MOTORCYCLE HELMET TEST HEADFORM AND TEST APPARATUS COMPARISON

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ABSTRACT

Internationally, there are two types of headforms used for impact attenuation testing of motorcycle helmets. These two types of test headforms follow specifications established by the International Standards Organization (ISO), or the U.S. Department of Transportation (DOT). Both headforms are low resonance, rigid castings, but they differ in size, shape and weight. The headforms are supported by a rigid guide assembly that limits their motion to the vertical direction only. Different impact locations are obtained by adjustment of the headform on a spherical ball joint. Performance criteria are based on acceleration time history measurements from a uniaxial accelerometer located at the headform center of mass.

A second variation on the ISO headform is found in some European helmet standards that utilize an unrestrained headform instrumented with a triaxial accelerometer. These constrained headforms respond to impact with motion in many directions and performance criteria are based on the resultant of three axis acceleration time histories.

Impact attenuation tests were performed on 180 motorcycle helmets of three different designs and under environmental conditions specified by helmet performance standards. Selected tests were recorded on high-speed (1000 Hz) videotape for motion analysis. Test apparatus designs differ greatly and guided free-fall apparatus with restrained headforms produces consistently more rigorous tests than apparatus without headform guide or restraint. Significant differences were also found between DOT and ISO headforms for both peak acceleration and dwell time on flat anvil impacts when tested on the DOT-type monorail apparatus.

INTRODUCTION

Table 1 summarizes the impact attenuation test methods and failure criteria for major international standards. Current FMVSS No. 218 impact energy levels are realistic, with the flat anvil impacts corresponding to the 90th percentile of all traffic accident impacts (Hurt, Ouellet & Thom, 1981). Double impacts that exist as part of the standard tests are not typical of accident events, but the requirement is an acceptable procedure which provides a margin of safety for the consumer. While there is always the temptation to increase the impact energy level with the expectation of providing greater protection, any change that is without support by research may adversely affect accident performance. For example, if the impact energy of the standard test were increased, the typical design change would be an increase in liner density. These changes could provide the greater impact attenuation but may increase headform accelerations for impacts less than the standard test (Smith, 1997; Thom & Hurt, 1992, Mills & Gilchrist, 1991).

The scientific community generally concurs that some relationship exists between head impact acceleration, time duration and tolerance to head injury. However, the exact nature of this relationship has not been clearly defined. Many methods currently consolidate the relationship between headform acceleration and time duration, for example, Head Injury Criterion (HIC) and Gadd Severity Index (SI), yet all methods have been criticized regarding their application to head protection (Newman, 1975, 1982). Until an acceptable means of analysis is developed, time duration appears to be acceptable since it does have some basis in human tolerance (Ono, 1980). However, the most frequent impact attenuation failure of otherwise well-qualified helmets is to exceed the 200g dwell time limit.

Table 1 also lists the type, sizes and weights of the test headforms used by major international helmet performance standards. Note that the majority of these standards use ISO headforms as specified in standard EN960, 1995 or its predecessor standard, ISO/DIS 6220, 1983.

Considerable work has been done over the years comparing the test performance of the twin guide-wire test apparatus and the monorail apparatus (Henderson, 1975; Bishop, 1989). Both of these systems hold the

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 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	< 400g 2.0 msec @ 200g 4.0 msec @ 150g
ANSI Z90.1	1992	Monorail or Guide-Wire	DOT or ISO	Small Medium Large or A,E,J,M	5.0 kg**	Flat Hemi	Velocity: Flat & Hemi: 1st 6.9 m/s 2nd 6.0 m/s	Two @ each of 4 sites	$\leq$ 300g
AS 1698	1988	"Guided Fall"*	Magnesium AS 2512.1 (DOT)	A B C D	3.5 kg 4.0 kg 5.0 kg 6.0 kg	Flat Hemi	Drop Height: 1830 mm 1385 mm	Two @ each of 4 sites	$\leq$ 300g 3.0 msec @ 200g 6.0 msec @ 150g
BS 6658	1985	"Guided Fall"*	ISO	A,E,J,M	5.0 kg	Type A Flat Hemi Type B 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)
CAN3-D230	1985	"Guided Fall"*	ISO	A,E,J,M	5.0 kg	Flat Hemi	Velocity: 1st 5.1 m/s 2nd 7.2 m/s 1st 4.3 m/s 2nd 6.1 m/s	Two @ each of 4 sites	Low Energy: $\leq$ 200g High Energy: $\leq$ 300g
Snell M-95	1995	Monorail or Guide-Wire	ISO	A,E,J,M	$\geq$ 5.0 kg, $\leq$ 6.5 kg	Flat Hemi Edge	Energy: Flat & Hemi 1st 150J 2nd 110J Edge 150J	Flat & Hemi: Two each @ 4 sites Edge: One impact @ one site	$\leq$ 300g
ECE 22.4	1995	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

