Final Report of Workshop on

Criteria for Head Injury and Helmet Standards

(Held in Milwaukee, Wisconsin on May 6, 2005)

December 16, 2005

Scientific Editors: Harold Fenner, Jr., Daniel J. Thomas, Thomas Gennarelli, Frank A. Pintar, Edward B. Becker, James A. Newman, Narayan Yoganandan

Editor and Recorder: Margie Patlak

MEDICAL COLLEGE OF WISCONSIN

Department of Neurosurgery, Medical College of Wisconsin

SNELL MEMORIAL FOUNDATION ® ESTABLISHED 1957

Snell Memorial Foundation, Inc.

Acknowledgements:

The editors wish to thank all workshop participants as well as Paul Walker and Brian Walker of Head Protection Evaluation (HPE) for their thoughtful, informative presentations and contribution to the workshop and this publication. The workshop would not have been possible without the excellent assistance of Judy Steinhart from the Medical College of Wisconsin Neurosurgery Department and Hong Zhang of the Snell Memorial Foundation. We also acknowledge the generous support of the Snell Memorial Foundation.

Library of Congress Control Number: 2006922792

Department of Neurosurgery
Medical College of Wisconsin
9200 W. Wisconsin Ave
Milwaukee, WI 53226, USA

Snell Memorial Foundation, Inc.
3628 Madison Avenue, Suite 11
North Highlands, CA 95660, USA

Table of Contents

Workshop Summary……………………………………………………………..4

Introduction…………………………………………..……….……………….5

Morning Presentations

Comparison Testing on Helmets Certified to Snell M2000 Versus

Those Certified to EC22-05 ……………………………………………..……….8

FIA Super Helmet Standard………………………………………………......10

FIA Evaluation of Crash Test Data…………………………………………......12

Spectrum of Brain Injury and How to Predict it……………………………......13

History of the Development of HIC………………………………………………..15

Strengths and Limits of HIC…………………………………………………..17

AFTERNOON DISCUSSION

Should HIC Be in Crash Helmet Standards? ……………………………………19

Lower G Threshold or Greater Energy Attenuation …………………………......21

One- or Two-Impact Testing of Helmets……………………………………..24

Optimal Head Forms and Masses in Testing ……………………………………24

Head Form Mass……………………………………………………………..25

Repeatability and Reliability/Biofidellic Versus Magnesium Head Forms….......26

Repeatability and Reliability/Guided Impact Versus Free Fall…………………..27

Retention……………………………………………………………………......29

Topics for Future Conferences…………………………………………......29

APPENDICES

Appendix 1—List of participants……………………………………………………31

Appendix 2—Conference Agenda…………………………………………………….36

Appendix 3—Slides from Edward Becker Presentation………………………….37

Appendix 4—Table Comparing Snell and ECE 22-05 Impact Requirements...102

Appendix 5—Slides from Andrew Mellor Presentation…………………………104

Appendix 6—Slides from Thomas Gennarelli Presentation…………………….134

Appendix 7—Slides from Narayan Yoganandan Presentation…………………174

Appendix 8—Slides from James Newman Presentation………………………..182

Appendix 9—Relevant Papers………………………………………………………..206

Workshop Summary

The Workshop on Criteria for Head Injury and Helmet Standards was hosted by the Medical College of Wisconsin and sponsored by the Snell Memorial Foundation, Inc. on May 6, 2005. There was extensive discussion of the Head Injury Criterion (HIC) and its application to a wide variety of engineering test standards. It was generally agreed that HIC should not be used for crash helmet test standards for all the reasons discussed in the report.

A list of important issues for crash helmet standards was identified by the participants. The list is contained in the workshop report. As identified in the report further discussion and research are needed to resolve the differences of opinion on the issues. The list will be used as a guide for future workshops.

Introduction

There are a number of different crash helmet standards for motorcyclists and race car drivers in effect in the United States and Europe. Each specifies various test procedures to be applied to helmet models and criteria for evaluating helmet performance. Since all these helmets are intended to protect their wearers in similar crash incidents, the standards are quite similar. But there are differences great enough that helmets considered appropriate by one standard will fail to satisfy another.

One significant difference between the United Nations Economic Commission for Europe (EC) standard[1] and those of other standards, including Snell, is that the former uses the Head Injury Criterion (HIC) as part of their helmet evaluations. The inclusion of the HIC as part of the EC standard poses a problem for helmet manufacturers who want to develop helmets that can be marketed worldwide, as helmets designed to this standard often do not meet other standards such as Snell, which do not include HIC. Conversely, helmets designed to the Snell standard, which emphasizes more high-end injury protection, often cannot meet the EC standard.

---

[1] *ECE22rv4 Helmet Standard* (Regulation No. 22: Uniform Provisions Concerning the Approval of Protective Helmets and of Their Visors for Drivers and Passengers of Motor Cycles and Mopeds, Incorporating the 5th Series of Amendments.)

To address this dilemma, the Medical College of Wisconsin and the Snell Memorial Foundation convened a meeting held at the Pfister Hotel in Milwaukee, Wisconsin on May 6th, 2005. The purpose of the meeting was to explore the differences between crash helmet standards with and without the HIC. The main question raised at this conference was whether HIC is useful in evaluating helmet performance. Experts on helmet standards and testing, brain injury, and human tolerance criteria gathered at the conference to illuminate the range of thinking on HIC, as well as to discuss other key issues relevant to differences in helmet standards. The intent of the conference was not to seek consensus on helmet standard criteria, but rather to air evidence-based opinions on these issues, and to identify areas that should be explored in more detail in future conferences.

The conference began with a series of five presentations in the morning. After each presentation, there was an abbreviated discussion during which participants identified issues for a more in-depth discussion during the afternoon session. This discussion session, led by Dr. Daniel Thomas of the Snell Memorial Foundation, focused on some of the points developed in the presentations, and the many related issues bearing on HIC and on helmet testing and evaluation.

This document is a summary of the conference and is divided up into three main sections. The first section summarizes the following presentations and their discussions:

- Comparison testing on different-sized helmets certified to Snell M2000 versus those certified to EC22-05;
- FIA super helmet standard, and the results of a FIA evaluation of crash test data;
- Spectrum of brain injury and how to predict it;
- History of the development of HIC; and
- Advantages and disadvantages of HIC.

The second section summarizes the general discussion held in the afternoon. This section explores the following issues:

- Whether HIC should be in the Snell standard for crash helmets;
- Whether helmet testing should include one or two impacts;
- The tradeoff in crash helmet test criteria between peak acceleration and energy attenuation, and which level is optimal for each;
- Optimal head forms and masses to include in testing;
- Testing that gives the optimal repeatability and reliability;
- The need for helmet retention testing; and
- Future issues to explore further.

The third section has appendices that provide the meeting agenda, presenters' slides, relevant papers, and a list of participants and their affiliations.

The intent of this document is to set out the full range of points and opinions advanced during the discussion clearly and without bias so that, where contradictions exist, the better ideas might prevail. Otherwise, the current confusion will continue. It is expected that this conference will be the first of a series of such conferences delving into appropriate test methods and criteria so that a better understanding of the proper evaluation of crash helmets will crystallize.

MORNING PRESENTATIONS

Comparison Testing on Helmets Certified to Snell M2000 Versus Those Certified to EC22-05

Edward Becker of the Snell Memorial Foundation presented the findings of an unpublished study Snell did in conjunction with Brian and Paul Walker of Head Protection Evaluation (HPE), an international helmet testing facility based in Farnham, Surrey, England. In the study, HPE and Snell did testing of two similar helmet models: one model certified to EC 22-05 and the other to Snell M2000 standards. Both models were built by a single manufacturer known for quality headgear. The tests were structured so that the performance of both models could be compared when tested to Snell requirements and when tested to EC 22-05 requirements. Two different sized helmets—medium and extra large—were tested.

This testing revealed that the two helmet standards are incompatible. Snell M2000-certified helmets failed the HIC requirements in the EC testing, even though Snell would consider the responses as protective. The EC22-05-certified helmets failed Snell impact energies in Snell testing. Details of the findings can be found in Appendix 3. A table comparing the impact requirements of Snell M2000 and EC 22-05 is provided in Appendix 4.

Mr. Becker noted several differences in the testing procedures for the two standards:

- Snell uses a guided fall system that:
    - Uses half-head forms (no chin)
    - Aligns impact through the center of gravity
    - Minimizes rotational response
    - Maximizes translational response
- EC uses guided *freefall* system that:
    - Uses full-head forms (with chin)
    - Accepts a range of alignments
    - Allows significant rotational response
    - Attenuates the translational response
- Snell tests in double impact, while EC applies single impact
- Snell uses hemispherical and flat impact surfaces, whereas EC uses flat and kerbstone
- EC impact energy and mass increase with head-form size, whereas Snell testing keeps the impact energy and mass constant for all head forms.
- All tests were conducted on a guided fall apparatus, thereby only approximating the EC test method and results. This actually eliminates the single largest variable of headform rotation in response to impact.

But the primary differences in the test results, Mr. Becker thought, stemmed from the HIC requirement of the EC standard. For EC, HIC must not exceed 2400, whereas

Snell has no HIC requirement. In addition, the Snell peak acceleration limit is 300g whereas for EC it is 275g. But this was considered a minor difference, and Dr. Thomas noted that Snell-certified helmets achieved the 275g limit except in one test that measured 279g.

After the presentation, participants noted that this study reveals how standards drive the development of helmets—the helmets only differed as to how they met each standard. Dr. Thomas noted that Snell helmets do not pass some EC tests, yet the tradeoff is that Snell helmets offer more high-end injury (energy) protection. Mr. Andrew Mellor of the Federation Internationale de L'Automobile (FIA) concurred and noted that the United Kingdom view is that the EC crash helmet standard has some benefits over the Snell because it considers surface friction and has chin guard and projectile tests. But when it comes to impact attenuation, the EC is inferior to the Snell standard, he claimed. The EC standard is aimed at softer impacts, he pointed out, and the Snell standard is aimed at harder impacts. It is the latter that needs to be focused on to save lives on the United Kingdom roads, he said, although softer helmets may reduce less severe injuries.

FIA Super Helmet Standard

Mr. Mellor of FIA's Institute for Motor Sport Safety started his presentation by noting that FIA developed its new super helmet standard because racecar drivers continued to suffer head impacts that caused injury or death. A new standard was also needed that took advantage of the newer composite technologies available to manufacturers to reduce the weight of crash helmets.

The main objectives of the new FIA super helmet standard were to:

- Improve headrest compatibility by 50 percent
- Improve impact energy attenuation by 50 percent
- Improve crush protection by 50 percent
- Improve penetration protection by 30 percent
- Improve rotational acceleration protection by 25 percent
- Improve shell hardness by 50 percent
- Improve chin guard impact protection by 50 percent
- Reduce helmet mass by 20 percent

More details of the helmet standard are provided in Appendix 5.

The FIA super helmet standard has more requirements than the Snell SA2000 standard including:

- Crush protection of 500 joules (Snell does not test for crush protection.);
- Impact energy attenuation of 225 joules (300g) versus Snell's impact energy attenuation of 150 joules[2];
- HIC of 3500

[2] The Snell test procedures call for a second impact of 110 joules. Analysis of test results indicates that both impacts together compare to a single impact of about 180 joules. See the previous presentation, Appendix 3.

- Penetration of 4kg at 3m versus Snell's penetration requirement of 3 kg at 3m;
- Rotation and hardness requirements (Snell does not test for this.); and
- More rigorous chin guard testing than Snell's "crush" test for this.

Mr. Mellor pointed out that super helmets that meet the new standard are extremely expensive. But the hope is that manufacturers can eventually reduce the cost of the super helmet so that it can be offered at a price amenable to motorcyclists, in addition to racecar drivers.

During the discussion following his presentation, Mr. Mellor said HIC was incorporated into the new super helmet standard as a way of considering the duration of impact, which is considered important from an engineering standpoint. The inclusion of HIC of 3500 as opposed to 2400 of the EC requirement was not based on any empirical evidence that it would reduce head injury or fatalities. He added in the afternoon discussion that more energy impact attenuation is needed to save more lives, if fatality reduction is the objective.

FIA Evaluation of Crash Test Data

In this presentation, Mr. Mellor discussed the results of a FIA evaluation of 17 recent racecar crashes.[3] In these evaluations, researchers determined the g level delivered to the helmet of the crash victims, based on the deformation of the

[3] Mellor A, Formula One Accident Investigations. SAE 00MSV-37, 2000.

helmets, black box crash data, and “reverse engineering” helmet tests in which the crash conditions were simulated.

This analysis revealed that HIC is almost always proportional to linear acceleration level and rotational acceleration level. It also showed that the Abbreviated Injury Severity (AIS) number correlates with the degree of linear acceleration, and suggested that the 300g peak acceleration limit is in the right ballpark to prevent significant head injuries.

Spectrum of Brain Injury and How to Predict it

Dr. Thomas Gennarelli, of the Medical College of Wisconsin, gave an overview of the spectrum of brain injury that can result from a head impact. He noted that this spectrum is quite wide and includes, at the lower end, mild concussion due to contusion, and at the higher end death from hemorrhage, hematoma, or severe diffuse axonal injury. The spectrum of brain injury has gotten wider over the past 50 years, he noted, because of a greater identification of, and appreciation for, mild traumatic brain injury (MTBI), which is extending the lower end of the spectrum. This has led to the suggestion that one should aim for protection down to AIS 2 brain injury categories.

Dr. Gennarelli also pointed out that for vehicular accidents the spectrum of brain injury has changed over the past 50 years. There has been a decrease in focal injury and an increase in diffuse injury because of the current softer environment in cars, thanks to airbags and other innovations. This also suggests that greater protection that encompasses MTBI might be more feasible now.

Most MTBIs are caused by head motion (rotational and translational), and a direct blow is not necessary, Dr. Gennarelli said. This motion causes surface and deep strains in the brain. The probability of a MTBI is correlated with a number of measures, according to Dr. Newman, including:

- Maximum linear acceleration (50^{th} percentile = 780 m/s^2)
- Maximum rotational acceleration (50^{th} percentile = 6200 r/s^2)
- Severity Index (50^{th} percentile SI = 300)
- Generalized Acceleration Model for Brain Injury and Tolerance (GAMBIT) (50^{th} percentile GAMBIT = .4)
- HIC15 (50^{th} percentile HIC15 = 230)
- Head Impact Power (HIP) (50^{th} percentile HIP = 12.5kW)

Referencing a paper by Dr. Albert King, Dr. Gennarelli pointed out that at least for MTBI, Dr. King suggests that the best predictor for injury is neither linear nor angular acceleration, but rather the product of the strain and strain rate.

During the afternoon discussion, Dr. James McElhaney of Duke University noted that rhesus monkey and human studies suggest tolerances to blows to the side of the head are half of what they are for blows to the front of the head.[4] This implies that there should be different tolerances or criteria for helmets depending on where they are hit.

Dr. Gennarelli's slides can be found in Appendix 6.

History of the Development of HIC

Dr. Narayan Yoganandan of the Medical College of Wisconsin gave an historic overview of the development of the criteria used to predict head injury that ultimately led to the development of HIC and its implementation in various standards. He noted that Ford Motor Company commissioned Wayne State University in 1954 to conduct drop tests of isolated cadaver heads and intact embalmed cadavers to find the tolerance for forward impacts to steel blocks. This led to fracture data as a function of time and acceleration. Eventually this data evolved into the Wayne State University Tolerance Curve (WSTC). Input into the development of this curve also came from data collected from the National Aeronautics and Space Agency's (NASA) head impact studies on chimpanzees.[5]

In 1966, Charles Gadd of General Motors Corporation proposed a weighted impulse criterion and checked against Federal Aviation Administration data to modify the

---

[4] McElhaney JH, Stalnaker RL, Roberts VL. Biomechanical Aspects of Head Injury. In: *Human Impact Response.* King W, and Mertz H (eds). Plenum Press, New York, 1973.

[5] Eiband, AM, 1955. Human tolerance to rapidly applied accelerations: a summary of the literature, NASA Memorandum 5-19-59E. Cleveland, OH: NASA Lewis Research Center, 1955.

Wayne State University Tolerance Curve.[6] The end result is the Gadd Severity Index (GSI), which is based on translational acceleration-time duration. This index is used in the football helmet standard of the National Operating Committee of Standards for Athletic Equipment (NOCSAE).

John Versace of the Automotive Safety Research Office of Ford Motor Company suggested another formulation to GSI to account for long duration and low-level g impacts.[7] Versace tried to more accurately describe acceleration by integrating it within specific boundaries, rather than relying on an average acceleration, added Dr. James Newman, of Newman Biomechanical Engineering Consulting, Inc. in his presentation. Versace's formulation was used to develop HIC in 1971. The graphs and mathematical formulas for the WSTC, GSI, Versace correction, and HIC can be found in Appendixes 7 and 8.

Dr. Yoganandan stated HIC was used in early automotive standards, but at first did not have time limits. Then the 36 millisecond contact time limit was established for an impact. In 1982, for belt-restrained test dummies, the International Standards Organization (ISO) Working Group recommended the HIC 1000 standard be

---

[6] Gadd CW. Use of weighted-impulse criterion for estimating injury hazard. In: *Proceedings of the Tenth Stapp Car Crash Conference*. Society of Automotive Engineers, Inc. New York, 1966.

[7] Versace J. A review of the severity index. In*: The Proceedings of the 15th Stapp Car Crash Conference*, Coronado, CA, 1971, pp. 771-796.

replaced by the HIC 1500. In a later analysis conducted in the United States,[8] it was shown that the 1500 limit cannot be supported, and a tentative risk curve was presented using available data; HIC, with a 15 ms time limit, of 1450 corresponds to 50 percent risk of skull fracture and 700 to 5 percent risk. This HIC criterion was incorporated into the United States Federal Motor Vehicle Safety Standard 208 (Frontal Impact Protection) in the year 2000. But as Dr. Yoganandan pointed out, even in cars with a five-star side impact rating, the HIC could be 1000 or greater, as side impact star-ratings do not use HIC. He also added that the Department of Transportation (DOT) FMVSS 218 Motorcycle Helmet Performance Requirements has no reference to HIC.

Strengths and Limits of HIC

Both Dr. Newman and Dr. Yoganandan pointed out the strengths and limitations of HIC. The main advantage of HIC, according to Dr. Newman, is that it considers maximum acceleration and actually correlates better than maximum acceleration because it introduces part of the time duration factor. Another advantage is that risk curves have been developed for HIC. There are several disadvantages to HIC including:

- It only deals with linear acceleration and not rotational acceleration, despite current thinking that most head injury is more likely linked to rotational rather than linear acceleration. There is, however, a strong correlation between

[8] Prasad P, Mertz HJ. The position of the United States Delegation to the ISO Working Group 6 on the use of HIC in the automotive environment. Warrendale, PA. Report No.: SAE 851246,1985.

linear acceleration and rotational acceleration, experiments show, Dr. Newman said.

- It only deals with frontal impacts and was not designed to be used for lateral impacts.
- It takes no consideration of injury type and mass.
- It assigns attributes to the acceleration pulse based on average acceleration.
- It arbitrarily defines an “unsafe pulse” within a “safe” pulse by discounting any data outside of the two time points chosen for the calculation.
- It has nonsensical units in seconds.

Dr. Newman concluded his presentation by noting that given the limitations of HIC, one can reasonably disregard it in helmet standards. But then another criterion that considers time duration should be used instead. Dr. Newman’s slides can be found in Appendix 8.

In the discussion that followed Dr. Newman’s presentation, one participant noted that if the head velocity is normal to the impact surface, linear acceleration correlates to angular acceleration. But if there is a significant component of tangential head velocity, then the rotational acceleration may be much greater than correlation to linear acceleration would imply. Another participant pointed out that it is important to measure the coefficient of friction between the impact surface and the surface of the head or helmet because it affects angular acceleration. The coupling of the head to the neck is also important to consider, he added, and the coefficient of friction may interact with such coupling.

AFTERNOON DISCUSSION

Should HIC Be in Crash Helmet Standards?

During this discussion, participants debated the advantages and disadvantages to using HIC in a crash helmet standard. Dr. John Melvin, of Tandelta, Inc., noted that HIC is useful in car testing when it is not known what exactly the driver or passenger is going to hit, and how hard the impact will be. But HIC is superfluous in helmet testing because during this testing input conditions and resulting energy of the impacts are highly controlled.

Another participant noted that HIC at the level of 800 to 1000 reflects the tolerance level for rotational acceleration for mild concussion, not for a skull fracture or brain hemorrhage or hematoma. If it has any value, he said, it is for predicting MTBI. High HIC values do not predict concussion, Dr. Newman pointed out in his presentation. The wide range of brain injury cannot be predicted by a single value, an attendee added.

Mr. Mellor pointed out that compatibility between the head and liner is an issue and a HIC limit, in addition to a peak acceleration limit, softens the liner of the helmet so that there is more compatibility. But perhaps the most compelling value of HIC, he added, is that it considers time duration.

A measure of rebound velocity, however, could substitute for the measure of time duration HIC provides, Dr. Newman countered. He pointed out that time duration serves as a proxy for velocity change. This change, rebound velocity, or some other measure of time duration could be easily measured with current Snell testing procedures, Mr. Becker added. But Mr. David Halstead of the University of Tennessee countered that it is not known for certain whether rebound velocity equates with time duration of impact.

Dr. Melvin noted that HIC accentuates acceleration. If one just used time duration and peak acceleration to assess velocity change, one eliminates the steep slope in HIC, which is really related to skull stiffness and contact time and does not necessarily correlate with brain injury, he said. Dr. Thomas pointed out that DOT has a duration limit of 2 milliseconds at 400g in its motorcycle helmet standard. But he added that the tradeoff for imposing both a duration limit and an acceleration limit is that it will also limit the degree of energy attenuation, unless manufacturers compensate by making helmets thicker. They are not likely to do so, however, because this will result in a bulkier and heavier helmet that consumers are not likely to want to wear. He added that a helmet cannot pass EC's HIC criterion and also manage the 180 joules of single-impact energy Snell helmets are able to withstand.

Dr. Newman said that outside of HIC there is no duration restraint in helmets other than the NOCSAE standard for football helmets, which may not be applicable to

Snell testing of motorcycle helmets. He stressed the importance of considering duration or velocity in helmet testing. After this discussion, a show of hands revealed that there was general consensus among conference attendees that HIC *not* be incorporated into crash helmet standards.

Lower G Threshold or Greater Energy Attenuation

Dr. Thomas opened this discussion by pointing out that greater energy attenuation in a helmet can only be achieved by raising the g threshold, or by making the helmet thicker with padding. The latter was not generally considered a viable option because it would make the helmet too unwieldy for popular use.

Mr. Mellor noted the importance of having greater energy attenuation so as to save more lives. He cited a United Kingdom study that suggested improved high-energy attenuating helmets could lower the fatality rate from motorcycle crashes by 15 percent.[9] He also cited the European Commission COST 327 final report that stated a 30 percent increase in energy absorption would be more protective.[10] He concluded that if one is trying to offer more protection from *fatalities*, then a greater energy-attenuating helmet, is warranted, while maintaining current g levels. If the goal is to offer more protection from non-fatal brain *injuries*, then a softer, lower g, and lower energy-attenuating helmet might be warranted. The main goal of the

[9] UK Department for Transport, Research Projects S100L and S0233VF.
[10] www.cordis.lu/cost-transport/home.html) *COST 327 Motorcycle Safety Helmets Final Report of the Action*. Chinn B, Chief Editor, Office for Official Publications of the European Community, Luxembourg, 2001.

United Kingdom is to prevent more lives lost due to fatal brain injuries, perhaps at the expense of preventing more common, but less serious brain injuries, he said.

Several participants pointed out that the tradeoff in making a greater energy-attenuating helmet with a higher g threshold is that it may foster more non-fatal head injuries because it is too stiff. Mr. Halstead noted he often has seen motorcycle or racecar accidents in which the helmets are not damaged, but the wearers of the helmets were profoundly brain injured. Mr. Halstead said that often such injury stems from a low-speed impact.

Other participants pointed out that high-energy impacts are often accompanied by other fatal somatic injuries for which a greater energy-absorbing helmet will not protect. This suggests that a helmet with greater energy attenuation may not necessarily save that many more lives. A University of Southern California study found that motorcyclists wearing helmets who suffer fatal head injuries also have far more severe bodily injuries than unhelmeted riders.[11] This study found many motorcyclists wearing helmets who experience a 150 joules impact were severely brain injured. Citing this study, one participant said he thought those brain injuries stemmed not from the helmet failing, but rather because the impact was so great that no helmet could offer sufficient protection. He noted it was unfeasible to try to

---

[11] Hurt HH, Jr., Ouellet JV, Rehman I. Epidemiology of Head and Neck Injuries in Motorcycle Fatalities. In: *Mechanisms of Head and Spine Trauma*. Sances, Jr. A, Thomas DJ, Ewing CL, Larson SJ, Unterharnscheidt (eds). Aloray Publisher, Goshen, New York, 1986, pp. 69-94.

offer high-energy impact protection, and added it was unreasonable to try to do so at the expense of protecting people in more common, lower-energy impact situations.

All participants agreed that more epidemiology data is needed to resolve this debate. Dr. Thomas pointed out that Snell commissioned an epidemiology study conducted by Fred Rivara at the University of Washington.[12] This well-designed study of bicycle accidents found that the 300g limit was appropriate for bicycle helmets, but more energy attenuation was warranted. A similar study should be conducted on motorcycle accidents, he suggested, but added that such studies are expensive to run properly, and finding funding for it might be problematic.

Mr. David Thom, of Collision and Injury Dynamics, noted that the National Agenda for Motorcycle Safety published a report in 2000 that was cosponsored by the National Highway Traffic Safety Administration (NHTSA) and the Motorcycle Safety Foundation.[13] This report recommended that researchers conduct such a study on motorcycle accidents. But participants noted the Department of Transportation is not likely to fund such a study, although the National Institutes of Health or the Centers for Disease Control and Prevention might be willing to do so. (After the conference, Congress passed the Transportation Safety Act, which includes three million dollars to study motorcycle crashes.) Dr. Melvin said that racecar drivers wearing ear-plug accelerators could also provide valuable data. The Indy Racing

[12] Rivara FP, Thompson DC, Thompson RS. *Circumstances and Severity of Bicycle Injuries.* Snell Memorial Foundation, New York, 1996.
[13] National Agenda for Motorcycle Safety. DOT HS 809 156, US Department of Transportation, National Highway Traffic Safety Administration, November 2000.

League (IRL) is already collecting such data, he said. He added that North American Stock Car Auto Racing (NASCAR) also might have some data that would be useful for resolving peak g and energy attenuation thresholds.

One- or Two-Impact Testing of Helmets

After Mr. Becker's presentation, and during the afternoon discussion, participants raised the issue of whether two-impact testing was a good approach to take for motorcycle helmets. One attendee pointed out that Snell's double-impact testing does not reflect the reality of a motorcycle accident, in which the head is rarely hit more than once. But Mr. Becker pointed out that if Snell did single-impact testing, it would need to raise the energy level of the single impact. It would be too expensive to modify their testing apparatus to accommodate such a change. The two-hit impact testing is done because it is less expensive than testing at higher energy conditions. Mr. Becker also noted that if they tested helmets with a single impact, then they would have to hit the helmet harder, and such hits are more likely to result in higher HIC values. So switching to single-impact testing would not resolve the current incompatibility between EC and Snell crash helmet standards if the single test includes equivalent impact energy to a double-impact test.

Optimal Head Forms and Masses in Testing

This discussion centered on two main issues:

- whether the mass of the head form should vary to account for size differences in people; and

- what head forms and test procedures give the best repeatability and reliability.

Head Form Mass

Mr. Joseph McEntire said his predecessor (Mr. Joe Haley) at the U.S. Army Aeromedical Research Laboratory developed three head forms (small, medium, and large) based on Department of Defense (DOD) head anthropometry data. This data was compiled by the Tri-Service Working Group on Biomechanics and published as a joint report.[14] This data was used by Mr. Haley to develop a medium size head with representative anthropometric and mass distribution characteristics. The medium head model was then used as a baseline and scaled (based on head circumference) to create the small and large heads. Each head is weighted appropriately. The head forms have facial features, chins, napes, and part of the neck. The heads were developed with the intent of using them in helmet impact tests on a free-fall (un-guided) drop tower. During helmet impact testing, the head forms are impacted at specific impact velocities and the drop height is not adjusted to account for different head form or helmet weights. Mr. McEntire also did a smaller report on anthropometry data for the head and what types of head forms it dictates, but this report is not published.

[14] *Anthropometry and Mass Distribution for Human Analogues, Volume I: Military Male Aviators*, Harry G. Armstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio 45433-6573 AAMRL-TR-88-010, Naval Aerospace Medical Research Laboratory, Pensacola, Florida 32508-5700, NAERL-1334, Naval Air Development Center, Warminister, Pennsylvania 18940-5000 NADC-88036-60, Naval Biodynamics Laboratory, New Orleans, Louisiana 70189-0407, NBDL 87R003, U.S. Air Force School of Aerospace Medicine, Brooks Air Force Base, Texas 78235-5301, USAFSAM-TR-88-6, U.S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama 36362-5292, USAARL Report No. 88-5, March 1988.

Mr. Halstead added that NOCSAE did a body form data study, but this also was not published. This study found the head mass varied from 4.01 kg to 5.83 kg. This corresponds to the 4.1 to 6.1 kg range that EC uses in its testing standard. Snell uses a median 5.0 kg mass for its helmet testing, regardless of size. This enables more repeatability, and avoids having to alter the joules or the velocity according to head form mass. But does this testing approach diminish the protection for people with smaller or larger heads?

Mr. Becker pointed out that smaller head size doesn't always equate with smaller weight. Indeed, a study done at Tulane suggests cubic size measurements of heads do not correlate with their weights, he said.[15] Mr. Halstead added that there is not much variation in head mass in adults and the real variation comes from comparing children to adults. Since the focus of the conference was adult helmets, varying helmet mass was not such a critical issue. But Dr. Thomas noted that it would help for crash test helmet testing if everyone used the same helmet forms. The US Government uses the DOT head forms for their testing, whereas most other organizations use ISO head forms.

Repeatability and Reliability/Biofidellic Versus Magnesium Head Forms

Mr. Thom pointed out that for repeatability and reliability, magnesium head forms should be used in crash helmet testing. They are already used by FIA and Snell as

[15] Walker Jr., LB, Harris EH, Pontius UR, Mass, Volume, Center of Mass and Mass Moment of Inertia of Head and Head and Neck of Human Body. *Proceedings of Seventeenth Stapp Car Crash Conference*, New York, Society of Automotive Engineers, Inc.,1973. Paper 730985, P-525.

well as by DOT for helmet testing. DOT uses the Hybrid 3 aluminum head form covered by a rubber skin for automotive crash testing so that it is more biofidelic. But with biofidelity comes fragility, noted Mr. Halstead. Biofidelic forms are more likely to break than magnesium head forms, he said.

Mr. Becker pointed out that the advantage of using rigid metal head forms is that one can use the same head forms over a year or so with the minimum amount of care and have reliable, repeatable results. Mr. Halstead countered that NOCSAE finds more repeatability when it tests its biofidelic head forms compared to when it tests ISO or DOT head forms, probably because impact location sensitivity is eliminated by NOCSAE testing standards. The biofidelic head forms NOCSAE uses come in 3 head sizes—the 5^{th}, 50^{th}, and 90^{th} percentile--and weigh 4, 4.85, and 5.3 kg, respectively. He noted that they do not have to replace these head forms often, and they are sufficiently durable for standard testing. He added that if Snell helmets were tested on biofidelic head forms, the energy level could be increased, and stated that testing on Snell head forms underestimates the energy attenuation capability of the real head.

Repeatability and Reliability/Guided Impact Versus Free Fall

Dr. Thomas opened this discussion by stating that between-laboratory repeatability and reliability are critical so that manufacturers can verify what Snell finds in its helmet testing, and because manufacturers benchmark their test results to those of

Snell. Mr. Halstead noted that the EC22-05 standard does not specify repeatable testing.

Mr. Mellor pointed out that the slight offset in free-fall drop tests between impact site and center of gravity makes a big difference in results because of substantial differences in rotations, which affect the peak g levels. His anecdotal observation is that a single lab can have ten to fifteen percent variability from day to day when doing free-fall drop tests. This compares unfavorably to the one to two percent variability seen between labs with the guided impact tests that Snell labs perform, Mr. Becker said.

Mr. Halstead and most other attendees agreed that guided impact testing was more repeatable than free-fall testing. But Dr. Newman noted there are many different types of guided impact testing, including the monorail, the Snell twin wire, the Biokinetics twin wire, and the NOCSAE twin wire. He pointed out that testing on each is likely to generate different results for the same helmet. So specifying guided impact testing will not solve the problem of variability between helmet standards. Dr. Newman was of the opinion that the monorail system is more repeatable because its rebound characteristics are more uniform than that of the twin wire. But according to Mr. Becker, the bearings in the monorail system do not last as long as they do for the twin wire, which results in the monorail having less reliability (or higher maintenance) than the twin wire system.

Retention

Dr. McElhaney pointed out that helmets need to be able to move somewhat on the head so as to be comfortable. Mr. Halstead added that if the helmet is loose enough to be comfortable, it is likely to substantially move about the head in an impact situation, although it usually will cover the head enough for the first impact. Problems arise, however, when the helmet slips back enough that the forehead is exposed. This situation would not be considered a helmet retention failure with current Snell tests. These tests merely assess if the helmet falls off the head form during an impact. A low-cost way of assessing whether the head is exposed during an impact might be to videotape the movement of the helmet on the head form during impact testing, Mr. Mellor suggested. He did such filming at FIA and found that the helmet could move as much as 90 degrees before it fell off.

Topics for Future Conferences

Many critical issues were merely touched on during the Milwaukee conference and warranted more exploration. Attendees made the following list of topics they would like to focus on at future conferences:

- Linear acceleration versus rotational acceleration as appropriate criteria
- Duration of impact and how it should affect standards

- Epidemiological review of whether lower g threshold or higher energy protection is needed (A research review on this topic might be more appropriate than a conference.)
- The role of biofidelic head forms in engineering testing
- Fixed versus variable head form mass and anthropometry (A research review on this topic might be more appropriate than a conference.)
- Mass and volume limits for a helmet
- Appropriate impact surfaces for testing
- The brain's response to different energy level impacts, different directional impacts, and to off-center-of-gravity impacts
- The use of brain modeling to augment understanding of test standard tradeoffs. Dr. King noted that the SIMON model has different criteria for different types of brain injuries. Mr. Mellor added that an EC project called APROSYS is currently doing comparison assessments of the ten leading brain injury models to see which works best so as to use it to establish new injury criteria for EC legislation.

