crashworthiness, 6:1, 53-64, 2001.

12) HIC workshop, Final report of workshop on criteria for head injury and helmet standards, Held in Milwaukee, Wisconsin, 2005.

13) Kostopoulos, V., Markopolous, Y.P., Giannopoulos, G., Vlachos, D.E., Finite element analysis of impact damage response of composite motorcycle safety helmets, Composites: Part B, 33, 99-107, 2002.

14) NHTSA's National Center for Statistics and Analysis, Traffic Safety Facts, Bodily Injury Locations in Fatally Injured Motorcycle Riders, USA, 2007.

15) NHTSA's National Center for Statistics and Analysis, Traffic Safety Facts, Motorcycles, USA, 2004.

16) prEN 398, Protective helmets for drivers and passengers of motorcycles and mopeds, Comite European de Normalisation, Berlin, 1991.

17) SHARP, The Helmet Safety Scheme, www.sharp.direct.gov.uk

18) Shuaeib, F.M., Hamouda, A.M.S., Radin Umar, R.S., Hamdan, M.M., Hashmi, M.S.J., Motorcycle Helmet. Part I. Biomechanics and Computational Issues, Journal of Materias Processing and Technology, 123, 406-421, 2002.

19) Snell, Standard for protective headgear , Snell Memorial Foundation, 2005.

20) The Motorcycle Industry in Europe, ACEM's view on PTW fatality statistics in Europe, Belgium, 2006.

21) Thom, D. R., Hurt, H. H., Smith, T. A., Motorcycle helmet test headform and test apparatus comparison, Proceedings of the 16th International Technical Conference on the Enhanced Safety Vehicle, Paper NO. 98-S10-P-29, Canada, 1998.

22) Vallee, H. et. al., The fracturing of helmet shells, IRCOBI conf., Delft, 99-109 (1984).

23) webBikeWorld, Motorcycle Accessories, Helmets, Clothing, News and More, www.webBikeWorld.com, 2008.