* Apparatus not further specified
** Small & Large DOT headforms not currently available in 5 kg.

headform relatively rigid during the impact and utilize a single axis accelerometer. FMVSS No. 218 specifies the use of the monorail test apparatus.

The ECE 22 standard for motorcycle helmets requires the use of a completely different type of test system (ECE 22.4, 1995). This system carries an unrestrained headform equipped with a triaxial accelerometer in a headform support assembly. In contrast to both the twin guide-wire and the monorail, the ECE apparatus allows unrestrained motion of the test headform during the impact attenuation test. Search of the literature did not locate any record of side-by-side comparison of the monorail or twin guide-wire and the ECE basket type apparatus.

METHODS

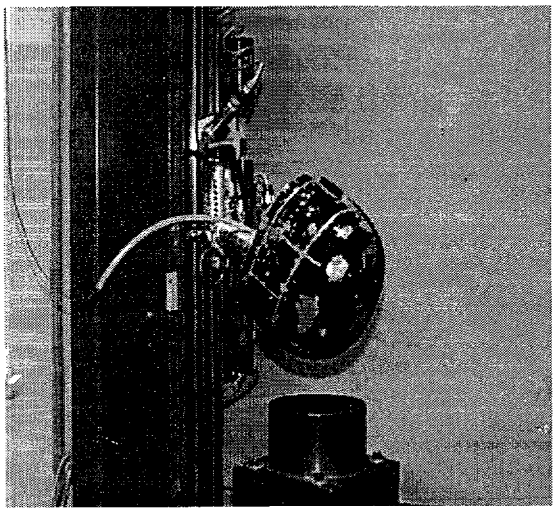
Baseline Tests and Test Criteria

The research was based upon comprehensive baseline testing of a large number of helmets to the current FMVSS No. 218. The test program consisted of:

i. 72 helmets selected for three levels of expected performance
ii. three headform sizes
iii. all environmental conditions of the standard.

These tests were conducted on the monorail test apparatus shown in Figure 1.

Figure 1.
Monorail Test Apparatus with DOT Medium Headform and Flat Anvil



In order to provide test data for all combinations of impact anvil type and impact location, duplicate samples of all helmets were used. This "double" test provided impact tests against both anvil configurations (flat and hemispherical) at four locations on each helmet. Subsequent tests made for comparative purposes were assured of complete data for direct comparison.