APPENDICES

Appendix 1—List of participants

Participants of the Workshop on Criteria for Head Injury and Helmet Standards

May 6, 2005 – Medical College of Wisconsin

Kristy Arbogast, Ph.D.
Research Assistant Professor
The Children's Hospital of Philadelphia
34th and Civic Center Blvd
3535 TraumaLink - 10th floor
Philadelphia, PA 19104
Tel. 215-590-6075
Fax: 215-590-5425
e-mail:arbogast@email.chop.edu

Ed Becker, M.S.
Executive Director
Snell Memorial Foundation, Inc.
3628 Madison Avenue, Suite 11
N. Highlands, CA 95660
Tel. 916-331-5073
Fax 916-331-0359
e-mail: Ed@smf.org

William C. Chilcott, Ph.D.
Director, Snell Memorial Foundation
15224 You Bet Road
Grass Valley, CA
Tel. 530-274-7654
Fax 530-274-2345

Randal Ching, Ph.D.
Research Associate Professor and Director
University of Washington
Department of Mechanical Engineering
Applied Biomechanics Lab
501 Eastlake Avenue E., Suite 102
Seattle, WA 98109
Tel. 206-625-0756
Fax 206-625-0847
e-mail: rc@u.washington.edu

Channing L. Ewing, M.D., M.P.H.
Scientific Director, Snell Memorial Foundation
1018 Napoleon Avenue
New Orleans, LA 70115
Tel. 504-891-5065
e-mail: ewingcarol@aol.com

Thomas Gennarelli, M.D.
Professor and Chair, Dept. of Neurosurgery
Medical College of Wisconsin
9200 West Wisconsin Ave.
Milwaukee, WI 53226
Tel. (414) 805-5410 or 805-5520
Fax (414) 262-6266
e-mail: tgenn@mcw.edu

P. David Halstead, M.S.
Technical Director UT Sports Biomechanics Impact Lab
University of Tennessee
304 Dunavant Drive
Rockford, TN 37853
Tel. 865- 523-1662
Fax 865- 523-1233
e-mail: daveh@soimpact.com

Thomas A. Hammeke, Ph.D.
Department of Neurology (Neuropsychology)
Medical College of Wisconsin
9200 West Wisconsin Ave.
Milwaukee, WI 53226

Albert King, Ph.D.
Director and Professor
Dept. of Biomedical Engineering
Wayne State University
818 W. Hancock
Detroit, MI 48202
Tel. 313-577-1347
Fax 313-577-8333
e-mail: king@rrb.eng.wayne.edu

James McElhaney, Ph.D.
Professor
Duke University
34ll Cambridge Road
Durham, N.C. 27707
Tel. 9l9-489-4159
Fax 9l9-402-9242
e-mail: mcelhaney@lycos.com

B. Joseph McEntire, M.S.
Research Mechanical Engineer
U.S. Army Aeromedical Research Laboratory
Injury Biomechanics Branch, Aircrew Protection Division
P.O. Box 620577
Fort Rucker, Alabama 36362-0577
Tel. (334) 255-6896
FAX (334) 255-7798
DSN 558-xxxx
joe.mcentire@us.army.mil

Andrew Mellor, BEng (Hons) CEng MIMechE
FIA Institute for Motor Sport Safety
8 Place de la Concorde
75008 Paris
France
amellor@FIAInstitute.com
M +44(0) 7770 402 987
T +44(0) 1483 426 411
F +44(0) 1483 425 797
e-mail: amellor@FIAinstitute.com

John W. Melvin, Ph.D.
President
Tandelta, Inc.
1218 Snyder Avenue
Ann Arbor, MI 48103
Tel. 734-913-4826
Fax 734- 913-5301
e-mail: Tandelta@earthlink.net

William H. Muzzy III, B.S.
Snell Board Member
3637 Peachtree Street
Slidell, LA 70458
Tel. 985-605-1000
Fax 985-605-1003
e-mail: bmuzz@aol.com

James A. Newman, Ph.D., P. Eng.
Newman Biomechanical Engineering Consulting, Inc.
1152 119th Street
Edmonton, Alberta T6J 7H6, Canada
Tel. 239-543-5116 (till April 28)
Tel. 780-432-1277 (after April 28)
e-mail: newman@biomechanical-engineering.com

Frank A. Pintar, Ph.D.
Professor
Department of Neurosurgery
Neuroscience Research Labs
VA Medical Center 151
5000 W. National Ave.
Milwaukee, WI 53295
Tel. (414) 384-2000 x41534
Fax (414)384-3493
e-mail: fpintar@mcw.edu

Priya Prasad, Ph.D.
Technical Fellow – Safety Research and Development
Ford Motor Company
Scientific Research Laboratory
2101 Village Drive, Room 2115
P.O. Box 2053 Maildrop 2115
Dearborn, MI 48124
Tel. 313- 594-0433
Fax 313 248-9051
e-mail: pprasad@ford.com

Terry Smith, Ph.D.
Principal scientist
Dynamic Research, Inc.
355 Van Ness Avenue
Torrance, CA 90501
Tel. 310-212-5211
Fax 310-212-5046
e-mail: tas@dynres.com

Richard G. Snyder, Ph.D.
Director, Snell Memorial Foundation
3720 N. Silver Drive
Tucson, AZ 85749
Tel. 520-749-2899
Fax 520-760-0794
e-mail: rgsbiodyn@msn.com

Daniel J. Thomas, M.D., M.P.H.
Treasurer
Snell Memorial Foundation, Inc.
3628 Madison Avenue, Suite 11
N. Highlands, CA 95660
Tel. 916-331-5073
Fax 916-331-0359

Larry Thibault, Ph.D.
Biomechanical Engineer
Biomechanics, Inc.
Quarters M-2
4601 S Broad Street
Philadelphia, PA 19112
Tel. 215- 271-7720
Fax 215- 271-7740
e-mail: lthibault@biomechanicsinc.com

David R. Thom, M.S.
Collision and Injury Dynamics
149 Sheldon Street
El Segundo, CA 90245
Tel. 310-414-0449
Fax 310-414-9490
e-mail: dthom@ci-dynamics.com

Narayan Yoganandan, Ph.D.
Professor & Chair, Biomed Eng.,
Department of Neurosurgery
9200 West Wisconsin Avenue
Medical College of Wisconsin
Milwaukee, WI 53226
Tel. 414-384-3453
Fax 414-384-3493
e-mail: yoga@mcw.edu

Appendix 2—Conference Agenda

Workshop on Criteria for Head Injury and Helmet Standards
Medical College of Wisconsin
Milwaukee, Wisconsin
May 6, 2005

Meeting Agenda

8:00 am Continental Breakfast

8:30 am Welcome and Introduction
- Tom Gennarelli and Daniel Thomas

8:45 am Use of HIC in Helmet Standards
a) Standards
b) Comparison of Helmet Testing to EC and Snell Standards
- Edward Becker

9:15 am Questions and Answers

9:30 am Development of FIA Advanced Helmet Specification (Super Helmet Standard)
- Andrew Mellor

10:15 am Questions and Answers

10:30 am Break

10:30 am Scientific and Experimental Basis of Head Injury Criteria and Peak Acceleration Limits
- Tom Gennarelli

11:00 am Questions and Answers

11:15 am Development and Application of Head Injury Criteria (HIC) to Helmet Testing
- Jim Newman

11:45 am Questions and Answers

12:00 noon Lunch

1:00 pm Compilation of Important Issues from Morning Presentations
- All Participants

1:30 pm Discussion
- All Participants

3:30 pm Summary of Discussion

4:30 pm Adjourn

Snell M2000 vs. EC 22-05

Comparison Testing on Helmets Certified to Either Standard

Testing Conducted by:

HPE

Farnham, Surrey

England

&

Snell Memorial Foundation

North Highlands, California

Paired Helmets

- All helmets were made by the same manufacturer
- Comparable EC 22-05 and Snell M2000 models were selected
- The helmets were paired, one EC 22-05 and one Snell M2000 sample to a pair.
- Within each pair, the samples were marked, conditioned and tested identically

That is…

- A Snell M2000 helmet and an EC 22-05 helmet both sized for the “J” headform, were conditioned hot and tested to Snell M2000 requirements with identical impacts at identical sites on the helmet.
- A similar pair of helmets was conditioned cold and tested to Snell M2000 requirements
- A similar pair was conditioned hot and tested to EC22-05 requirements
- A similar pair was conditioned cold and tested to EC22-05 requirements
- And we did the same thing for Snell and EC helmets fitting the “M” headform

Test Matrix

	Snell M2000 Type Tests	EC 22-05 Type Tests
Hot Condition	A Snell “J” Helmet & an EC“J” Helmet ---------------------------- A Snell “M” Helmet & an EC “M Helmet	A Snell “J” Helmet & an EC“J” Helmet ----------------------------- A Snell “M” Helmet & an EC “M Helmet
Cold Condition	A Snell “J” Helmet & an EC“J” Helmet ------------------------------ A Snell “M” Helmet & an EC “M Helmet	A Snell “J” Helmet & an EC“J” Helmet ----------------------------- A Snell “M” Helmet & an EC “M Helmet

Quick Summary of Results

- The Snell M2000 and EC 22-05 Standards are Incompatible
- For size XL and smaller, Snell M2000 qualified helmets will not satisfy HIC requirements in EC Testing
  - Snell would consider the responses as protective
- For size XL and smaller, EC 22-05 qualified helmets will not manage Snell impact energies in Snell testing
  - The responses would be considered hazardous by any standards

Headform Breakout

- “A” Headform – Snell 5.0 kg vs EC 3.1 kg
  - 50 cm circumference, Size XXX-Small
- “E” Headform – Snell 5.0 kg vs EC 4.1 kg
  - 54 cm circumference, Size X-Small
- “J” Headform – Snell 5.0 kg vs EC 4.7 kg
  - 57 cm circumference, size Medium
- “M” Headform – Snell 5.0 kg vs EC 5.6 kg
  - 60 cm circumference, size X-Large
- “O” Headform – Snell 5.0 kg vs EC 6.1 kg
  - 62 cm circumference, size XXX-Large

Impact Gear Considerations

Snell M2000	EC 22-05	(EC 22-05 approximation)
Drop mass 5.0 kg J & M Twin Wire Half Headform ***rotational components controlled and minimized*	Drop Mass 4.7 kg J 5.6 kg M Guided Free Fall Full Headform	Drop Mass 4.7 kg J 5.6 kg M Twin Wire Half Headform ***rotational control may make this approximation more severe than actual test*

Impact Test Considerations

- Snell M2000 Flat & Hemi
  - Double Impact
  - 7.74 m/s, 6.63 m/s
  - 150 Joules, 110 Joules
- Snell M2000 Edge
  - Single Impact
  - 7.74 m/s
- No Kerbstone
- Test Criterion
  - Peak must not exceed 300g

- EC 22-05 Flat & Kerb
  - Single Impact
  - 7.5 m/s
  - (87 to 172 Joules depending on headform)
- No Hemisphere
- No Edge
- Test Criteria
  - HIC must not exceed 2400
  - Peak must not exceed 275g

Results

- 16 Helmets tested
  - On the M Headform
    - 2 pair in size XL to Snell (one pair hot & one cold)
    - 2 pair in size XL to EC 22-05 (as above)
  - On the J Headform
    - similarly
- 101 separate impacts, 70 sites

Note on Graphs

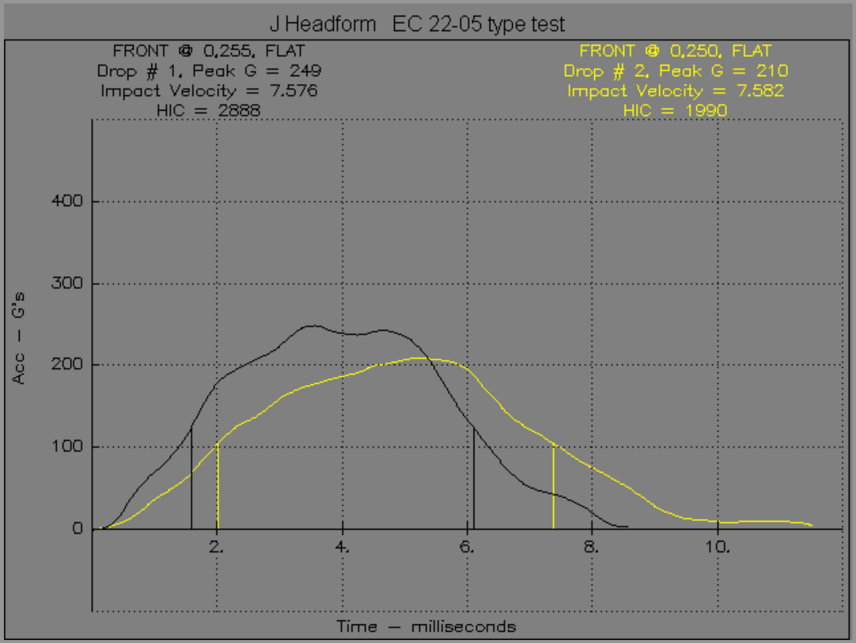
- Data presented in two formats:
  - Acceleration plotted versus time
  - Acceleration cross-plotted versus calculated displacement
    - Displacement versus time is calculated from the measured impact velocity and the acceleration time history
  - For Snell double impacts, the crossplots start the instant the tab clears the velocity gate

Results: ‘J’ EC Tests

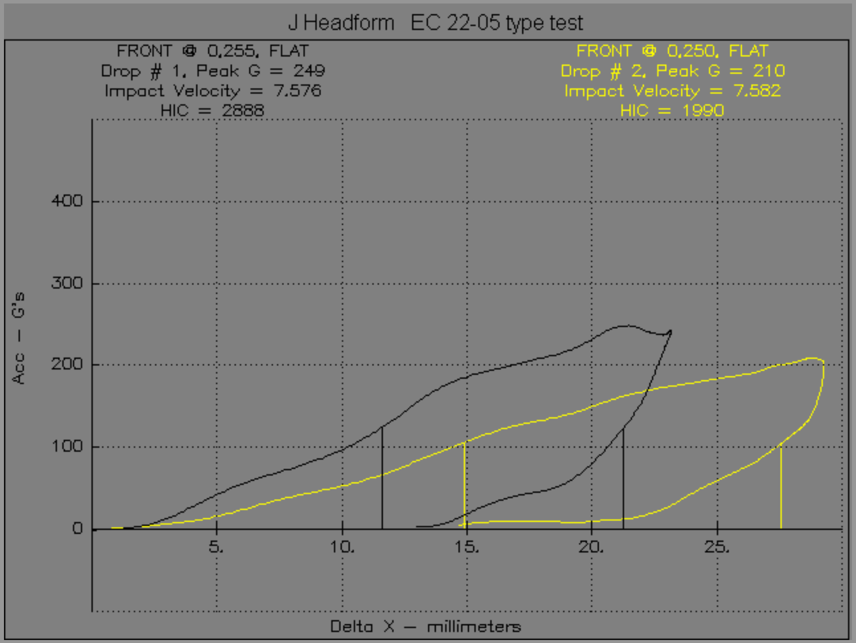
- All the EC 22-05 Helmets meet EC 22-05 impact test requirements
- Snell Helmets
  - Failed HIC criteria for all flat impacts
    - 2888, 3233, 2571 and 2784 versus 2400
  - One Flat impact failed the Peak G limit
    - Measured 279 G versus a limit of 275 G

EC 22-05 Front Flat
J Headform

Snell Helmet EC 22-05 Helmet

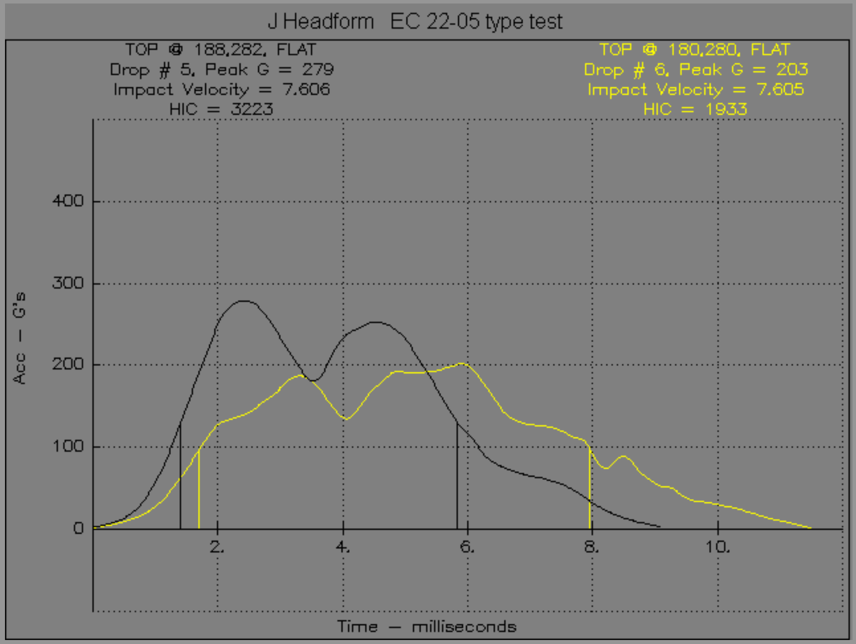


Snell Helmet EC 22-05 Helmet

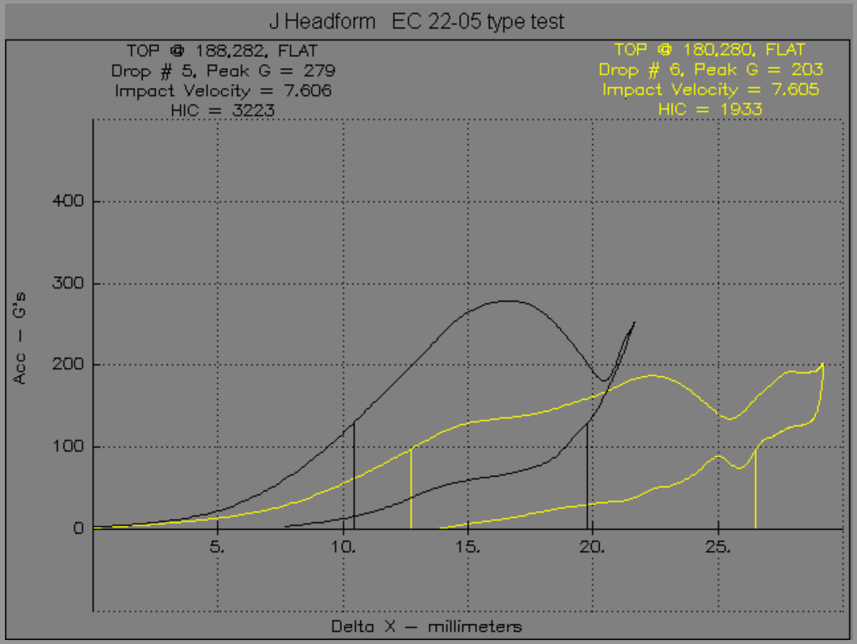


EC 22-05 Top Flat
J Headform

Snell Helmet EC 22-05 Helmet

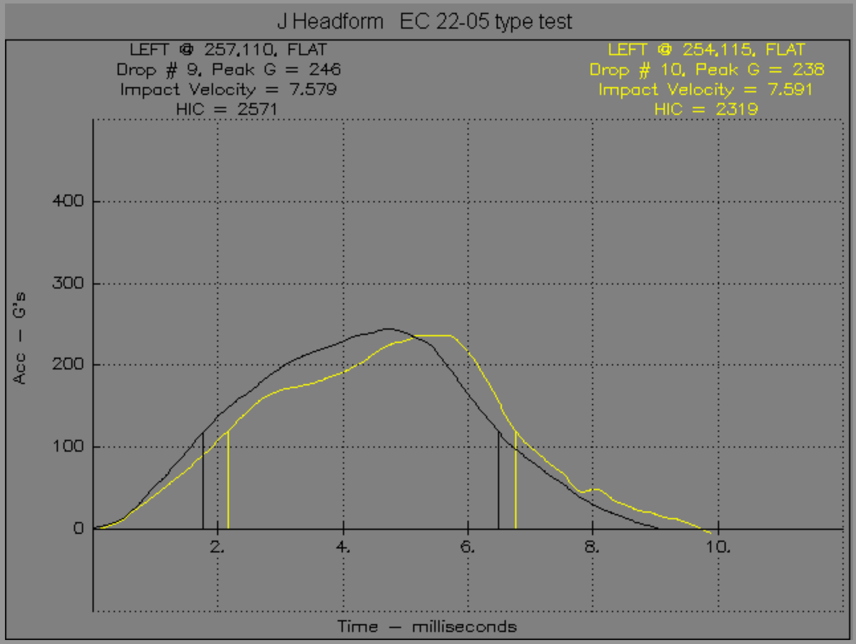


Snell Helmet EC 22-05 Helmet

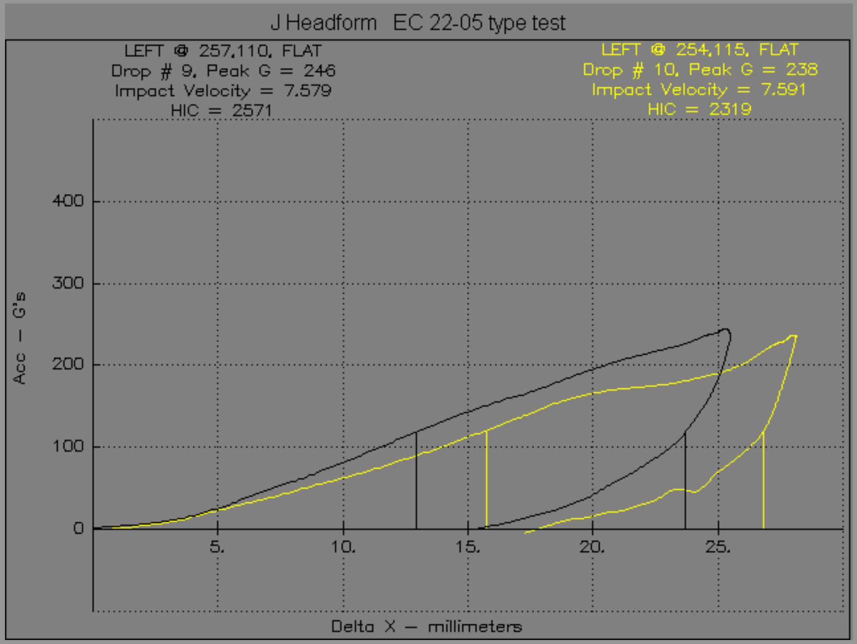


EC 22-05 Left Flat
J Headform

Snell Helmet EC 22-05 Helmet

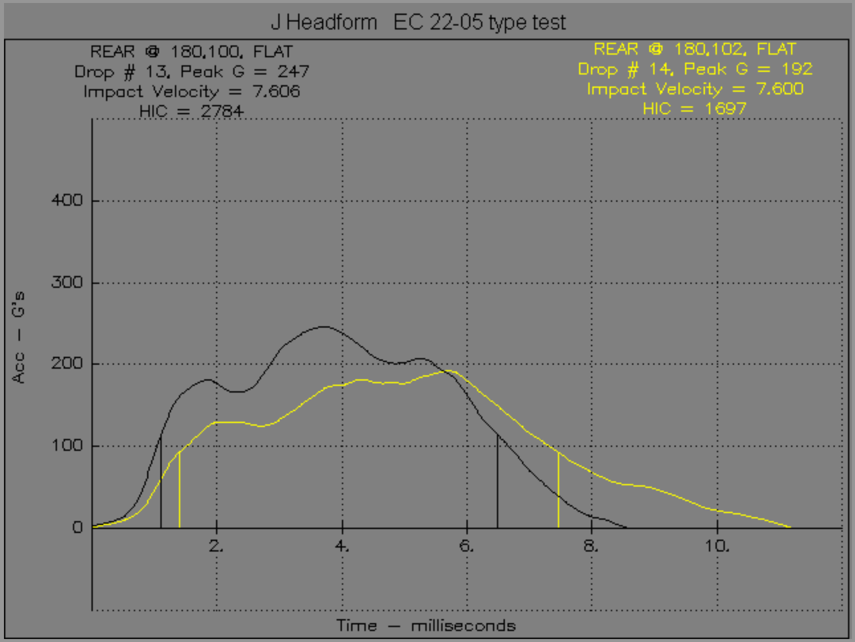


Snell Helmet EC 22-05 Helmet

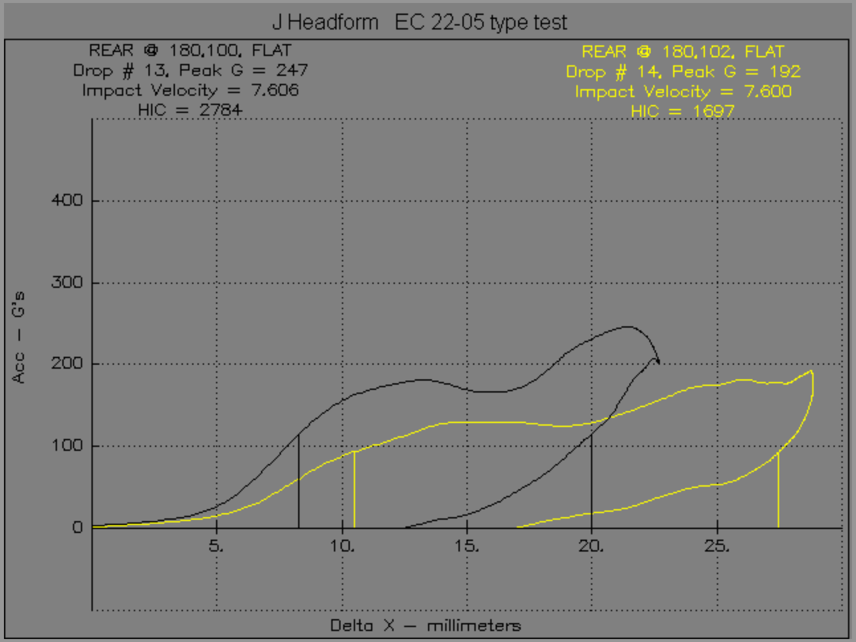


EC 22-05 Rear Flat
J Headform

Snell Helmet EC 22-05 Helmet



Snell Helmet EC 22-05 Helmet

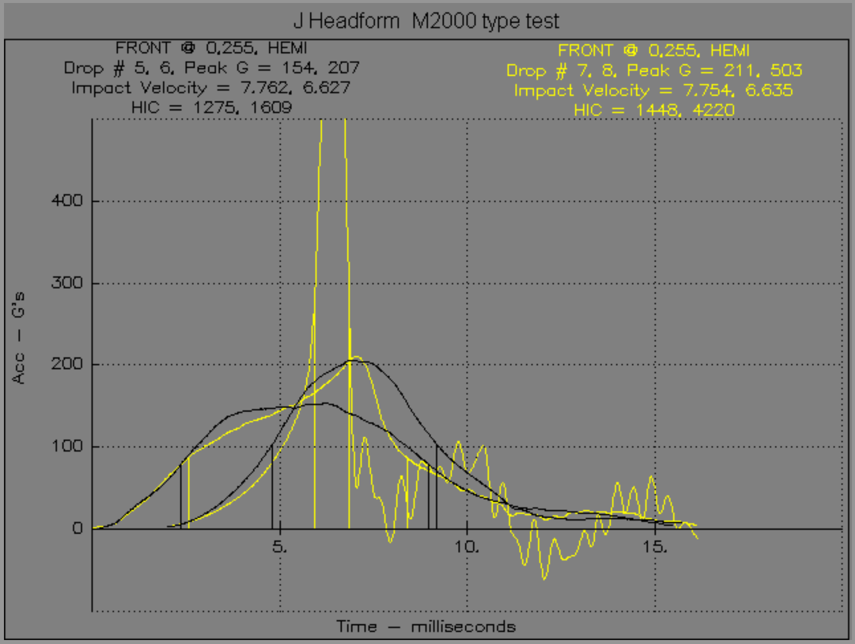


Results: ‘J’ Snell M2000 Tests

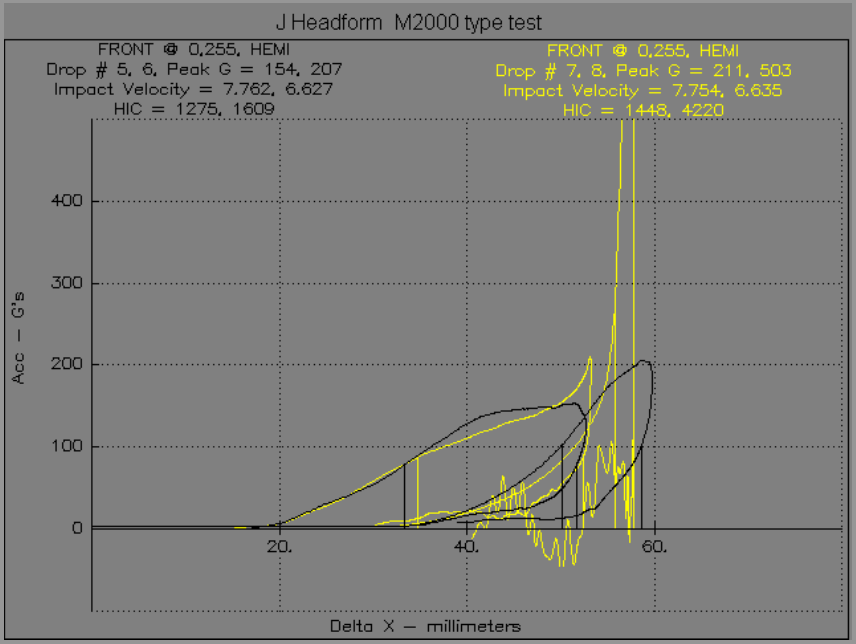
- All the Snell helmets meet M2000 impact test requirements
- The EC Helmets
  - Failed one edge anvil impact
    - Measured 410 G versus the 300 G criterion
  - Failed two hemi anvil impact series
    - 2nd front impact overload (~500 G)
    - 1st and 2nd Rear, 438 G and overload

Snell M2000 Front Hemi J Headform

Snell Helmet EC 22-05 Helmet

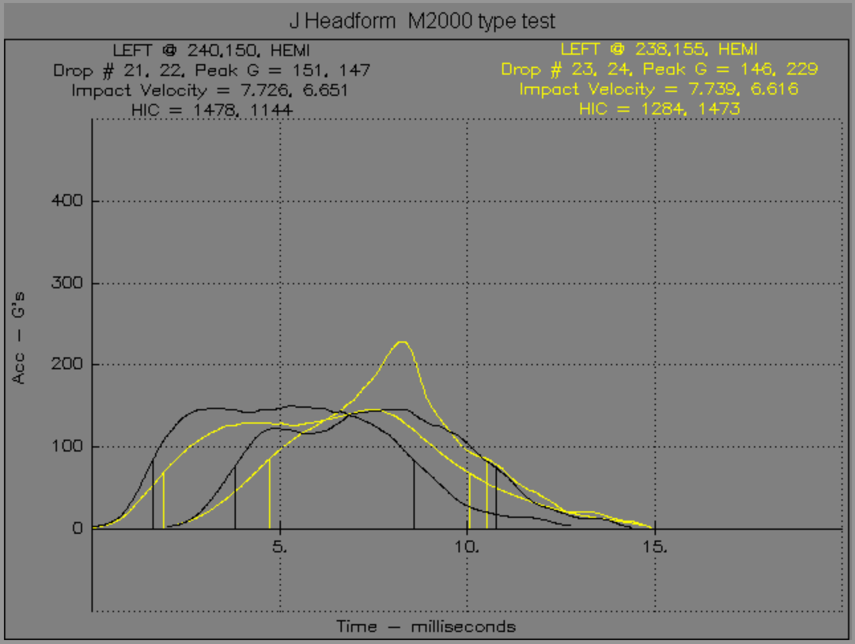


Snell Helmet EC 22-05 Helmet

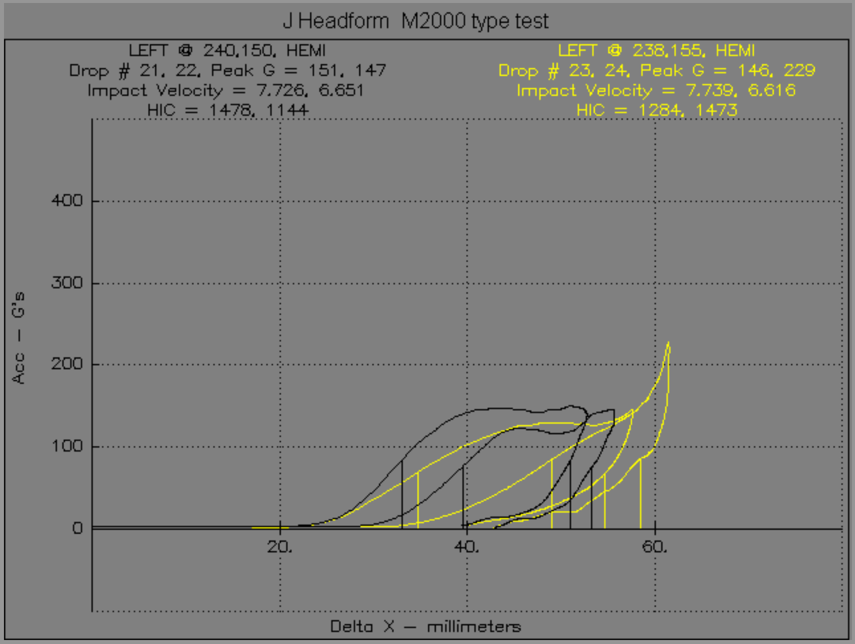


Snell M2000 Left Hemi
J Headform

Snell Helmet EC 22-05 Helmet

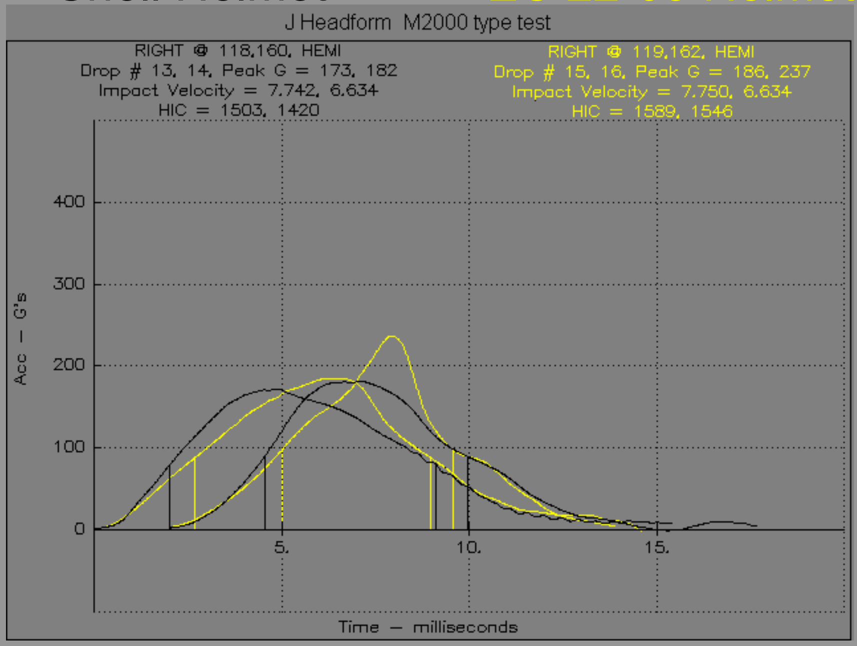


Snell Helmet EC 22-05 Helmet

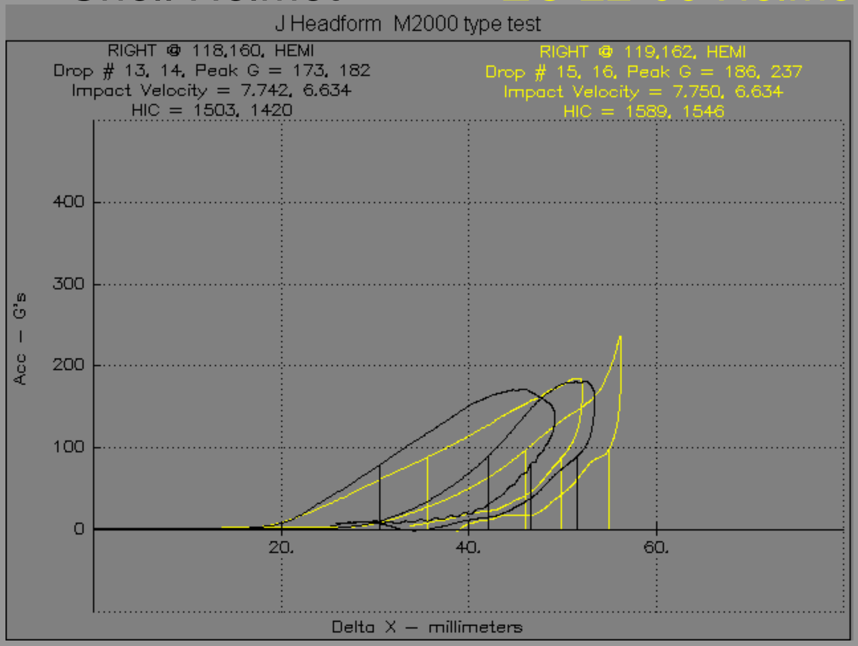


Snell M2000 Right Hemi
J Headform

Snell Helmet EC 22-05 Helmet

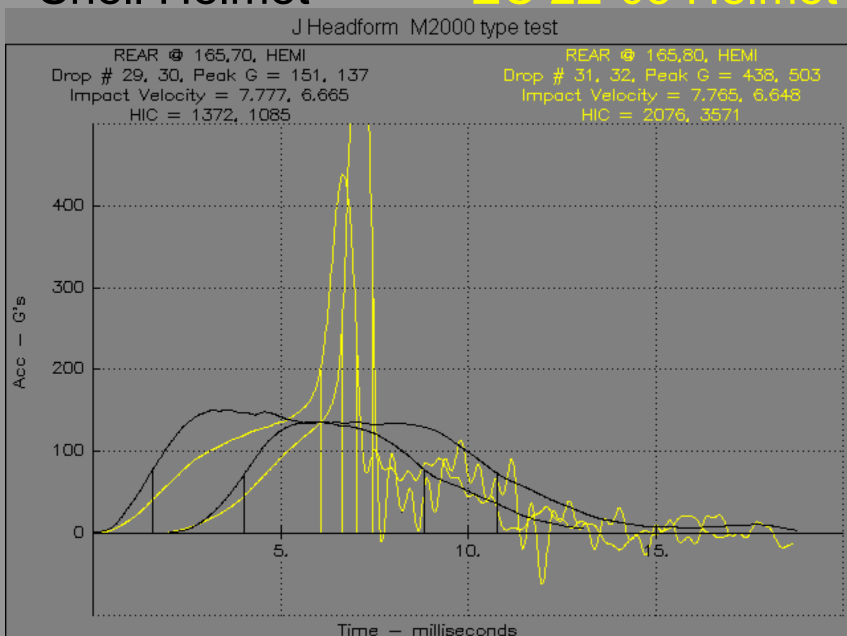


Snell Helmet EC 22-05 Helmet

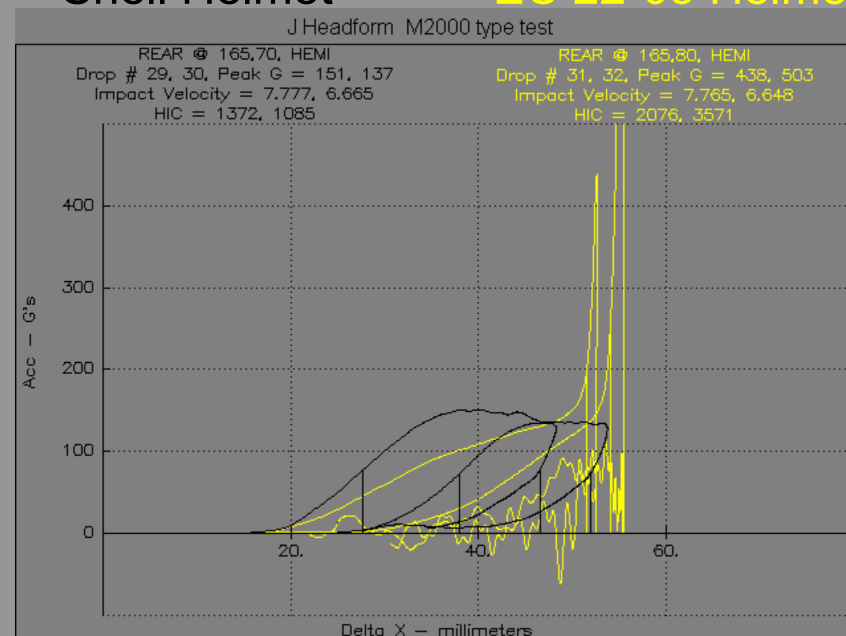


Snell M2000 Rear Hemi
J Headform

Snell Helmet EC 22-05 Helmet

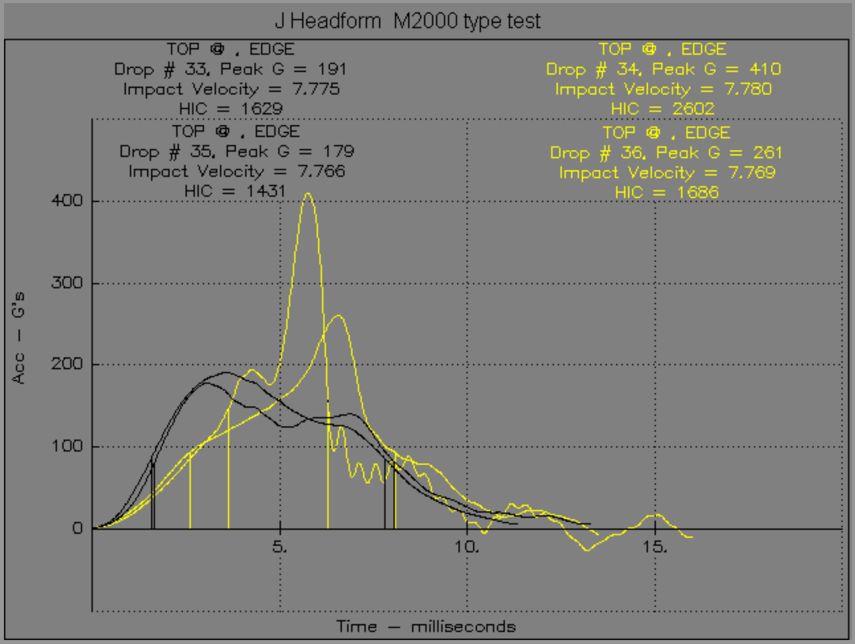


Snell Helmet EC 22-05 Helmet

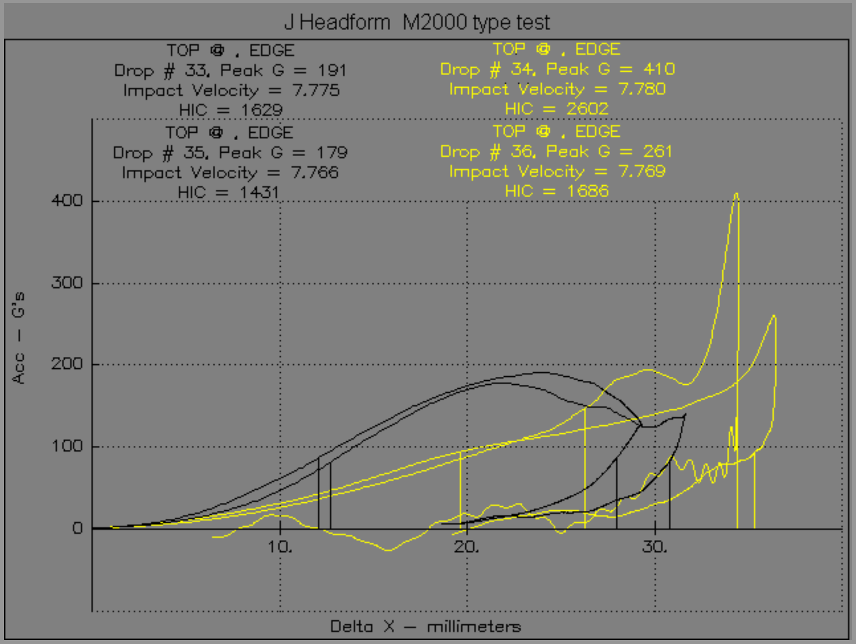


Snell M2000 Top Edge
J Headform

Snell Helmet EC 22-05 Helmet



Snell Helmet EC 22-05 Helmet

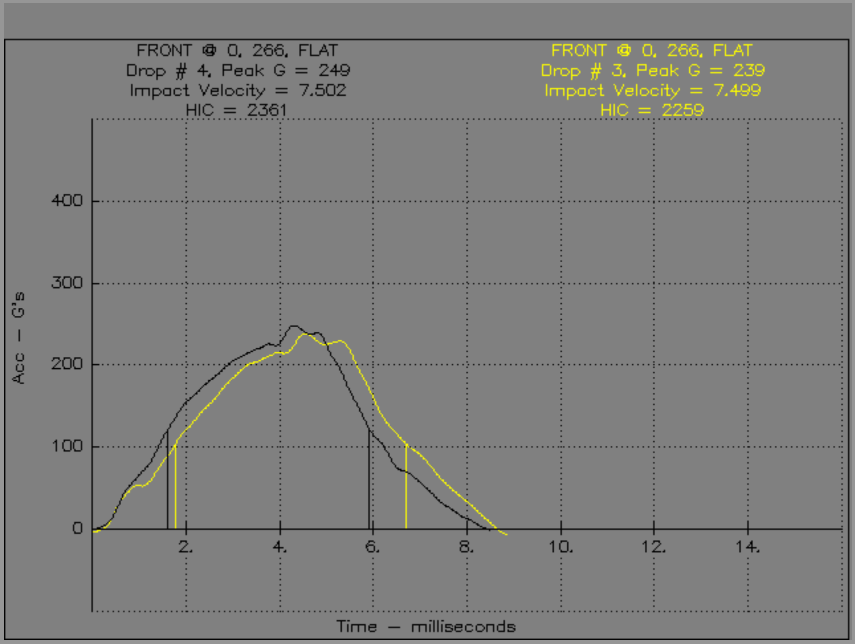


Results: ‘M’ EC Tests

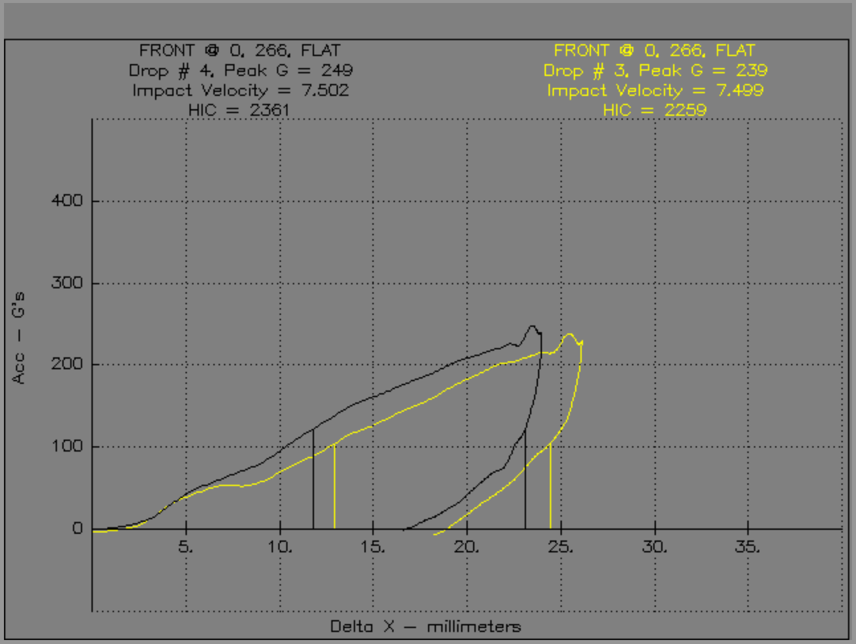
- All Snell helmets and all EC helmets passed all the prescribed impacts.

