Comparison Tests of Motorcycle Helmets Qualified to International Standards

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ABSTRACT

Thirty-two contemporary full-facial coverage motorcycle helmets consisting of 16 different models, two samples each, were destructively tested. Two anvil configurations were used: flat pavement and a narrow metal edge.

These tests were designed to compare the helmets' relative performance under identical, realistic test conditions rather than to determine compliance with any particular standard. All flat surface impact test results could be ranked by order of best performance: DOT, ECE, BSI, and Snell. Metal edge impact test performance was ranked with BSI performing best followed by DOT, ECE, and Snell.

These results were also compared to similar tests of helmets meeting DOT and Snell M1985 standards (Thom & Hurt, 1992). Energy-absorbing liners on modern helmets are generally more complex and perform better than helmets made 15 years ago. The overall best performing model was qualified only to the DOT standard. Helmets qualified to the high-energy Snell standards generally had the highest peak accelerations in these tests.

INTRODUCTION

Accident research has found motorcycle helmets to be highly effective in reducing head injuries (Hurt, et al, 1981, Ouellet and Kasantikul, 2006). There have been different helmet performance standards in effect over the years. Some standards express a "minimum performance" philosophy while others strive to provide maximum protection. Actual field research has never shown helmets qualified to one standard to be significantly better or worse in actual crash protection.

Historically, two helmet standards have predominated in the United States: the US Department of Transportation's Federal Motor Vehicle Safety Standard No. 218 (DOT) and the Snell Memorial Foundation's standard (Snell). Because of the differing protection philosophies, laboratory tests have been done over the years to explore the differences between these helmet standards. Some of these tests were reported at the 1990 Motorcycle Safety Foundation International Conference. Additional helmet tests were reported in the proceedings of the Association for the Advancement of Automotive Medicine in 1992 (Thom, et al, 1990, 1992). The current test results were compared to the previous tests.

In recent years, other international standards have been introduced into the US market. Federal law requires that all helmets meet DOT regardless of other qualification, manufacturers are now importing helmets meeting the British Standards Institution 6658-1985 (Type A) standard (BSI) and the European Community standard No. 22.05 (ECE). The Snell M2000 (recently revised to M2005) standard continues to be very common in the marketplace. Both European standards require higher impact energies than DOT, but not as severe as Snell.

Different Standards, Different Philosophies

FMVSS 218 includes the following statement, “This standard establishes minimum performance requirements for helmets designed for use by motorcyclists and other motor vehicle users.” That is, the DOT standard sets a level of protection that is targeted at most accidents but does not demand that helmets meet the most extreme impact threats.

The scope of ECE notes, “This regulation applies to protective helmets for drivers and passengers of mopeds and of motor cycles…” with the footnote that, “Protective helmets for wear in competitions may have to comply with stricter provisions.” Additionally, the ECE definition includes the phrase, “Protective helmet means a helmet primarily intended to protect the wearer’s head against impact. Some helmets may provide additional protection.” ECE is the required qualification for international motorcycle racing competition.

Snell Memorial Foundation standards were originally developed for automobile racing in 1957. Previous versions of Snell’s motorcycle helmet standards included the Foreword phrase, “The basic premise of the helmet standard is that the circumstances representing the greatest potential hazard will be reproduced under test conditions.” That is, the Snell standards have explicitly specified tests under the most severe impact conditions. The current Snell motorcycle helmet standard no longer includes the preceding phrase but instead states, “The Snell Foundation urges that protective helmets be required for all individuals participating in supervised racing events…” The foreword goes on to state, “Neither does the Foundation distinguish between the needs of participants in competitive events and those of the general public.”

The fourth standard addressed in the current work is the British Standards Institution (BSI) 6658-1985. This standard includes two types of helmets, both of which are deemed “adequate for use on public roads.” Type A is “intended for competitive events and for use by wearers who demand an especially high degree of protection. Type B is intended for the ordinary motor cycle rider on public roads." Only Type A helmets are imported into the US and were tested here.

These differing philosophies are evident when comparing the impact attenuation requirements summarized in Table 1. Snell's maximum philosophy is evidenced by the highest impact velocities and by the high velocities and double impacts to each location on both flat and hemispherical anvils.

It is worthwhile to note that BSI has not been updated since 1985 and DOT since 1988. Since the United Kingdom is now accepting helmets qualified to ECE, any urgency for updating BSI may have passed. The DOT standard has had numerous efforts toward updates over the last decade. Extensive testing was performed at the University of Southern California Head Protection Research Laboratory in 1997 for possible changes to impact velocity (slight increase), headform and anvil types, helmet coverage, labeling, penetration resistance, and addition of a positional stability test. The National Agenda for Motorcycle Safety recommended in 2000 that the standard be updated but that effort has not progressed in several years (Thom et al, 2001).

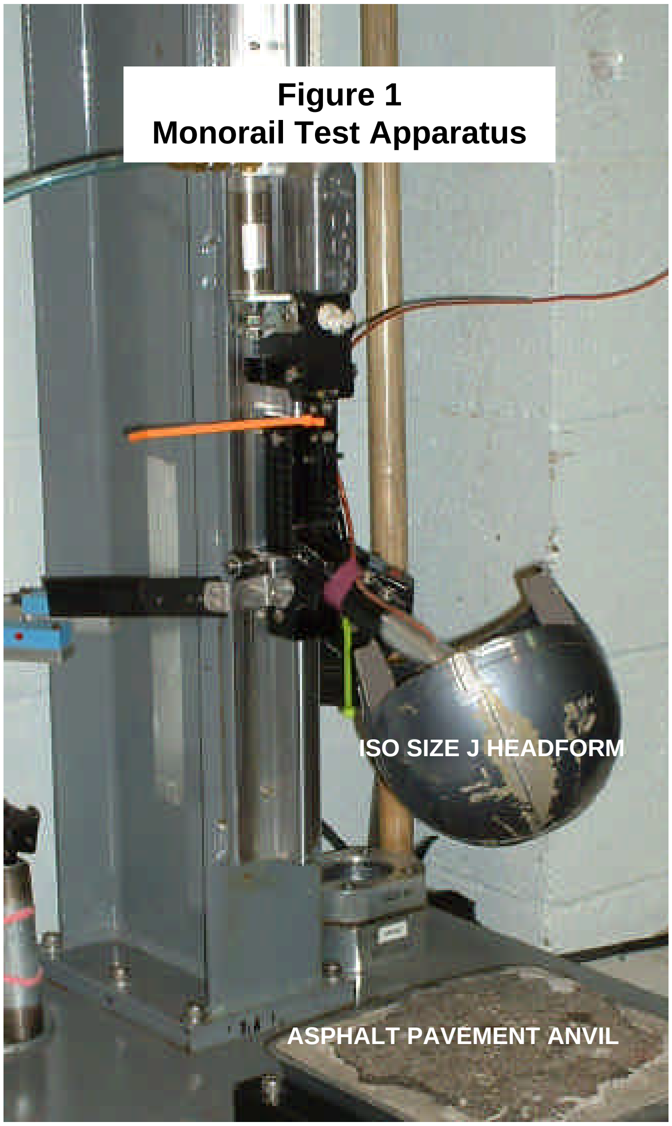
Figure 1
Monorail Test Apparatus

Table 1 compares the performance tests and failure criterion for each of the above standards.

Table 1
Summary of International Helmet Standards

Standard	Year	Drop Test Apparatus	Headforms	Headform Sizes	Drop Assembly Weight	Anvils	Impact Criteria	Number of Impacts	Failure Criteria
FMVSS No. 218	1988	Monorail	DOT	Small[1] Medium Large	3.5 kg 5.0 kg 6.1 kg	Flat Hemi	Velocity: 6.0 m/s 5.2 m/s	Two @ each of 4 sites	$\leq$ 400g $\leq$2.0 msec @ 200g $\leq$4.0 msec @ 150g
British Standards Institution BS 6658	1985	"Guided Fall"[2]	ISO	A,E,J,M	5.0 kg	<u>Type A</u> Flat Hemi <u>Type B</u> Flat Hemi	Velocity: 1st 7.5 m/s 2nd 5.3 m/s 1st 7.0 m/s 2nd 5.0 m/s 1st 6.5 m/s 2nd 4.6 m/s 1st 6.0 m/s 2nd 4.3 m/s	Two (same anvil) @ each of 3 sites Two (same anvil) @ each of 3 sites	$\leq$ 300g (Multi-part shells shall remain intact)
Snell M2000 M2005	2000/ 2005	Monorail or Guide-Wire	ISO	A,E,J,M,O[3]	5.0 kg	Flat Hemi Edge	Energy (Velocity): Flat & Hemi 1st 150J (7.8 m/s) 2nd 110J (6.6 m/s) Edge 150J (7.8 m/s)	Flat & Hemi: Two each @ 4 sites Edge: One impact @ one site	$\leq$ 290g[4]
ECE 22.05	2000	Unrestrained Headform with Tri-Axial Accelerometer	ISO	A E J M O	3.1 4.1 4.7 5.6 6.0	Flat Curb	Velocity: 7.5 m/s for both anvils	4 sites per helmet in sequence with 5th test @ 4 m/s or 8.5 m/s	Resultant $\leq$ 275g HIC $\leq$ 2400

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[1] 49, 56, 60cm circumference
[2] Apparatus not further specified
[3] Sizes 50, 54, 57, 60, 62cm circumference
[4] 290g for any certification impact, 300g for any other impact

METHODOLOGY

The purpose of this study was to test helmets that met differing standards under test conditions that resemble impact situations seen in actual street crashes. Flat pavement is the most common surface that motorcycle riders strike their heads against (Hurt, et al, 1981). Therefore, a test anvil of pavement is used in most of these tests. Another surface that motorcyclists may strike is a hard metal edge such as on a roadside barrier. Thus, a narrow steel edge was chosen for a more concentrated impact surface.

Thirty-two contemporary full facial coverage motorcycle helmets consisting of sixteen different models, two samples each, were tested at Collision and Injury Dynamics in El Segundo, California. All helmets were size medium and/or fit snugly on the 57cm test headform. No tests of retention system strength or penetration resistance tests were performed. Impact attenuation tests were done using ISO size J headform on a monorail test apparatus, see figure 1. Two anvil configurations were used, flat pavement and a 6.3mm (1/4 in.) wide metal edge.

These tests were not to determine compliance with any particular standard, but were designed to compare the helmets' performance under test conditions that resemble the impact threats riders most often face in street crashes. These results were also compared to similar tests of helmets meeting DOT and Snell M1985 (Thom, et al, 1992).

The matched pairs of helmets are identified as the same by a single letter, e.g. "A" and the two samples are identified by a random two digit number, e.g. 27.

RESULTS

Test results are found in Table 2 below. The results have been organized by the standard(s) to which the helmets were qualified and averages are included for all variables.

Helmets meeting ECE were lightest, averaging 1517gm, followed by BSI averaging 1577gm, DOT averaging 1587gm, and Snell averaging 1621gm.

Shell thicknesses vary dramatically by shell material. Thermoplastic shells were generally 4-5 mm thick while composite shells were 2-3 mm thick.

Impact Test Results

The tests at the left front and right rear were done from a drop height of two meters resulting in a drop velocity of 6.3 m/sec (14mph) onto a flat asphalt pavement surface. This drop height was chosen because Hurt et al (1981) found that it represented the 90th percentile impact to helmets involved in street crashes. The lowest acceleration for a single test was 149g and the highest was 209g. The average accelerations can be ranked by standard: DOT = 157g, ECE=162g, BSI=175g and Snell= 187g.

An identical impact test was performed at the left rear and the results are very similar, but not identical, to those at the left front. Again average accelerations can be ranked by standard: DOT=164g, ECE=183g, BSI=197g and Snell= 198g. These impact accelerations differ from the brow location because helmets provide different impact attenuation depending on the location of the impact on the helmet.

The helmets received a more severe impact threat at the right front location. The test surface was again asphalt pavement, but the drop height was increased to three meters (10 ft.) for an impact velocity of 7.6m/sec (17mph). This is generally comparable to the highest impact velocities required to meet some Snell, ECE and BSI requirements, see Table 1. This impact velocity has also been equated to the 99th percentile motorcycle crash impact (Hurt & Thom 1990). That is, 99% of all street crashes are less severe than this impact test. Although the impact energy increased by almost 50% due to the increased velocity, the peak accelerations were only 13 to 19% higher. Helmets qualified to DOT only had the lowest acceleration increase from two to three meters at 12.7% while all other helmets qualified to the other three standards increased a minimum of 18.5%.

The fourth and final impact test was against a metal edge 6.3mm (1/4 inch) wide from a drop height of two meters for an impact velocity of 6.3m/sec (14 mph). All helmets kept the peak acceleration quite low in this test: BSI=126g, DOT=138g, ECE=144g, and Snell=167g. This aggressive surface tests not only the ability of the shell to resist cutting and penetration, but also the EPS liner’s ability to absorb the impact energy.

Table 2
Summary of Results

ID 1	*ID 2*	*Stan-dard(s) Met*	*Weight, grams*	*Shell Material*	*Shell Thick-ness, mm*	*Liner Thick-ness, mm*	*No. EPS liner parts in crown*	*Overall liner density, kg/cu.m (lb/cu.ft.)*	*Peak g Front Left, 2m Asphalt*	*Peak g Front right, 3m Asphalt*	*Peak g Rear Left, 2m Asphalt*	*Peak g Rear Right, 2m Edge*
M	27	DOT	1583	Thermoplastic[5]	4.0	39	1	53 (3.3)	152	173	175	130
M	29	DOT	1552	Thermoplastic	4.0	39	1	53 (3.3)	154	173	175	129
R	36	DOT	1662	ABS[6]	4.6	39	1	55 (3.4)	163	199	185	152
R	37	DOT	1672	ABS	4.6	39	1	55 (3.4)	163	196	185	154
F	13	DOT	1514	ABS/PC[7]	4.7	31	1	39 (3.4)	149	176	154	130
F	14	DOT	1538	ABS/PC	4.7	31	1	39 (3.4)	157	177	164	138
		Average DOT	1587		4.7	36		49 (3.1)	157	177	164	138
C	7	DOT+ECE	1711	FRP[8]	3.2	34	5	47 (2.9)	151	180	176	137
C	8	DOT+ECE	1750	FRP	3.2	34	5	47 (2.9)	161	194	178	138
Q	34	DOT+ECE	1416	FRP & Kevlar & CF[9]	2.9	38	1[10]	47 (2.9)	166	187	201	141
Q	35	DOT+ECE	1407	FRP & Kevlar & CF	2.9	38	1	47 (2.9)	166	187	194	136
P	32	DOT+ECE	1422	FRP	2.7	30	1	55 (3.4)	156	200	190	140
P	33	DOT+ECE	1472	FRP	2.7	30	1	55 (3.4)	155	196	190	138
G	15	DOT+ECE	1489	FRP	2.2	33	1[8]	61 (3.8)	171	198	166	162
G	16	DOT+ECE	1469	FRP	2.2	33	1	61 (3.8)	172	197	166	158
		Average ECE	1517		2.8	34		53 (3.3)	162	192	183	144

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[5] Thermoplastic, actual material not specified
[6] Acrylonitrile Butadiene Styrene
[7] Acrylonitrile Butadiene Styrene & Polycarbonate alloy
[8] Fiber reinforced plastic, a.k.a. Fiberglass
[9] Carbon Fiber
[10] Deeply grooved “crumple zone” design

ID 1	***ID 2***	***Standard(s) Met***	***Weight***	***Shell Material***	***Shell Thickness, mm***	***Liner Thickness, mm***	***No. EPS liner parts in crown***	***Overall liner density, kg/cu.m (lb/cu.ft.)***	***Peak g Front Left, 2m Asphalt***	***Peak g Front right, 3m Asphalt***	***Peak g Rear Left, 2m Asphalt***	***Peak g Rear Right, 2m Edge***
N	30	DOT+BSI	1610	FRP & Kevlar	2.4	38	1	60 (3.8)	156	199	195	129
N	31	DOT+BSI	1644	FRP & Kevlar	2.4	38	1	60 (3.8)	154	205	196	131
K	21	DOT+BSI	1561	FRP	2.2	31	1	52 (3.2)	192	215	197	126
K	22	DOT+BSI	1494	FRP	2.2	31	1	52 (3.2)	196	215	198	119
		Average BSI	1577		2.3	34.5		56 (3.5)	175	209	197	126
L	24	DOT+Snell	1631	FRP & Kevlar	3.1	31	1	52 (3.3)	192	226	166	167
L	25	DOT+Snell	1621	FRP & Kevlar	3.1	31	1	52 (3.3)	186	225	170	183
A	3	DOT+Snell	1475	FRP	3.3	33	1	43 (2.7)	193	243	203	166
A	4	DOT+Snell	1492	FRP	3.3	33	1	43 (2.7)	194	241	204	163
B	5	DOT+Snell	1605	FRP	2.9	35	1	54 (3.4)	195	230	231	163
B	6	DOT+Snell	1610	FRP	2.9	35	1	54 (3.4)	187	234	231	178
D	9	DOT+Snell	1670	ABS/PC	5.1	37	2	47 (3.0)	179	200	179	175
D	10	DOT+Snell	1666	ABS/PC	5.1	37	2	47 (3.0)	172	199	177	175
E	11	DOT+Snell	1655	FRP	2.5	38	2	43 (2.7)	168	217	189	152
E	12	DOT+Snell	1694	FRP	2.5	38	2	43 (2.7)	168	224	186	152
H	17	DOT+Snell	1662	FRP	2.9	35	2	43 (2.7)	207	236	226	176
H	18	DOT+Snell	1665	FRP	2.9	35	2	43 (2.7)	209	233	223	177
J	20	DOT+Snell	1639	TP	4.2	35	2	41 (2.6)	185	212	193	158
J	19	DOT+Snell	1610	TP	4.2	35	2	41 (2.6)	184	206	192	153
		Average Snell	1621		3.4	35		46 (2.9)	187	223	198	167

Comparison to Previous Testing

In all comparable tests, current helmets outperformed those reported in 1992. DOT-only qualified helmets showed the greatest improvement. In the 3m (10 ft.) drop test onto the pavement anvil, DOT-only helmets recorded peak accelerations that averaged 28% lower than the DOT-only helmets from 1992. The least improvement (2%) was seen in the DOT-Snell qualified helmets subjected to the moderate 2m (6ft.) drop test.

Table 3a
Comparison of 1992 Tests to Current Results, 3m tests

Standard(s)	1992 10 foot (3m) drop height (Average for all helmets)	2005 3 meter (9.8 ft) drop height (Average for all helmets)	% change
DOT	254g	182g	-28.3
DOT-BSI	None Tested	207g	NA
DOT-ECE	None Tested	191g	NA
DOT-Snell	252g	223g	-11.5

Table 3b
Comparison of 1992 Tests to Current Results, 2m tests

Standard(s)	1992 6 foot (1.8m) drop height (Average for all helmets)	2005 2 meter (6.6 ft) drop height (Average for all helmets)	% change
DOT	181g	163g	-9.9
DOT-BSI	None Tested	185g	NA
DOT-ECE	None Tested	172g	NA
DOT-Snell	197g	193g	-2.0

DISCUSSION

Impact Energy

There are two primary differences between helmet standards: impact energy (determined by impact velocity and headform weight) and pass/fail criteria. DOT, BSI and ECE all use variable weight headforms: that is smaller headforms weigh correspondingly less than larger headforms. The Snell and BSI standards specify that the impact energy must be consistent regardless of the headform size. By contrast, DOT and ECE standards specify an impact velocity so the impact energy varies with the headform size and weight.

Shell Material

There are two primary types of shells used in modern motorcycle helmets: injection molded thermoplastic (TP) and composites. The composite structure helmets were resin reinforced with a fiber material, usually fiberglass and sometimes including Kevlar or carbon fibers.

Energy-Absorbing Liner Configuration

The last time similar testing was done, all tested helmets had a single piece molded EPS liner (Thom, 1992). Many of the current helmets have liners that consist of more than one part, anywhere from two to five in the crown region and more in the ear and chin portions of the helmets. Figure 2 shows the main configurations now used to tailor the liner for improved impact attenuation. The myriad liner configurations for ear and chin regions will not be discussed here.

In the past, when energy-absorbing liners were one piece and of uniform density, liner density had a simple relationship to impact acceleration. Previous work showed that soft, low-density EPS was more successful at passing DOT standard requirements while firmer, higher-density EPS was necessary to pass the high-energy Snell tests (Thom, et al., 1992). In these tests, four of seven Snell qualified helmets used a low density crown cap over a higher density main liner. This appears to be a design feature to help the helmets meet both the strict lower energy DOT and high-energy Snell impacts. However, not all Snell qualified helmets had multi-part liners and these tests did not evaluate whether or not the helmets actually met any or all of the standard(s) that they were labeled as meeting.

Energy-Absorbing Liner Thickness

All energy-absorbing liners were made of expanded polystyrene (EPS) bead foam and varied from 30 to 39 mm thick. Many of the helmets had multi-part liners of differing densities forming complex shapes for ventilation and performance. See Figure 2 for these configurations. The number of liner components in the crown area is noted in Table 2. The most common multi-part configuration is a main liner of higher density with a crown cap of lower density. Most of the helmets had separate EPS lining for the temple/ear regions as well

Figure 2
Energy-Absorbing Liner Configurations

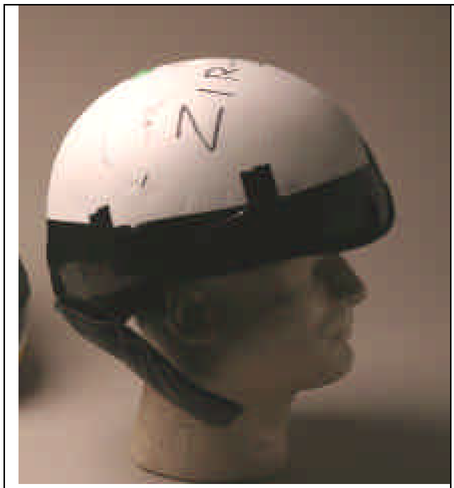

Figure 2a
Single Part EPS Crown Liner

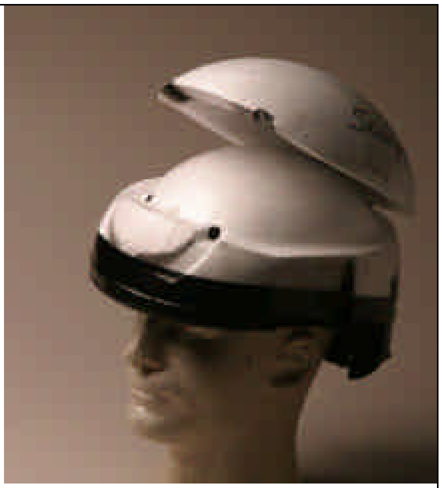

Figure 2b
Crown Cap and Main Liner

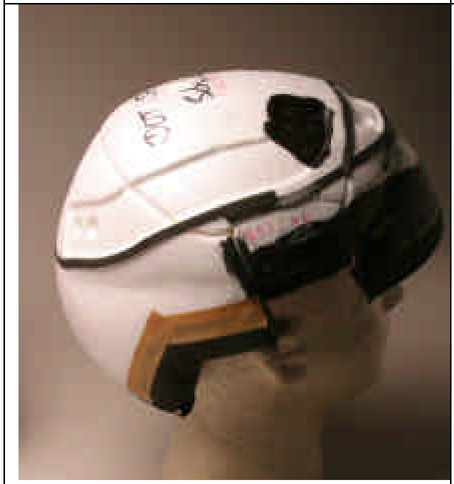

Figure 2c
Multi-Part Crown Liner

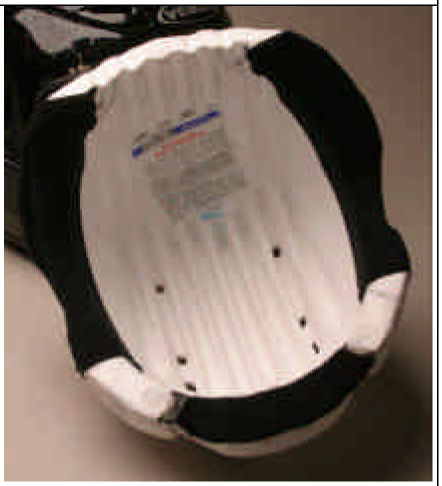

Figure 2d
Deeply grooved “Crumple Zone” Liner (Interior surface)

as the chinbar area. Only two models did not have EPS in the chinbar area. Both did have substantial resilient chinbar padding but no method of energy absorption in the event of facial impact.

Another noteworthy design is shown in Figure 2d in which the liner is constructed of higher density EPS with deep channels molded in the interior surface creating “walls” of EPS that crush, crack and deform to absorb impact. Helmets Q and G were both ECE qualified and use this “crumple zone” technology. Both performed well, similar to the other ECE qualified helmets.

Energy-Absorbing Liner Density

The function of the liner is to be damaged in order to absorb energy. The predominating method of energy absorption is accomplished by permanent crushing of the expanded polystyrene material. During this crushing process, the liner will often bend and crack as well, particularly those utilizing complex shapes.

Liner densities varied from 39kg/m^3 (3.4 lb/ft^3) to 61kg/m^3 (3.8lb/ft^3). The varied liner configurations with multiple density components defied simple analysis since each impact site may engage several shapes and densities of EPS for energy absorption.

Differences in European helmet standards

There are two significant differences between North American helmet standards and those in force in Europe.

The British standard (BSI) apparatus is directly comparable to North American test equipment. However, BSI also includes an oblique impact test. The oblique test measures force transmitted to an oblique anvil struck by an unrestrained helmet.

The ECE standard impact attenuation requirements are tested on a significantly different type of test apparatus, refer to Table 1 for a summary. All other standards in this comparison use a vertically-guided headform that cannot rotate during impact. The unrestrained headform method in ECE allows rotation in any direction as the headform responds to the test impact. The test headform includes a short neck and is not spherical, nor is the helmet being tested. Therefore the impact is often not aligned with the center of gravity of the headform/helmet assembly, causing rotation upon impact. This rotational motion and acceleration is not monitored in any way and important data is therefore lost. These methodologies have been compared in detail previously (Thom et al, 1998 & Johnson, undated).

While the impact velocities in the ECE standard are higher than those compared here (7.5 m/sec or 17 mph), some of the impact energy is lost as a function of the test method reducing its severity when compared to fixed headform equipment. This also prevents any direct comparison between results from the two machines, particularly for flat anvil impacts (Thom, et al, 1997). These apparatus differences appear to result in a “softer” helmet being able to pass ECE requirements.

Why Does it Matter?

The fundamental function of a motorcycle helmet is to reduce the acceleration caused by your head striking a rigid object such as the street. The primary measure of helmets’ effectiveness is the peak acceleration, or “g” felt by the head. Helmet standards limit acceptable acceleration to 300g (BSI and Snell), 275g (ECE), and 400g (DOT). DOT’s peak acceleration limit is significantly reduced from the published 400g because of the imposition of a maximum 2.0 millisecond on any acceleration over 200g, a limit that no other standard imposes. Previous research showed that the 2.0 msec. dwell time limit correlates to an acceleration limit of approximately 250g (Thom & Hurt, 1992).

Since the function of a motorcycle helmet is to reduce impact-caused acceleration of the head, it stands to reason that one should choose a helmet that minimizes peak acceleration. This topic was well illuminated in Motorcyclist magazine (Ford, 2005). Motorcyclists are the fortunate beneficiaries of significant improvements in helmet performance in the last decade. However, helmets qualified to DOT and DOT+ECE provide better protection as measured in these laboratory tests than helmets qualified to BSI and Snell.

ACKNOWLEGEMENT

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