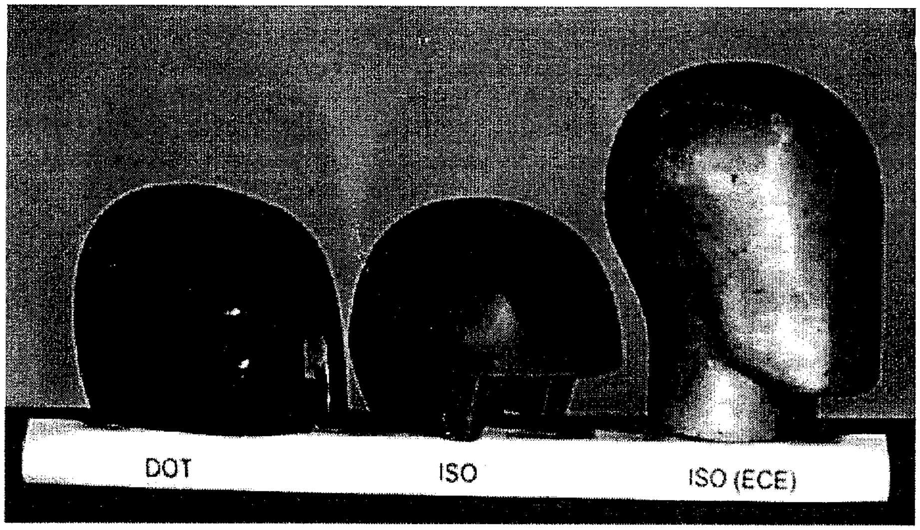
Alternative Headforms

HPRL conducted comprehensive tests of identical 36 helmets using International Standards Organization (ISO) headforms). These tests were conducted on the monorail test apparatus. But this test series duplicated the baseline tests and used ISO headforms. Table 2 gives data for the comparison of the two types of headforms. Figure 2 shows the three types of headforms in equivalent sizes (ISO J and DOT Medium). The ISO headforms are most closely comparable by size rather than weight. While there is a much smaller, size "A" ISO headform, it is applicable to very small children who are not part of the motorcycle user population. There is an extra large (62 cm) ISO size "O" headform, but there is no comparable extra large DOT headform size.

Table 2.
Test Headform Comparison

Headform	Circumference	Weight
DOT Small	49 cm	3.5 kg
DOT Medium	56 cm	5.0 kg
DOT Large	60 cm	6.1 kg
ISO E	54 cm	4.1 kg
ISO J	57 cm	4.7 kg
ISO M	60 cm	5.6 kg

Figure 2.
Test Headforms (DOT Medium, ISO J)



Alternative Test Apparatus

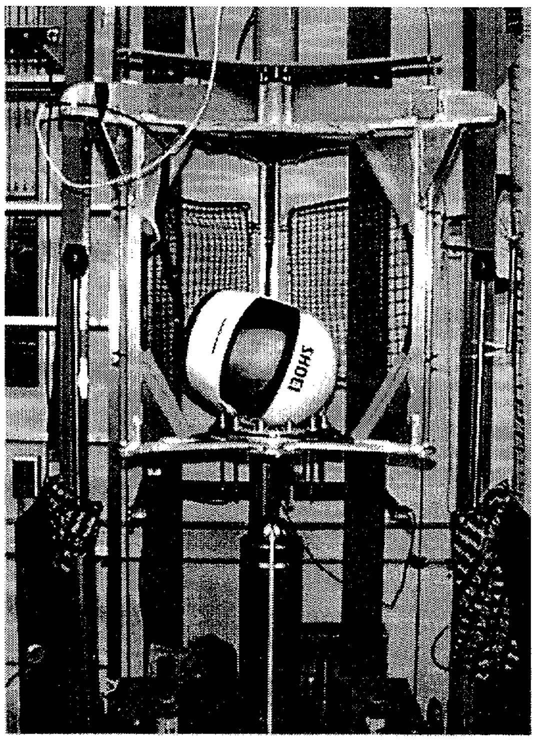
Selected tests of 36 equivalent helmets using the guided free-fall test apparatus as specified by ECE 22, etc. Because of the mechanics of this test, the ISO test headforms include the neck, however they have the same weights as the ISO headform impact assembly (see Figure 2).

The ECE-type test machinery and electronic instrumentation are considerably more complicated than those currently required by FMVSS No. 218. The ECE apparatus used in this work is shown in Figure 3. The helmeted headform is guided only until impact, then unrestrained rebound response is limited by the basket walls. Triaxial accelerometer instrumentation is required with the ECE test, and then the resultant of the three-axis peak acceleration is computed.

Alternative Impact Velocities

These tests were performed on an additional 36 helmets for direct comparison to the Baseline tests. These tests following the current FMVSS No. 218 specifications and used the same locations and anvils as the Baseline 1 tests. The only difference in the tests was increased impact velocity for the first of two impacts at each location. The results of this test series determined the impact velocities used for the following tests.

Figure 3.
ECE-Type Test Apparatus



Selection of Impact Locations

HPRL performed preliminary tests to determine the effect of modifying full-facial coverage helmets by removal of the chinbar. Five full-facial coverage, polycarbonate shell helmets were tested on the flat anvil with varying degrees of modification as noted below. Helmets 1-4 were tested squarely on the sides and mid-sagittal at front and rear (0, 90, 180, 270 degrees).

- Helmet 1 No modification (1401 gm as tested).
- Helmet 2 Chinbar removed prior to any testing (1173 gm).
- Helmet 3 Lower portion of helmet removed, leaving the test area only intact (809 gm).
- Helmet 4 No modification for first three impacts (1401gm), chinbar removed to allow center of brow impact (1144 gm).
- Helmet 5 No modification, impacts at "corners" of helmet (50, 145, 210, 310 degrees—impact locations accessible without modification of helmet, 1399 gm).

Table 3 shows the results of these DOT flat anvil tests. The peak acceleration results vary within impact location by 0.8% to 7% for all tests but one (front impact #1, 11%) including the highly modified helmet No. 3. This variation is unremarkable and far less than the 20-24% difference shown between critical side and sub-critical "corner" impact locations.

In order to minimize any question of the effect of chinbar removal on overall results, the first three impact tests on each helmet were done with the helmets completely intact. The chinbar was then removed for the fourth and final test at the center of the brow.

High-Speed Video Analysis

A series of impact tests with the ECE test apparatus and monorail test apparatus were conducted using a Kodak Ektapro high speed video system which captured the entire helmet impact sequence at a rate of 1000 frames per second.

Test Helmet Construction

Representative helmets of those tested in this work were disassembled and their construction details are noted in Table 4.

Table 3.
Effect Of Impact Location On Peak Headform Acceleration

	Condition	Location	Right #1	Right #2	Rear #1	Rear #2	Left #1	Left #2	Front #1	Front #2
Helmet 1 ***	OEM	Peak g	212	252	219	253	201	246	**	**
		T@200g	1.0	2.6	0.9	2.7	0.1	2.7	**	**
Helmet 4 ***	OEM*	Peak g	208	252	217	250	215	245	178	222
		T@200g	0.9	2.6	0.8	2.9	0.4	2.7	0.0	1.8
Helmet 2	CB removed	Peak g	207	240	207	238	224	260	175	224
		T@200g	0.6	2.4	0.4	2.9	0.6	2.7	0.0	1.9
Helmet 3	Test Area	Peak g	200	227	207	242	205	243	186	224
		T@200g	0.1	2.1	0.6	2.0	0.7	2.2	0.0	1.9
		Location	**Right Front #1**	**Right Front #2**	**Left Front #1**	**Left Front # 2**	**Left Rear #1**	**Left Rear #2**	**Right Rear #1**	**Right Rear #2**
Helmet 5	OEM	Peak g	167	208	173	206	196	227	216	265
		T@200g	0.0	0.9	0.0	0.2	0.0	2.7	0.9	2.9

* Helmet intact for first 3 impacts, chinbar removed for last impact at brow
** No impact possible due to mechanical interference of monorail apparatus
*** Helmets and impacts identical for first 3 impacts

Table 4.
Test Helmet Construction

			HELMET SHELL		HELMET LINER			
Group	Coverage	Helmet Size	Shell Material	Shell Thickness (mm)	Liner Weight (gm)	Liner Volume (ml)	Density (Kg/cu.m..)	Nominal Thickness (mm)
A	Partial	XS	ABS	5.0	110	2450	45	30
A	Partial	M	ABS	5.0	131	2250	58	35
A	Partial	XL	ABS	5.0	113	2000	57	25
B	Full	XS	Polycarbonate	3.8	147	2900	51	30
B	Full Face	L	Polycarbonate	3.8	222	3700	60	35
B	Full Face	XL	Polycarbonate	3.8	183	3100	59	35
C	Full Face	XS	Fiberglass and Polyester Resin	3.8	136	4250	32	38
C	Full Face	M	Fiberglass and Polyester Resin	3.8	124	3500	35	36
C	Full Face	L	Fiberglass and Polyester Resin	3.8	121	3700	33	32

RESULTS

Peak Headform Acceleration by Test Groups

Table 5 lists the summary results and statistical significance of the peak headform accelerations for the test groups for the anvil configurations. All peak headform accelerations above 300g occurred for impacts at the center of the brow (front) location.

__Test Headforms: DOT FMVSS No. 218 vs. International Standards Organization__. These tests of DOT FMVSS No. 218 headforms (AV) and International Standards Organization (ISO) headforms (HF) are at the higher impact velocities specified in Table 6. The only variable between these tests is the headform type. For flat and hemispherical anvil tests combined, there was no statistically significant difference of peak headform accelerations (see Table 5). However, the flat anvil tests did show a statistically significant increase for the ISO headforms. The hemispherical anvil tests showed a slight decrease in mean peak headform acceleration that was not statistically significant.

__Test Apparatus: Monorail vs. ECE-Type__. Comparison of the ISO test headform (HF) group to the Alternative Apparatus (AA) group allows a direct comparison of test equipment, since both groups used ISO headforms and the higher impact velocities noted in Table 6. The result was a statistically significant 33g reduction of overall peak acceleration (see Table 5). This reduction is primarily due to decreased accelerations for the flat anvil tests, a difference of 52g. The hemispherical anvil test results involved much lower peak accelerations and were not statistically different.

__Test Apparatus: Monorail Using DOT Headforms vs. ECE-Type__. All peak accelerations shown in Table 5 were significantly lower on the ECE-Type apparatus. Unlike the apparatus comparison with ISO headforms (HF vs. AA), these tests showed similar reductions of peak acceleration, averaging 26g for both flat and hemispherical anvils.

__Increased Impact Velocity__. The current FMVSS No. 218 specifies impact velocity of 6.0 m/s for flat anvil impacts (both first and second impacts at each site) and 5.2 m/s for both hemispherical anvil impacts. The increased velocity test series used a flat anvil test velocity of 6.9 m/s for the first impact and retained the original 6.0 m/s for the second impact at each site. The hemispherical anvil test velocity was increased to 6.0 m/s for the first impact and retained the original 5.2 m/s for the second impact at each site. These velocities and the increased impact energies for the different test headforms are shown in Table 6.

Higher impact velocities showed statistically significant increases in peak acceleration for both flat and hemispherical anvils when compared to the baseline tests. There is a greatly increased incidence of failure of all impact attenuation criteria, with the mean value for headform acceleration increasing 34g (hemispherical anvil). The helmets also begin to show high peak accelerations in locations other than the brow at these higher impact velocities.

Dwell Time Differences by Test Groups. The various test groups were compared for the statistical differences between dwell times at 150 and 200g. Table 7 shows the summary of these comparisons.

Dwell Time at 150g. It is important to note that this criterion of helmet impact performance has never been a critical measure. In the current FMVSS No. 218, essentially any helmet which succeeds in qualifying to the 200g-2.0 msec. limit will also qualify to the 150g-4.0 msec. limit. In the 576 test impacts of the Baseline tests, there was only one exceedance of the 4.0 msec. limit. In subsequent tests with greater impact velocity, there were more frequent exceedance of the 4.0 msec. limit at 150g (see Table 8). These comparisons show statistically significant differences for several groups comparing velocity and test equipment.

Table 5.
Peak Headform Acceleration by Test Groups

Test Type	Test Group	Anvil	Mean Peak Acceleration	t-value	Significance
Baseline 1 (B1) vs. Baseline 2 (B2)	Baseline 1	Flat & Hemi	173	0.54	0.590
	Baseline 2	Flat & Hemi	170		
	Baseline 1	Flat	209	0.31	0.756
	Baseline 2	Flat	210		
	Baseline 1	Hemispherical	137	1.34	0.180
	Baseline 2	Hemispherical	130		
Baseline 1 (B1) vs. Increased Velocity (AV)	Baseline 1	Flat & Hemi	173	4.93	**0.000**
	Incr. Vel.	Flat & Hemi	201		
	Baseline 1	Flat	209	6.22	**0.000**
	Incr. Vel.	Flat	228		
	Baseline 1	Hemispherical	137	-3.84	**0.000**
	Incr. Vel.	Hemispherical	174		
ISO Headforms (HF) vs. DOT Headforms (AV)	ISO	Flat & Hemi	210	1.37	0.171
	DOT	Flat & Hemi	201		
	ISO	Flat	252	5.53	**0.000**
	DOT	Flat	228		
	ISO	Hemispherical	167	-0.59	0.556
	DOT	Hemispherical	173		
Monorail, ISO Headforms (HF) vs. Alternate Apparatus (AA)	Monorail	Flat & Hemi	210	5.12	**0.000**
	ECE	Flat & Hemi	177		
	Monorail	Flat	252	11.79	**0.000**
	ECE	Flat	200		
	Monorail	Hemispherical	167	1.27	0.205
	ECE	Hemispherical	154		
Monorail, DOT Headforms (AV) vs. Alternate Apparatus (AA)	Monorail	Flat & Hemi	201	-4.51	**0.000**
	ECE	Flat & Hemi	175		
	Monorail	Flat	228	-7.87	**0.000**
	ECE	Flat	200		
	Monorail	Hemispherical	173	-2.42	**0.016**
	ECE	Hemispherical	149		

Table 6.
Increased Impact Velocity and Energy

Headform (Weight)	Flat Anvil Velocity 1 (m/s)	Energy (Joules)	Flat Anvil Velocity 2 (m/s)	Energy (Joules)	Hemi Anvil Velocity 1 (m/s)	Energy (Joules)	Hemi Anvil Velocity 2 (m/s)	Energy (Joules)
DOT Small (3.5 kg.)	6.9	84	6.0	63	6.0	63	5.2	47
DOT Medium (5.0 kg.)	6.9	119	6.0	90	6.0	90	5.2	68
DOT Large (6.1 kg.)	6.9	145	6.0	110	6.0	110	5.2	82
ISO E (4.1 kg.)	6.9	98	6.0	74	6.0	74	5.2	55
ISO J (4.7 kg.)	6.9	112	6.0	85	6.0	85	5.2	64
ISO M (5.6 kg.)	6.9	133	6.0	101	6.0	101	5.2	76

Dwell time at 200g—Baseline Tests. The two baseline tests (B1, B2) show no overall difference when data for both flat and hemispherical anvils are combined for comparison. However, when the data for the two anvils are separated, there is a statistically significant difference between the hemispherical anvil test results, due to the increased vulnerability of the front (brow) to the more aggressive hemispherical anvil.

Dwell time at 200g—DOT vs. ISO Headforms. The ISO headforms overall produced a statistically significant increase in dwell time at 200g. In particular, this was due to the significant increase of dwell time on the flat anvil impacts. Hemispherical impacts were not significantly different.

Dwell time at 200g—Monorail vs. ECE-Type. The results show a statistically significant reduction in dwell time at 200g for the flat anvil tests. This is one of the most dramatic reductions in these tests, from a mean of 2.03 msec. for the monorail with ISO headforms to 0.594 msec. on the ECE apparatus. There was no statistically significant difference between results for the hemispherical anvil tests.

Dwell time at 200g—Monorail Using DOT Headforms vs. ECE-Type. As with the previous comparison of headform types with alternative test apparatus (HF vs. AA), there was a statistically significant decrease in the dwell times on flat anvil tests, but no statistically significant difference for the hemispherical anvil tests.

Summary of Test Criteria for All Test Groups. Table 8 summarizes the count and percentage of the total number of tests for any failures of test criteria for the seven test groups. Note that this summary table combines all helmet types and sizes, and counts each of the 1440 impact tests. Note that dwell times at 200g are included at several values: 2.0, 2.2, 2.4, 2.6, and 2.8 msec. The total number of impacts exceeding 2.0 msec @ 200g is 33 (5.7% of 576 impacts) for the Baseline tests. The number of impacts exceeding 2.2 msec @ 200g is 23 (4.0%): the majority (69.7%) of the impacts failing at 2.0 msec still fail at 2.2 msec.

Table 7.
Dwell Time Differences Between Test Groups

Test Type	Test Group	Anvil	Mean Time @ 150g	t value	Significance	Mean Time @ 200g	t value	Significance
Baseline 1 (B1) vs. Baseline 2 (B2)	Baseline 1	Flat & Hemi Combined	1.717	1.83	0.670	0.446	1.19	0.236
	Baseline 2	Flat & Hemi Combined	1.484			0.373		
	Baseline 1	Flat	3.208	5.23	**0.000**	0.855	1.06	0.292
	Baseline 2	Flat	2.759			0.747		
	Baseline 1	Hemispherical	0.225	0.29	0.773	0.037	2.51	**0.013**
	Baseline 2	Hemispherical	0.208			0.000		
Baseline 1 (B1) vs. Increased Velocity (AV)	Baseline 1	Flat & Hemi	1.717	-1.65	0.100	0.446	-5.35	**0.000**
	Increased Velocity	Flat & Hemi Combined	1.936			0.855		
	Baseline 1	Flat	3.208	-4.58	**0.000**	0.855	-6.46	**0.000**
	Increased Velocity	Flat	3.442			1.583		
	Baseline 1	Hemispherical	0.225	-2.77	**0.006**	0.037	-2.9	**0.004**
	Increased Velocity	Hemispherical	0.353			0.126		
Baseline 1 (B1) vs. Alternate Apparatus (AA)	Baseline 1	Flat & Hemi	1.716	-1.32	0.186	0.446	1.82	0.069
	ECE	Flat & Hemi Combined	1.549			0.340		
	Baseline 1	Flat	3.208	-5.20	**0.000**	0.855	2.64	**0.009**
	ECE	Flat	2.745			0.594		
	Baseline 1	Hemispherical	0.225	-1.84	0.066	0.037	1.82	0.069
	ECE	Hemispherical	0.353			0.085		
ISO Headforms (HF) vs. DOT Headforms (AV)	ISO	Flat & Hemi Combined	2.056	0.9	0.368	1.054	2.13	**0.034**
	DOT	Flat & Hemi Combined	1.936			0.855		
	ISO	Flat	3.509	-1.41	0.160	2.030	3.87	**0.000**
	DOT	Flat	3.442			1.583		
	ISO	Hemispherical	0.603	-1.91	0.058	0.078	-1.38	0.168
	DOT	Hemispherical	0.429			0.126		
Monorail, ISO Headforms (HF) vs. Alternative Apparatus(AA)	Monorail	Flat & Hemi Combined	2.056	-3.99	**0.000**	1.054	8.96	**0.000**
	ECE	Flat & Hemi Combined	1.549			0.340		
	Monorail	Flat	3.509	-8.79	**0.000**	2.030	14.12	**0.000**
	ECE	Flat	2.745			0.594		
	Monorail	Hemispherical	0.603	-2.84	**0.005**	0.078	-0.22	0.822
	ECE	Hemispherical	0.353			0.085		
Monorail, DOT Headforms (AV) vs. Alternative Apparatus(AA)	Monorail	Flat & Hemi Combined	1.935	-3.02	**0.003**	0.855	7.17	**0.000**
	ECE	Flat & Hemi Combined	1.549			0.340		
	Monorail	Flat	3.442	-7.95	**0.000**	1.583	9.35	**0.000**
	ECE	Flat	2.745			0.594		
	Monorail	Hemispherical	0.429	-0.95	0.343	0.126	1.18	0.238
	ECE	Hemispherical	0.353			0.085		

Dwell time at 200g—Baseline Tests. The two baseline tests (B1, B2) show no overall difference when data for both flat and hemispherical anvils are combined for comparison. However, when the data for the two anvils are separated, there is a statistically significant difference between the hemispherical anvil test results, due to the increased vulnerability of the front (brow) to the more aggressive hemispherical anvil.

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Table 8.
Test Group by Failure Criteria
(N=1440)

	Baseline			ISO Headforms	Increased Velocity	Alternative Apparatus
Values greater than: count, (%)	B1 (n=288)	B2 (n=288)	B1 + B2 (n=576)	HF (n=288)	AV (n=288)	AA (n=288)
400g	3 (1.0)	3 (1.0)	6 (1.0)	6 (2.1)	11 (3.8)	4 (1.4)
300g	3 (1.0)	7 (2.4)	10 (1.7)	37 (12.8)	19 (6.6)	10 (3.5)
4.0 ms @ 150g	1 (0.3)	0	1 (0.15)	9 (3.1)	7 (2.4)	5 (1.7)
2.0 ms @ 200g	20 (6.9)	13 (4.5)	33 (5.7)	84 (29.2)	55 (19.1)	8 (2.8)
2.2 ms @ 200g	15 (5.2)	8 (2.8)	23 (4.0)	74 (25.7)	46 (16.0)	6 (2.1)
2.4 ms @ 200g	9 (3.1)	4 (1.4)	13 (2.3)	55 (19.1)	40 (13.9)	5 (1.7)
2.6 ms @ 200g	6 (2.1)	1 (0.3)	7 (1.2)	46 (16.0)	20 (6.9)	3 (1.0)
2.8 ms @ 200g	1 (0.3)	0	1 (0.15)	28 (9.7)	11 (3.8)	1 (0.3)

High Speed Video Analysis. A series of impact tests with the ECE test apparatus and monorail test apparatus were conducted using a Kodak Ektapro high speed video system which captured the entire helmet impact sequence at a rate of 1000 frames per second. Images were stored digitally and subsequently downloaded to a VHS video system at several different playback speeds.

The ECE test equipment consists of a full configuration (complete with neck) ISO test headform fitted with a tri-axial accelerometer at the center of gravity (See Figure 2). A helmet was placed on the test headform and the headform and helmet were oriented to make contact at the appropriate site and supported using a free fall support cage assembly. The headform, helmet and support cage assembly were raised to the appropriate drop height and released. The cage assembly proceeded to fall towards the impact anvil which then projects through a hole located in the bottom of the cage assembly (See Figure 3). This allows the cage assembly to clear the test anvil while the anvil makes direct contact with the helmet. Since the helmet was not fixed inside the cage assembly, it was free to move in any direction following the initial impact. Although there was very little motion during the primary impact into the test anvil, the secondary motion following the primary impact (i.e. the impact into the roof of the carriage assembly and the second impact onto the test anvil) caused a great deal of secondary damage to the helmet and the headform system. Additional tests in which there were secondary impacts may not indicate the true performance of the helmet, since the helmet could already have experienced some damage due to these secondary impacts. This characteristic may be unique to this particular design of ECE test apparatus; however, the potential of secondary helmet impacts does relate a problem with the ECE test procedures.

The amount of helmet and headform rotational motion observed during the ECE test procedures was obviously greater than the rotation observed during the monorail test procedures. This was because the center of gravity of the ISO test headform is not aligned with the point of impact on the test helmet. As a result of this offset, a moment was generated about the center of mass of the headform and helmet system, causing helmet rotation. The presence of rotation during the ECE test procedures indicates that some of the kinetic energy of the impact is directed into rotational kinetic energy rather than impact energy with the test anvil. A monorail test apparatus has a fixed and guided impact; therefore none of the kinetic energy of the impact is converted into post-impact rotational kinetic energy. Therefore, the amount of energy creating linear acceleration during an ECE test impact is less than for the monorail. This agreement of video and accelerometer data confirm that the ECE test is less severe than those tests conducted with the monorail.

DISCUSSION

The series of tests conducted for this project gives detailed test data for a small selection of the many helmet brands and models that are available in the market today. The selected helmet models are broadly representative of the categories currently available. Therefore, these tests provide depth of test data for the helmet models actually tested, and represent a limited selection of the wide variety of brands and models of helmets currently available. In this way, these tests correctly represent the helmets currently available to motorcyclists.

Helmets are constructed of an outer shell and energy-absorbing liner. There are two major areas for comparison: shell material type and thickness, and energy-absorbing liner thickness and density. Previous research has found that liner density has a dramatic effect on test performance (Mills & Gilchrist, 1991, Thom & Hurt, 1992). Note that the group C helmets which had the highest pass rate have the lowest density liners: 33 Kg per cubic meter (two pounds per cubic foot, see Table 4). This excellent performance is possible because of the combination of the strong and stiff shell and the soft, low-density liner. The group B helmets have considerably denser liners and showed consistently longer dwell times in all tests.

Test Headforms: DOT FMVSS No. 218 vs. ISO. A significant difference was observed between the DOT test headforms (AV) and the ISO test headforms (HF) when tested under identical conditions. The data indicated that the peak headform acceleration values for the flat anvil tests are higher when ISO test headforms were used in place of DOT test headforms. The difference was not sufficient to cause failures in well designed motorcycle helmets; however, it could cause marginally qualified helmets to fail a flat anvil test given the fact that ISO test headforms would result in higher peak headform accelerations. No significant differences were noted between headforms for the hemispherical anvil tests.

The adoption of the ISO test headforms would harmonize the DOT standard with other international motorcycle helmet standards which already use the ISO test headform. The anthropometric characteristics of the ISO test headforms are also considered to be more representative of the general population of human head shapes than the DOT test headforms (Gilchrist, et al., 1988).

Test Apparatus: Monorail vs. ECE-Type. The data presented in Table 6 indicated that there was a significant difference in peak headform acceleration and dwell time at 200g for the flat anvil tests. These differences were attributed largely to the differences in mass distribution of the test apparatus and the subsequent dynamics of the impact. Given the fact that the peak headform accelerations were consistently higher for the monorail tests, it may be assumed that these tests are more rigorous and represent a worst case scenario when compared to the same tests conducted using the ECE test apparatus. The ECE-type apparatus is considerably more complicated and yet it is a less severe test.

The ECE-22.4 standard sets limits of than 275g and a HIC value no greater than 2400. None of the other motorcycle helmet standards use HIC. The use of HIC has been both supported (Lockett, 1985) and criticized (Newman, 1975, 1982). It should be noted that HIC was developed for use with the Hybrid III headform in automotive crash testing, not any of the rigid alloy headforms used in motorcycle helmet testing.

As the comparison of test headforms and test apparatus show, there is little harmony in international motorcycle helmet standards. Comparisons of equipment or performance criteria must be carefully scrutinized in order to distinguish those few items that can be directly compared.

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