EC 22-05 Front Flat
M Headform

Snell Helmet EC 22-05 Helmet

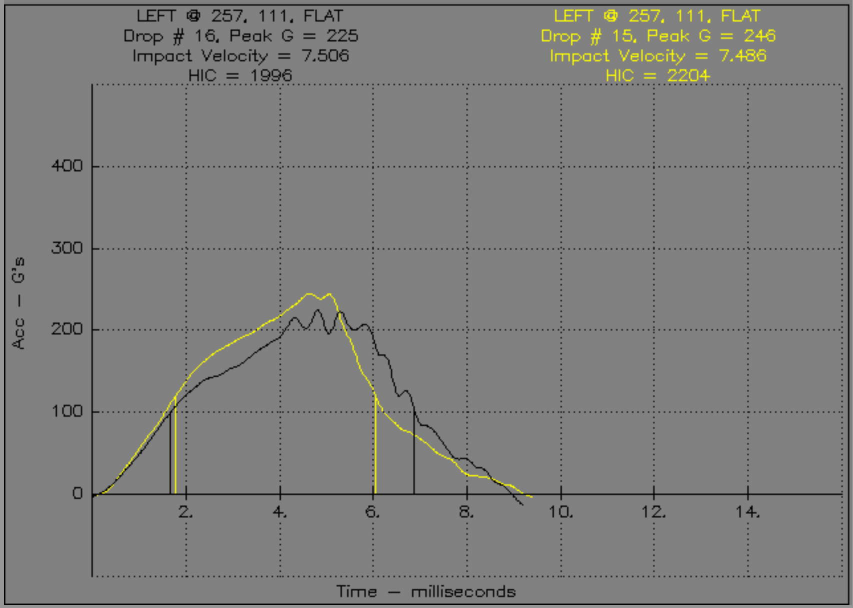


Snell Helmet EC 22-05 Helmet

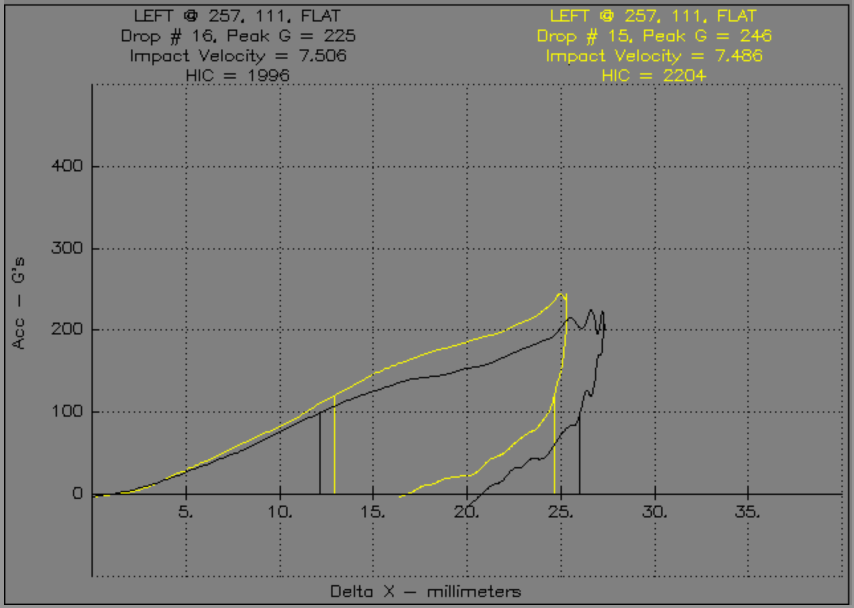


EC 22-05 Left Flat
M Headform

Snell Helmet EC 22-05 Helmet

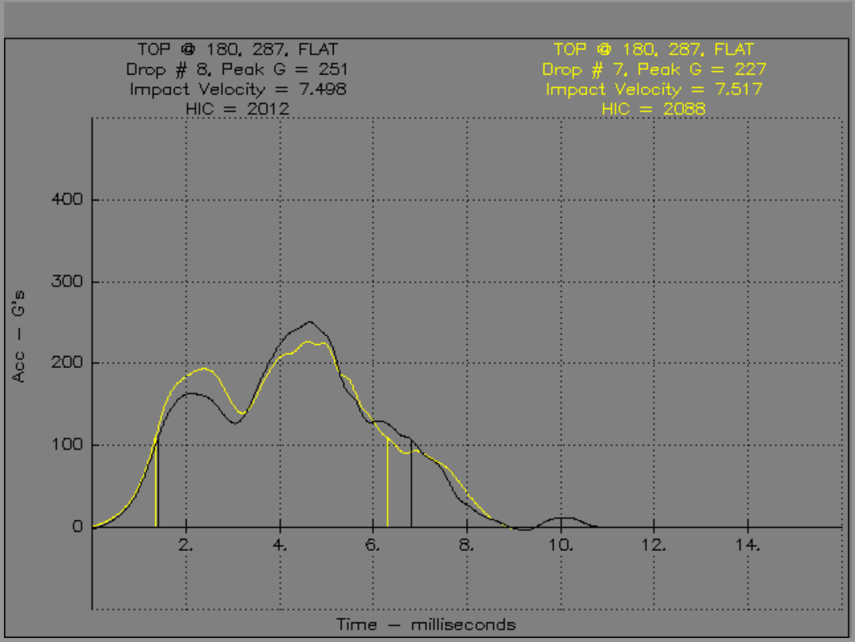


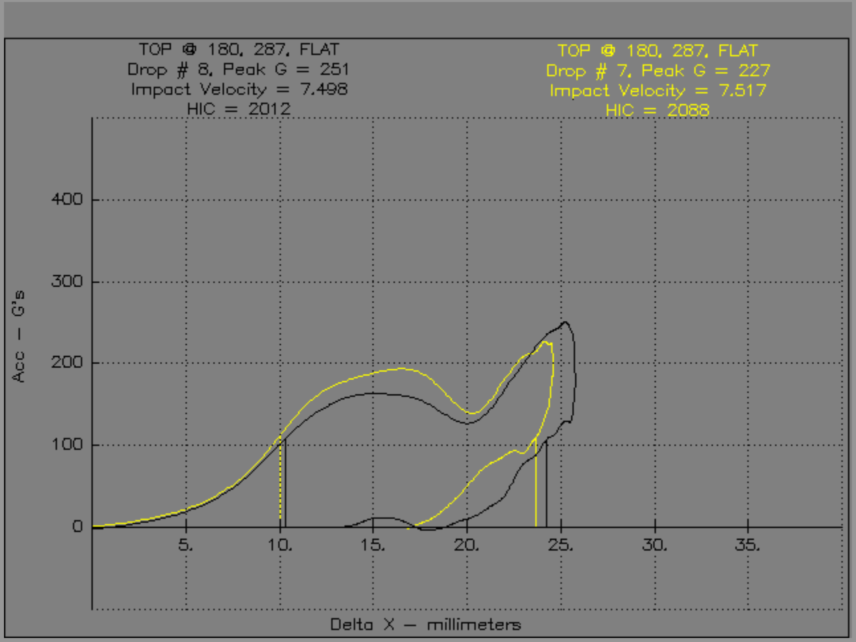
Snell Helmet EC 22-05 Helmet



EC 22-05 Top Flat
M Headform

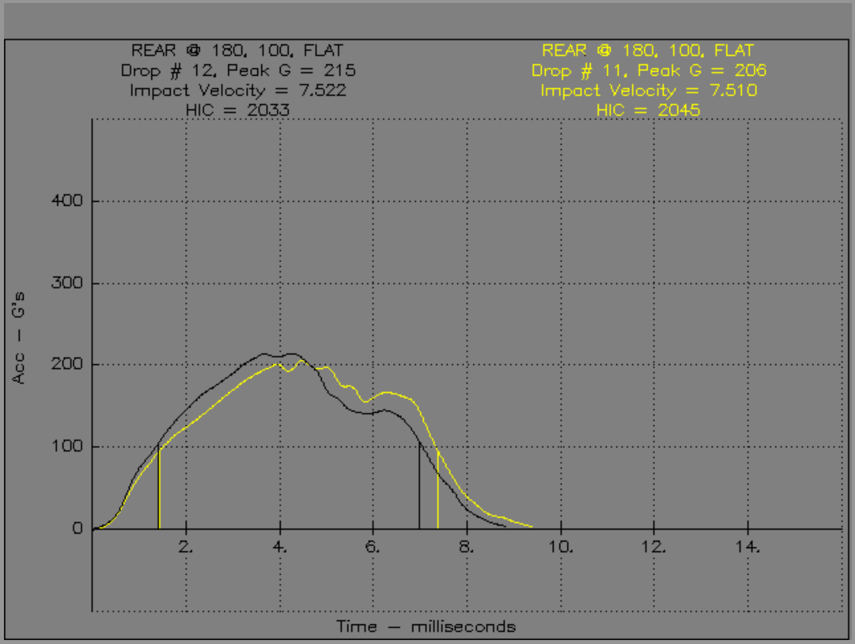
Snell Helmet | EC 22-05 Helmet | Snell Helmet | EC 22-05 Helmet



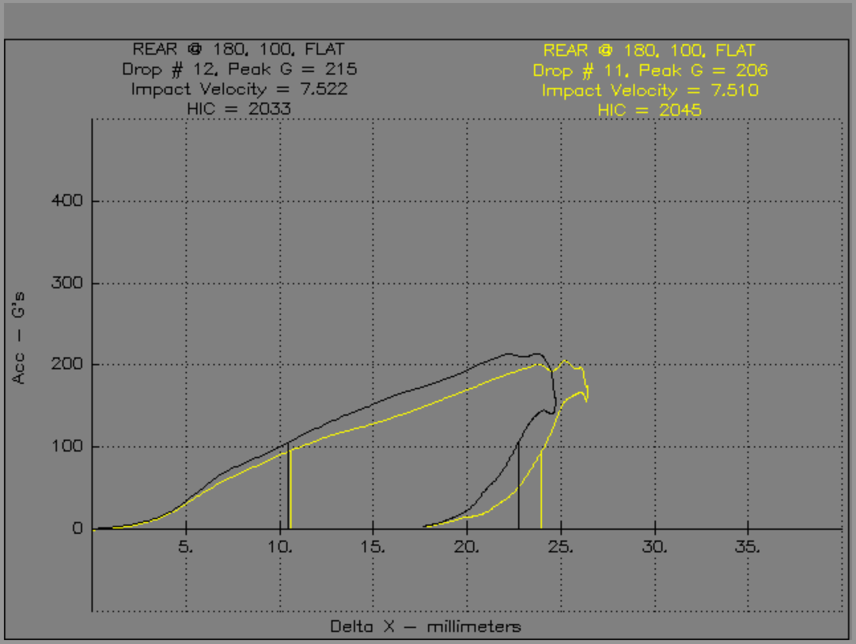


EC 22-05 Rear Flat
M Headform

Snell Helmet EC 22-05 Helmet



Snell Helmet EC 22-05 Helmet

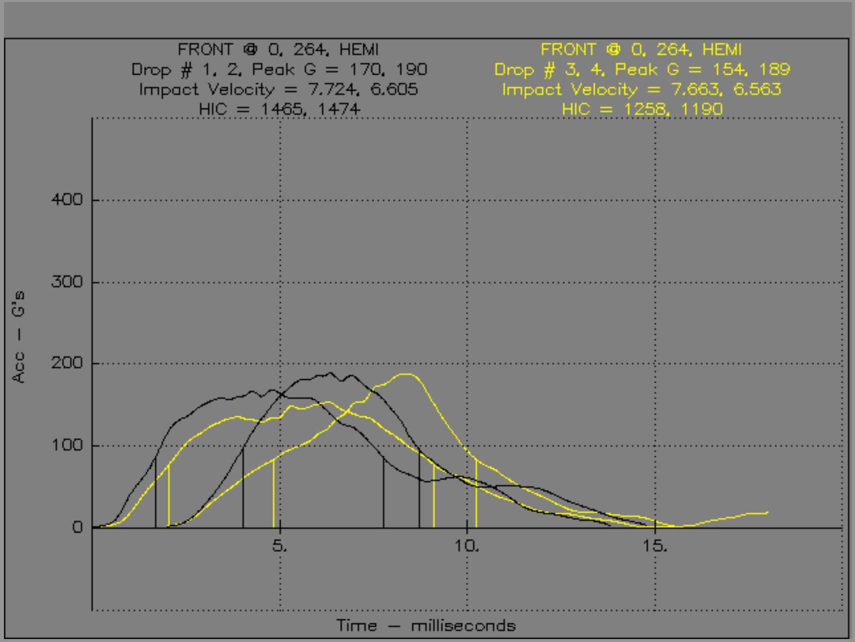


Results: ‘M’ Snell M2000 Tests

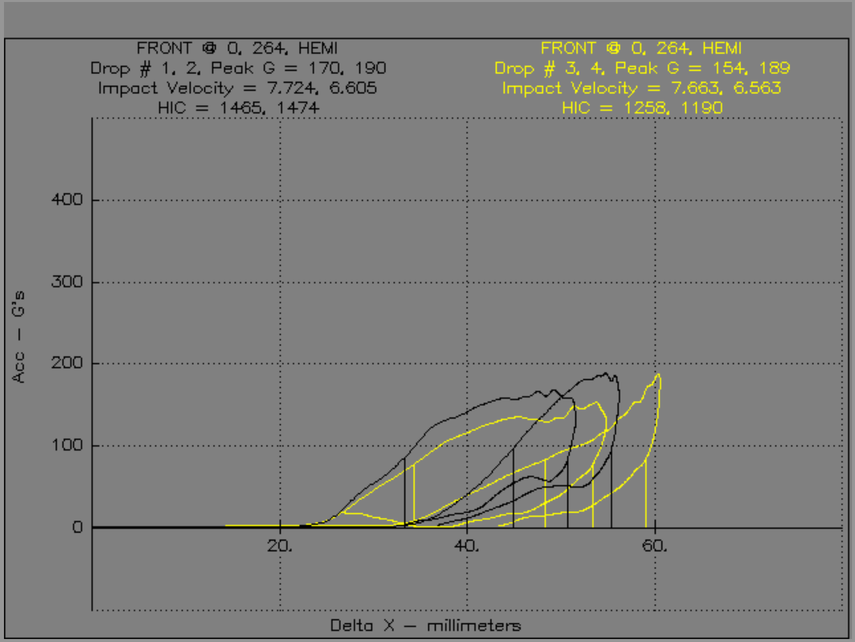
- All Snell Helmets and all EC Helmets passed all the Snell M2000 impacts
- BUT..
  - The Rear hemi impacts were performed 1 centimeter too low.. At the M2005 test line
  - The Snell helmet failed in the second of two impacts after managing the first
  - The EC helmet failed in the first impact

Snell M2000 Front Hemi
M Headform

Snell Helmet EC 22-05 Helmet

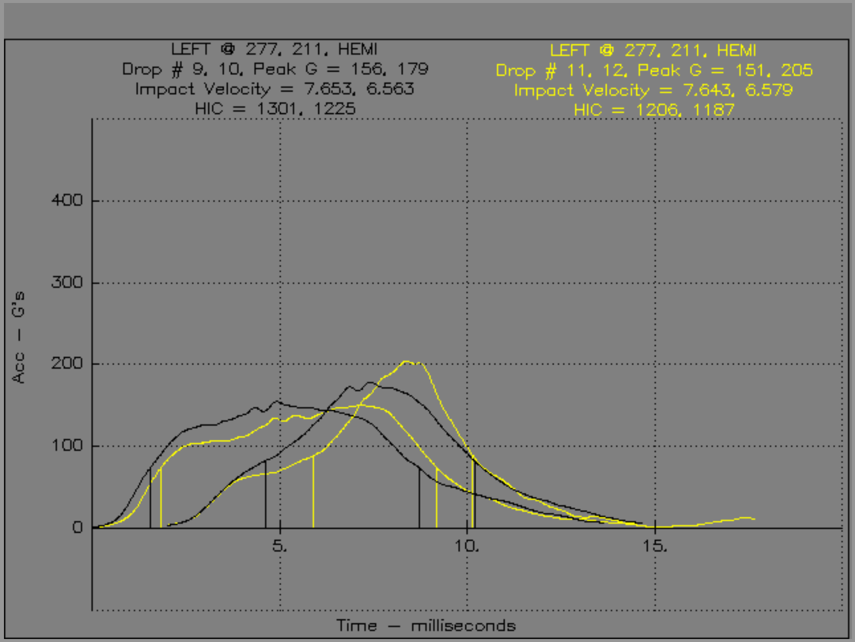


Snell Helmet EC 22-05 Helmet

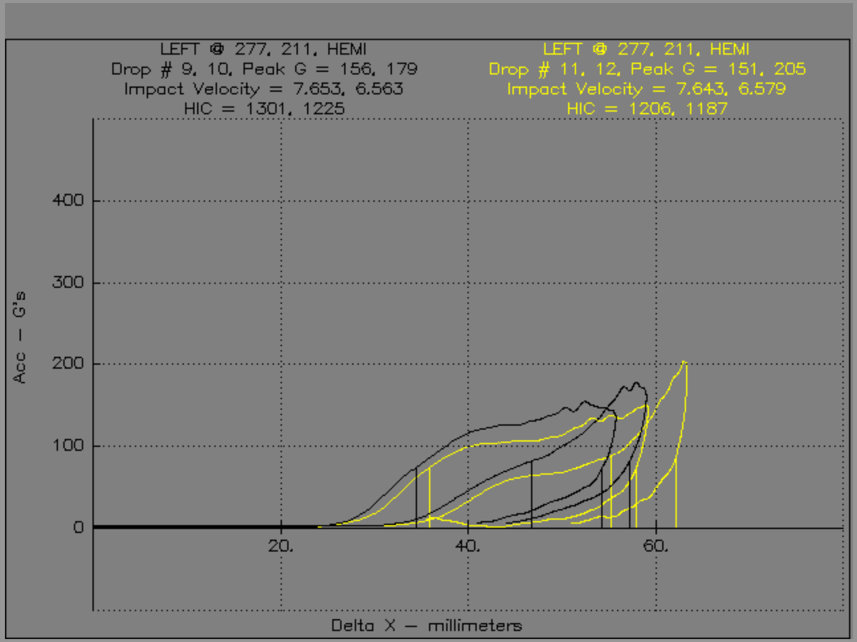


Snell M2000 Left Hemi
M Headform

Snell Helmet EC 22-05 Helmet

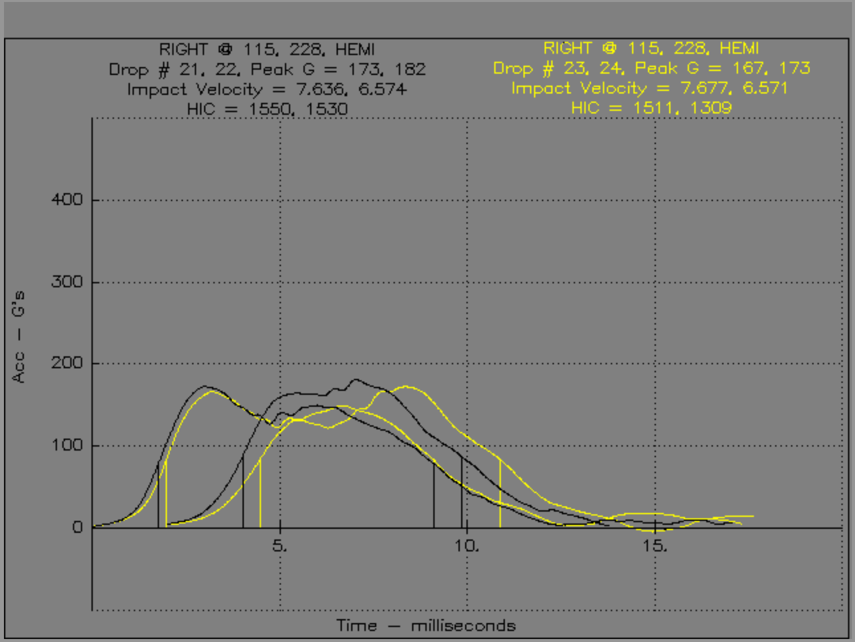


Snell Helmet EC 22-05 Helmet

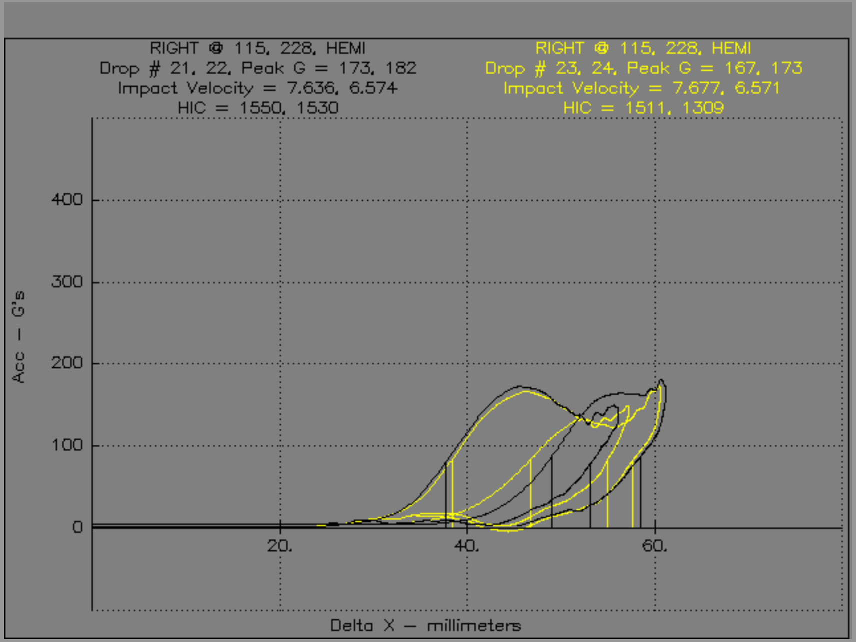


Snell M2000 Right Hemi M Headform

Snell Helmet EC 22-05 Helmet

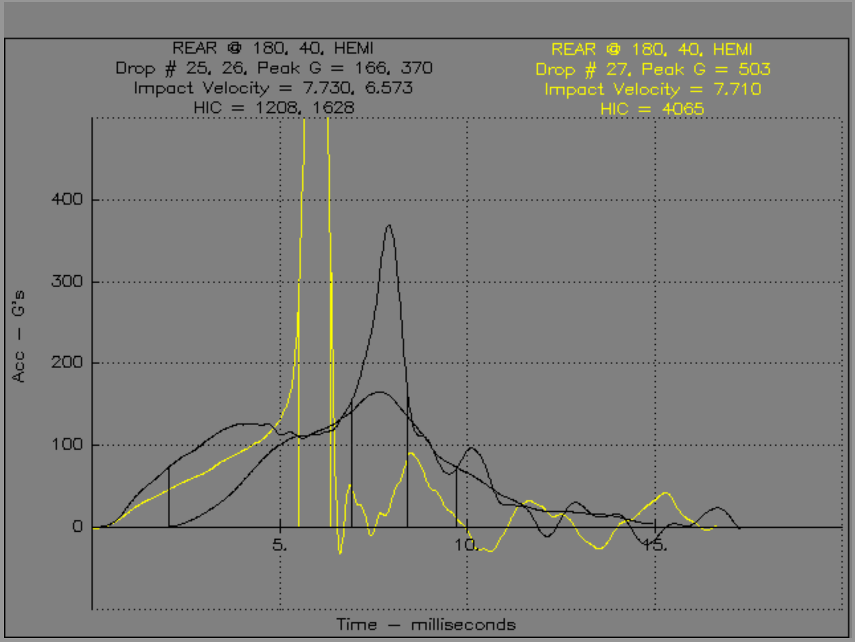


Snell Helmet EC 22-05 Helmet

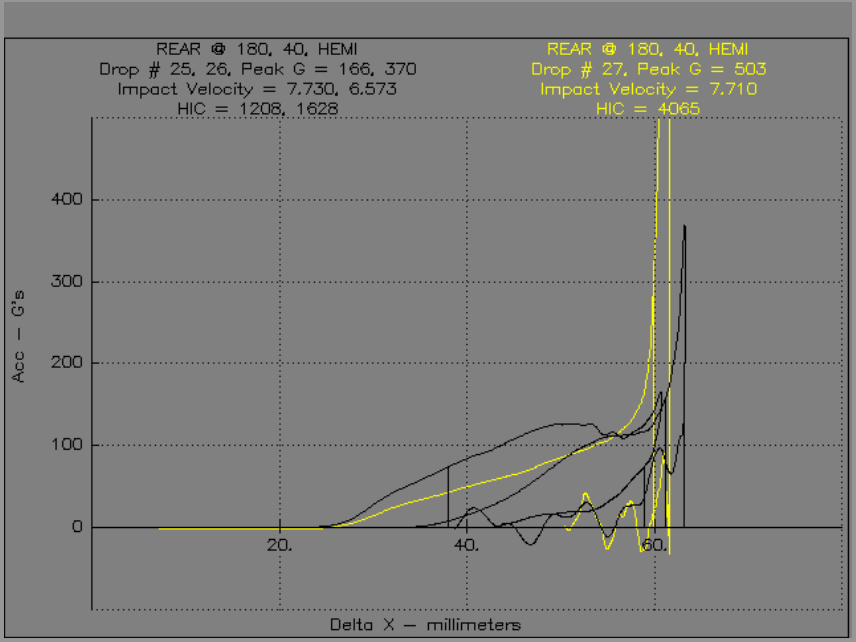


Snell M2000 Rear Hemi
M Headform

Snell Helmet EC 22-05 Helmet



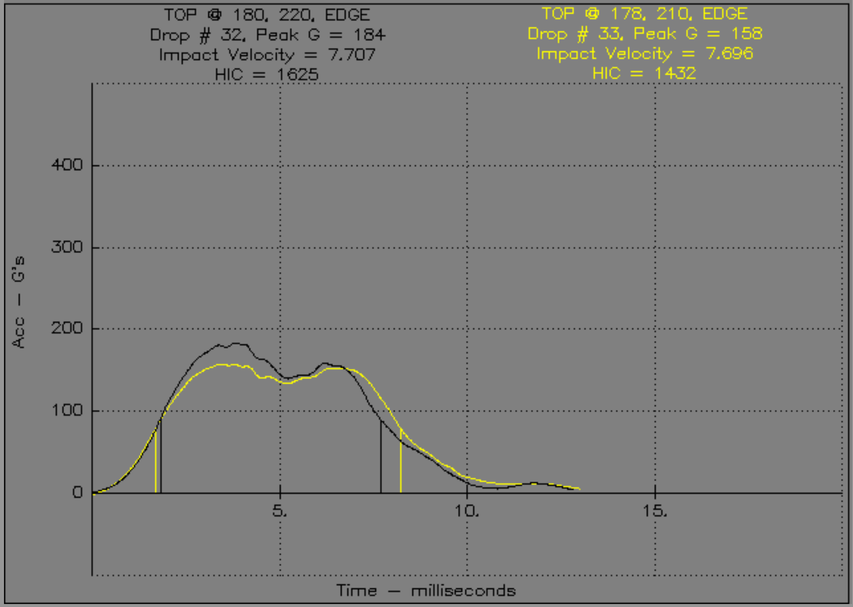
Snell Helmet EC 22-05 Helmet



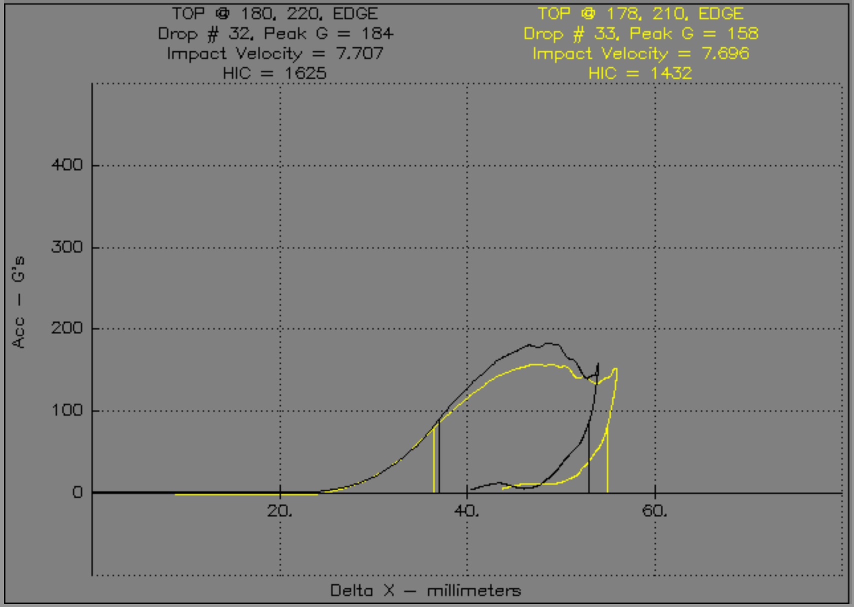
~1 cm. below test line… (an M2005 type impact)

Snell M2000 Top Edge
M Headform

Snell Helmet EC 22-05 Helmet



Snell Helmet EC 22-05 Helmet



A, E and O Headforms

- Helmets fitting only two of five headforms have been evaluated… BUT
- It may be possible to draw some inferences for the A, E and O headforms based on the J and M results
- In general, the standards diverge even further as headform size decreases to the E and A sizes but, as with M, Snell/EC compatible helmets may be possible on the O headform.

The Critical Considerations

- Snell Impact energies, velocities and headform masses are constant across headforms
- EC velocities are constant but impact energy and mass increase with headform size – roughly with the cube of the headform circumference

Mass Effects

- Flat Impact –
  - Likely an inversely proportionate change in Peak G
  - If shock energy is the same, there may be an inverse square effect on HIC
  - If impact velocity is the same the effect on HIC is inverse and may be to the 1.5 power

Mass Effects

- Hemi & Kerbstone Impact –
  - – If shock energy is the same, an inverse effect on Peak G
  - – If Impact velocity is the same
    - Peak G may vary as the inverse square root
    - But if shock approaches the limits of the helmet… Peak G may suddenly go through the roof
  - – HIC will remain well below Flat Anvil figures so long as shock is within capabilities

Snell M2000 Helmets in EC Testing

- ‘A’ Headform (size x-small) – failures expected
  - Peak G and HIC for Flat impact
- ‘E’ Headform (size small) – failures expected
  - Peak G and HIC for Flat (not so bad as ‘A’)
- ‘J’ Headform (size medium) – failures expected
  - Mostly Flat HIC (not so bad as ‘E’)
- ‘M’ Headform (size x-large) – Passes likely
- ‘O’ Headform (size xxx-large) – Passes likely
  - (kerbstone impacts are worth a look)

EC Helmets in Snell M2000 Testing

- ‘A’ Headform (size x-small) – failures expected
  - Catastrophic Hemi Anvil Results (worse than ‘E’)
- ‘E’ Headform (size small) – failures expected
  - Catastrophic Hemi Anvil Results (worse than ‘J’)
- ‘J’ Headform (size medium) – failures expected
  - Catastrophic Hemi Anvil Results
- ‘M’ Headform (size x-large) – Passes possible
- ‘O’ Headform (size xxx-large) – Passes likely
  - (But Flat Impacts may approach Snell 300 G limit)

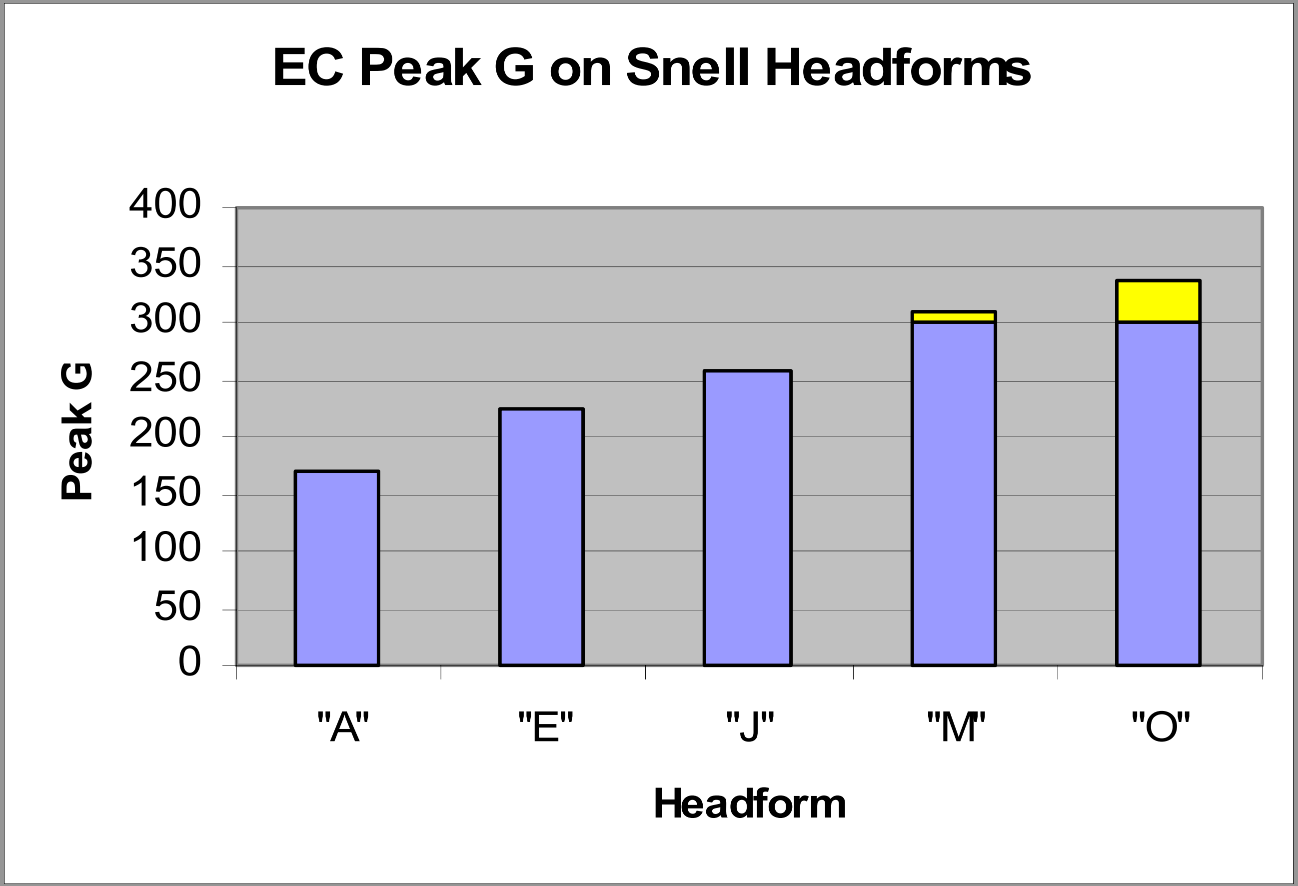
Conclusions

- There is a conflict between Snell and EC 22-05 requirements for motorcycle helmets smaller than size X-Large
- XXX-Small through Large size Snell Helmets will not meet the EC HIC criterion in EC type testing
  - But helmet response would be deemed protective by Snell criteria
- XXX-Small through Large size EC Helmets will be overwhelmed in Snell testing
  - The helmet response would be deemed unprotective by any criteria

Mass Effects – Peak G

EC 275 G translated to Snell Headforms

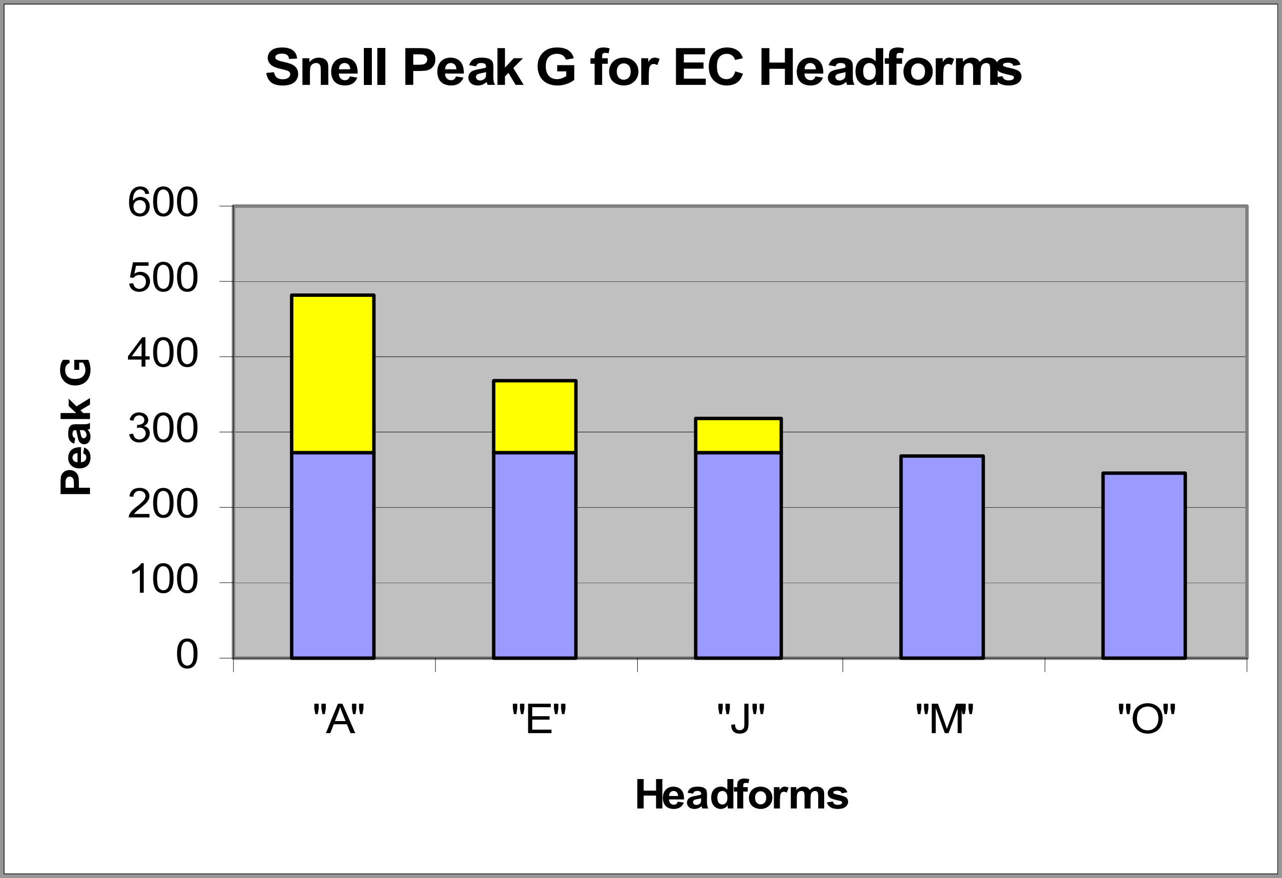
Columns equal 275 g times mass ratios



Mass Effects – Peak G

Snell 300 G translated to EC Headforms

Columns equal 300 g times inverse mass ratio



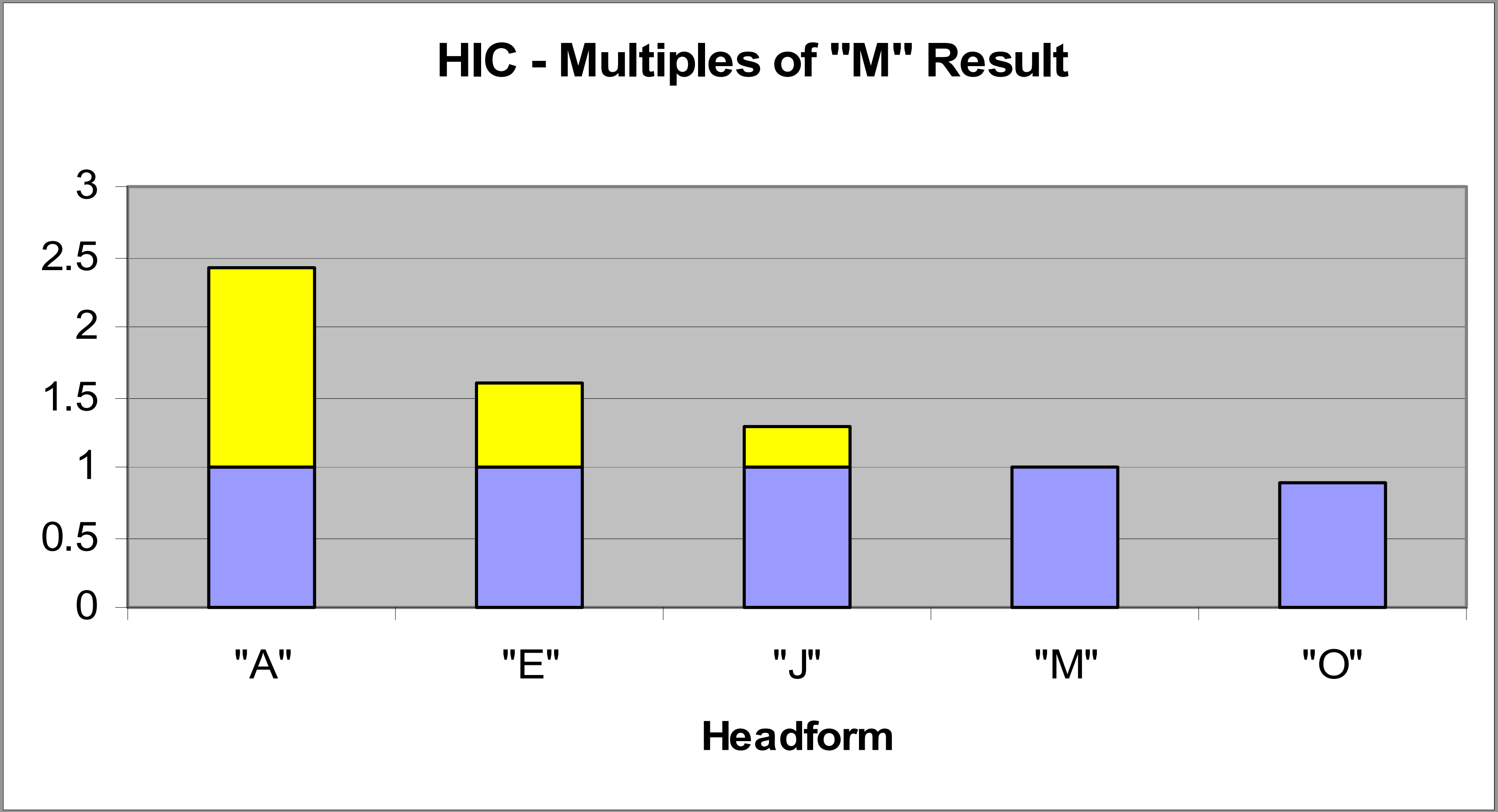
Estimates of EC HIC values for Snell Helmets

- Since Snell calls out 5.0 kg headform weights regardless of size,
  - Reasonably, similar values of HIC might be expected for comparable flat impacts on Snell helmets of any size.
- If so, the HIC responses of Snell helmets in EC testing might be expected to vary inversely with headform mass raised to the 1.5 power

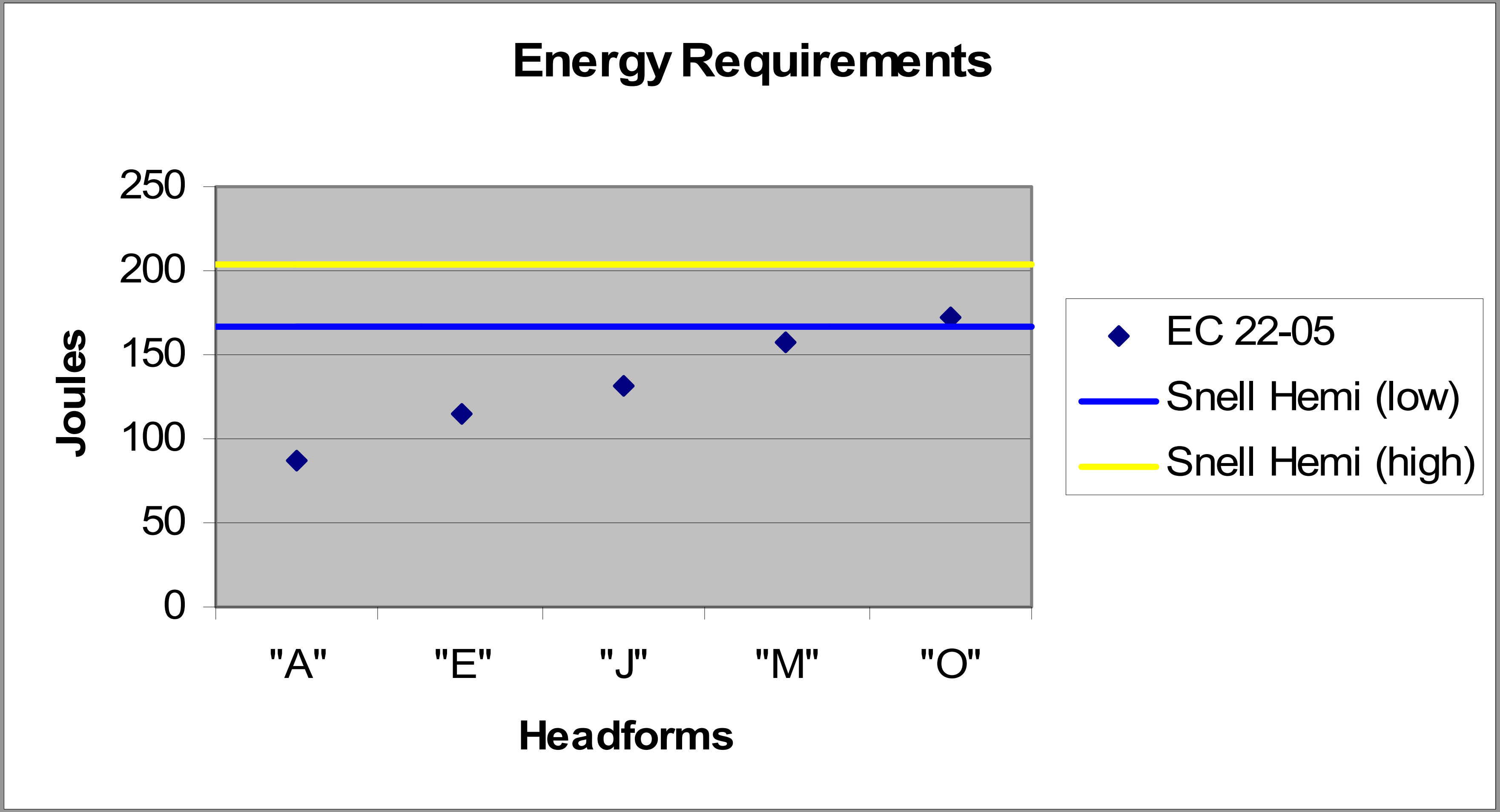
Mass Effects

Expected Snell HIC in EC Testing

Taking the EC “M” headform response as a baseline



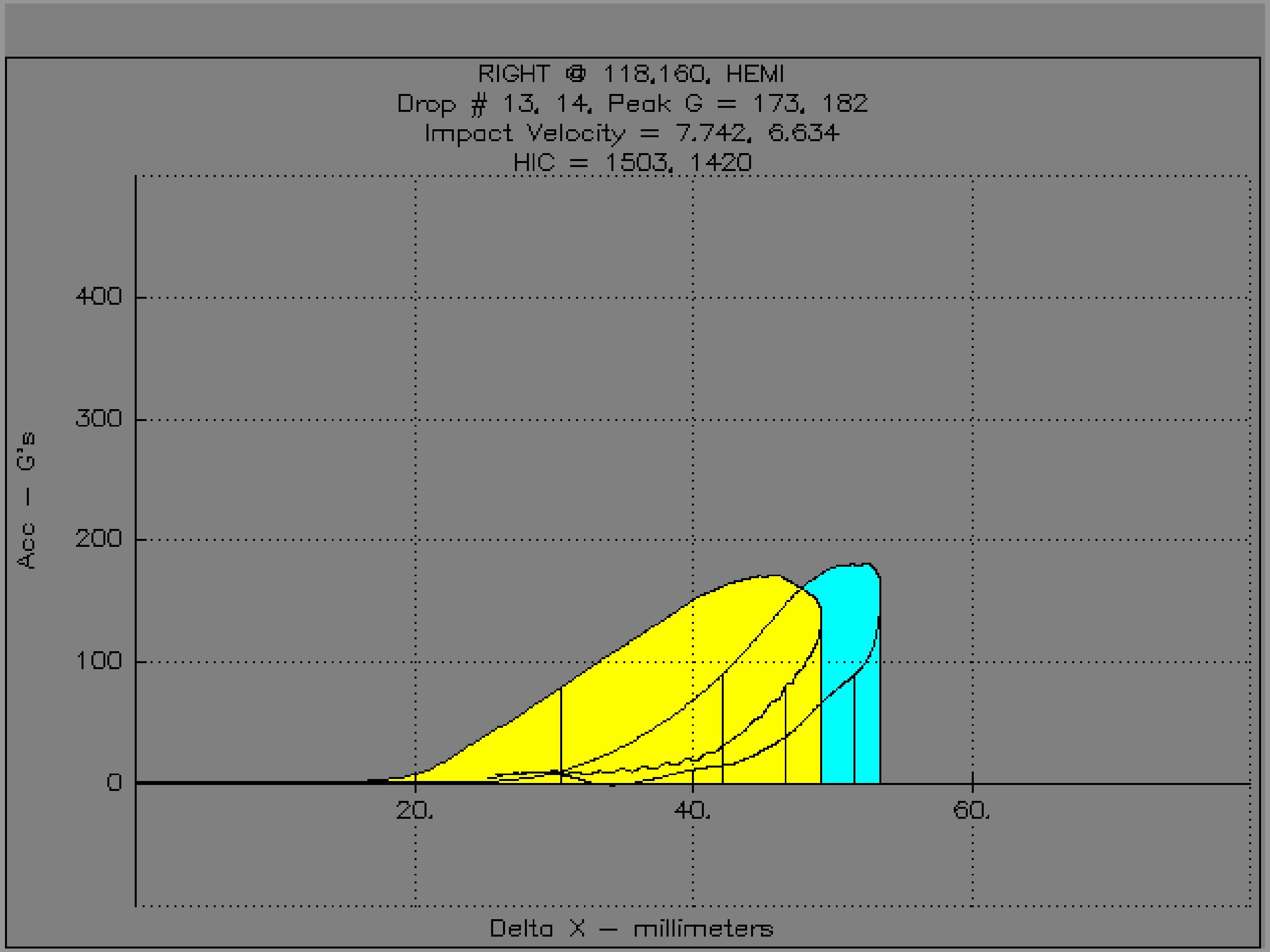
Snell Hemi Energies vs EC

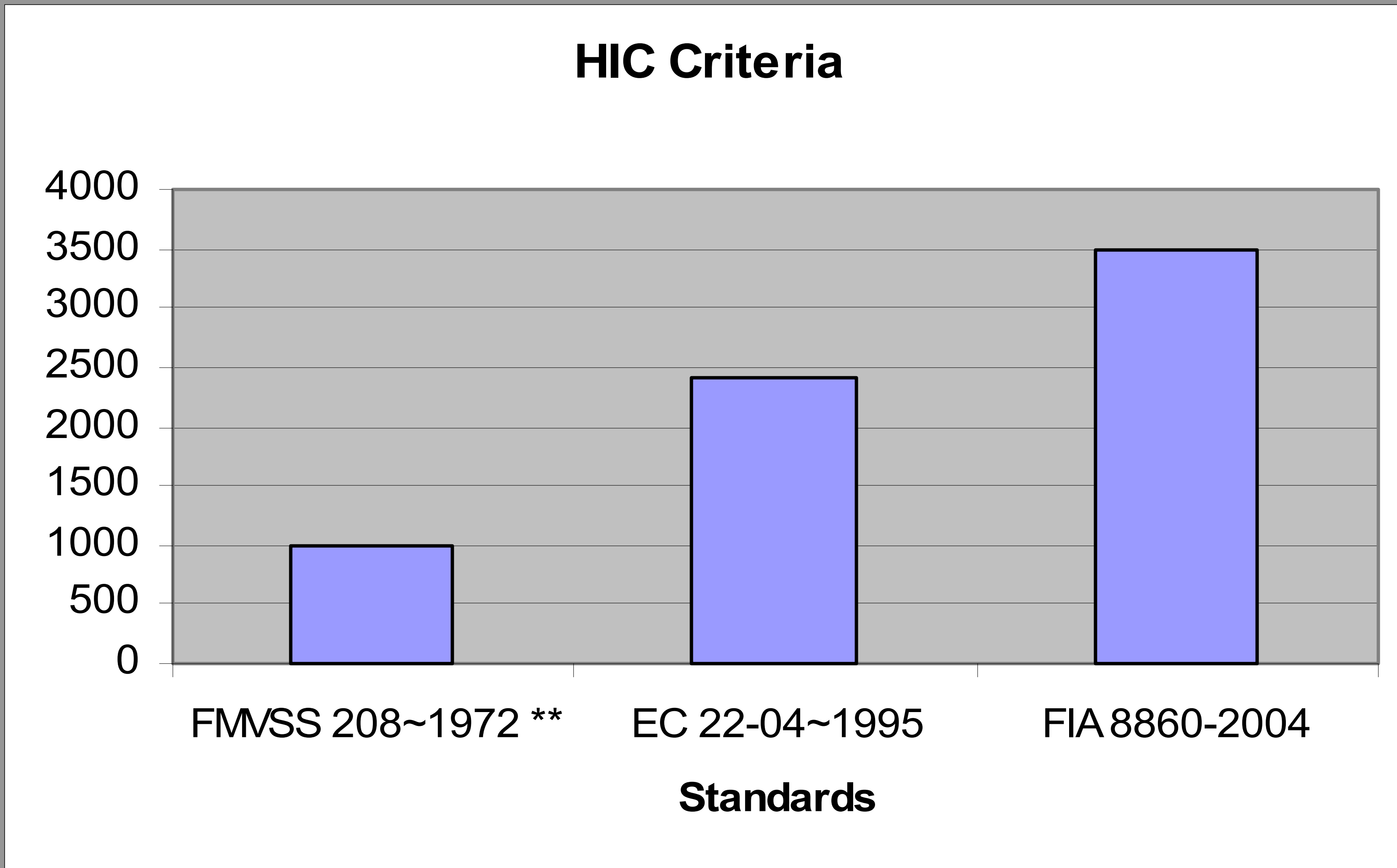


Snell Hemi Energy Estimate

- From RST data
- Energies from double impacts are <u>not</u> additive
- Estimates are based on the union of the areas from cross-plots of the loading portions of both impacts
- For 2500 plus hemi impacts the total energy averaged 185 joules ± 19 joules

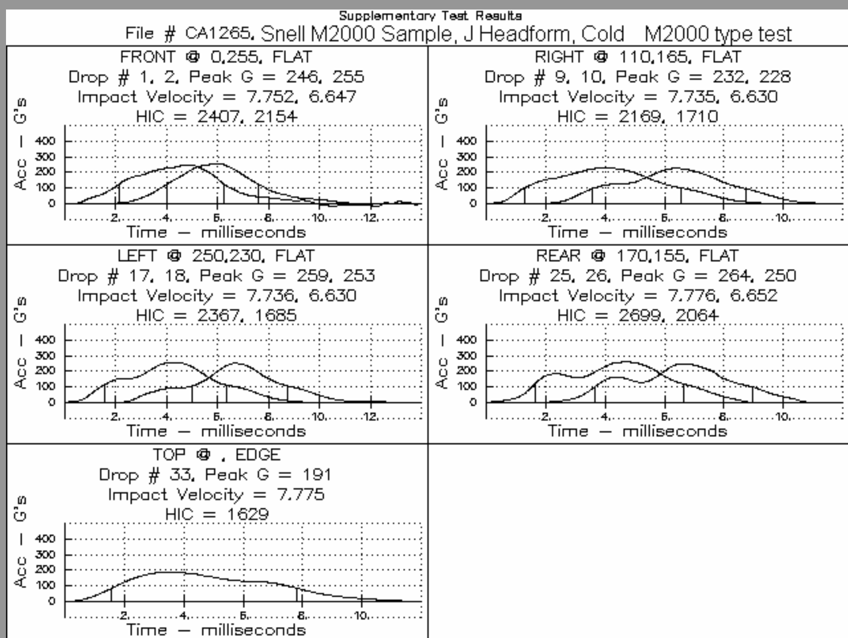
Total Impact Energy
Union of the Areas Under the Loading Portion of the Impacts

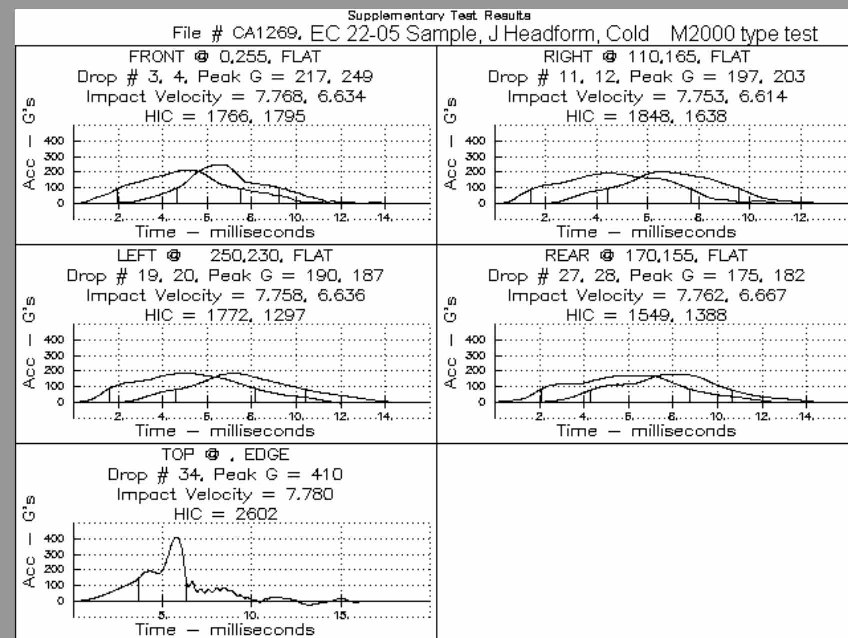




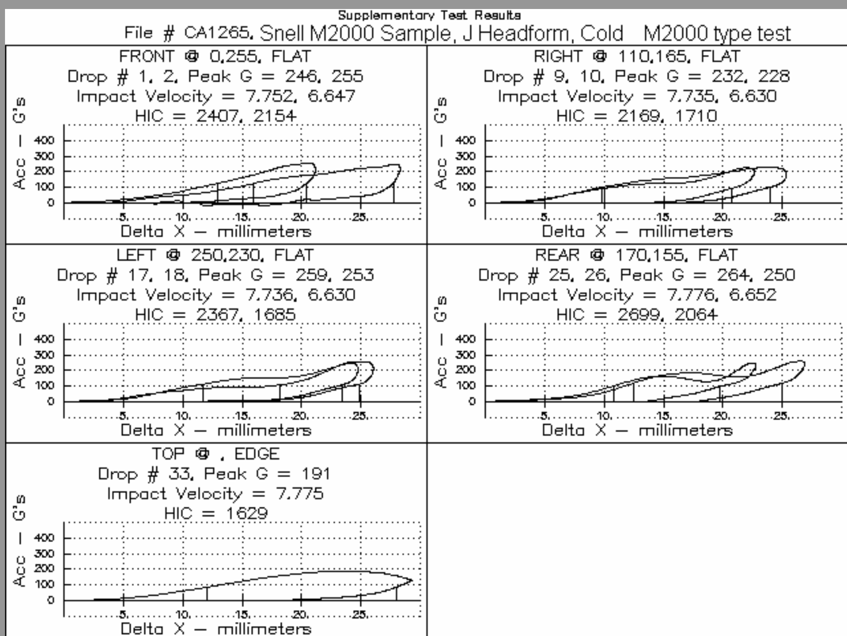
**Not a Helmet Standard – applies to vehicle cabins for bareheaded occupants

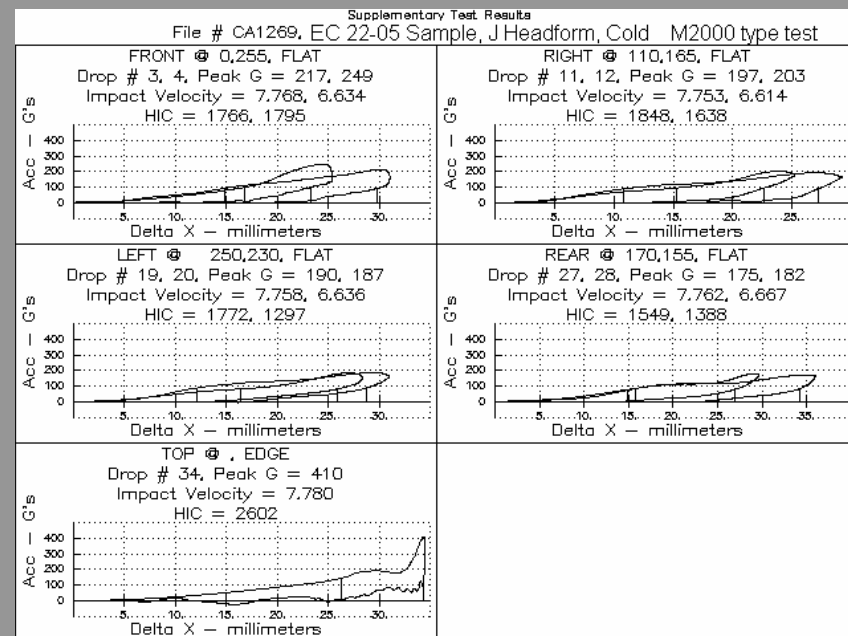
Snell M2000 Cold Results J Headform Time Domain



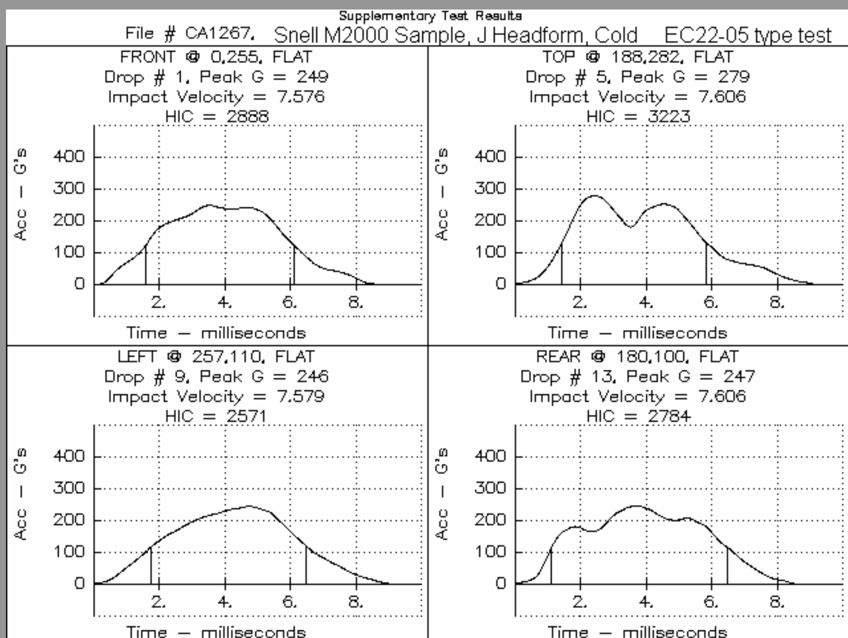


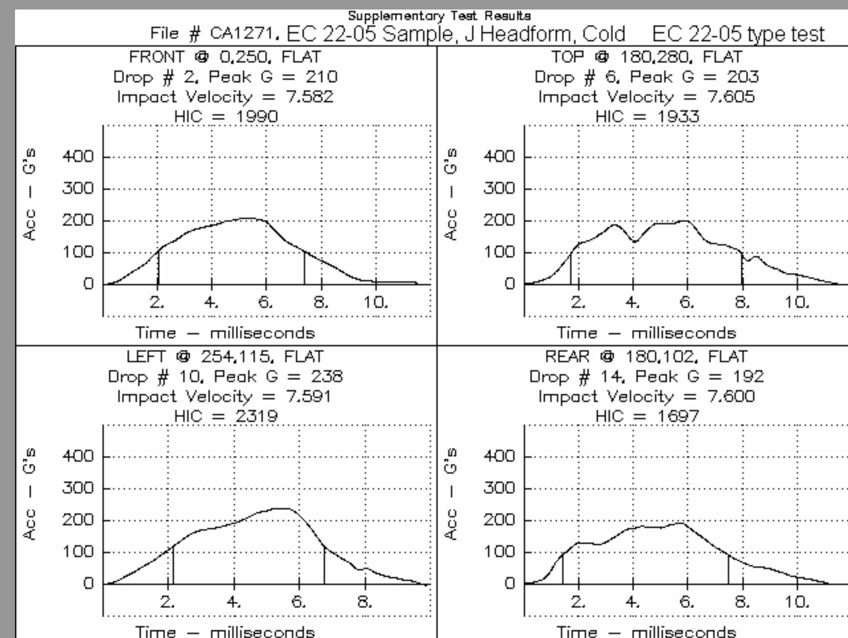
Snell M2000 Cold Results J Headform Displacement Domain



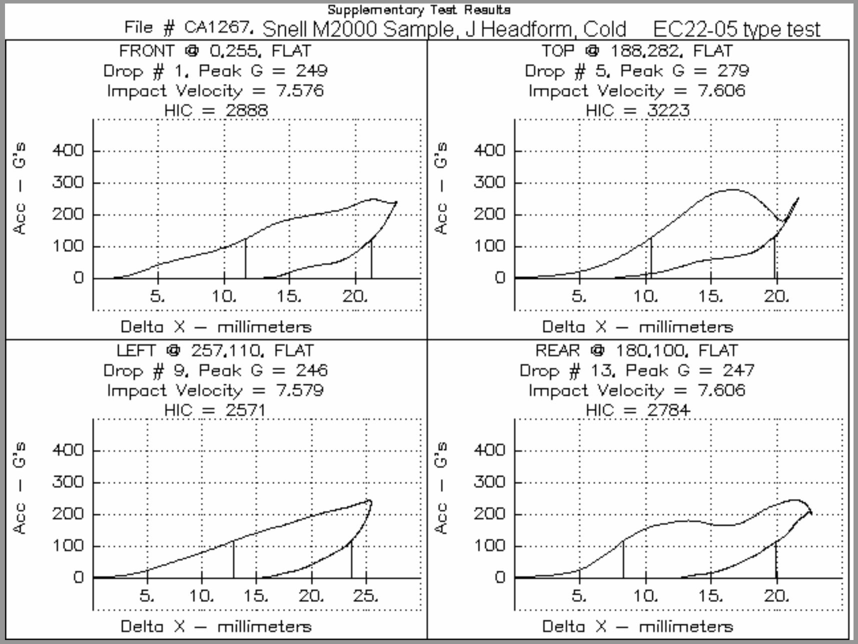


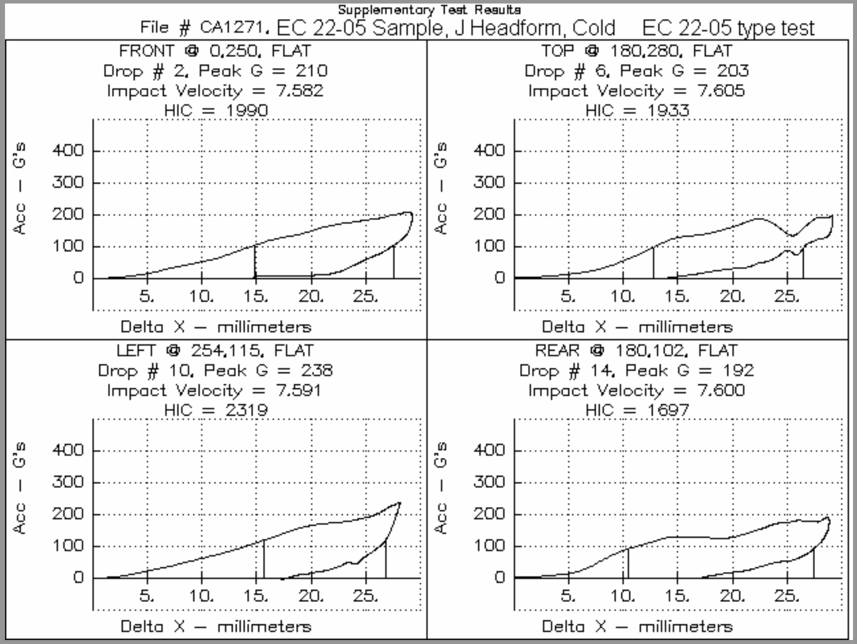
EC 22-05 Cold Results J Headform Time Domain



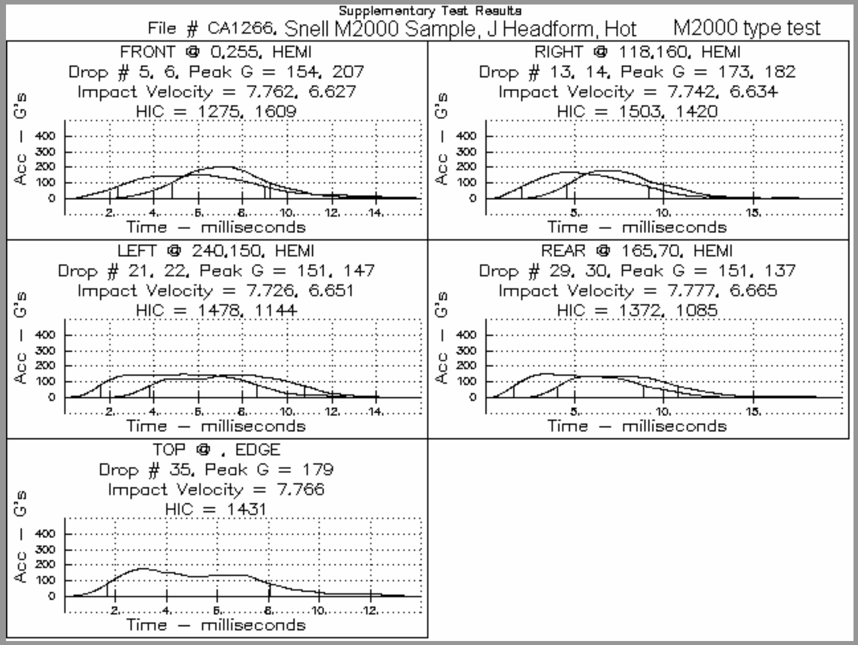


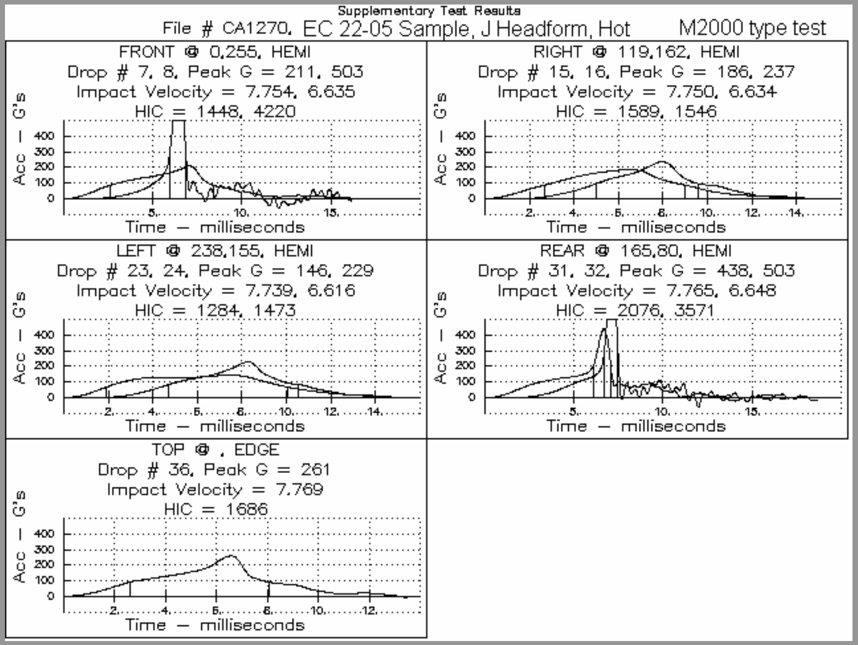
EC 22-05 Cold Results
J Headform
Displacement Domain



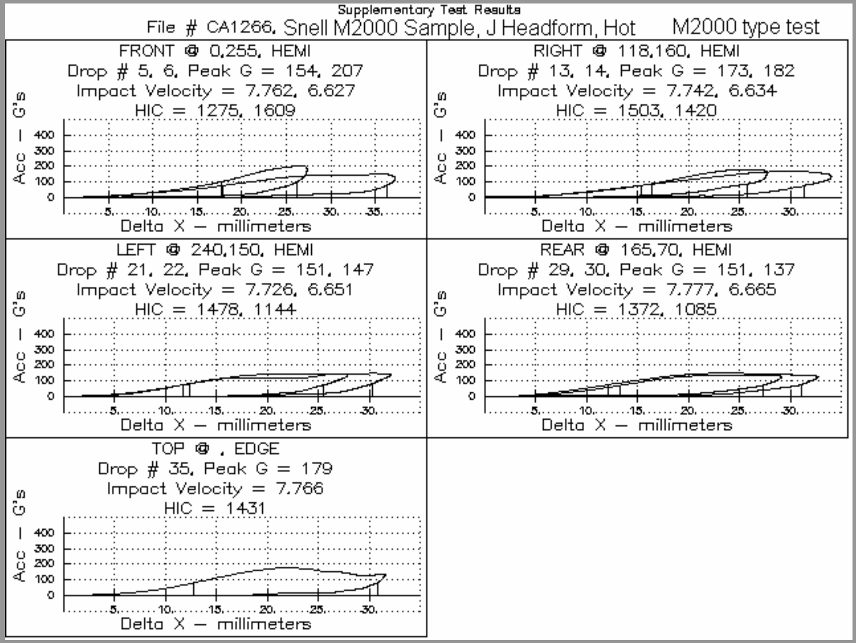


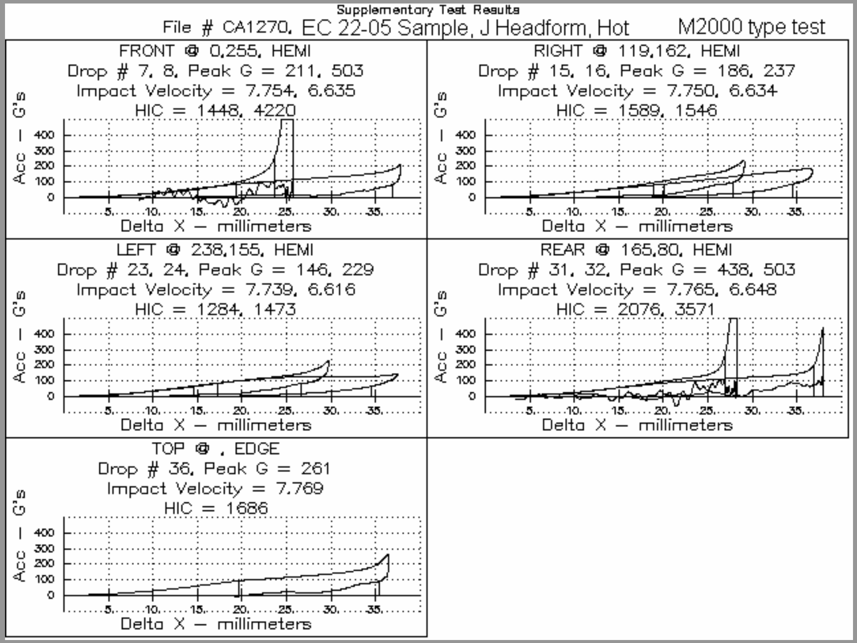
Snell M2000 Hot Results
J Headform
Time Domain



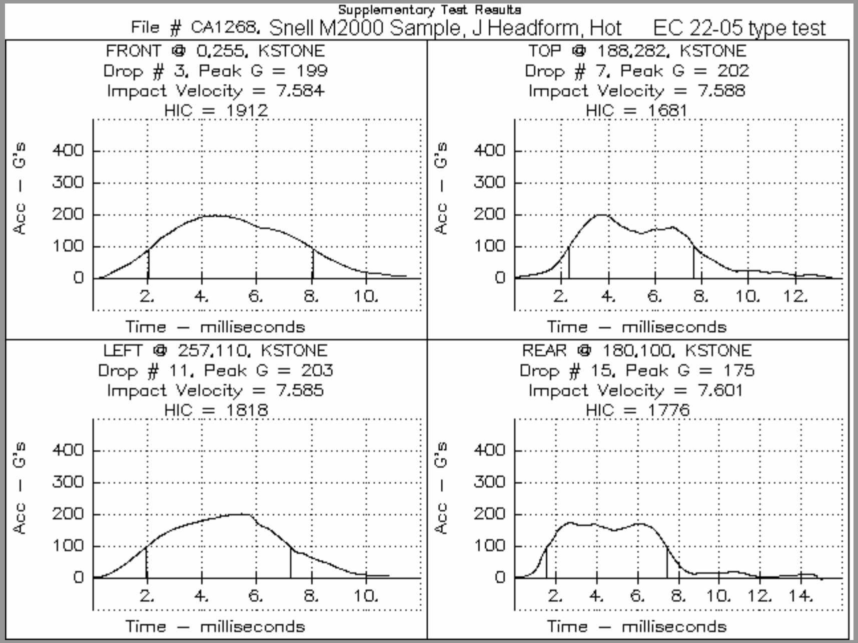


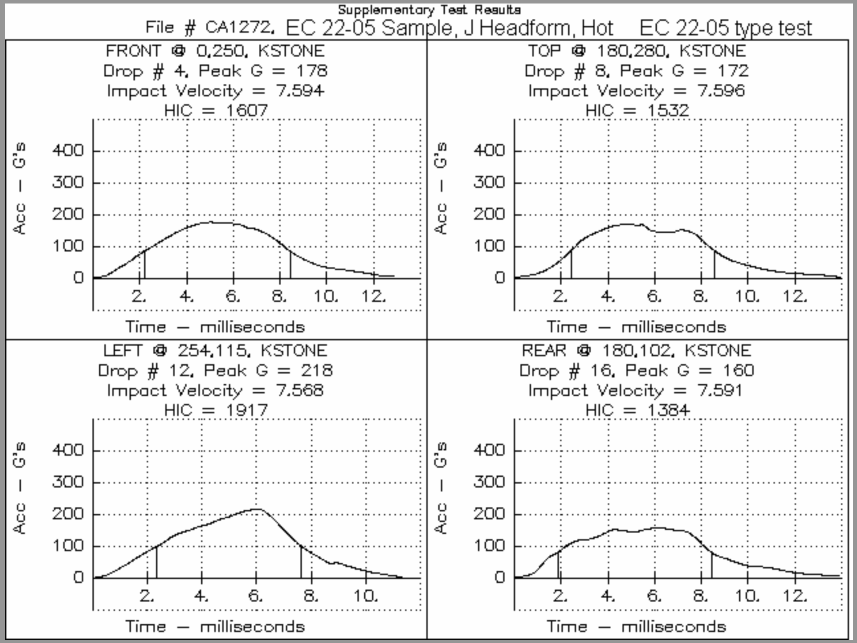
Snell M2000 Hot Results J Headform Displacement Domain



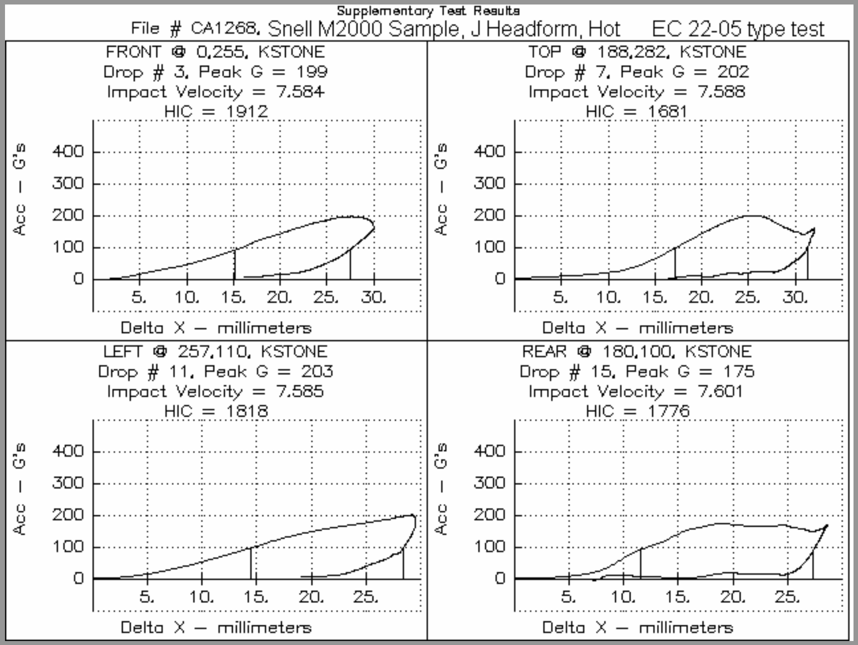


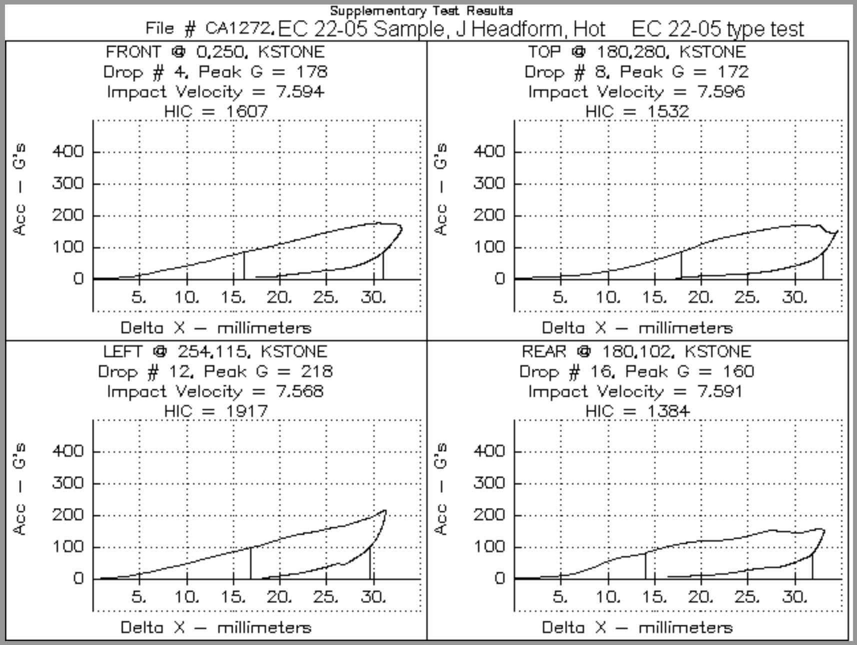
EC 22-05 Hot Results
J Headform
Time Domain



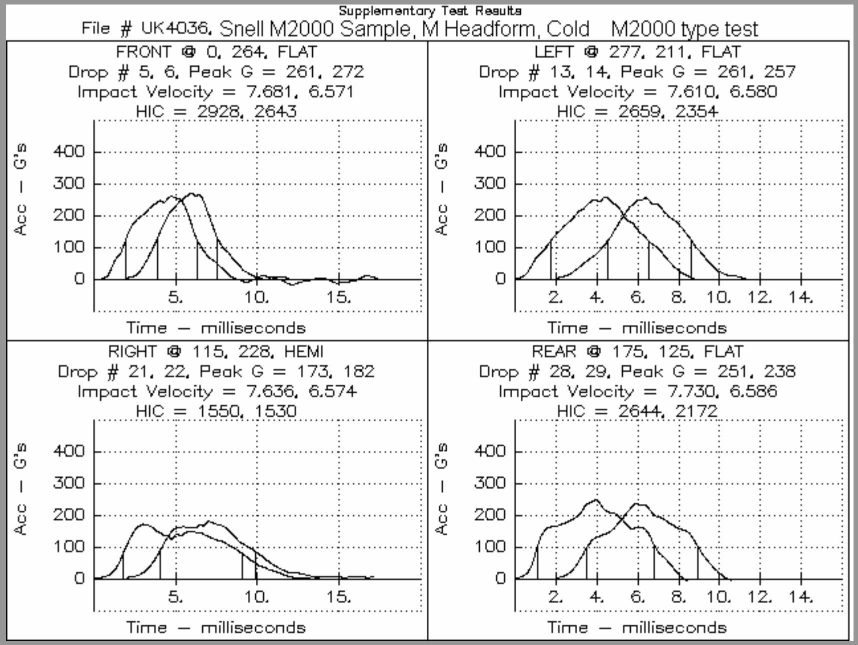


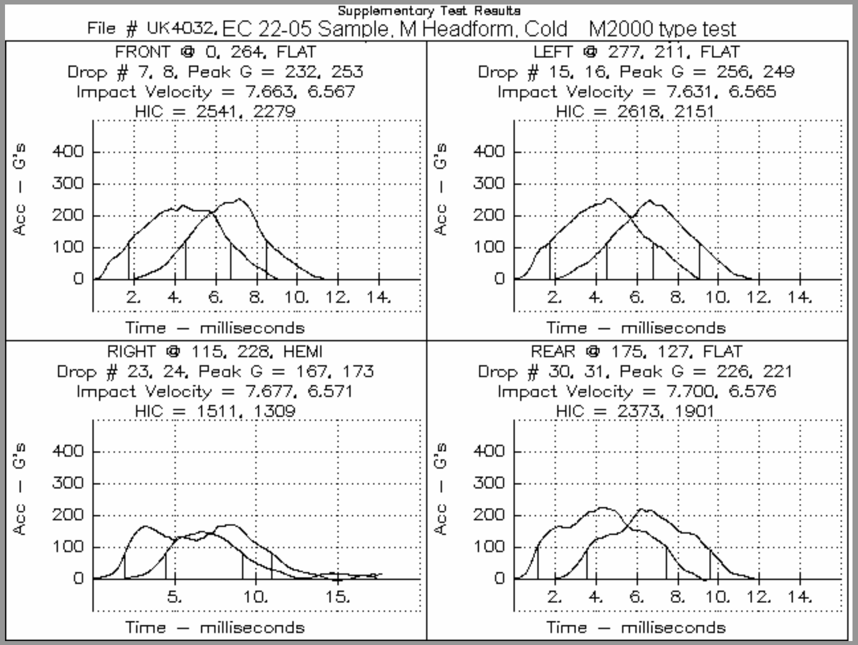
EC 22-05 Hot Results J Headform Displacement Domain



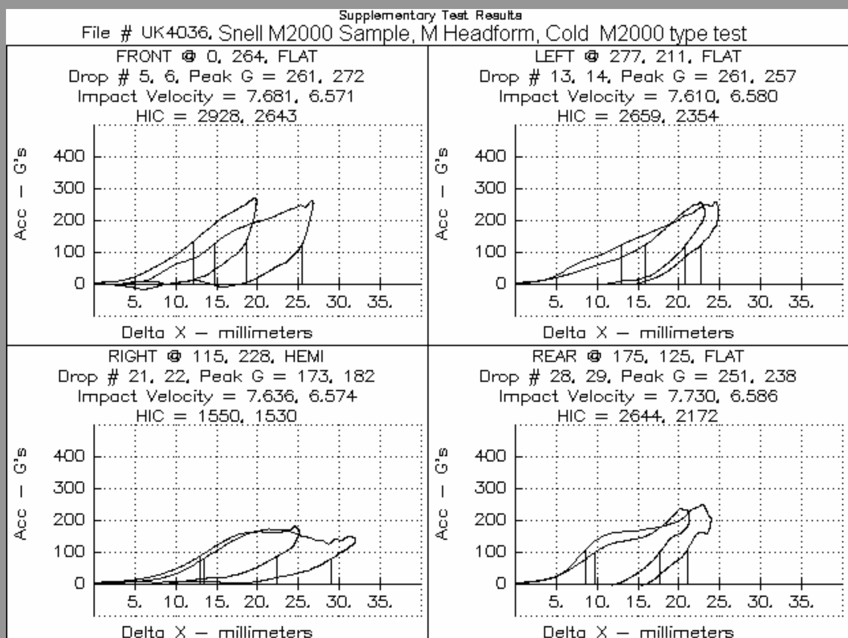


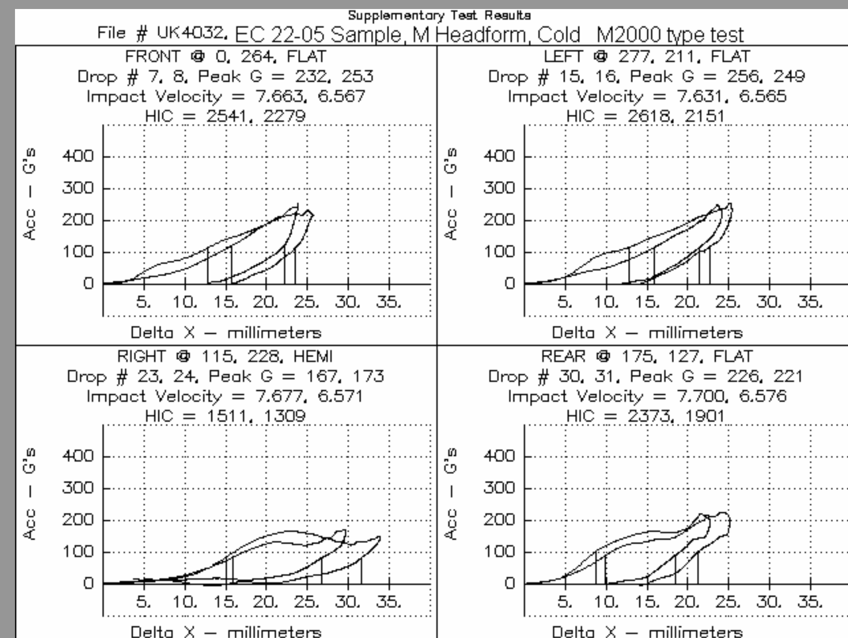
Snell M2000 Cold Results
M Headform
Time Domain



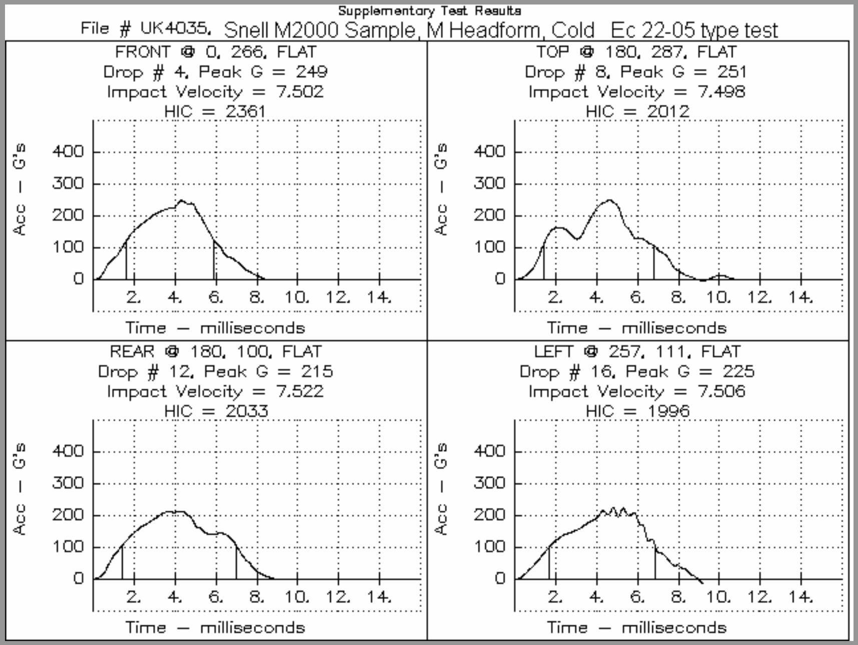


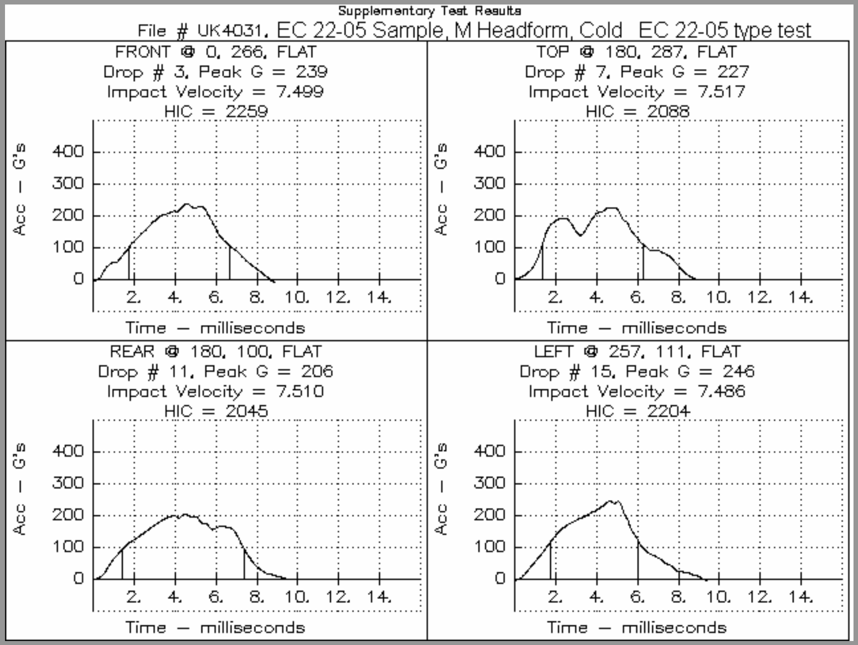
Snell M2000 Cold Results
M Headform
Displacement Domain



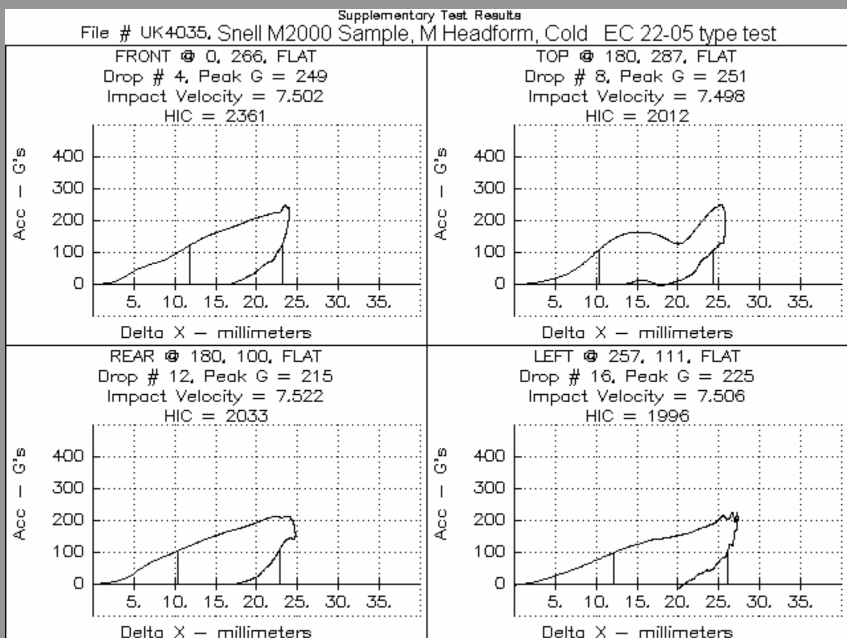


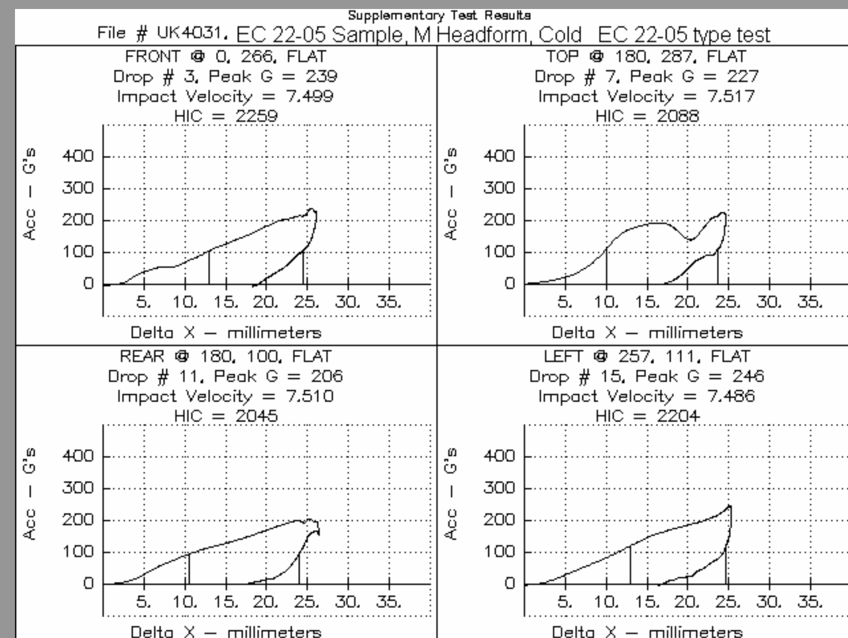
EC 22-05 Cold Results
M Headform
Time Domain



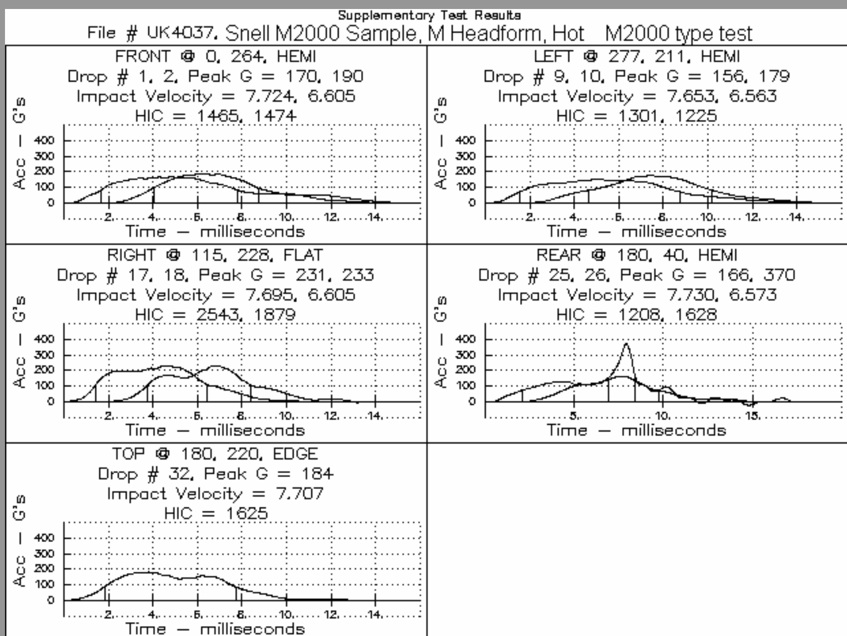


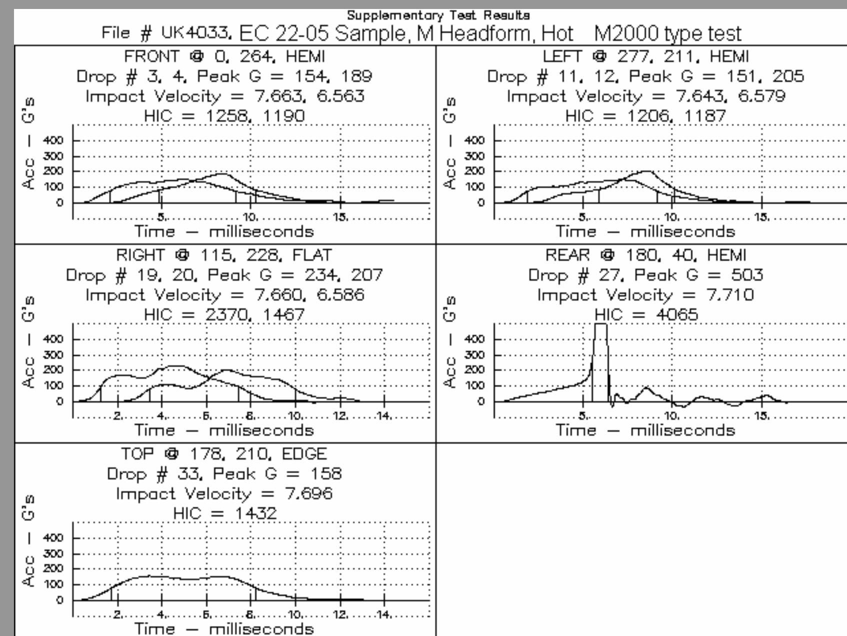
EC 22-05 Cold Results
M Headform
Displacement Domain



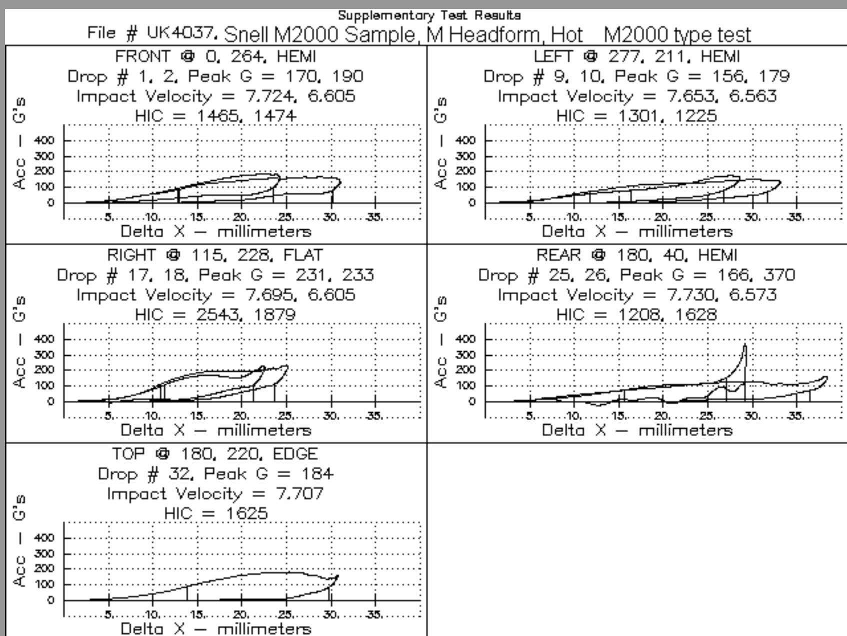


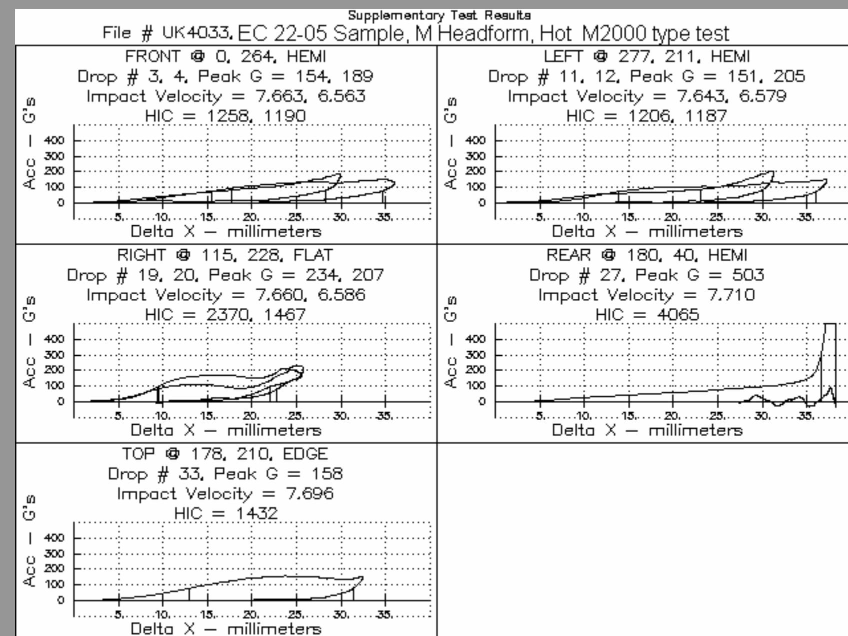
Snell M2000 Hot Results
M Headform
Time Domain



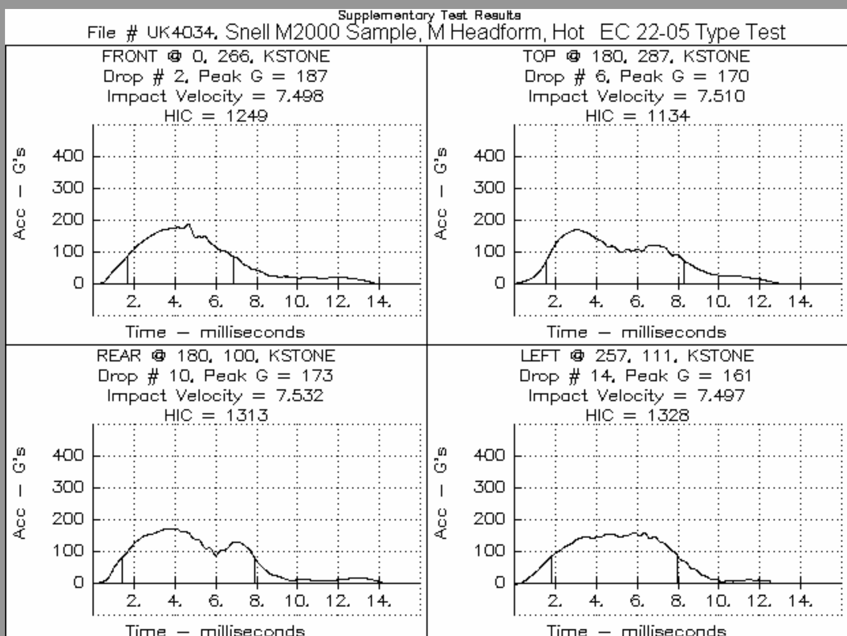


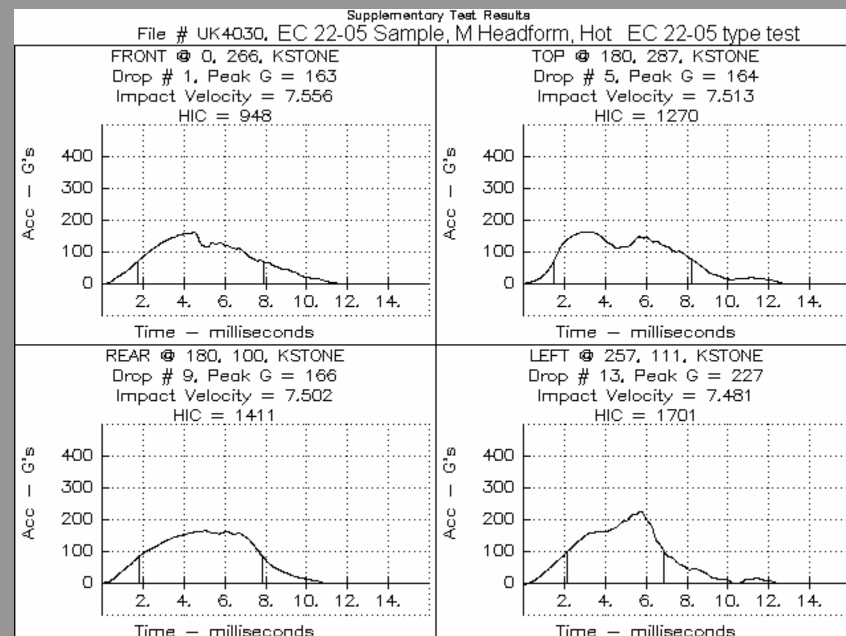
Snell M2000 Hot Results M Headform Displacement Domain



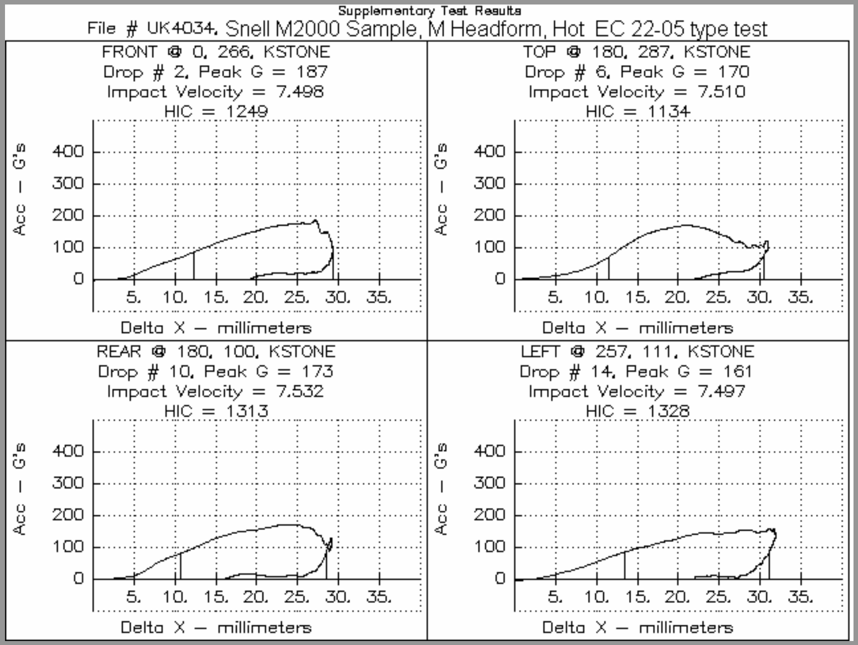


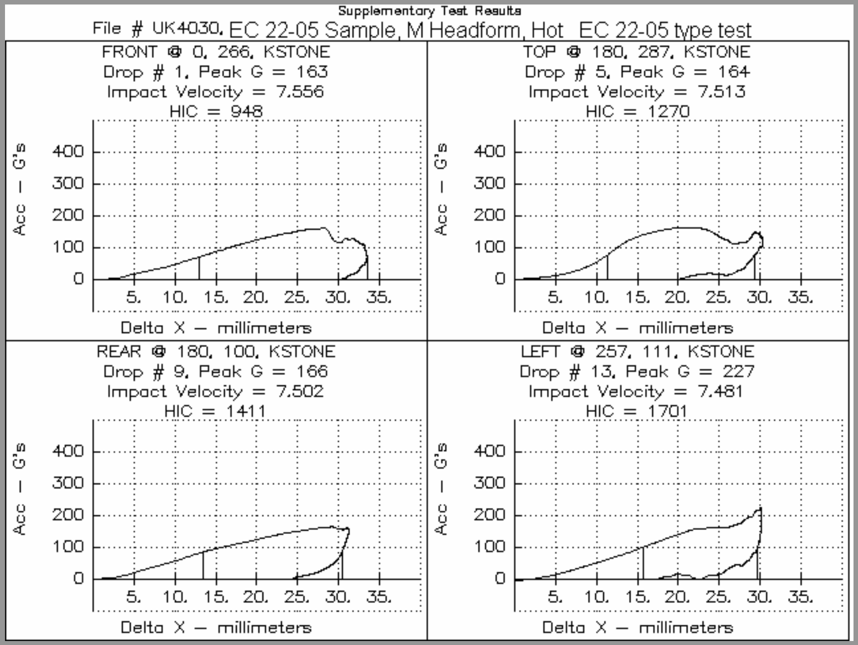
EC 22-05 Hot Results
M Headform
Time Domain





EC 22-05 Hot Results
M Headform
Displacement Domain





Appendix 4. **Impact Test Comparison**

Standard	M2000	DOT (current)	BSI 6658-85 Type A	ECE 22-05
Impact Gear				
Headforms	ISO/EN 960	DOT	ISO/EN 960	ISO/EN 960
Impact Mass	5.0 kg	3.5 kg 5.0 kg 6.1 kg	5.0 kg	3.1 kg 4.1 kg 4.7 kg 5.6 kg 6.1 kg
Device Type	Guided Fall Twin Wire	Guided Fall Monorail	Guided Fall Twin Wire	Free Fall[1]
Impact Regimen				
Flat Anvil	Two Drops 1st 7.75 m/s 2nd 6.63 m/s	Two Drops 6.0 m/s (both)	Two Drops 1st 7.5 m/s 2nd 5.3 m/s	One Drop 7.5 m/s
Hemi Anvil	Two Drops 1st 7.75 m/s 2nd 6.63 m/s	Two Drops 5.2 m/s (both)	Two Drops 1st 7.0 m/s 2nd 5.0 m/s	-
Kerbstone Anvil	-	-	-	One Drop 7.5 m/s
Edge Anvil	One Drop 7.75 m/s	-	-	-
Coverage[2] (Medium Sizes)	(baseline)	Front -25 mm Side -20 mm Back -15 mm	Front -26 mm Side -33 mm Back -3 mm	Four Prescribed Locations Top Front -18 mm Side -46 mm Back +42 mm
Impact Criteria				
Peak G	300 g	400 g	300 g	275 g
Dur @150	-	4 msec	-	-
Dur @200	-	2 msec	-	-
HIC	-	-	-	2400

[1]Employs full headforms and does not control alignment of headform c.g with impact surface. Comparison with guided fall results suggest that impact is appreciably attenuated by rotational effects.

[2]Above (+) or below (-) the lowest impact site allowed by Snell M2000, Lower implies more coverage.

FIA Institute
for Motor Sport Safety

ADVANCED PROTECTIVE HELMET FOR FORMULA ONE

SNELL HIC CONFERENCE
May 2005

Andrew Mellor

Q. WHY MORE PROTECTION?

Since accidents of Senna, Ratzenberger, Wendlinger, Hakkinen FIA introduced:

- Extensive survival cell and crashworthiness improvements
- high cockpit sides
- energy absorbing headrests
- collapsible steering columns
- wheel tethers
- HANS system

Is more head protection required?

Q. WHY MORE PROTECTION?

A. Drivers continue to suffer head injuries

Q. WHY MORE PROTECTION?

A. Opportunity to use latest composite technologies to advance helmet safety performance and reduce weight

Alternatively, manufacturers may exploit this technology to reduce size of helmets with no increase in safety performance

A. Establish the 'state of the art' then transfer technology to all levels of Motor Sport

AGREED AREAS FOR IMPROVEMENT

Headrest compatibility

Impact attenuation

Crush protection

Penetration

Rotation

Shell hardness

Chinguard impact

Reduced mass (same geometry)

PERFORMANCE IMPROVEMENTS

Headrest compatibility	50%
Impact attenuation	50%
Crush protection*	50%
Penetration	30%
Rotation**	25%
Shell hardness	50%
Chinguard impact**	50%
Reduced mass	20%

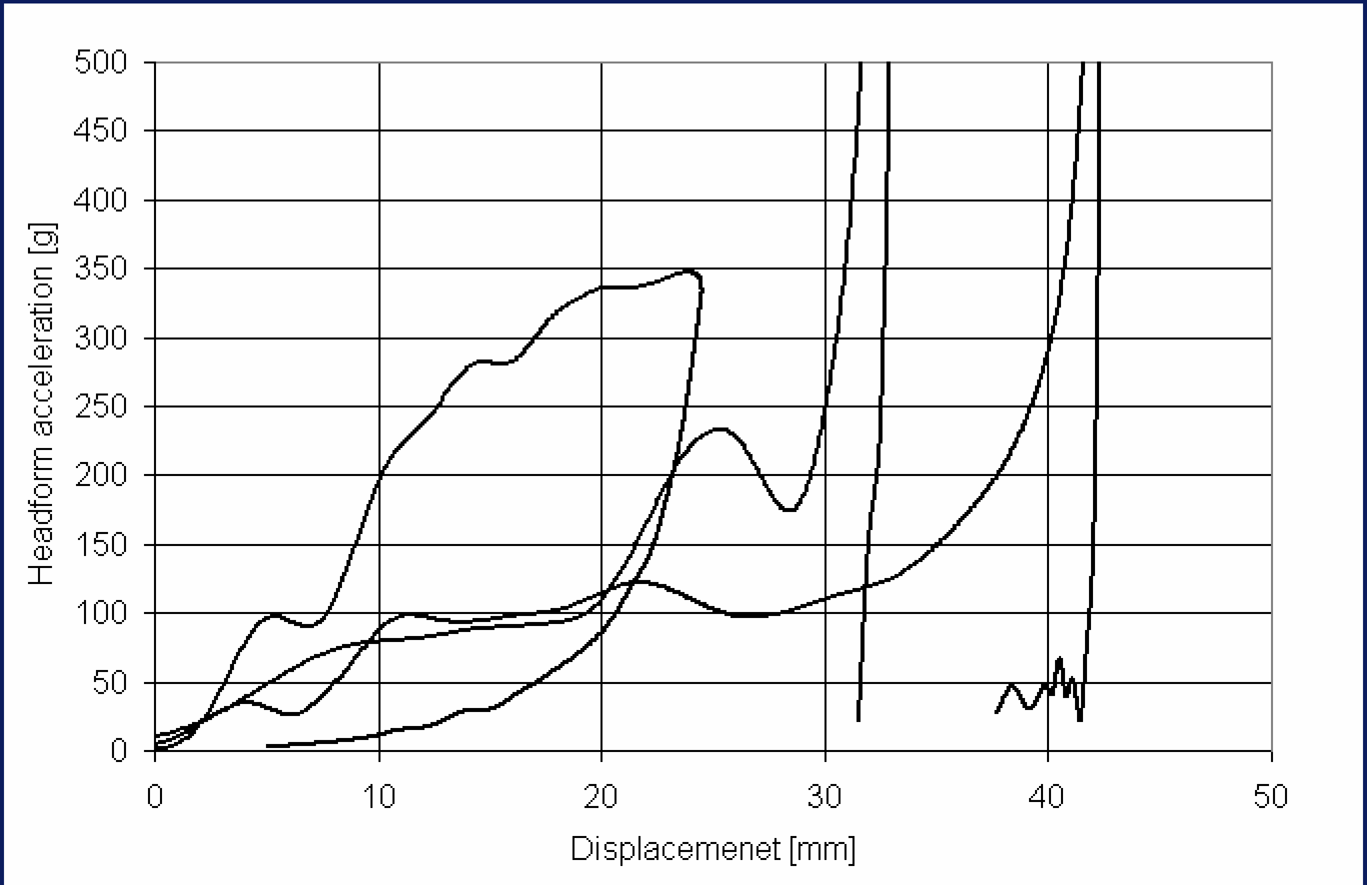
* new dynamic crush test

** new test based on ECE Regulation 22-05

FIA Institute
for Motor Sport Safety

TEST TOOLS (SNELL and ECE R22)

CURRENT HELMET IMPACTS @ 10m/s Hemi-Flat-Edge



DESIGN TARGET: LINEAR IMPACT

- Current 300g@7.5m/s
- Target 300g@10m/s

Absorb impact energy over controlled volume of liner material independent of impact surface

STRONG STIFF SHELL – OPTIMISED LINER

DESIGN TARGET: PENETRATION

- Current 3kg spike falling from 3m
- Target 3kg spike falling from 4m

Tolerate high stress concentration at point of contact.

Dissipate load to liner

STRONG STIFF SHELL (Kevlar net)

DESIGN TARGET: CRUSH

- Current — No requirement
- Target — 30% improvement

Absorb kinetic energy whilst ensuring load exerted on drivers head does not exceed tolerance for injury

STRONG DUCTILE SHELL

OPTIMISED LINER

DESIGN TARGET: OBLIQUE IMPACT

- Current No requirement
- Target 30% improvement

Minimise tangential impact load and maintain angular inertia of helmet

LOW SURFACE FRICTION
LOW NORMAL IMPACT LOAD
MASS AT EXTREMITY

SPECIFICATION FOR NEW HELMET

SHELL

• Bending stiffness EI	450 N/m² (10x)
• Bending strength	1200 Nm (8x)
• Weight	0.85kg
• Thickness	5mm (max)
• Outer surface	BARCOL 60

CARBON and KEVLAR

SOLID LAMINATE and SANDWICH CONSTRUCTIONS

SPECIFICATION FOR NEW HELMET

LINER

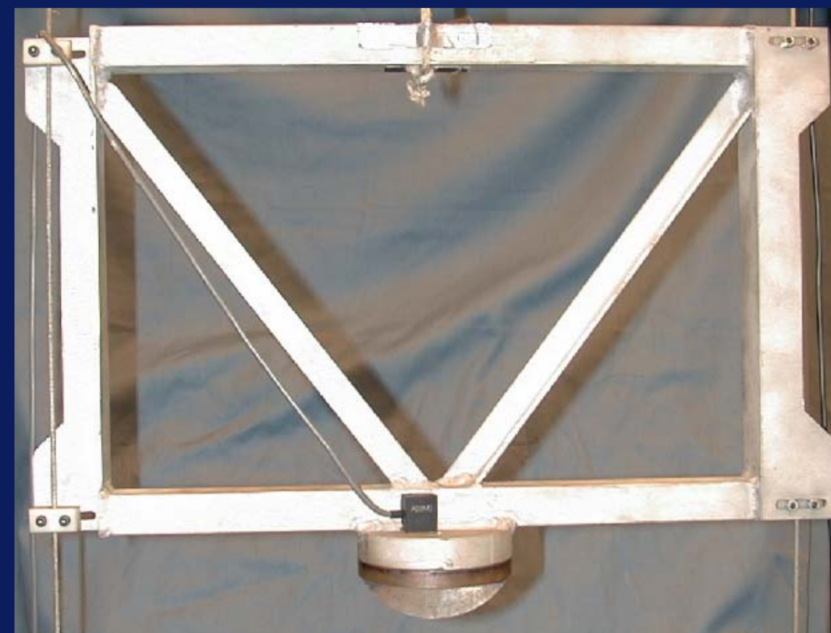
- Efficient energy absorption ($0.4N/mm^2$)
- Temperature stability (-20’C to + 50’C)
- Lightweight (<50g/l)
- (Hybrid structure)

EPS EPU EPE RATE-RESPONSIVE

CERAMIC BALLS HONEYCOMB

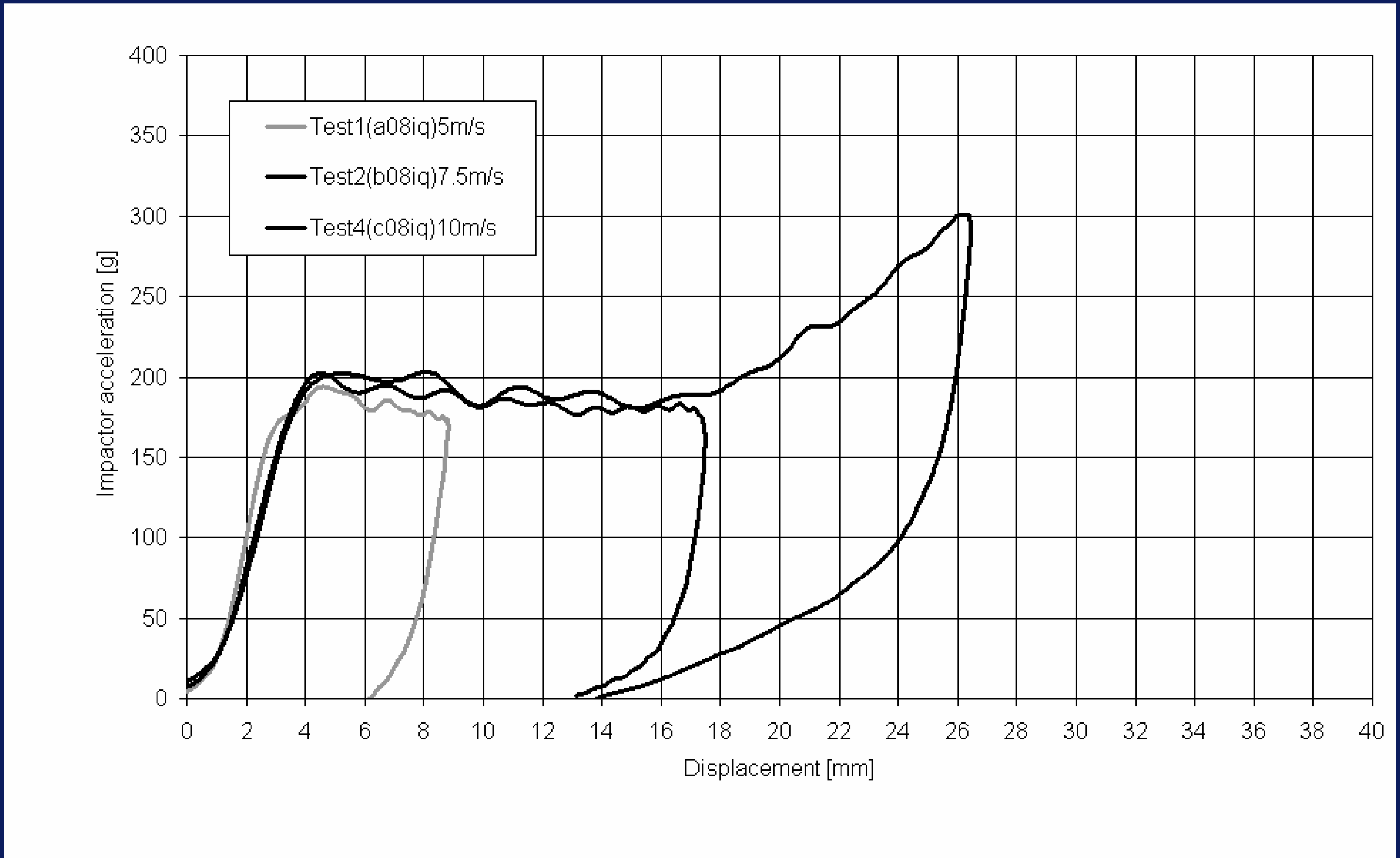
Tests on flat samples to evaluate stiffness, strength and penetration

- Conditioning (-20’C and + 50’C)
- Impact tests at 5m/s, 7.5m/s and 10m/s
- Penetration tests at 3m and 4m

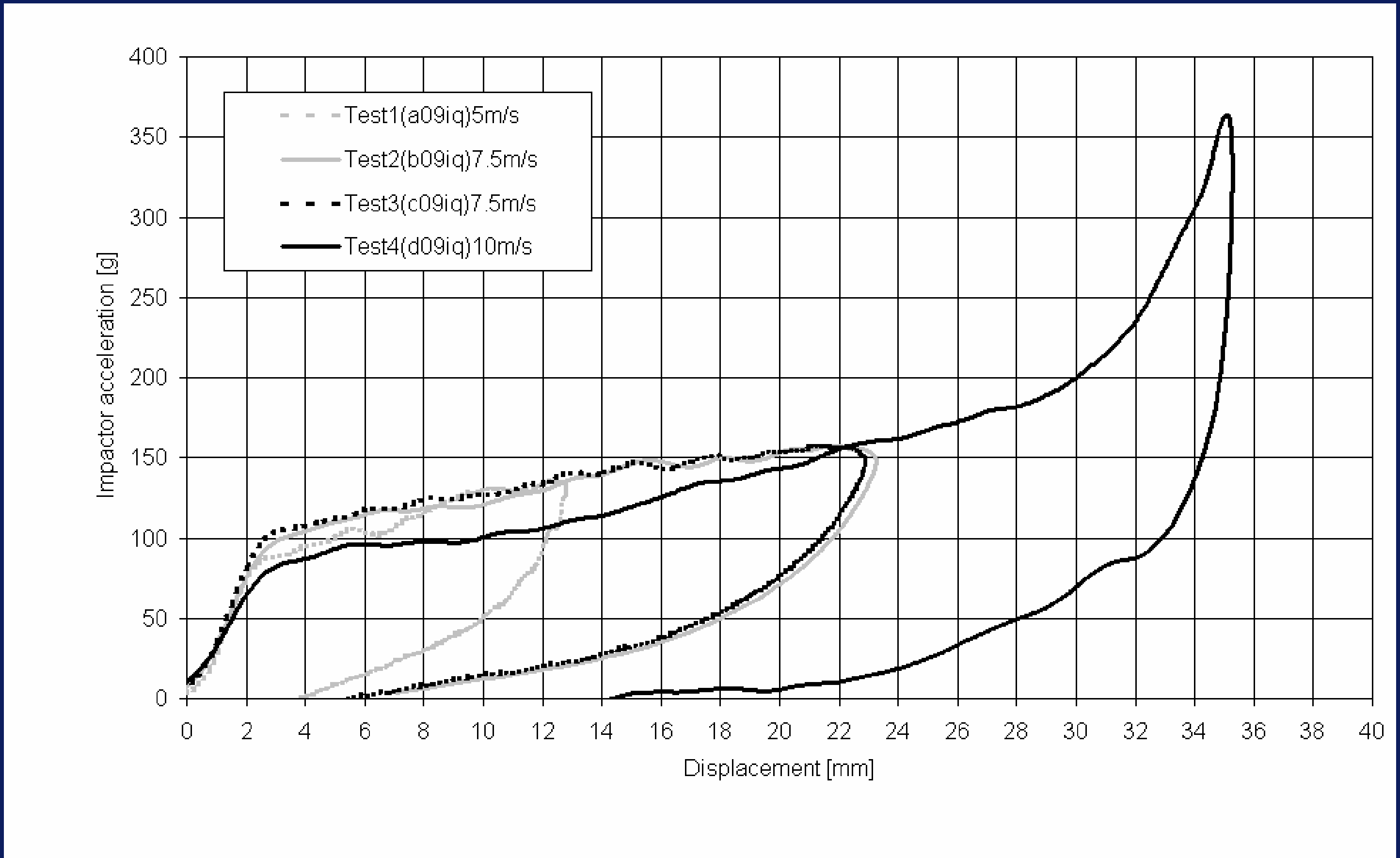


3 manufacturers
Total of 20 laminates

INFINITELY STIFF LAMINATE

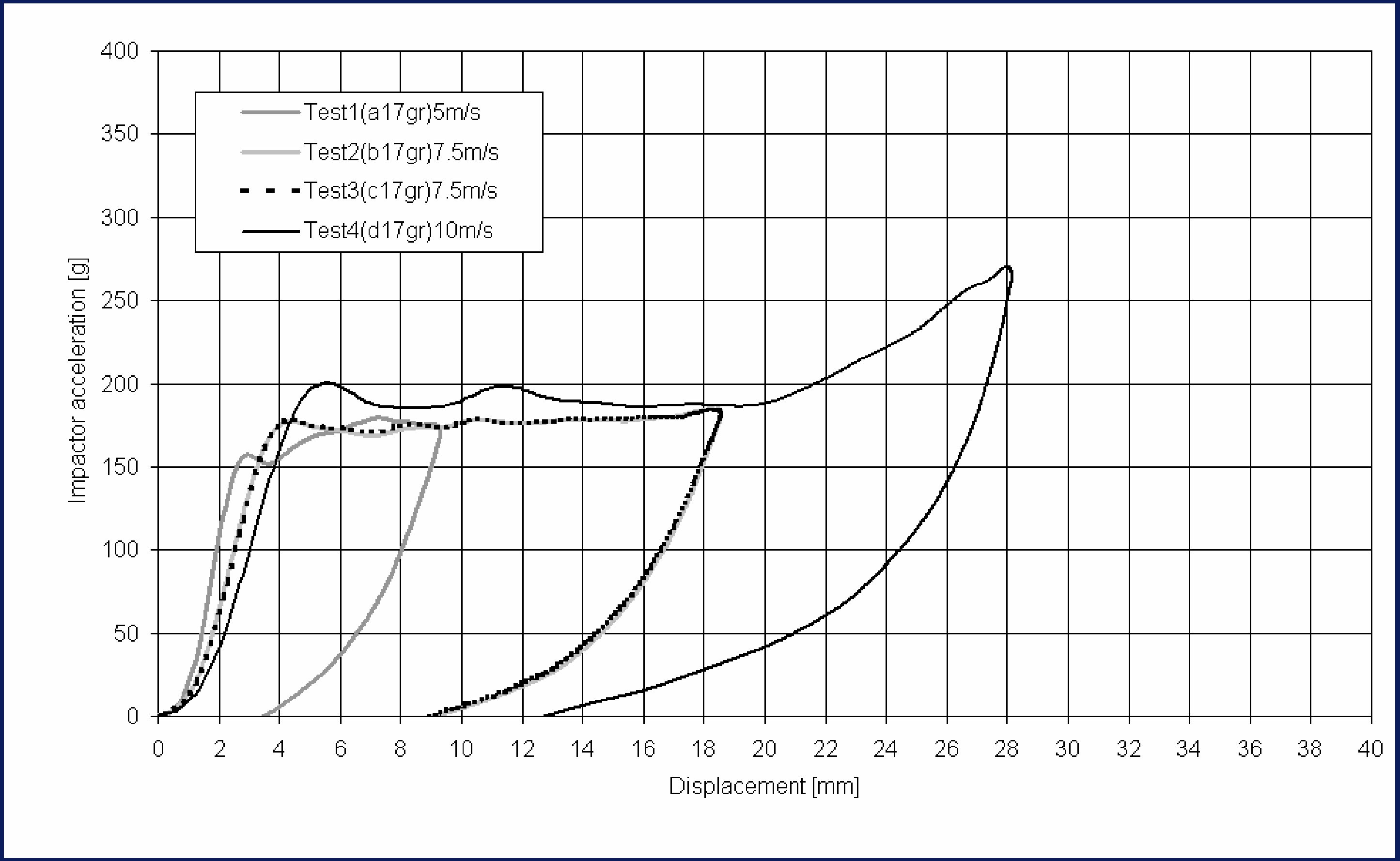


CURRENT SHELL LAMINATE



FIA Institute
for Motor Sport Safety

BEST SOLUTION SHELL LAMINATE



BEST SOLUTION (equivalent to 5mm carbon steel)

Carbon sandwich with foam core (CFT Ltd – UK)

Kevlar improved penetration but reduced strength

Thickness	*4.1mm*	*(Target <5mm)*
Mass	*0.81kg*	*(Target <0.85kg)*
7.5m/s	*185g*	*(Target <200g)*
10m/s	*270g*	*(Target <300g)*
Penetration	*4m*	*(Target >3m)*

FULL GEOMETRY EVALUATION

- 5 laminates (sandwich vs solid)
- Polyethylene foam energy absorber

- *Linear impact tests*
- *Penetration tests*
- *Crush tests*
- *Oblique impact tests*

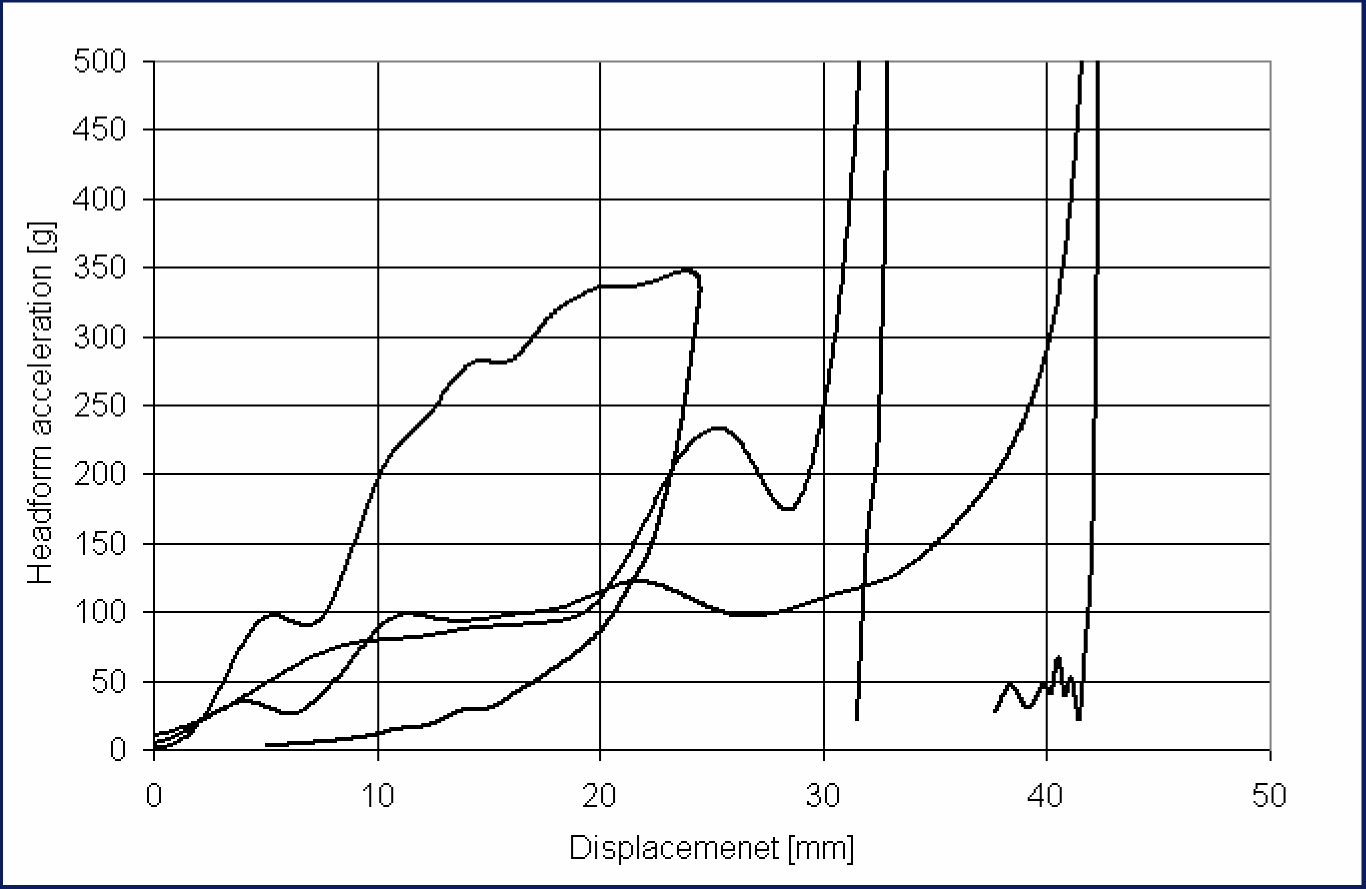
BEST SOLUTION

T800 Solid carbon laminate 13 plys @ 0.22mm (<800g)

7.5m/s	*<190g*	*(current ~270g)*
10m/s	*<230g*	*(current ~ 620g)*
Penetration	*4m*	*(current 3m)*
Mass	*1.3kg*	*(current 1.4kg)*
Crush	*72mm*	*(current 82mm)*
Oblique	*4,200rad/s²*	*(current 5,900rad/s²)*

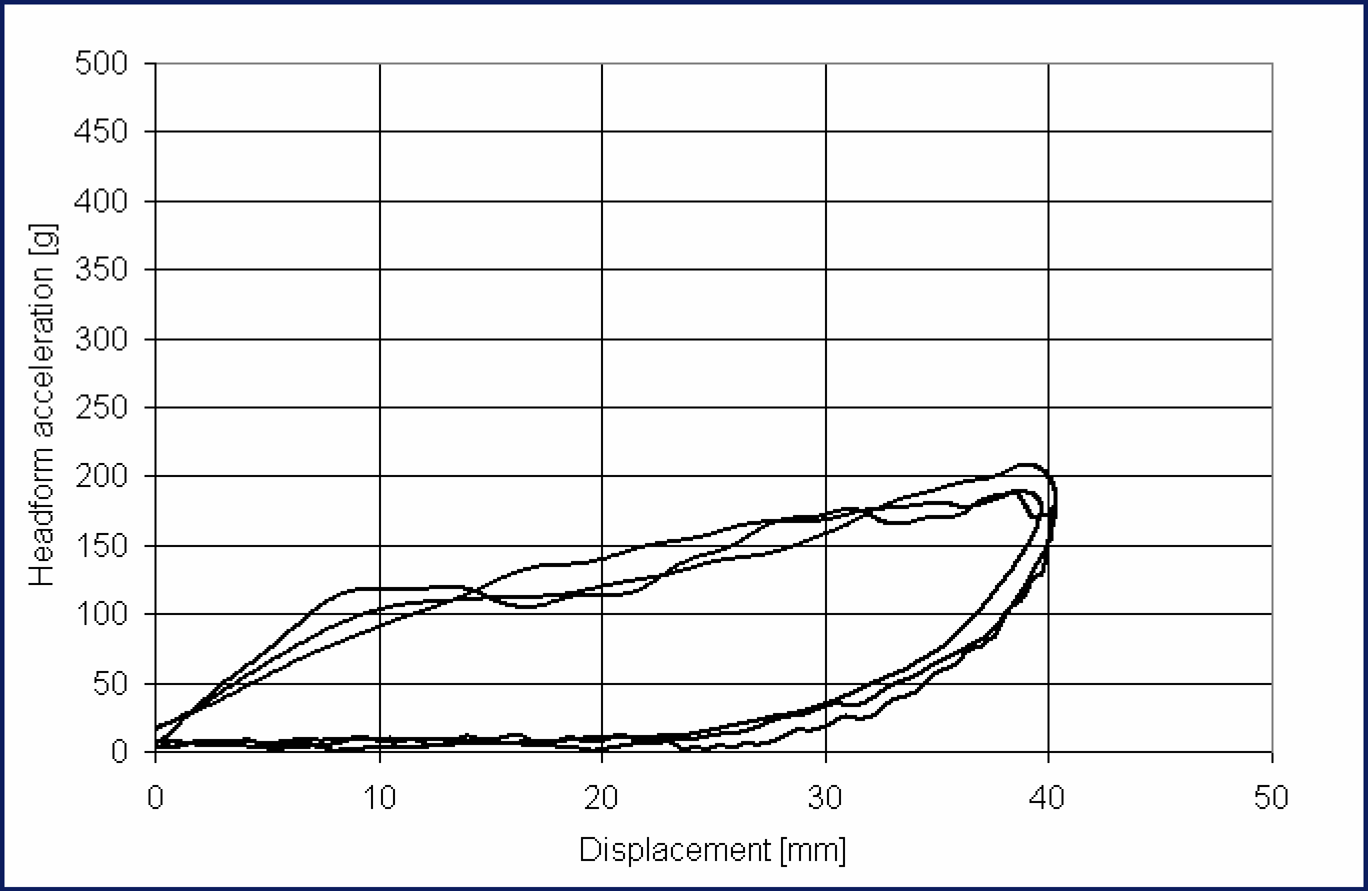
FIA Institute
for Motor Sport Safety

CURRENT HELMET IMPACTS @ 10m/s Hemi-Flat-Edge

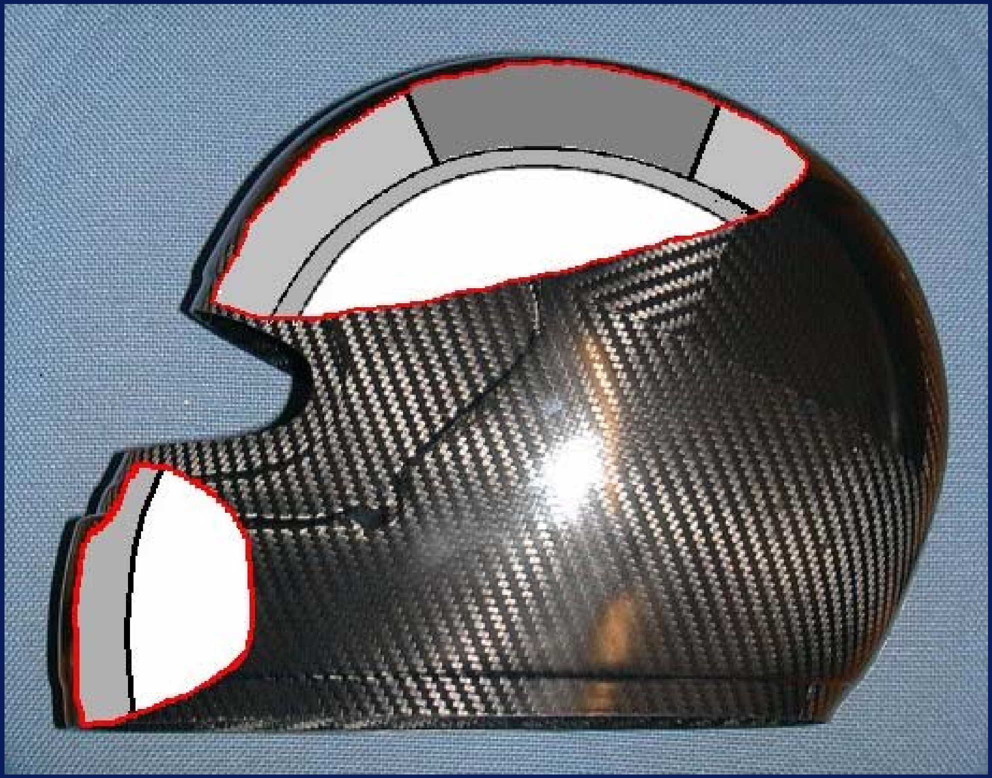


FIA Institute
for Motor Sport Safety

ADVANCED HELMET IMPACTS @ 10m/s Hemi-Flat-Edge



ADVANCED PRODUCTION HELMET



Partnership FIA-TRL-CFT-SPORTS BELL Europe

6 variants of shell laminate

BEST SOLUTION ACHIEVED ALL PERFORMANCE OBJECTIVES

- SHELL
  T1000 11 ply carbon fibre with UD reinforcement
  Shell (only) mass 670g

- LINER
  Hybrid EPS 25g/l and 30g/l
  with PP interface between shell and liner
  Rate responsive comfort padding fitted after certification
  Chin guard padding (to ECE Reg 22-05)

  Rate responsive comfort padding
  (fitted after homologation for further protection)

FIA Institute
for Motor Sport Safety

DEVELOPMENT AND AGREEMENT OF NEW STANDARD

- March 2003. Draft FIA standard proposed (complimentary to Snell)
- May 2003. Meeting of FIA helmets group
  - Repeatability and reproducibility
  - Energy vs performance consistency / Hardness
  - Technology transfer to second manufacturer (Schuberth Engineering)
- November 2003. Performance agreement with BELL and SE
- December 2003. FIA 8860-2004 to World Council
- January 2004. SE and BELL achieved FIA and Snell
- May-June 2004. Arai and SPARCO achieved FIA and Snell
- 1 July 2004. Successful introduction to Formula One (4 manufacturers)

FIA 8860-2004 vs SNELL SA2000

	Snell SA2000	FIA 8860
Impact attenuation	150J (300g)	225J (300g HIC 3500)
Crush protection	-	500J
Penetration	3kg@3m	4kg@3m
Rotation	-	ECE Reg 22
Hardness	-	BARCOL 60
Chinguard test	'Crush'	ECE Reg 22

FUTURE WORK

- Transfer of technology and cost reduction
- Helmets for young drivers

FIA Institute
for Motor Sport Safety

ADVANCED PROTECTIVE HELMET FOR FORMULA ONE

SNELL HIC CONFERENCE
May 2005

Andrew Mellor

Head Injuries: How to Protect What

Snell Conference on HIC

May 6, 2005

Thomas A. Gennarelli, M.D.

Professor and Chair

Department of Neurosurgery

Medical College of Wisconsin

Milwaukee, Wisconsin, USA

tgenn@mcw.edu

INJURY:

The result of the application of mechanical energy above the ability of the tissue to withstand it without anatomical or physiological alteration.

MEDICAL COLLEGE OF WISCONSIN

BRAIN INJURY IS NOT UNIDIMENSIONAL!!

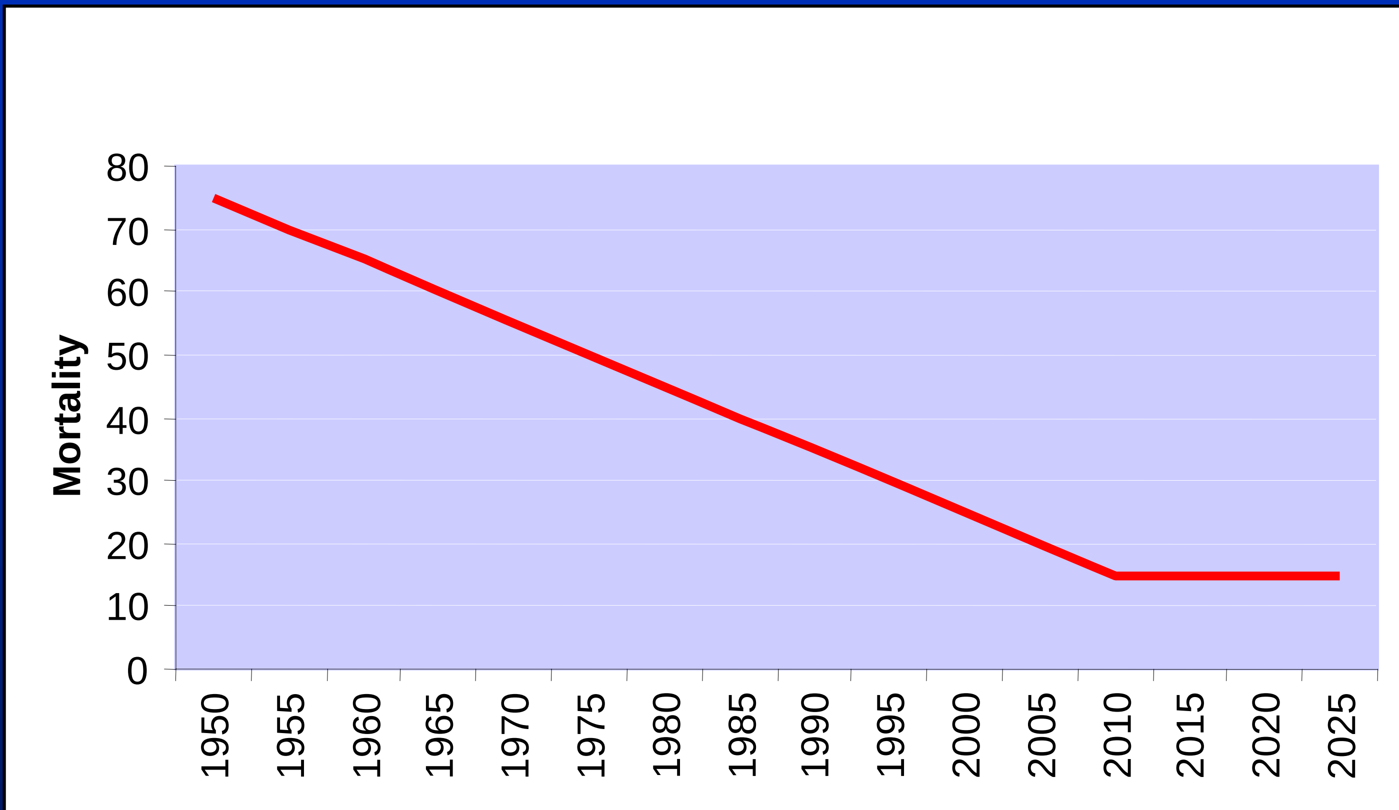
- DIFFERENT CAUSES
- DIFFERENT MECHANISMS
- DIFFERENT TYPES
- DIFFERENT AMOUNTS
- DIFFERENT LOCATIONS
- DIFFERENT PATHOPHYSIOLOGY
- DIFFERENT TREATMENTS

So is one tolerance reasonable?????

What are we trying to prevent?

- Which TBI are "acceptible?"
- Which TBI are unacceptibl;e?
- Are these the same for all circumstances?
- Given the advances in the last 50 years. Don't we have to lower the bar and prevent more TBI?

Mortality of severe TBI

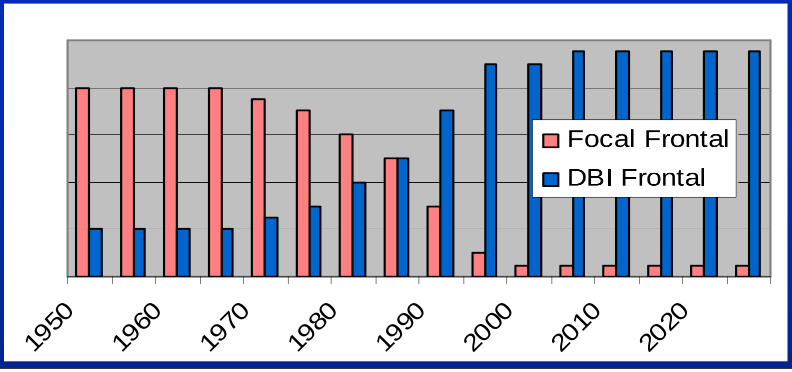


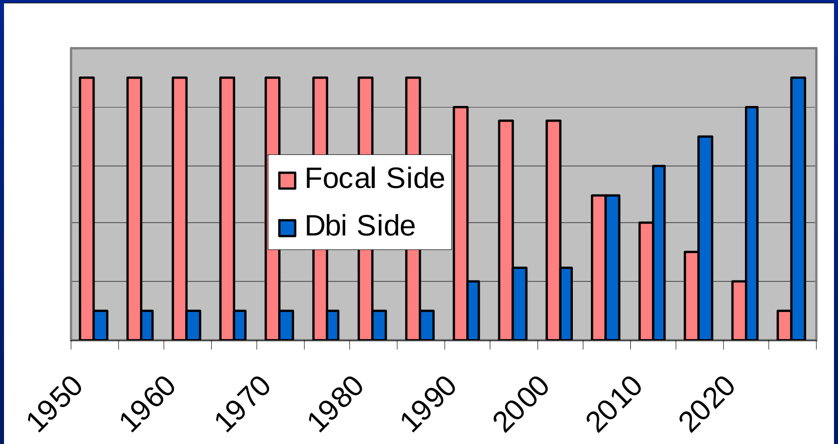
- Uniform injury descriptors; improved care; trauma care systems
- GCS: Teasdale ,Jennett 1974
- Widespread adoption of GCS, Langfitt, Gennarelli 1982

Importance of Biomechanics

- Shift of TBI type
- Shift of TBI severity
- Reduction of mortality
- Potential of virtual elimination of severe TBI in certain situations

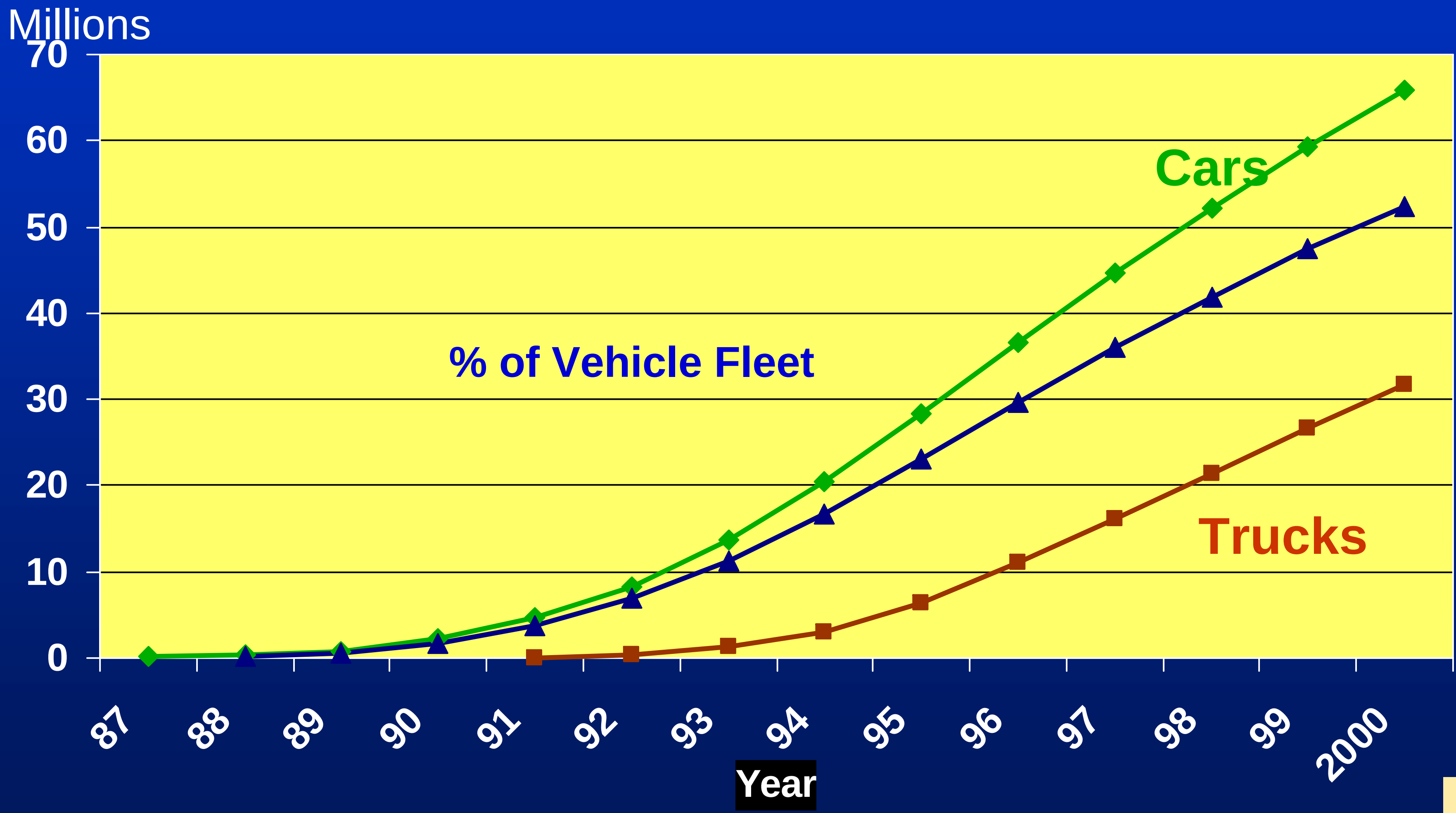
Vehicular Head Injuries





MEDICAL COLLEGE OF WISCONSIN

Number of Vehicles with Airbags

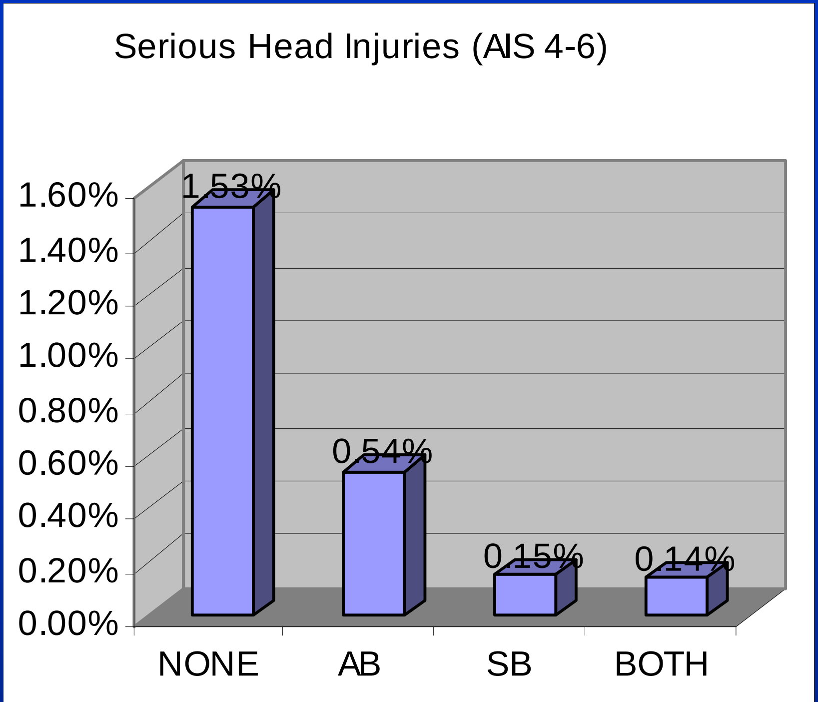


MEDICAL COLLEGE OF WISCONSIN

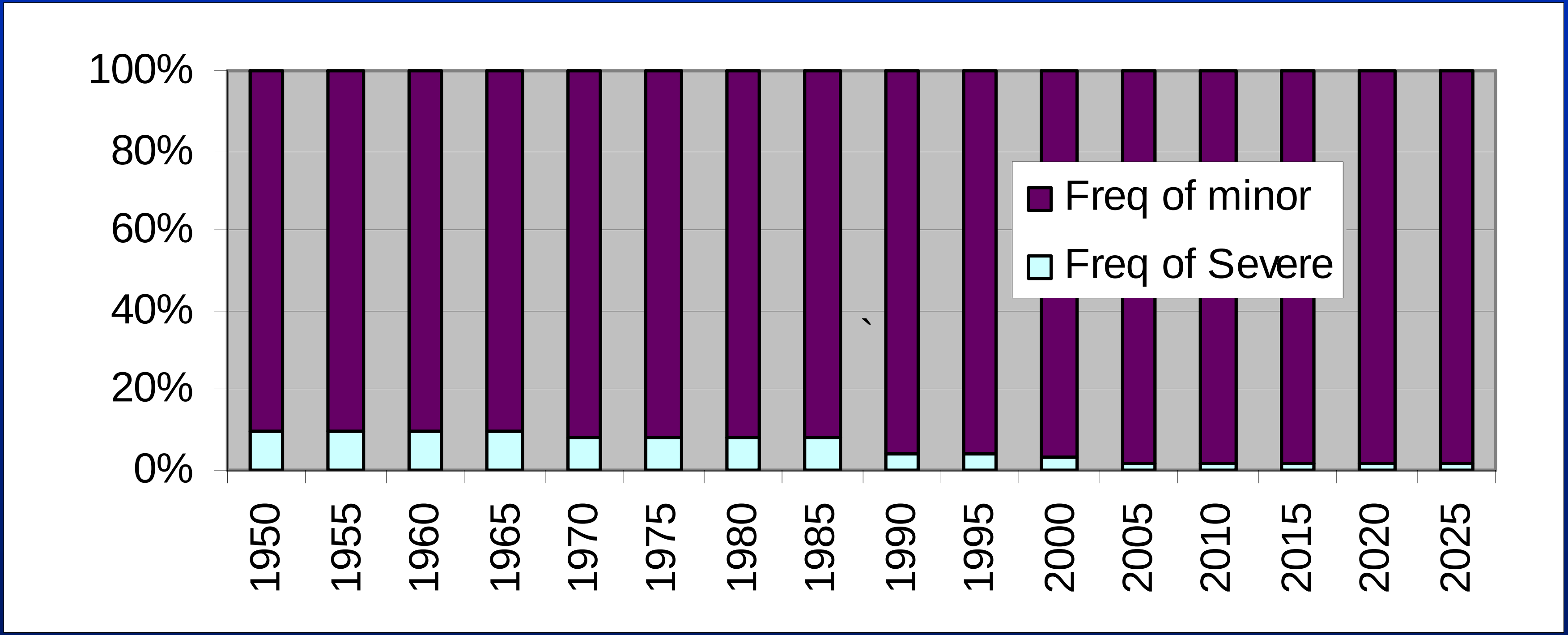
Future of TBI

- The chances of getting an AIS 4-6 head injury when restrained with seat belt and airbag are very small in a frontal crash .. 0.14%. So if all 1.5M frontal occupants had SB+AB:
  - 1.5 *0.14% =2100/yr = 1 per hospital per year

- If a serious head injury occurs, it will be at far higher crash speeds than with other restraint systems.



Minor TBI will be more important

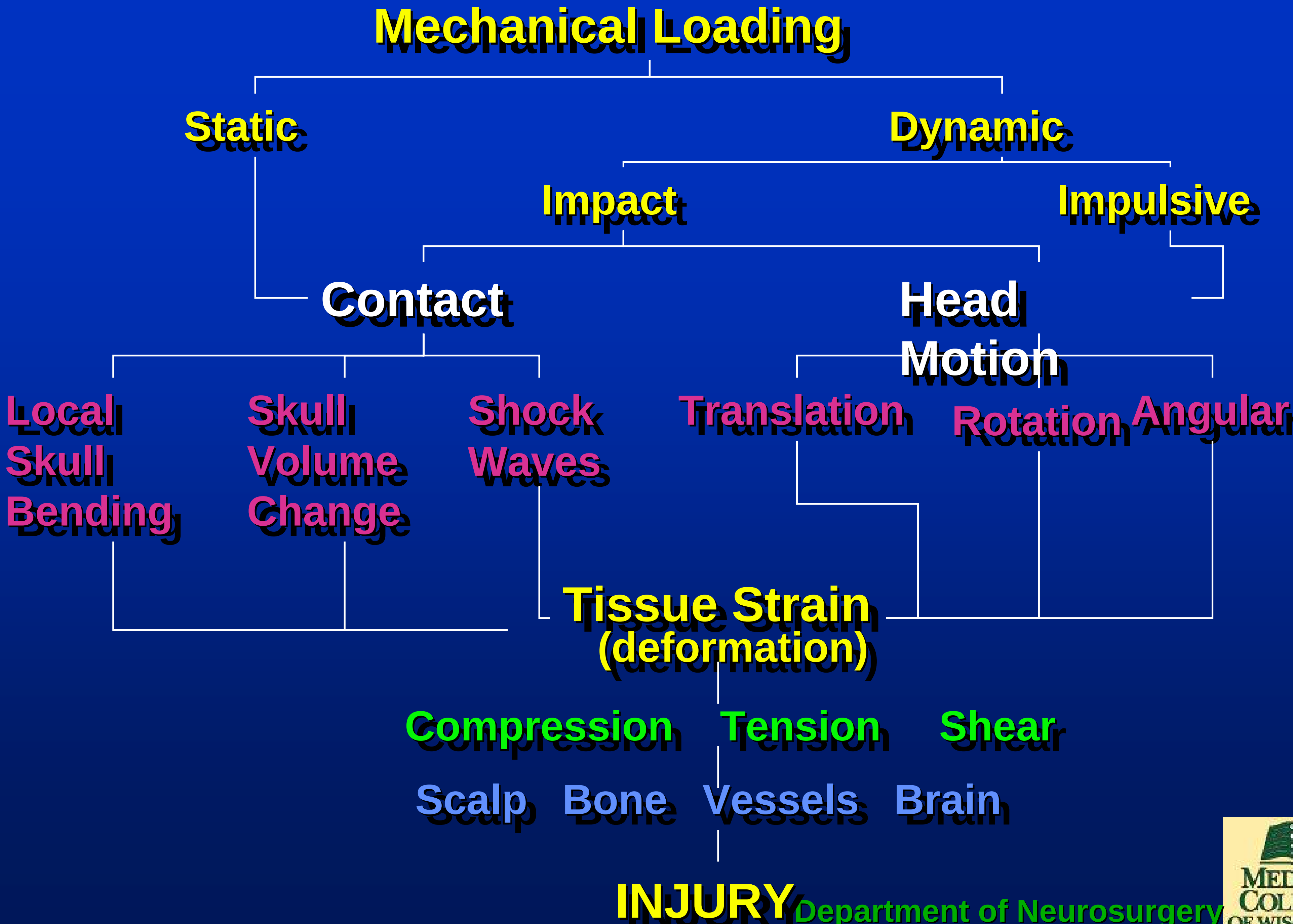


So, do we need to think about preventing mTBI?

Department of Neurosurgery
MEDICAL COLLEGE OF WISCONSIN

TYPES OF HEAD INJURY

- SCALP LACERATIONS
- SKULL FRACTURES
- FOCAL BRAIN INJURIES
  - CONTUSION, LACERATION
  - HEMORRHAGE: EDH, SAH, SDH, ICH
- DIFFUSE BRAIN INJURIES
  - CONCUSSION SYNDROMES
  - DIFFUSE AXONAL INJURY
- PENETRATING INJURIES
- BLAST-EXPLOSIVE INJURIES



Mechanical Loading
Static
Dynamic
Impact
Impulsive
Contact
Head Motion
Local Skull Bending
Skull Volume Change
Shock Waves
Translation
Rotation
Angular
Tissue Strain (deformation)
Compression
Tension
Shear
Scalp
Bone
Vessels
Brain
INJURY

Mechanisms of the Head Injuries

- Contact Injuries
  - Skull Fracture
  - Epidural Hematoma
  - Coup Contusion
  - ICH
  - Penetrating Inj.
- Head Motion Injuries
  - Contre Coup Contusion
  - Subdural Hematoma
  - Concussion
  - Diffuse Axonal Injury

HEAD CONTACT INJURIES

MOTION NOT REQUIRED; DIRECT BLOW NECESSARY

- Skull Bending
  - Skull Fracture
  - Coup Contusion
- Skull Volume Changes
  - Contre Coup Contusion
- Shock Waves
  - Intracerebral Hemorrhage
  - Penetrating (Missile) injury

HEAD MOTION INJURIES

Motion required: direct blow not necessary

- SURFACE STRAINS
  - SUBDURAL HEMATOMA
  - CONTRE COUP CONTUSION
- DEEP STRAINS
  - CONCUSSION SYNDROMES
  - DIFFUSE AXONAL INJURY`

When you break the skull, the brain may remain intact.

Isolated HI Lesions

Lesion	n	% single
CSDH	24	70.8
Concussion	199	26.6
DAI - sev	17	23.5
DAI mod	57	22.8
Ped Swelling	28	17.9
ICH	33	9.1
Scalp	144	6.9
ASDH	67	3.0
Fx Vault	128	1.6
Contusion	135	1.5

INCIDENCE OF INJURIES

	OCCUPANT	PEDESTRIAN	NON-VEHICULAR
SKULL FRACTURE			
VAULT	25	40	39
BASILAR	21	18	12
DIFFUSE INJURY			
CONCUSSION	43	49	45
MODERATE DAI	22	50	2
SEVERE DAI	13	1	1
FOCAL INJURY			
CONTUSION	33	25	32
ALL SDH	16	8	18
SDH main injury	4	5	9
EDH	4	22	8
ICH	3		12

Skull Fracture Incidence

Percent

	Occupants	Pedestrians	Non-Vehicular
Concussion	29	52	50
Moderate DAI	46	32	50
Severe DAI	30	50	0
SDH	45	75	52
Contusion	53	60	58

Diffuse Brain Injury Categories

Abbreviation	Adjective	AIS	Ommaya Gennarelli Concussion Grade[1]	LOC
MC	Mild Concussion	1	1-3	0
CC	Classical Concussion	2	4	<1hr
SC	Severe Concussion	3	4	1-6 hr
Mild DAI	Mild DAI	4	5	6-24 hr
Mod DAI	Moderate DAI	5	5	> 24 hr[a]
Sev DAI	Severe DAI	5	5	>24 hr[b]

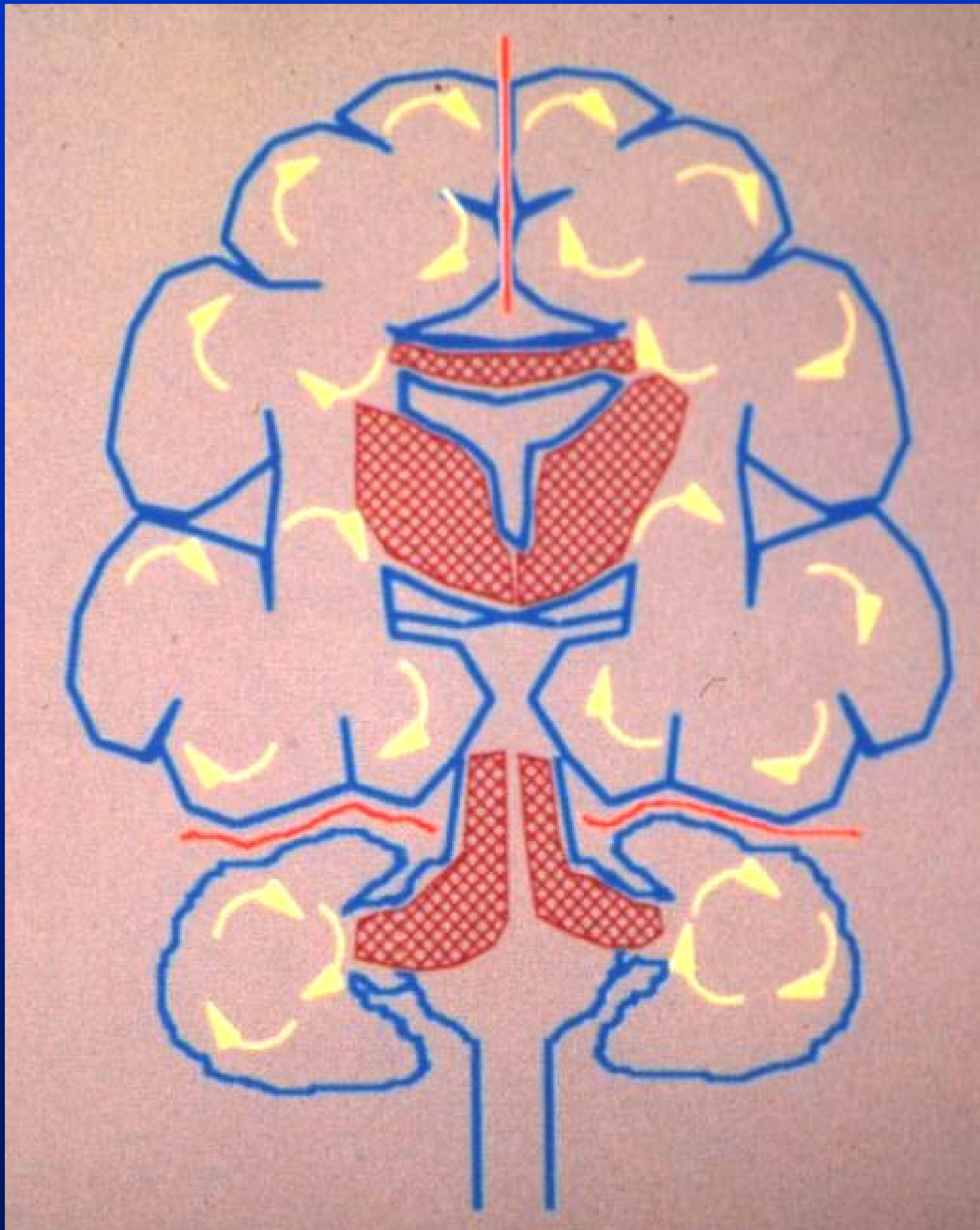
a = no brainstem abnormaility; b = with decerebration, decortication

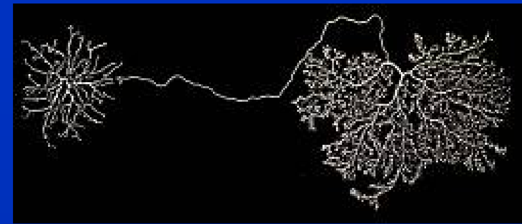
Directional Dependence of Diffuse Brain Injury

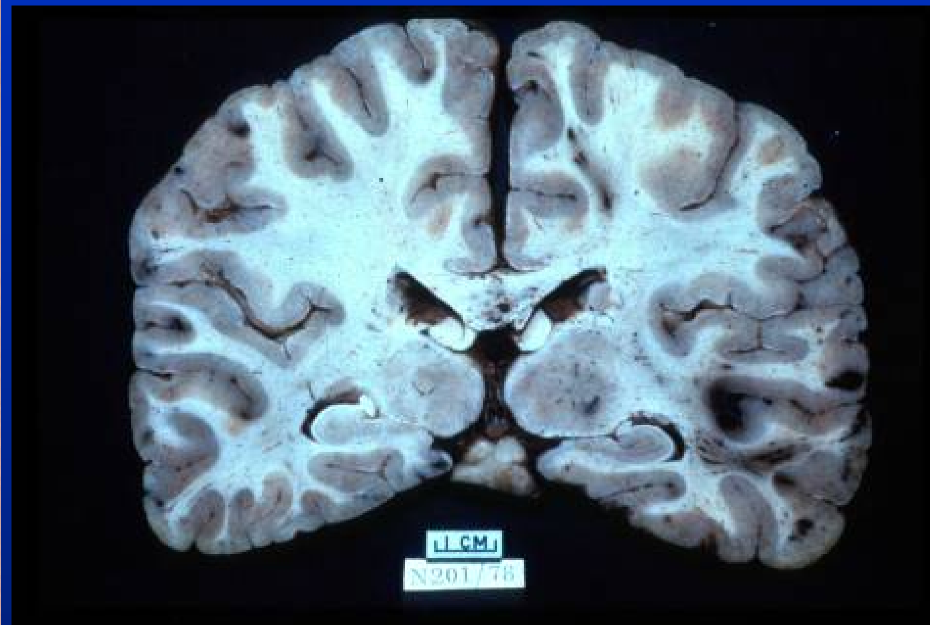
Experimental Subjects with comparable acceleration input

DAI GRADE	SAGITTAL	HORIZONTAL	CORONAL
0	4	0	0
1	5	1	0
2	0	9	1
3	0	0	8

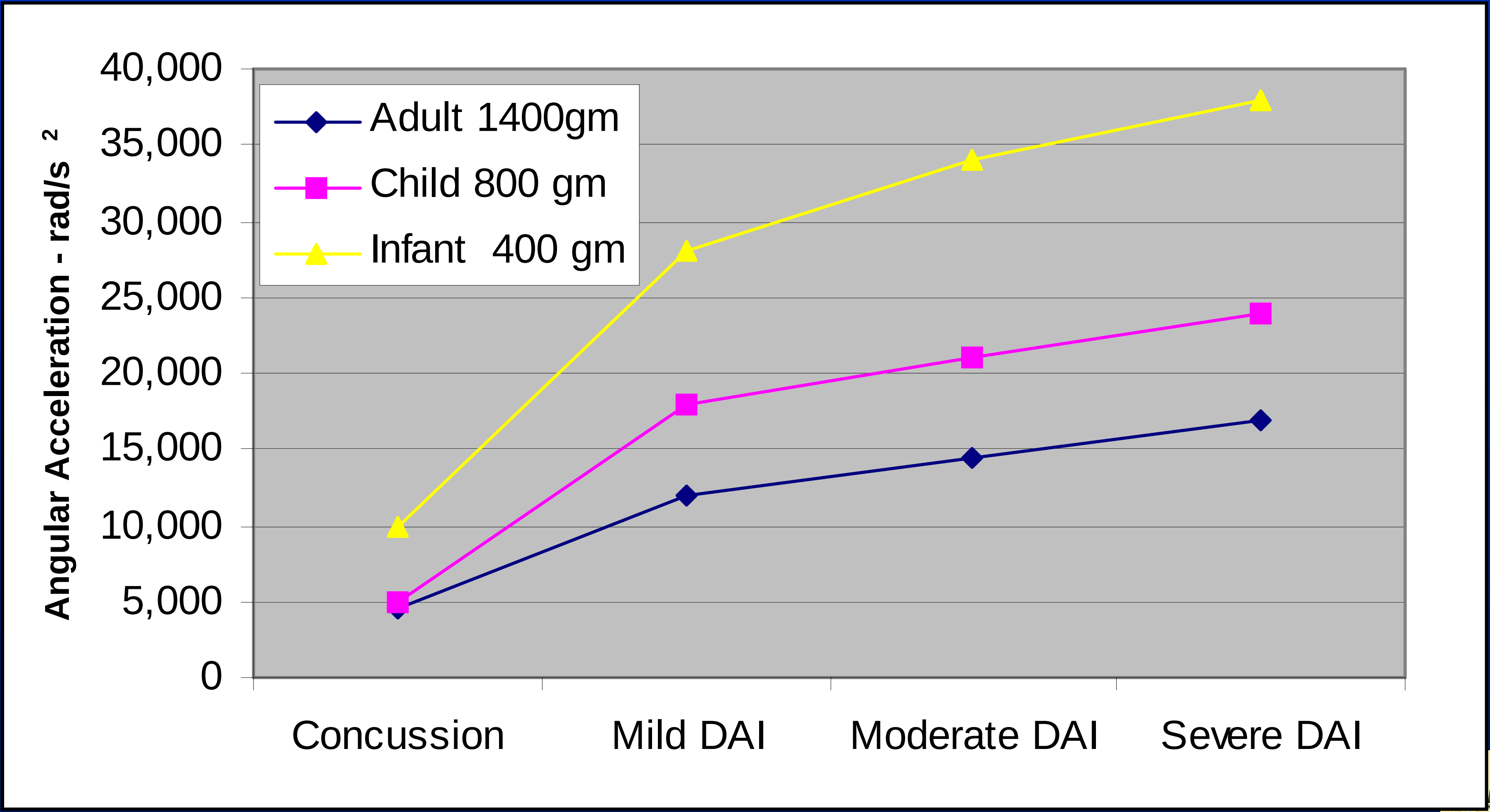
Gennarelli, 31st Stapp 1987






1 CM
N201/78

Inertial Tolerances



Relation of Tolerances to Adjectival Descriptors of Diffuse Brain Injury

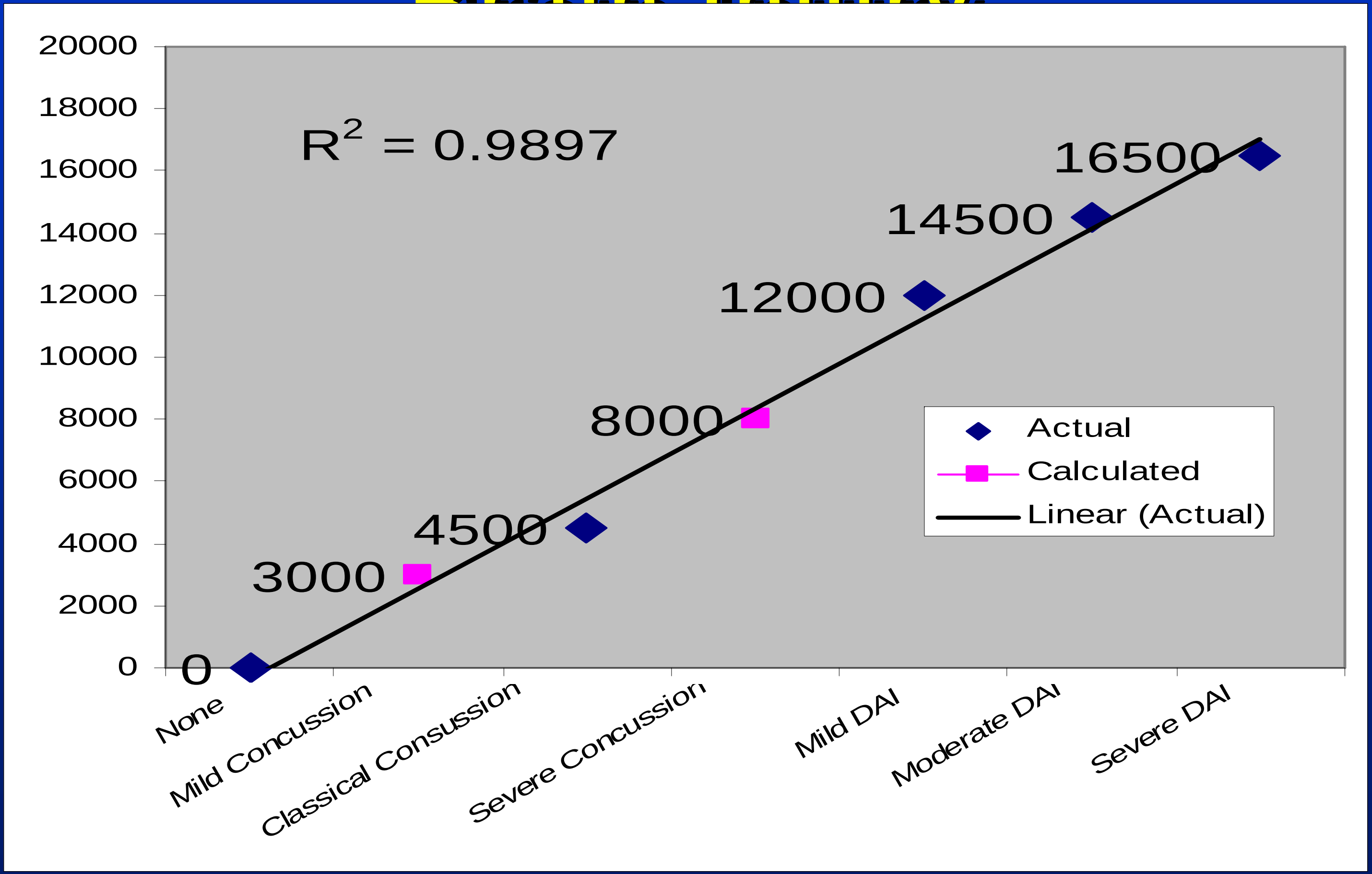


Fig 2. Results of using scaled tolerances values from Margulies to equivalent adjectival descriptors (actual = Margulies values) and interpolating values for mild and severe concussion (calculated)

Relation of Diffuse Brain Injury Tolerances to AIS

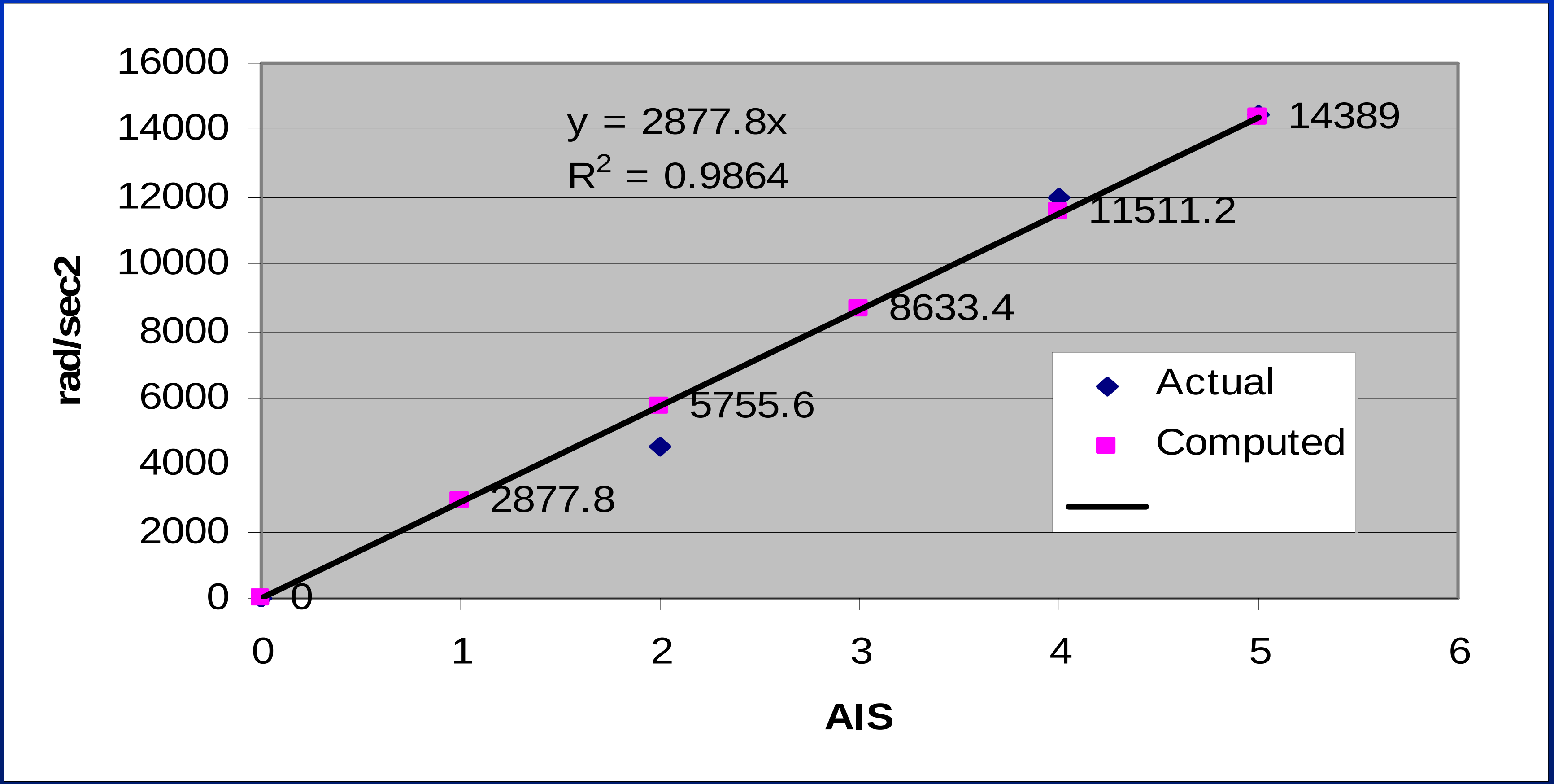


Fig 1. Results of using scaled tolerances values from Margulies to equivalent AIS values (actual; AIS = 0, 2,4,5) and interpolating values for AIS values 1,3 (computed)

Concussion Symptom Inventory (CSI)

Randolph, Barr, McCrea, Millis, Guskiewicz, Hammeke, Kelly, 2005

Symptom	**Absent**	**Present**
HEADACHE	**0**	**0**
NAUSEA	**0**	**1**
BALANCE PROBLEMS/DIZZINESS	**0**	**1**
FATIGUE	**0**	**1**
DROWSINESS	**0**	**1**
FEELING LIKE “IN A FOG”	**0**	**1**
DIFFICULTY CONCENTRATING	**0**	**1**
DIFFICULTY REMEMBERING	**0**	**1**
SENSITIVITY TO LIGHT	**0**	**1**
SENSITIVITY TO NOISE	**0**	**1**
BLURRED VISION	**0**	**1**
FEELING SLOWED DOWN	**0**	**1**

TOTAL__________

Grades of Concussion

		Grade 1	Grade 2	Grade 3
AAN 1997	LOC	-	-	+
	Sx	<15 min	>15 min	
Cantu 1997	LOC	-	<5min	>5min
	PTA	<1hr	1-24hr	>24hr
CO Med 1991	LOC	-	-	+
	Confusion	+	+	+
	Amnesia	-	+	+
Torg 1985	LOC	-	few min	+
	amnesia	PTA	PTA or RGA	PTA+RGA

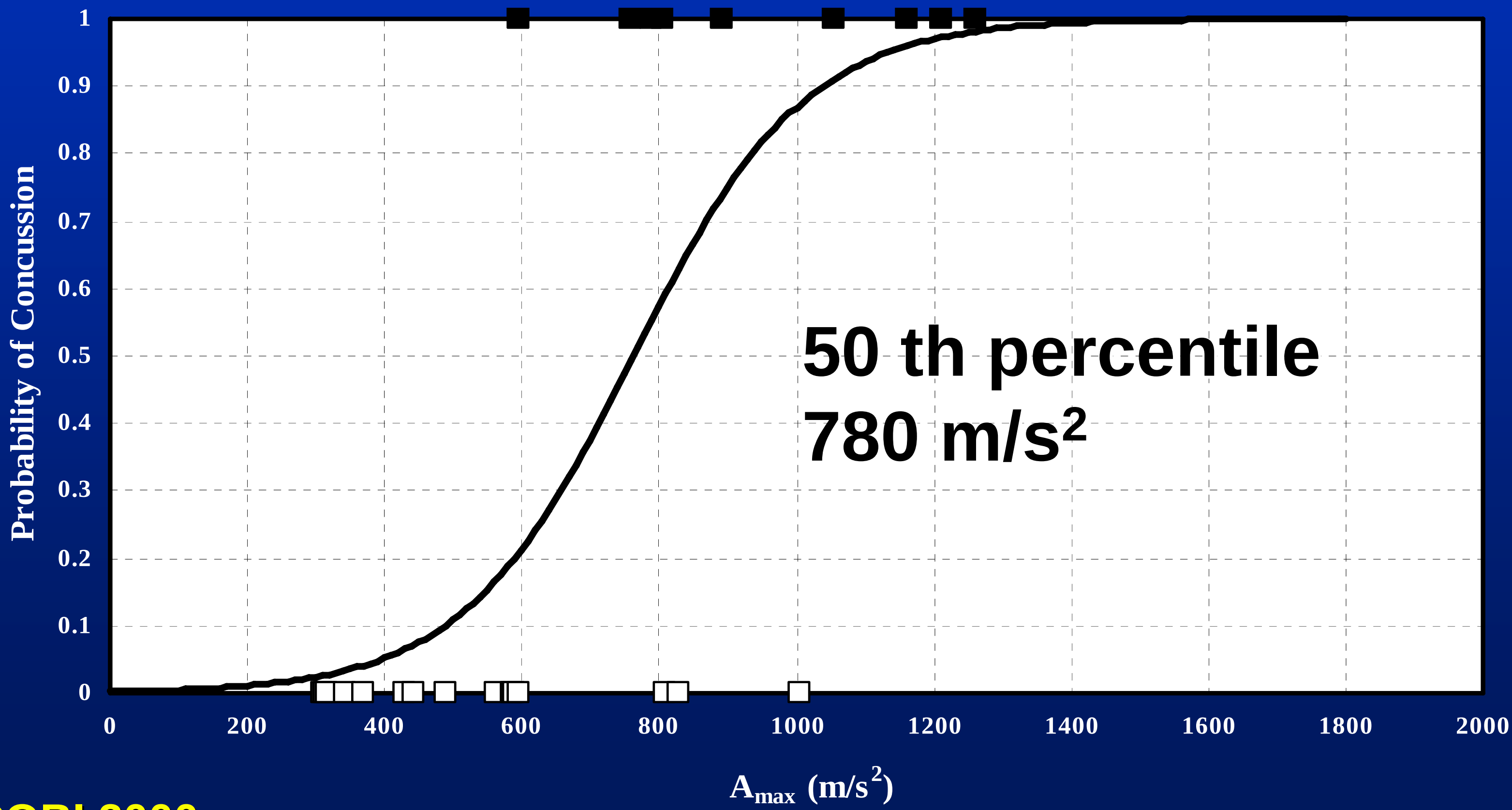
Results

- Production of risk curves
  - Each curve represents the probability of Mild Traumatic Brain Injury being associated with a specific value of injury measure
- Results of Logistic Regression Analyses

	a_m	α_m	SI	HIC_{15}	GAMBIT	HIP
Significance P-value	**0.011**	**0.029**	**0.024**	**0.020**	**0.013**	**0.008**
-2LLR	**18.059**	**20.676**	**18.195**	**19.347**	**18.031**	**14.826**

Probability of MTBI: A_{max}

(n=24)

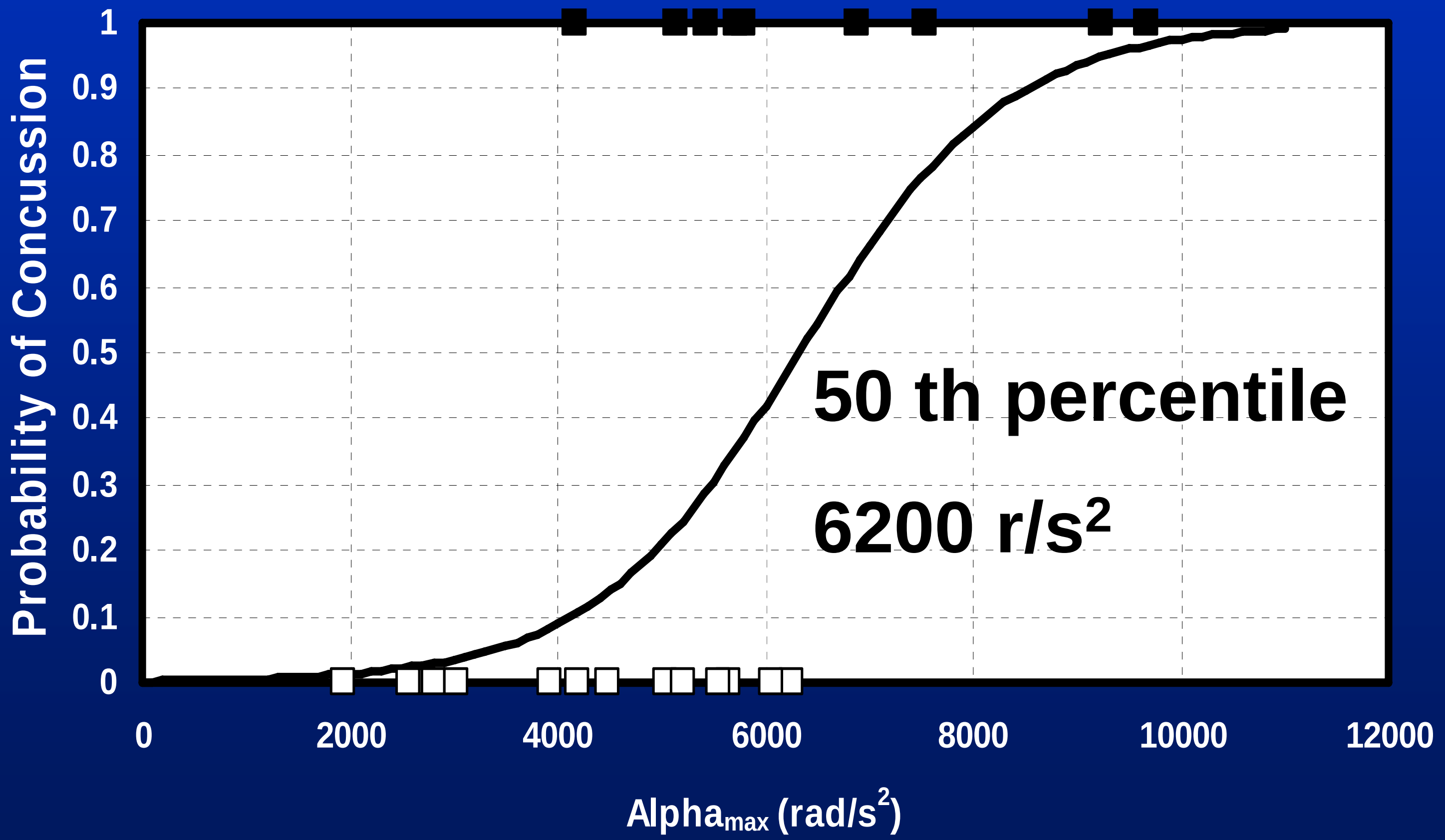


Newman IRCOBI 2000

Department of Neurosurgery

Probability of MTBI: α_{max}

(n=24)

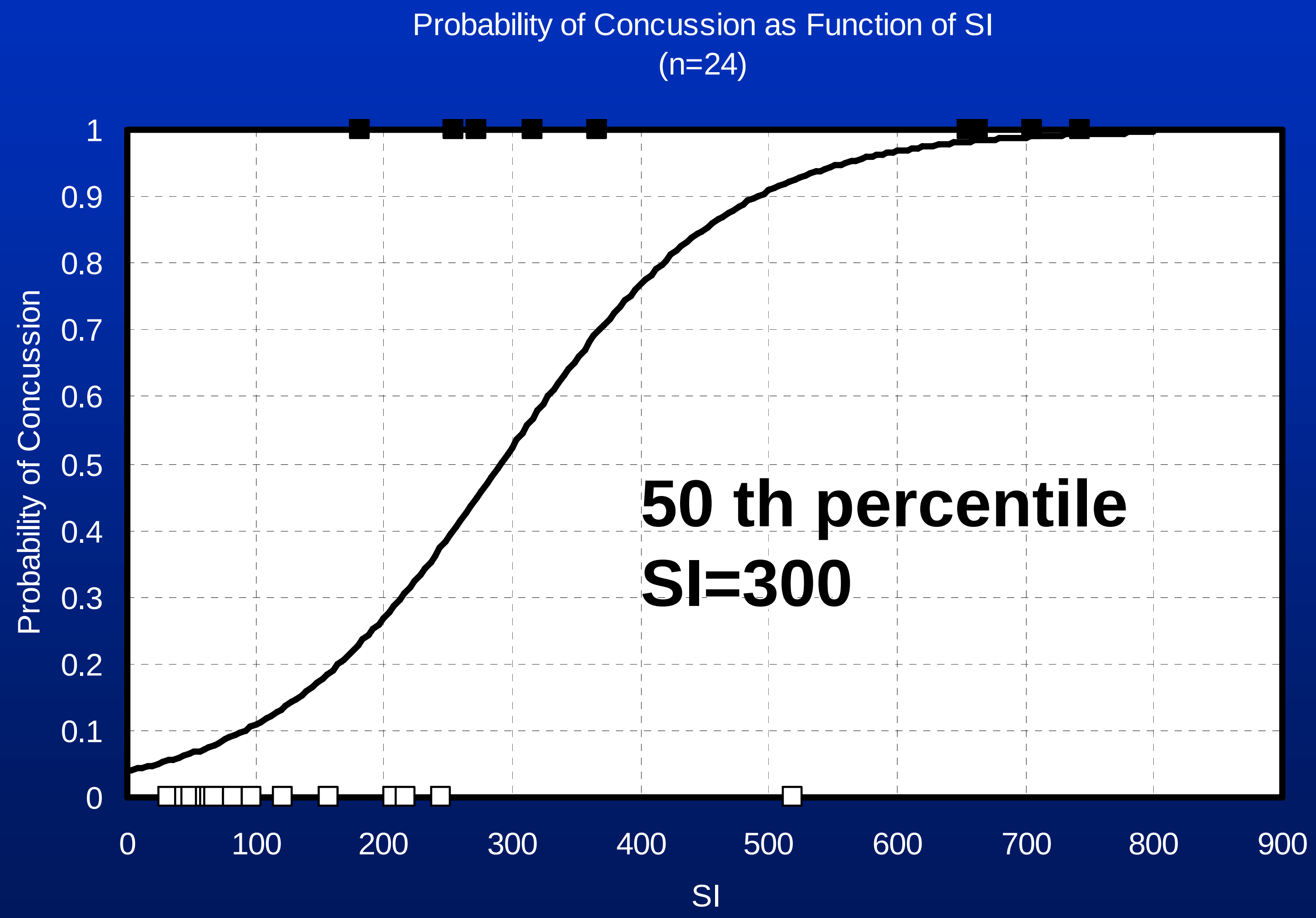


Newman IRCOBI 2000

Department of Neurosurgery

MEDICAL COLLEGE OF WISCONSIN

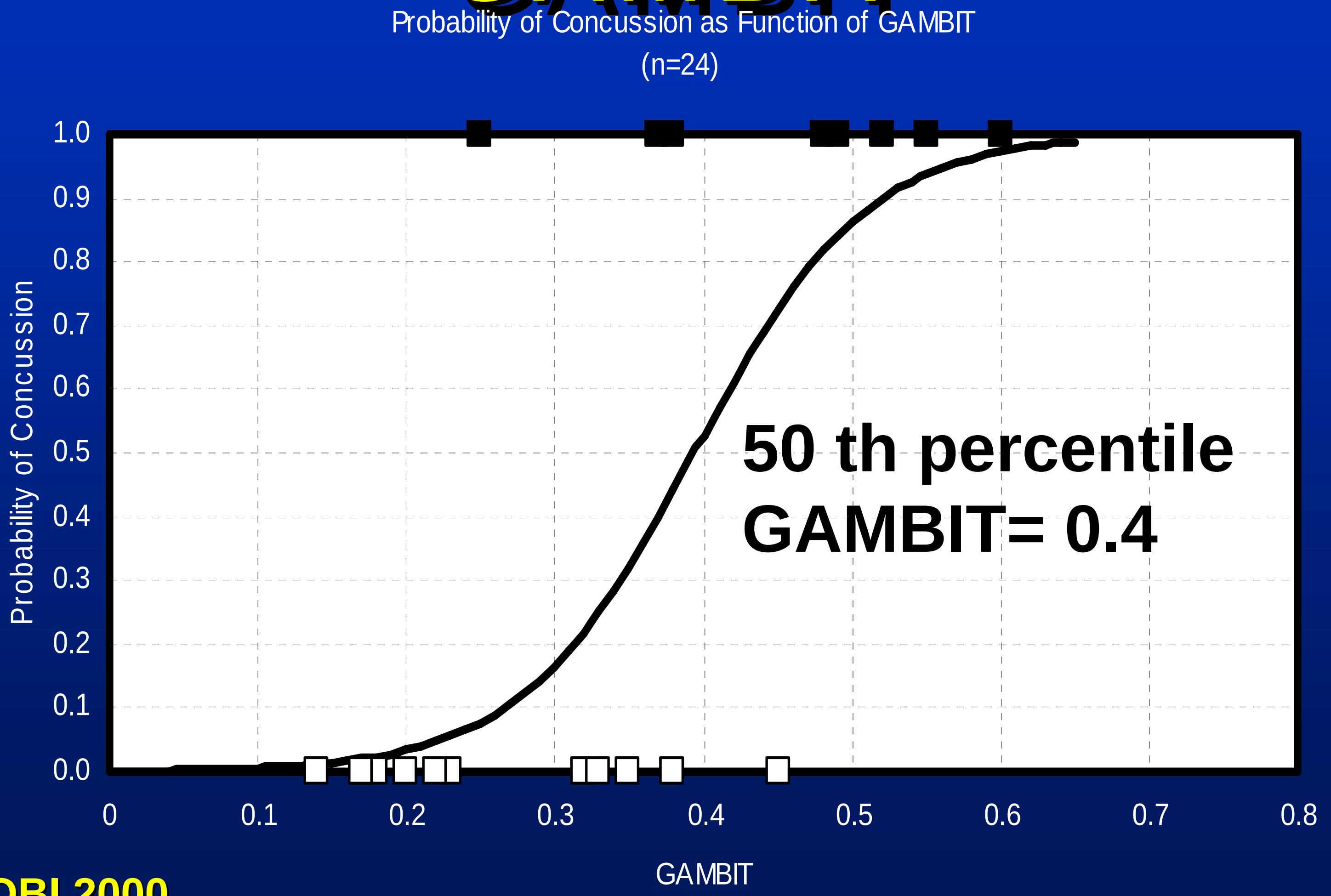
Probability of MTBI: SI



Newman IRCOBI 2000

Department of Neurosurgery
MEDICAL COLLEGE OF WISCONSIN

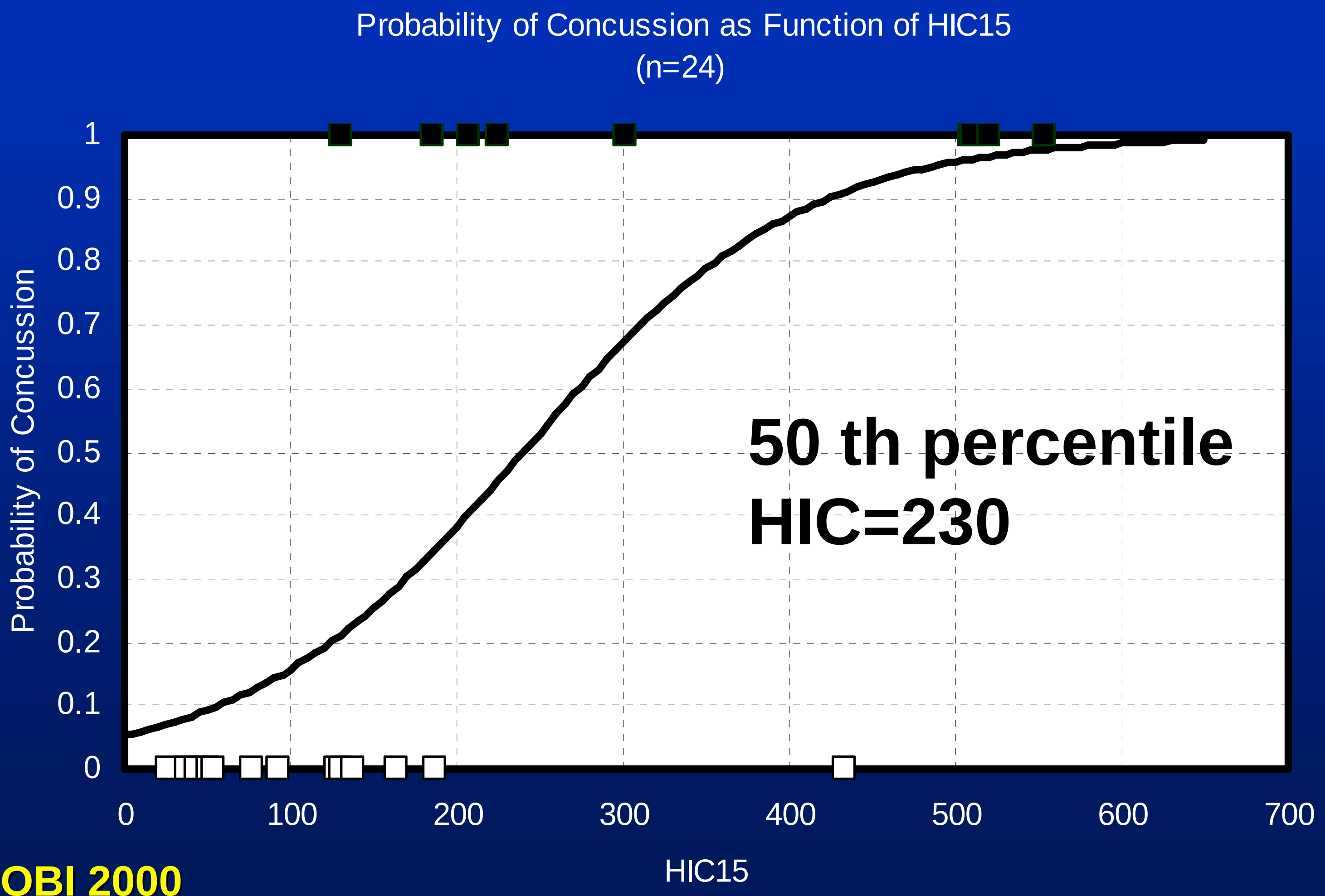
Probability of MTBI: GAMBIT



Newman IRCOBI 2000

Department of Neurosurgery
MEDICAL COLLEGE OF WISCONSIN

Probability of MTBI: HIC_{15}

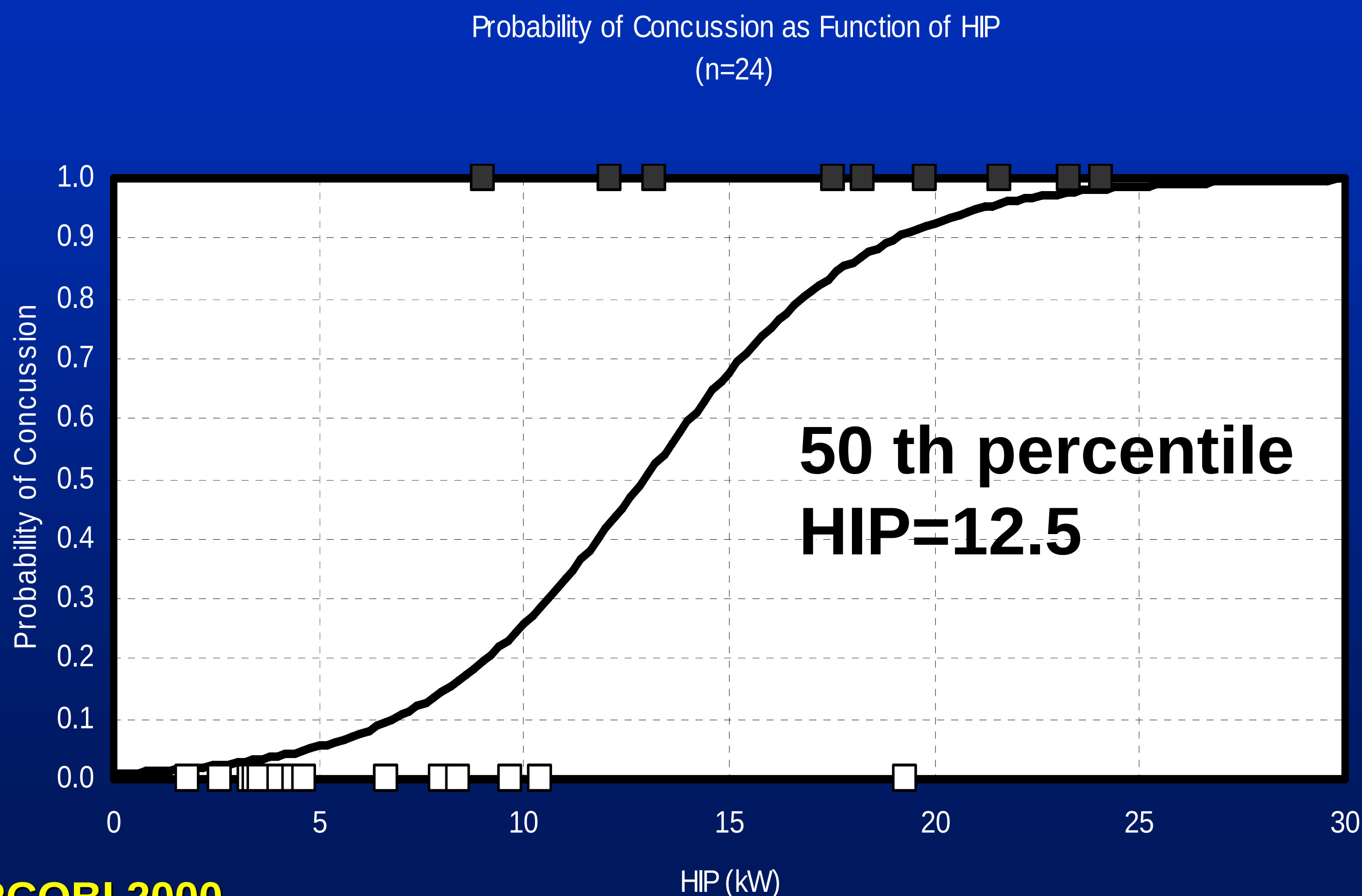


Newman IRCOBI 2000

Department of Neurosurgery

MEDICAL COLLEGE OF WISCONSIN

Probability of MTBI: HIP



Newman IRCOBI 2000

Tolerances for mTBI: King 2003

Predictor Variable	Threshold Values for Likelihood of MTBI		
	25%	50%	75%
$A_{r\ max}$ (m/s^2)	559	778	965
$R_{r\ max}$ (rad/s^2)	4384	5757	7130
HIC_{15}	136	235	333
ε_{max}	0.25	0.37	0.49
$d\varepsilon/dt_{max}$ (s^{-1})	46	60	79
$\varepsilon \bullet d\varepsilon/dt_{max}$ (s^{-1})	14	20	25

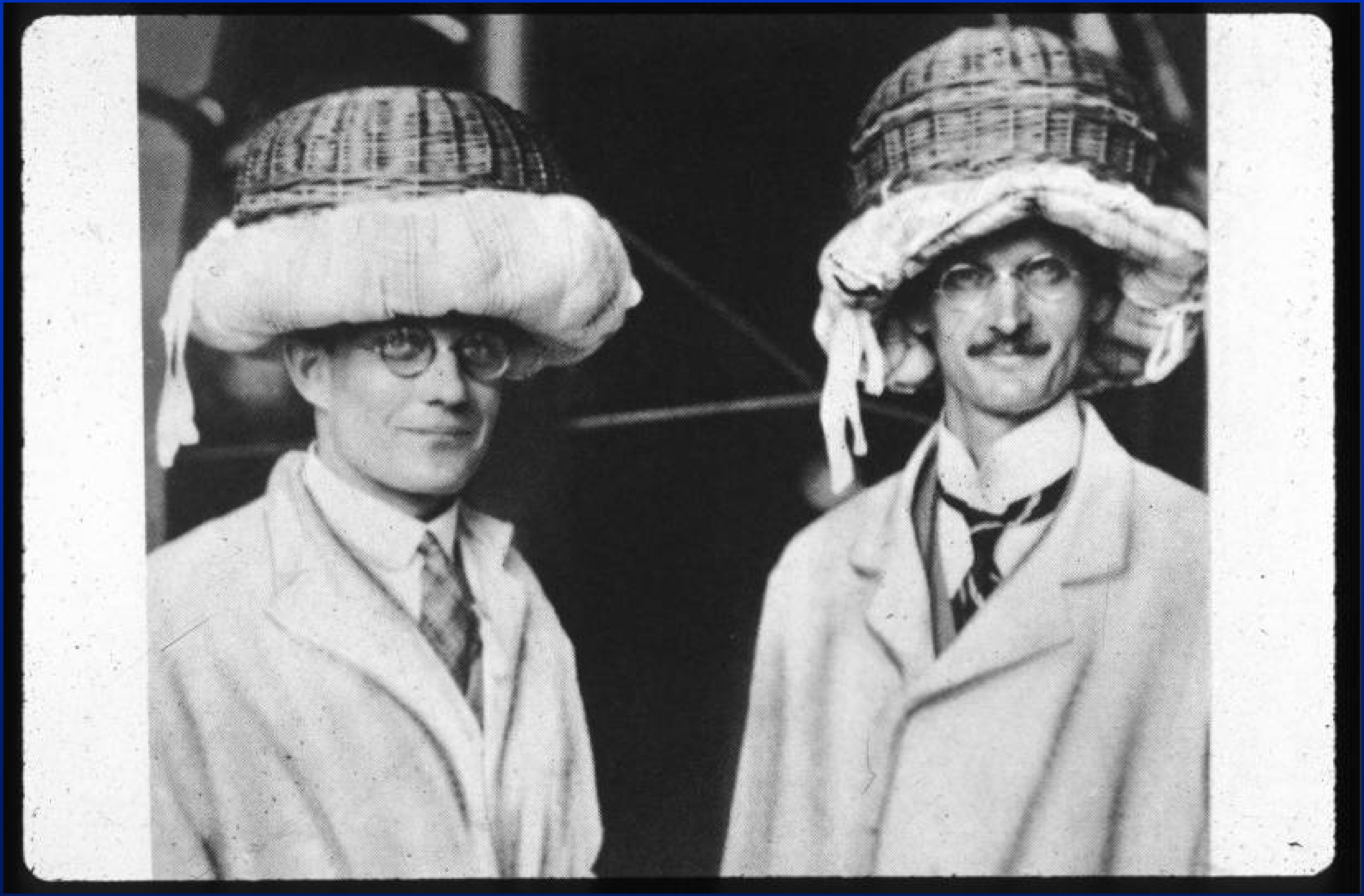
King: 2003

- At least for MTBI, the best predictor for injury is neither linear nor angular acceleration
- It is the product of strain and strain rate
- This may be controversial but it is biomechanically reasonable because brain response governs injury, not the input

What are we trying to prevent?

- Which TBI are “acceptible?”
- Which TBI are unacceptibl;e?
- Are these the same for all circumstances?
- Given the advances in the last 50 years. Don’t we have to lower the bar and prevent more TBI?

Total Protection from TBI



Cheesehead saves day, life of plane passenger

STEVENS POINT (AP) — A Green Bay Packers fan who survived a plane crash credits his yellow foam rubber cheesehead for giving him another chance to cheer on the home team.

"It was in my lap, because I was using it as pillow when I was snoozing an hour before," Frank Emmert, 36, said Tuesday. "You know when you crash in the big ones, they tell you to cover your head with a pillow."

Emmert was flying back home to Superior on Sunday after spending a week in Ohio following the Nov. 19 Packers-Browns game. His traveling companion, Baron Bryan, 25, also from Superior, was the pilot.

Ice on the wings may have caused the small plane to crash near the Stevens Point Municipal Airport, Emmert said.

"We went straight down," Emmert said.

As the plane dropped, Emmert grabbed the wedge-shaped cheesehead and covered his head. Once on the ground, he discovered Bryan had suffered a head injury. Emmert kicked the door open.

"That's when I found out I had a broken ankle," he said.

Emmert won't have to buy a new cheesehead to replace the one he used in the crash.

"The gentleman that owns the company sent cheeseheads to my family and my boys," Emmert said.

HIC Background and Applications

Ancient Protective Devices

Ancient Protective Devices

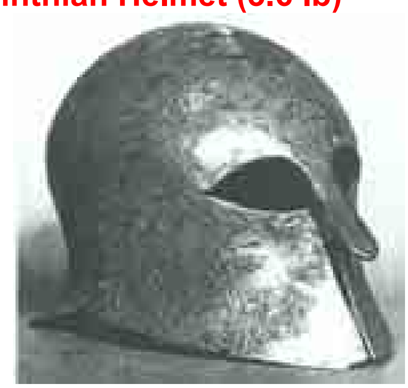
MEDICAL COLLEGE OF WISCONSIN Department of Neurosurgery, Milwaukee, WI, USA

History

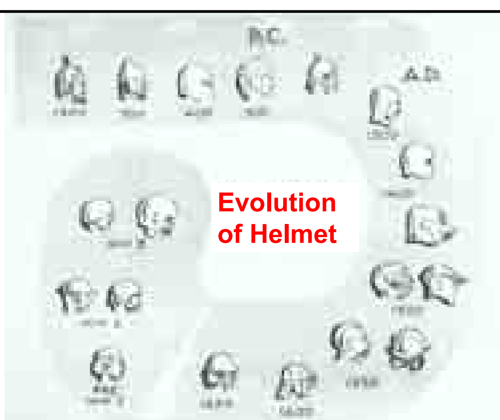
Early reference to present helmets is in the temple of Amon at Karnak, illustrating the conquest of Thotmoses III receiving a golden helmet and iron suit of armor

MEDICAL COLLEGE OF WISCONSIN Department of Neurosurgery, Milwaukee, WI, USA

Corinthian Helmet (3.6 lb)



MEDICAL COLLEGE OF WISCONSIN Department of Neurosurgery, Milwaukee, WI, USA



MEDICAL COLLEGE OF WISCONSIN Department of Neurosurgery, Milwaukee, WI, USA

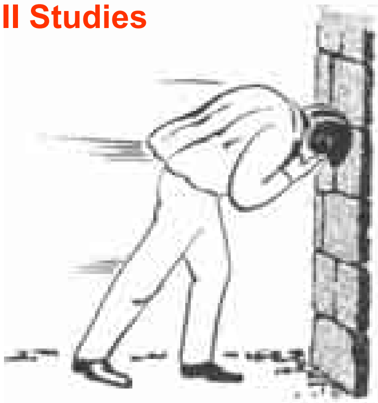
Early Head Injury Quantification

Messerer 1880

- 7 males 18-69 years
- 6 females 22-82 years
- 1142 lb (770-1760) trans
- 1430 lb (880-2650) long

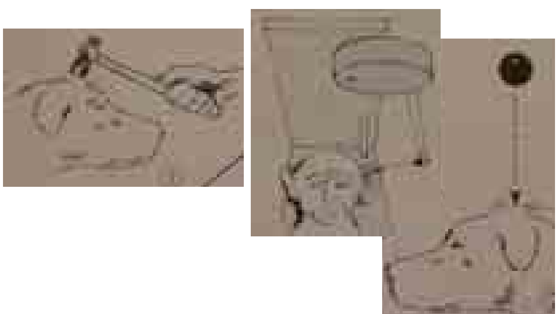
MEDICAL COLLEGE OF WISCONSIN Department of Neurosurgery, Milwaukee, WI, USA

World War II Studies



Early Head Injury Quantification

- Studies initiated in 1930s
- Sudden increase of ICP 300 mm Hg – concussion
  - ➔(Scott, 1940)
- 28 f/s "hand blow" resulted in concussion in cat
  - ➔(Denny-Brown and Russel, 1941)
- Additional quantifications
  - ➔Gurdjian and co-workers



Gurdjian et al

Early Head Injury Studies

Gurdjian and co-workers 1944-1962

- J Neurosurgery 1944
- American J Surgery 1949
- Surgery Gynecology & Obstetrics
  - ➔1945, 1947, 1955, 1958, 1960
- Neurology 1953
- Stapp 1961, 1963
- JAMA 1962
- J Trauma 1966

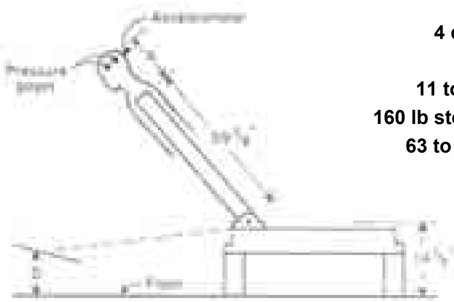
Experimental Head Impact Studies

Ford Motor Company
sponsored head impact studies
at the
Medical College of Wayne State University
in 1954

Haynes and Lissner 1961

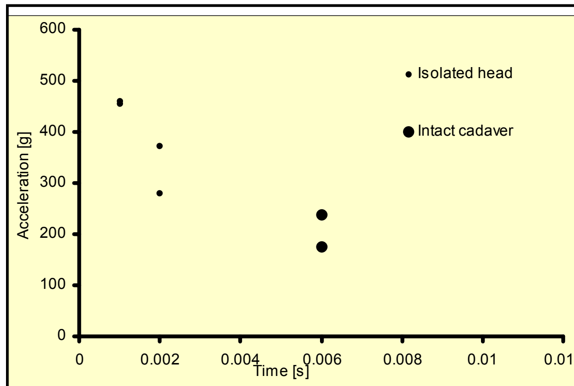
Isolated Heads

Intact Embalmed Cadaver Drops

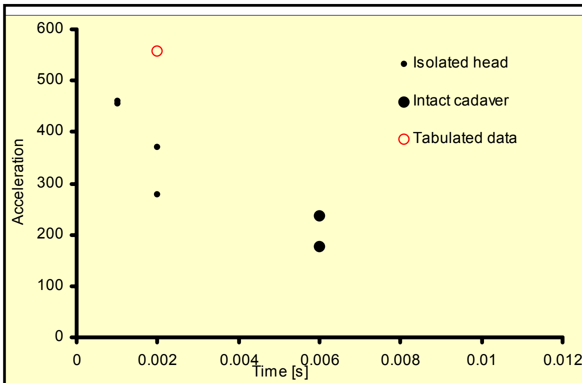


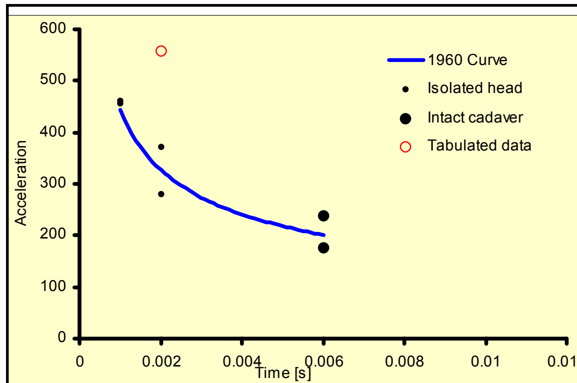
4 cadavers
23 drops
11 to 15 mph
160 lb steel block
63 to 76 years

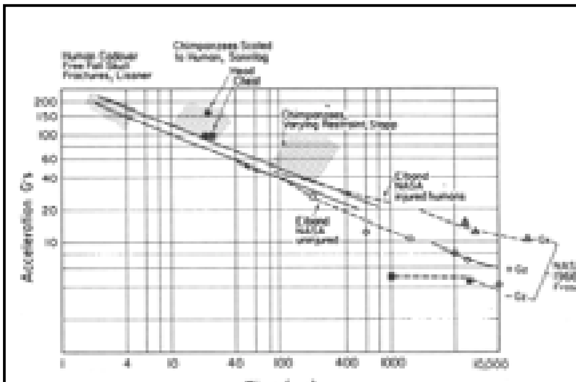
Lissner et al., 1960



Lissner et al., 1960

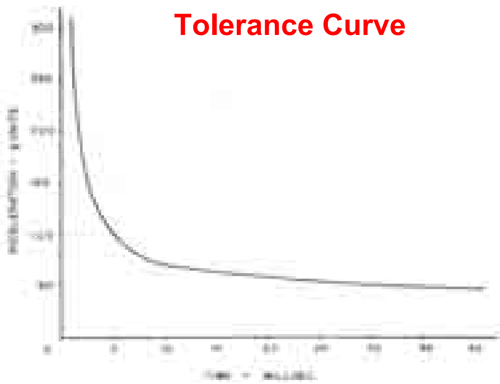






Eiband 1959

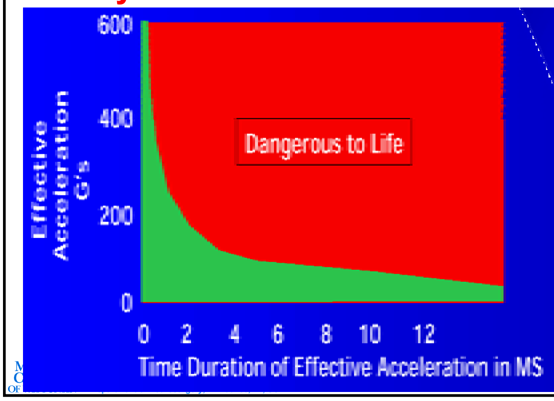
Tolerance Curve



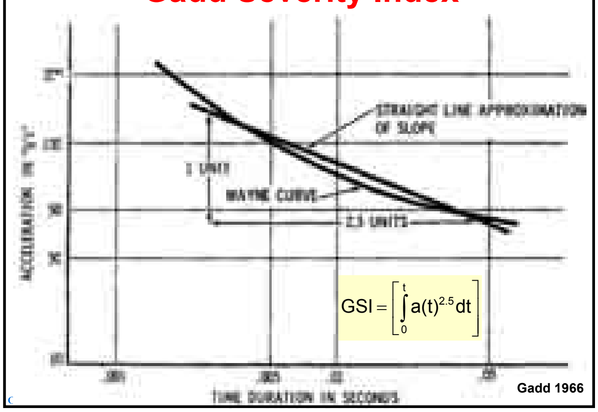
Gurdjian 1973

MEDICAL COLLEGE OF WISCONSIN Department of Neurosurgery, Milwaukee, WI, USA

Wayne State Tolerance Curve



Gadd Severity Index



$$GSI = \left[\int_0^t a(t)^{2.5} dt \right]$$

Gadd 1966

Head Injury Criterion (HIC)

$$HIC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} (t_2 - t_1)$$

HIC formulation – long duration, low level g, >1 peak g level

$$GSI = \left[\int_0^t a(t)^{2.5} dt \right]$$

In adequate biomechanical data to have an accurate exponent
Index represented an intermediate stage in chain of events

Versace 1971

MEDICAL COLLEGE OF WISCONSIN Department of Neurosurgery, Milwaukee, WI, USA

Physical Meaning - Interpretation

$$HIC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} (t_2 - t_1)$$

$$HIC = \left[\frac{V}{t} \right]^{0.5} \left[\frac{V}{t} \right]^{2}$$

ONLY LINEAR ACCELERATION

MEDICAL COLLEGE OF WISCONSIN Department of Neurosurgery, Milwaukee, WI, USA

HIC in Crashworthiness Research

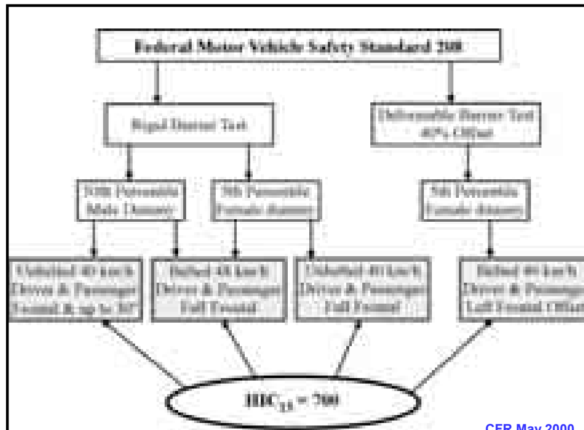
- **1971 (SI)**
- **1972**
- **1984**
- **1986 HIC_{36}**
- **ECE 96/79**
- **1982 ISO- HIC 1500**
- **1985 US delegation***
  - → **recommended**
  - → **HIC_{15}**
  - → **1450 (50% risk)**
  - → **700 (5% risk)**

* Prasad and Mertz, 1985

MEDICAL COLLEGE OF WISCONSIN Department of Neurosurgery, Milwaukee, WI, USA

US Federal Motor Vehicle Safety Standards - FMVSS

- 208 Frontal impact
- 213 Frontal impact - children
- 214 Lateral impact
- 201 Interior impact



CFR May 2000

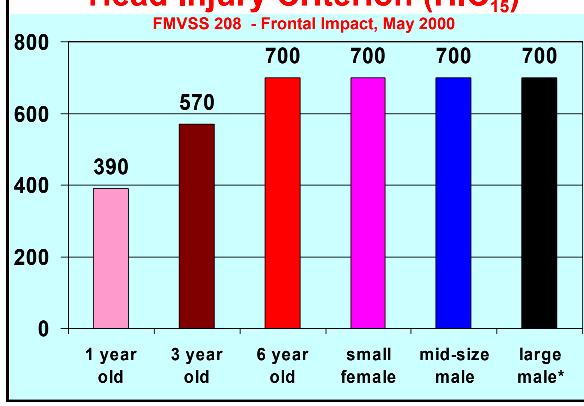
MEDICAL COLLEGE OF WISCONSIN Department of Neurosurgery, Milwaukee, WI, USA

FMVSS 208 – Frontal Impact HIC_{15}

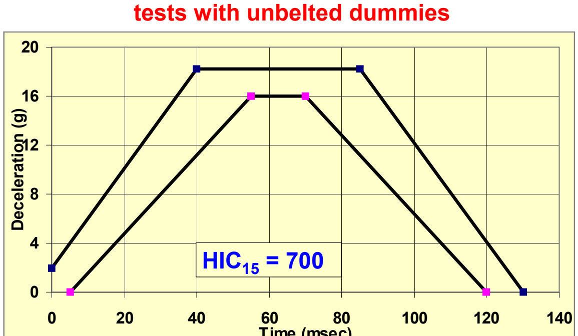
Acceleration gathered for 300 ms after the vehicle strikes barrier

MEDICAL COLLEGE OF WISCONSIN Department of Neurosurgery, Milwaukee, WI, USA

Head Injury Criterion (HIC_{15})

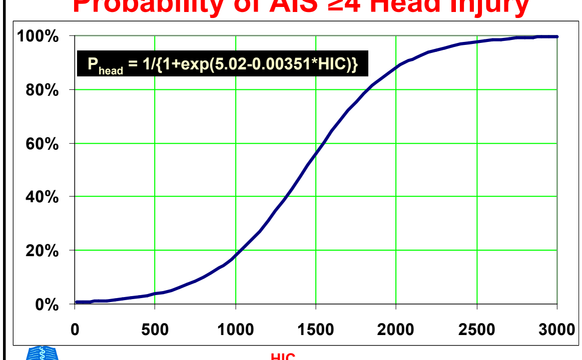


Deceleration pulse corridors for alternative sled tests with unbelted dummies



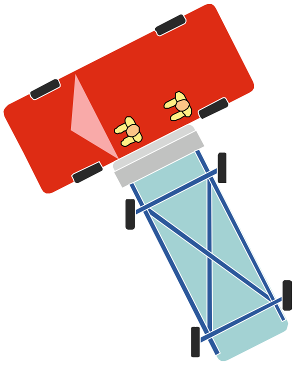
MEDICAL COLLEGE OF WISCONSIN Department of Neurosurgery, Milwaukee, WI, USA

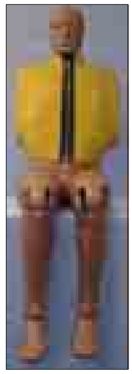
Probability of AIS ≥4 Head Injury



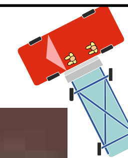
MEDICAL COLLEGE OF WISCONSIN Department of Neurosurgery, Milwaukee, WI, USA

FMVSS 214 Side Impact

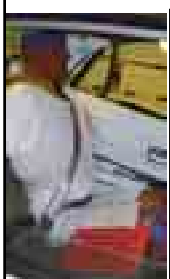


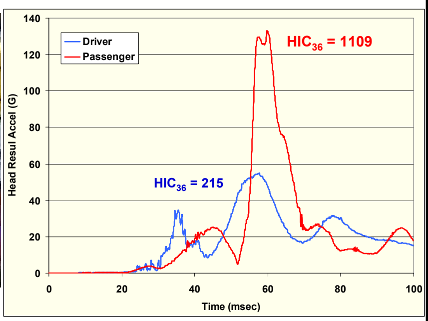


NCAP Test at MCW



US Side NCAP Test

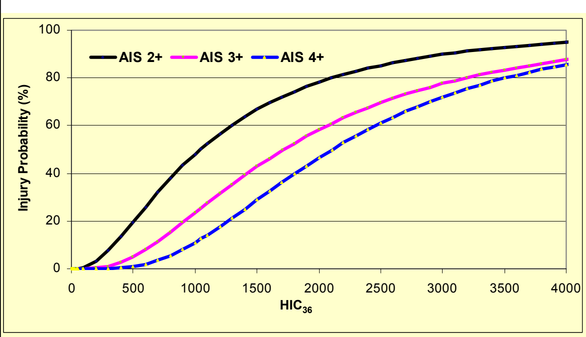




April 2002

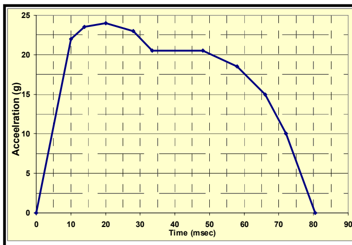
A higher likelihood of head injury is noted if test results in a HIC_{36} value exceeding 1000

Probability of Head Injury

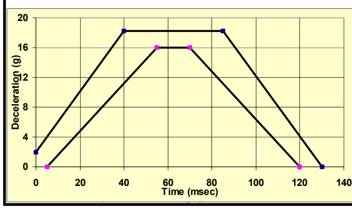


FMVSS 213
Child occupant protection in frontal impact

- Newborn*, 9-month*, 12-month, 3/6-year old dummies
- ΔV of 48 km/h in a sled environment
- HIC_{36} = 1000 is independent of age
- HIC interval changes to 36 ms 8/05



Current



After August 2005

FMVSS 201
Occupant protection in interior impact

HIC = 0.75446 (free motion headform HIC_{36}) + 166.4 <1000

- A-pillar and B-pillar and instrument panel tests
- 6.8 kg, 165-mm diameter, free motion headform
- Impacts speed 24 km/h
- Head g ