Motorcycle Helmet Impact Response at Various Levels of Severity for Different Standard Certifications

Edward B. Becker, Denis V. Anishchenko, Stephanie B. Palmer

Abstract It is unclear whether increased demands for impact management for severe impacts may result in helmets which transmit unacceptably high levels of shock in more frequent, lower severity crash incidents. This study investigates how two different helmet test standards, reflecting different demands of impact management, affect helmet protective performance in impacts at varying levels of severity.

Fifteen different helmet models; seven of which were certified to both Snell M2010 and DOT (M2010/DOT), and eight of which were certified only to DOT (DOT-only), were considered. Eight identical samples of each model were tested in single impacts at four standard sites on the helmet shell; four in flat impact and four in hemispherical at one of four impact velocities: 3, 5, 8 and 10 (9 for the hemisphere) m/sec.

In statistical analysis of those samples appropriate for the ISO J (57 cm) head form, significant differences ($p < 0.05$) were found only when comparing peak decelerations at impact velocities exceeding 8 m/sec for both flat impact and for hemispherical impact, the results support that M2010/DOT helmets transmit equivalent shock to that of DOT-only helmets in minor impacts. The results further demonstrate that the M2010/DOT helmets have significantly superior impact management in higher severity impacts.

Keywords Crash helmet standards, crash helmet performance, impact velocity, Snell vs DOT, shock attenuation

I. INTRODUCTION

Most crash helmet standards call for helmets to be tested in impacts at or near the highest levels of severity deemed reasonable. Helmets which meet specified protective criteria in those tests are considered reasonably protective for all crash impacts of equal or lesser severity. However, there is concern that this approach ignores helmet response to lower severity impacts and the potential for further injury risk reduction that might be achieved with improved performance in low severity impact events. The effort described here is an investigation of helmet performance over a broad range of impact severities and whether current helmet evaluation methods might be improved by considering tests conducted at lower levels of severity.

Standards for crash helmets commonly require helmets to be tested by placing an instrumented head form into the helmet, dropping the helmeted head form onto an unyielding surface of specified geometry at a specified velocity, and then measuring the shock transmitted through the helmet into the head form in terms of the head form deceleration. Most standards limit the peak deceleration in gravitational units (G's) allowed although some also impose additional criteria on the deceleration pulse such as time duration and Head Impact Criterion (HIC).

The limits on the deceleration pulse have traditionally been set according to estimates of human tolerance to head impact. Standards drafters posited that lower level head impacts might be tolerated safely but beyond some threshold level, there would be a risk of death or serious, long-term injury. Recoverable injuries were generally not considered but, recently, concerns have arisen regarding concussions. Although early investigators noted a reduction in concussion severity associated with motorcycle helmet use [1], recoverable injuries including slight concussions were considered acceptable outcomes of crash impact events.

Once these limits on the deceleration pulse had been set, impact test severities were set according to limits consistent with the capabilities of existing helmet technology and user acceptance. The effect is that helmets

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are now evaluated based on their performance in the most severe impacts for which the standards drafters considered protection from death or severe injury reasonably possible. Protective performance in lesser impacts was generally not considered. Reasonably, it was assumed that a helmet which is protective at a higher impact severity would be at least as protective in any lesser impact.

However, a few critics of this approach have maintained that helmets meeting the minimum mandatory government requirements are inherently safer than other helmets which meet those minimums but which are also tested at much more severe levels of impact [2]. Their rationale is that any improvement in high end performance must be due to harder helmets which would likely transmit greater levels of shock especially in less severe and more commonly encountered incidents.

A few programs require testing at several levels of impact severity. For example, the SHARP helmet ratings program [3] tests helmets at several levels of impact severity and calculates fatality risk scores based on statistical likelihoods of crash impact severity along with the risk of fatality associated with the helmet performance at these severities. Snell SA2015 [4] currently calls for helmets to be tested in low severity impacts as well as tests at high severity with the response to these low severity impacts subjected to much more stringent criteria. Helmets which meet test requirements in high severity tests and which also meet more stringent criteria in low severity tests might further reduce the risk of serious injury and, perhaps, even of mild injuries in much more frequently encountered low severity head impact incidents.

However, it is uncertain whether fatality risks are well enough understood to calculate fatality scores over the expected spectrum of crash exposures, or whether the mechanisms of mild traumatic brain injury are well enough understood to assign tolerance levels with any confidence. But it appears possible to respond to some standards criticisms without a good understanding of injury risk. Investigation of the impact response of several helmet models at progressive levels of impact strongly suggests that the peak shock (deceleration in G's) transmitted through helmets built to current technology is proportional to impact velocity, at least until the limits of the helmet structure are reached and the slope of the peak shock versus velocity bends sharply upward [5]. If this is true, then it may be possible to infer helmet performance at lower levels of impact from the results of tests at levels approaching the helmet's limits obviating the need for additional physical testing.

Hence, it was decided to conduct a helmet study similar to DeMarco et al. [5], spanning a range of impact severities, specifically to examine whether helmets certified at more severe levels of impact transmit, as found in that report, peak impact accelerations approximately proportional to impact velocity or whether they transmit higher levels than might reasonably have been expected. Helmet models meeting Snell M2010 [6] as well as Federal Motor Vehicle Safety Standard 218 (DOT) [7] and others meeting DOT-only were to be tested at several levels of impact severity against two impact surfaces called out in both Snell and DOT requirements. The results could then be examined to determine what differences there might be between the performances of the two helmet types and also whether the peak G in low velocity impacts can be inferred from testing conducted at higher velocities.

II. METHODS

At the Snell Memorial Foundation, four samples each of seventeen different motorcycle helmet configurations were obtained and tested in impacts against flat, unyielding surfaces at nominal impact velocities of three, five, eight and ten meters per second. Four more samples of each of these configurations were tested in impacts against hemispherical surfaces at nominal velocities of three, five, eight and nine meters per second. The reduction of the most severe of the hemispherical surface impacts from ten to nine meters per second was made to protect the test gear from damage. Each helmet sample received one impact at each of four sites. The locations were centered front and rear on the longitudinal plane of the test head form and right and left on the head form transverse plane so that all the helmets were tested at roughly corresponding positions. The sites were generally well away from the edges of the shell so that the flat impact response was reasonably representative of the helmet behavior over much of its surface. All in all, there were a total of 136 helmet units tested and 544 impacts conducted.

Seven of the helmet configurations involved were certified to Snell M2010 and to DOT. All these were full face or motocross style. Eight more helmet configurations were certified to DOT only; five of these were full face or motocross models, one was a three quarter open face model and two were half helmet models.

All the samples of the seven Snell certified configurations were donated by their manufacturers and the samples of three of the DOT-only configurations in the study were also manufactured by companies in Snell programs and were also donated for this effort. This was in response to a general solicitation sent to all Snell clients in October, 2012. The language of the request described the purpose of this study as a research of low velocity impact responses. Since the type of tests to be performed were non-standard single instead of double impacts and at velocities specified in neither standard, no reasonable conclusions could be drawn about standards compliance. Thus, there were no reasons for manufacturers to be concerned about performance of their helmets. The request also included an assurance that results would be anonymized and not traceable to manufacturer or model.

An additional eight samples each of the five more DOT-only configurations were purchased from retail outlets. These five configurations included two half helmet models and a full face and three quarter model from mass market retail stores and one high end motocross model being promoted for a new, anti-concussive design innovation.

These helmets were selected to be representative of the broad range of M2010/DOT and DOT-only helmet models available in the market. However, they will not be identified in the following discussion by brand and model designations.

The tests were performed on twin-wire, guided fall devices with head form masses set according to Snell M2010. Head form deceleration pulses were measured using an Endevco 2262CA-2000 linear accelerometer and the peak shocks were recorded. Most of the helmet configurations were sized for the J head form but one of the DOT-only models and one of the M2010/DOT models were appropriate to the M head form and one each of the M2010/DOT models was appropriate to the E and to the C head forms.

A statistical analysis was performed on the results obtained for all the J head form sized models in the test series: four different M2010/DOT certified models and seven different DOT-only models. There were a total of 87 samples and 320 observations in all. Single median value at each nominal impact velocity for each model was used. A breakout of these is shown in Table I. Welch's t-test was chosen because of its tolerance to violation of the variances homogeneity assumption. Results are shown in Table II.

III. RESULTS

The following charts compares various aspects of performance at each of the nominal velocities in the test matrix, However, since the measured impact velocities vary slightly from the nominal values, the peak G response was normalized by straight line interpolation or extrapolation within each model line as appropriate.

The chart in Fig.1 shows the median values of peak deceleration calculated for each of the nominal impact velocities regardless of impact site for all the M2010/DOT units, all the DOT-only units and, finally, all the DOT-only units except for the two half helmet configurations (DOT*). During the testing, it was noted that the half helmets appeared markedly stiffer in flat impact than full face and three quarter configurations. The chart also indicates the effective requirements of the DOT and M2010 flat impact tests. DOT calls for flat impact testing at 6.0 meters per second and, although the peak acceleration criterion is given as 400 G, the time duration criteria are widely held to limit peak acceleration to no more than 250 G for flat impact. However, since the DOT medium head form masses 5.0 kg versus the comparably sized 4.7 kg head form called out in M2010, this 250 G figure was charted as 266 G and the 6 m/s figure as 6.19 m/s. M2010 calls for first impacts at 7.75 meters per second and limits peak acceleration to no more than 275 G.

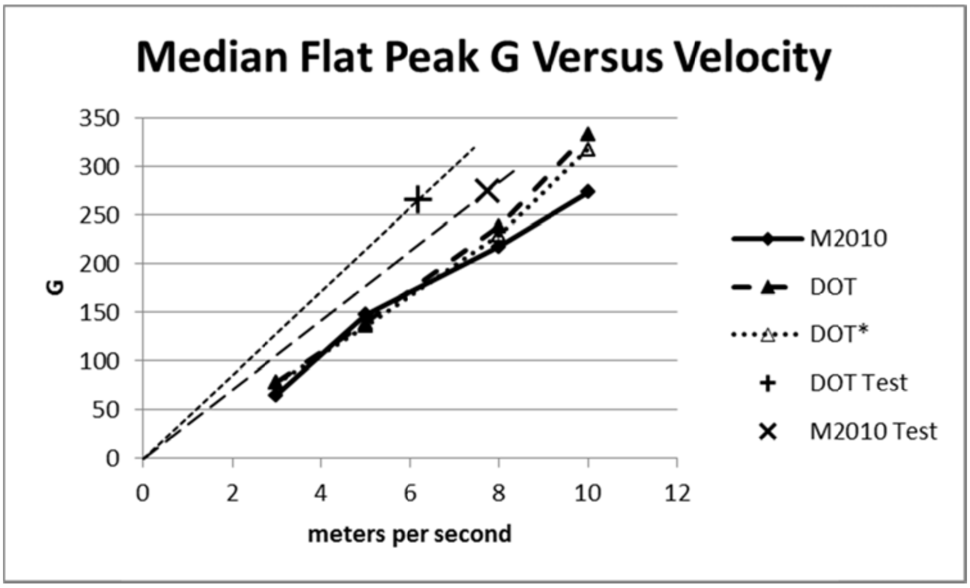

Fig. 1. Median Peak deceleration vs impact velocity, measured in head form with helmets certified to different performance standards, impacts performed on flat anvil.

The chart in Fig. 1 suggests minimal differences in flat impact response between M2010/DOT and DOT-only helmets at impact velocities below six meters per second and perceptible differences in peak deceleration attenuation at higher impact velocities (above 6 m/s).

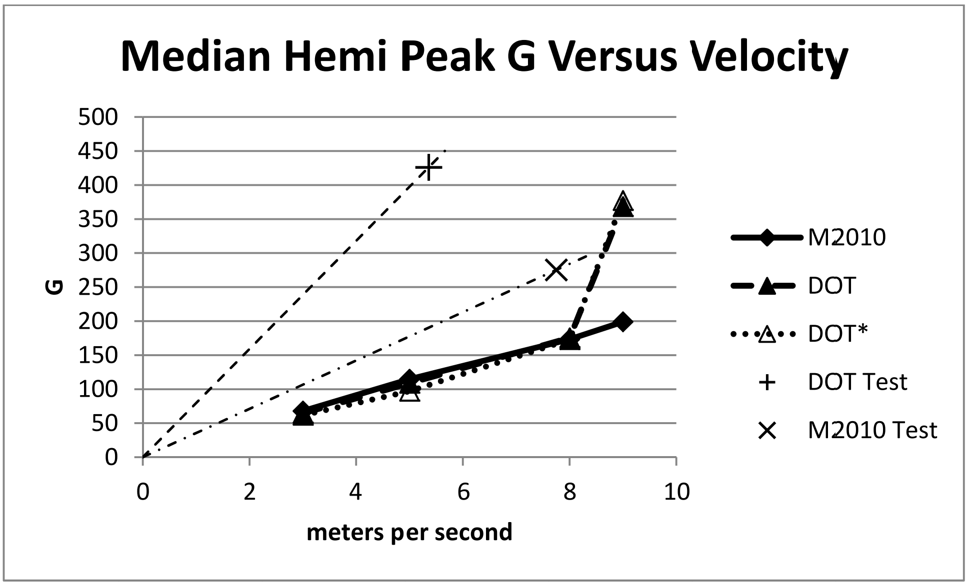

Fig. 2. Median Peak deceleration vs impact velocity, measured in head form with helmets certified to different certifications, impacts performed on hemispherical anvil.

The corresponding chart for the hemi impact response shows similar results (see Fig. 2). Although the responses of both M2010/DOT and DOT-only samples appear to be considerably more attenuated than in flat impact, the M2010/DOT hemi response appears slightly stiffer than full face and three quarter DOT-only helmets for impacts below eight meters per second. The greatest difference is about 18 G for five meter per second impacts. But after eight meters per second, many of the DOT only samples begin to be overwhelmed. This increase in peak G versus impact velocity is much sharper but appears to begin a little later than the more gradual increase seen in flat impact (Fig. 1). This chart also shows the effective requirements of the two standards. The M2010 requirements are the same as those for flat impact but the DOT tests call out 5.2 m/sec impacts and, since the time duration demands do not seem to bear on hemispherical impact, the standard's 400 G criterion applies. These DOT figures have been adjusted to compensate for the differences in head form mass.

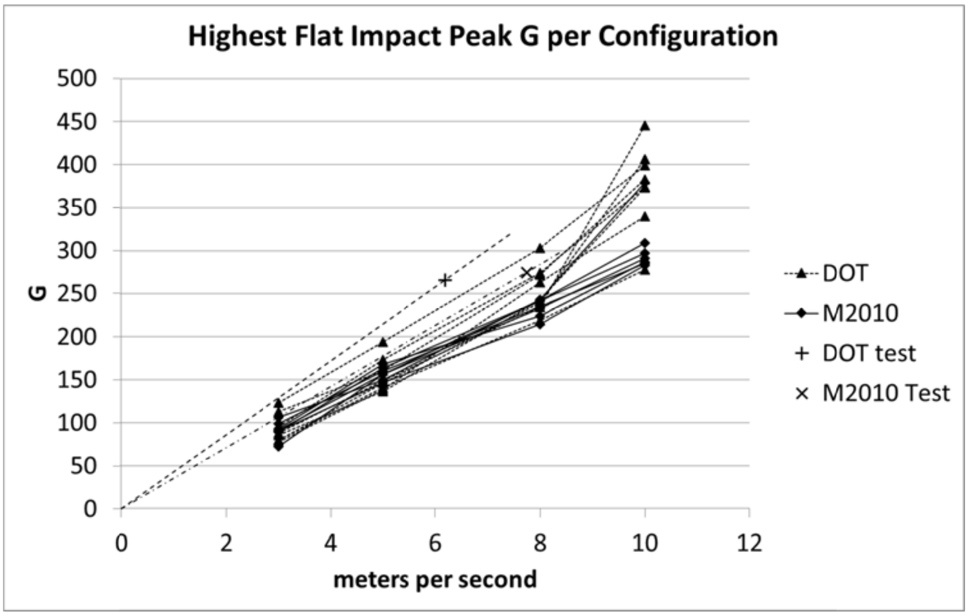

Fig. 3. Highest individual Peak deceleration vs impact velocity, measured in head form with helmets certified to different certifications, impacts performed on flat anvil.

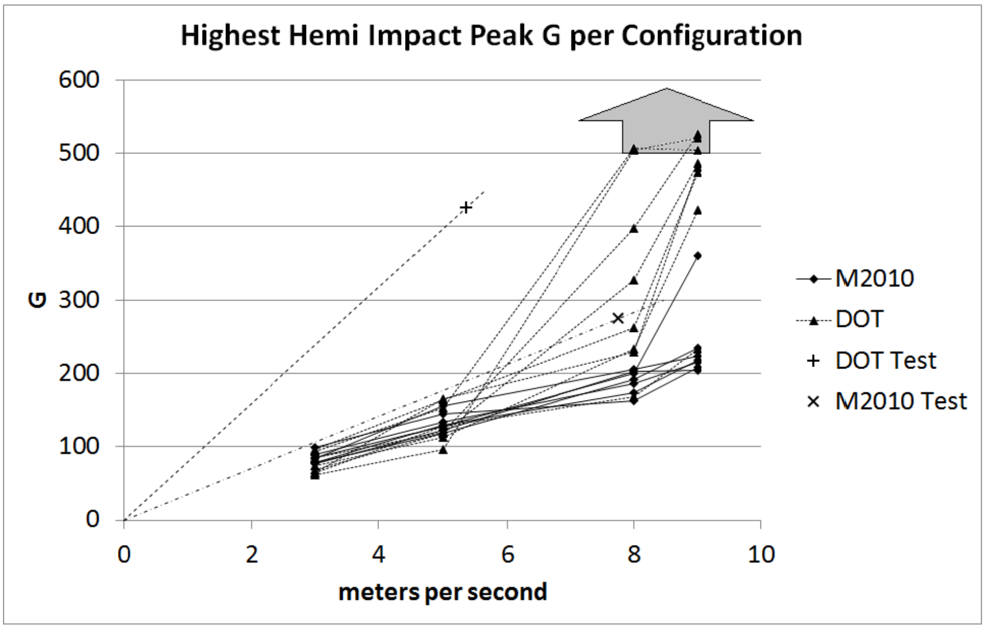

Fig. 4. Highest individual Peak deceleration vs impact velocity, measured in head form with helmets certified to different certifications, impacts performed on hemispherical anvil. The gray arrow indicates where accelerations exceeded the range of the instrumentation.

Charts 1. and 2. reflect all the impacts performed on all helmets, but helmet evaluations generally depend only on the impact for which the highest peak G was recorded. Charts 3-6 show only the highest peak G at each velocity for each helmet sample tested. Essentially, the front, rear, right and left side results at a particular velocity for a particular sample were compared and all but the highest were dropped from further consideration. What remained was the worst-case result for each configuration at each nominal velocity. Figures 3 and 4 show the worst case flat and hemi impact results for each of the 7 M2010/DOT configurations and each of the DOT-only configurations in the study. Figures 5 and 6 summarize the data in Figures 3 and 4 showing medians and ranges for the worst-case results of the M2010/DOT and DOT-only configurations.

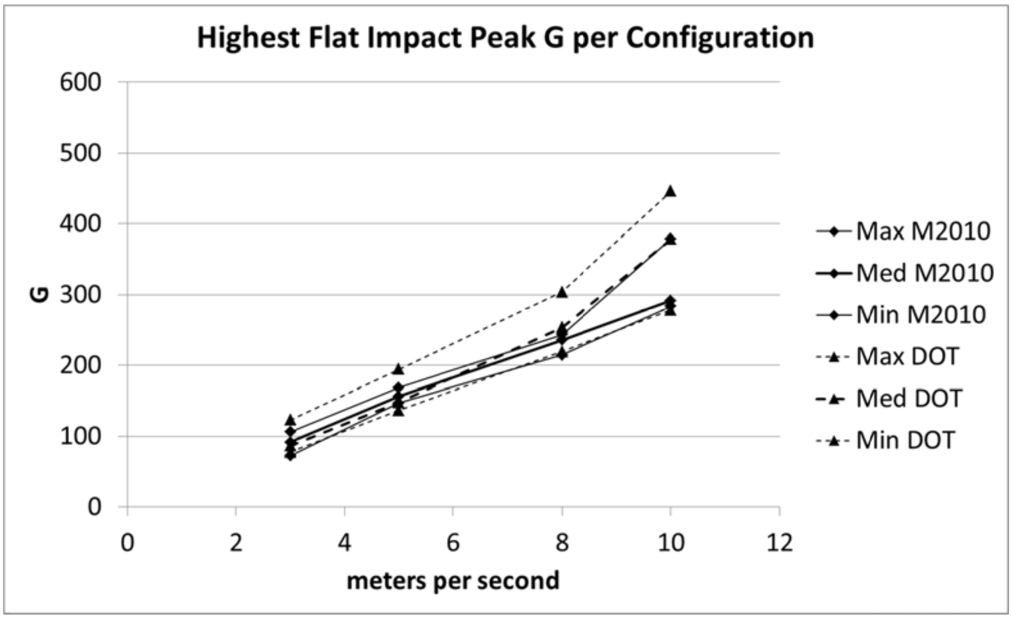

Fig. 5. Maximum, median and minimum highest individual Peak deceleration vs impact velocity, measured in head form with helmets certified to different certifications, impacts performed on flat anvil.

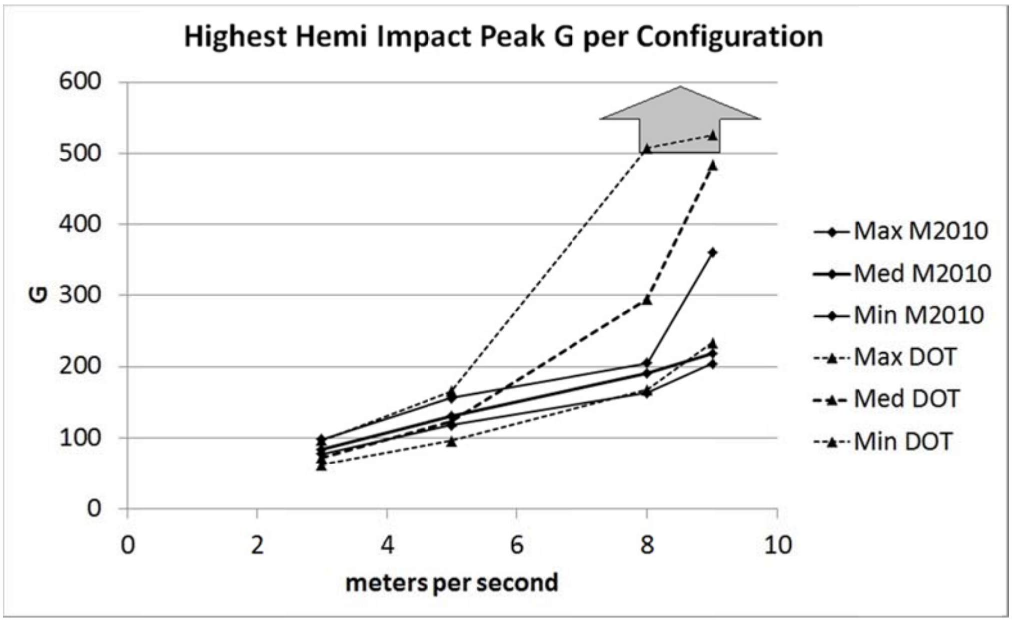

Fig. 6. Maximum, median and minimum highest individual Peak deceleration vs impact velocity, measured in head form with helmets certified to different certifications, impacts performed on hemispherical anvil. The gray arrow indicates where accelerations exceeded the range of the instrumentation.

Impact acceleration measurements were limited by the approximately 500 G range of the instrumentation. The grayed arrows indicate those measures for which clipping was observed and which may have exceeded the recorded value appreciably.

Statistical Analysis of samples tested on the ISO J headform.

TABLE I. SAMPLE SIZES AND TEST CONFIGURATIONS[1]

		3 m/s	5 m/s	8 m/s	10[flat] (9[hemi]) m/s
FLAT	SNELL M2010	12 impacts 4 samples	16 impacts 4 samples	16 impacts 4 samples	16 impacts 4 samples
	DOT	23 impacts 7 samples	27 impacts 7 samples	28 impacts 7 samples	23 impacts 6 samples
HEMI	SNELL M2010	15 impacts 4 samples	15 impacts 4 samples	14 impacts 4 samples	13 impacts 4 samples
	DOT	26 impacts 7 samples	28 impacts 7 samples	25 impacts 7 samples	23 impacts 7 samples

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[1] Each sample was impacted at four separate sites; results from the impacts suitable for further analysis were aggregated into single median value.

Null hypothesis: there is no difference between means of distributions of Peak Deceleration for Snell-certified and DOT-only-certified helmets for each selected impact velocity

Alternative: there is a difference between means of distributions of Peak Deceleration for Snell-certified and DOT-only-certified helmets for each selected impact velocity

Significance level: 0.05

Test: Welch's t-test (two-tail)

TABLE II

WELCH'S TEST RESULTS – DIFFERENCE IN MEANS OF DISTRIBUTIONS OF PEAK DECELERATION BETWEEN TWO STANDARDS

	3 m/s		5 m/s		8 m/s		10[flat] (9[hemi]) m/s	
	Not statistically significant		Not statistically significant		Not statistically significant		Statistically significant Snell Peak Deceleration lower	
SNELL	Mean1	62 G	Mean1	142 G	Mean1	221 G	Mean1	273 G
M2010	Mean2	76 G	Mean2	144 G	Mean2	240 G	Mean2	316 G
vs	t	-1.744	t	-0.242	t	-1.319	t	-2.641
DOT	df	7.905	df	8.977	df	8.515	df	5.938
	N1	4	N1	4	N1	4	N1	4
FLAT	N2	7	N2	7	N2	7	N2	6
	p	0.120	p	0.814	p	0.221	p	0.039
	95% CI	-32, 5	95% CI	-24, 19	95% CI	-51, 13	95% CI	-83, -3
	Not statistically significant		Not statistically significant		Not statistically significant		Statistically significant Snell Peak Deceleration lower	
SNELL	Mean1	70 G	Mean1	115 G	Mean1	171 G	Mean1	200 G
M2010	Mean2	65 G	Mean2	105 G	Mean2	248 G	Mean2	415 G
vs	t	1.08	t	1.257	t	-1.640	t	-4.984
DOT	df	8.129	df	7.777	df	6.225	df	6.225
	N1	4	N1	4	N1	4	N1	4
HEMI	N2	7	N2	7	N2	7	N2	7
	p	0.311	p	0.245	p	0.150	p	0.002
	95% CI	-7, 18	95% CI	-8, 28	95% CI	-189, 37	95% CI	-319,-110

The statistical analysis found no significant differences in the hemispherical impact results for M2010/DOT and DOT-only helmets for impacts at a nominal 8.0 m/sec even though the chart in Fig. 6 suggests a difference of about 100 G in the median values. However, this seeming contradiction is due to the fact that Fig 6. is based on the greatest of the four values, front, right, left and rear, of peak deceleration recorded for each helmet model at a particular nominal velocity rather than all the recorded values.

IV. DISCUSSION

This study cannot speak directly to concerns about concussion and other recoverable injuries. However, it does permit some conclusions about the value of low level impact testing and may resolve some concerns about high level standards.

All the configurations tested showed progressively higher levels of peak deceleration as impact velocity increased. The progressions all appeared approximately linear until, at some threshold velocity, a particular model's response would break upward at an increased slope suggesting that the helmet was approaching the limit of its protective capability. This is consistent with the results reported in 2010 by DeMarco [5].

Given this, it seems reasonable to presume that the response of most helmets at lower levels of impact is largely determined by current deceleration criteria set for tests conducted at a single impact severity. If a low velocity test were imposed, it seems likely that either the low-level deceleration criteria would be within the helmet capability rendering the tests unnecessary or that the imposition would equate to a more stringent set of criteria for tests at the higher level. Reasonably, for helmets meeting this more stringent set of criteria at the higher level, the low level tests would again be unnecessary.

The results also suggest that the DOT helmets tested that also met the more severe tests imposed in Snell M2010 still provide approximately the same attenuation as DOT-only helmets in low severity crash impacts. Apparently, either current technology does not afford tuning helmet impact response to obtain greater attenuation in high severity impacts by accepting lower attenuation in less severe impacts, or manufacturers did not attempt to implement this into their designs. Whichever the case, the protective capabilities for both M2010/DOT and DOT-only helmets in low severity incidents are similar. The differences between these helmet types are largely a matter of the impact velocities at which the limits of impact management capability are reached and at which the slope of the peak deceleration versus impact velocity for a particular helmet increases sharply.

The Snell Memorial Foundation considers that helmets ought to attenuate impact shock to within some accepted tolerance for the most severe impacts current helmet technology might reasonably manage. For this reason, Snell seeks to demand the most impact management reasonably possible in helmets which motorcyclists might reasonably be expected to wear. The implication is that there is a threshold for serious injury. Shocks which do not exceed this threshold are likely to be non-injurious while others are likely to have catastrophic consequences. The divergence between M2010/DOT and DOT-only performance in higher severity impacts demonstrates the greater impact management capability Snell certification seeks to identify.

As yet, however, there is little epidemiological evidence that there is any difference in injury outcomes for riders equipped with Snell certified helmets versus those with DOT-only helmets. But a survey of 425 accidents occurring in England in 1974 [8] which involved 450 injured motorcyclists suggests that helmets conforming to the higher of two British Standards then in use slightly reduced the likelihood of head injury below that of helmets conforming to the lower standard. The lower of the two standards [9] limited peak force transmitted through the helmet to 5000 lbs when mounted on a stationary head form and struck by a 10 lb block with a horizontal striking face and dropped through a distance of 9 ft. The more demanding of the two standards [10] calls out an identical test except that the dropping distance is increased to 12 ft. These tests compare to current procedures using a 4.7 kg head form with an impact criterion of 483 G and impact velocities of 7.21 m/s and 8.32 m/s respectively.

An article published in the June 2005 issue of a motorcycling magazine popular in the United States [2] implied instead that helmets ought to be optimized to transmit the lowest reasonably possible levels shock over the range of head impacts which might be reasonably expected in a survivable motorcycle incident. The article went on to describe the outcomes of a series of tests intended to duplicate such impacts. The findings were that helmets certified to the then Snell M2000 standard transmitted higher levels of shock than helmets certified only to DOT including particularly favorable results for two inexpensive models. However, there is little available evidence that there is any difference in injury outcomes for riders equipped with softer, DOT compliant helmets than for those equipped with harder, comparable DOT compliant helmets either Snell certified or not.

Since this study was primarily interested in helmet performance in impacts against flat surfaces, the findings may overestimate the performance capabilities of these helmets in impacts against the hemispherical surface. The reason for this is that the impact sites were selected primarily to investigate flat impact response. In tests against the hemisphere, sites closer to the helmet edges would have stressed the samples much more. In flat impact, a broad area of the shell and impact managing liner is loaded and as the liner is crushed, it applies a controlled braking force to the head form slowing it to a relatively gentle stop. Helmets fail against the flat anvil generally because the liner is too stiff and they are most liable to fail in areas well away from the helmet's edges where the shell stiffness is greatest and the loading is over the greatest area of liner.

However, when the helmet strikes the hemisphere, it sees a concentrated loading. The helmet shell bends about the hemisphere allowing it to punch through a more limited area of the helmet's impact managing liner. Since a smaller area of impact liner is involved, the braking forces are lower than for flat surfaces but the liner thickness is more quickly exhausted. Helmets fail against the hemisphere because the liner is too thin and this effect is greatest in areas near the helmet edges where the shell stiffness is least and where the loading is over an even more limited area of liner. Therefore, for lower velocity impacts, load-concentrating surfaces like the hemisphere will yield lower decelerations than flat surfaces; at least up until the moment at which the helmet liner has been compressed to its minimum thickness. Then, the deceleration spikes sharply upward to a catastrophic failure. In this case, the value selected for the failure criterion hardly matters since the deceleration spike will exceed it.

Since the impact sites selected for this study were well within the boundaries of protection called out in Snell and DOT requirements, it seems reasonable that the results were worst case for flat impact and optimal for the hemisphere. Had these sites been selected closer to the required boundaries, the divergence between the M2010/DOT and DOT-only results for impacts with the hemisphere would have been seen at a lower velocity and, possibly, the charts would also have shown velocities at which the M2010/DOT results also started to break upward.

The kinetic energy demands of current helmet standards are implied in their test specifications. The chart in Figure 7 [11] shown below presents estimates of necessary energy management for medium sized helmets set by several different standards. The Snell demands are well above those of ECE 22-05 and DOT but are still 20% below those set by FIA for helmets used in Formula 1 racing. The Snell Memorial Foundation would base its motorcycle helmet standard on the same technologies used in these Formula 1 helmets except that the retail prices for these helmets are often greater than three thousand dollars and quite beyond the bounds of reason for most motorcyclists.

A potential limitation in this study is that the selection of the helmet models was neither extensive nor purely random. Most of the samples tested were donated by manufacturers in Snell programs who themselves chose which of their models would be surveyed. The same applies for the DOT-only samples since only a few additional configurations were randomly chosen from retail stores. However, all the samples appeared to comply with the relevant performance standards and the results are expected to be reasonably representative of headgear available in North America.

This study did not consider helmets certified to other standards and combinations of standards. Comparisons with helmets meeting ECE 22-05, currently required for street motorcycling throughout Europe, would be interesting but likely difficult. Both DOT and Snell require that helmets withstand test impacts sited over broad areas of the helmet shell. Reasonably, so long as the same impact sites were selected for all the samples in the test series, the comparisons would be similar no matter what sites were selected. However, ECE 22-05 limits testing to a few specific points. An earlier study [11] showed that at least some ECE 22-05 certified models perform very poorly in impacts sited even a few centimeters away from these specific locations. Relative comparisons between ECE 22-05 and Snell or DOT models would depend greatly on the impact sites selected for the study.

This study also did not attempt to consider tangential impacts and rotational accelerations. Neither DOT nor Snell standards have formal tests or performance criteria provisions for either of these. Although there is considerable interest in the role of angular acceleration in brain injury and, particularly, in concussion, there is no real consensus in how best to test helmets for relevant protective capability.

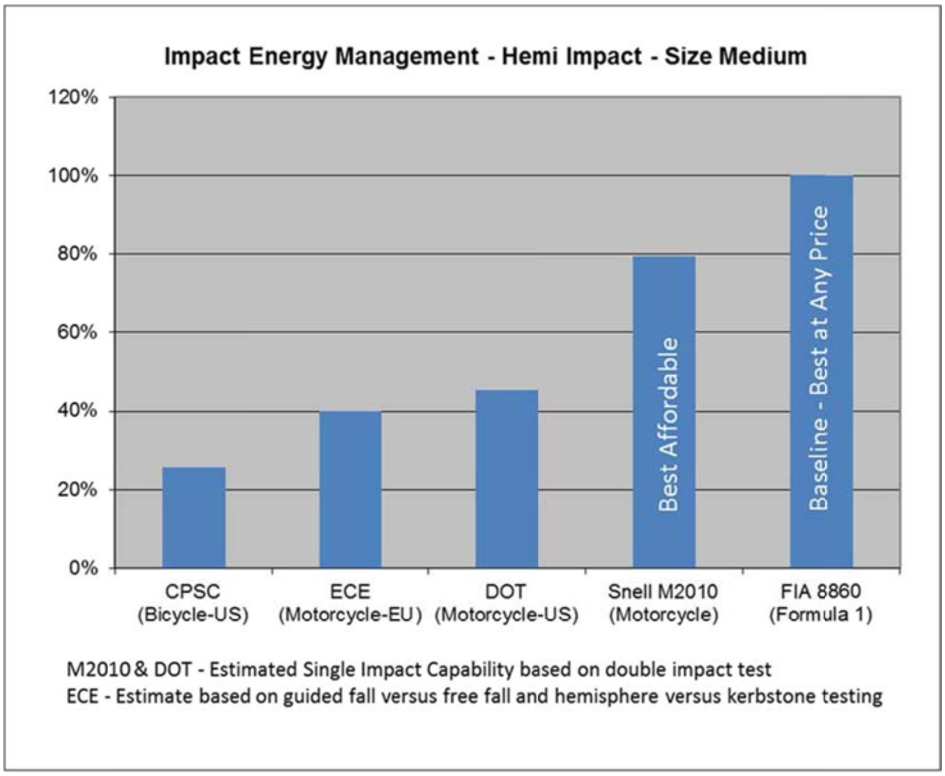

Fig. 7. Impact energy management comparison between different crash helmets standards.

V. CONCLUSIONS

The findings of this investigation show that the low severity impact performance of motorcycle helmets certified to Snell M2010 requirements as well as DOT (FMVSS 218), the US mandatory requirement, is effectively the same as that of helmets certified only to DOT. However, these same tests show that helmets certified to Snell M2010 and DOT transmit lower levels of peak deceleration than do DOT-only helmets in more severe impacts. It is expected that the improved crash outcomes resulting from this difference in performance will be identified in future epidemiological studies; particularly those directed towards more severe motorcycle crash incidents as studies including outcomes of less severe incidents are unlikely to detect differences. Until then the improved impact management performance of M2010/DOT helmets in higher severity impacts remains the best argument for seeking Snell certification in motorcycle helmets.

The findings also indicate that low severity impact tests for helmets in addition to tests at high levels of impact are unnecessary. Testing on a number of current helmet models suggests that helmet response to impacts within prescribed helmet capabilities is largely determined by the maximum severity test and the deceleration criterion set for any single impact severity in that range. Within that range, the peak deceleration versus impact severity for all the helmets tested is approximately linear; the designer can choose the range of severities and possibly the slope at which peak deceleration increases throughout that range but not much else. Tests and well selected criteria based on the most severe impacts for which the helmet is to be effective should be sufficient to establish reasonable compliance with the deceleration limits identified for injury reduction at all levels of impact severity. The concern that helmets might be somehow “excessively optimized” increasing the risk of injury in low severity crashes is baseless.

VI. ACKNOWLEDGEMENT

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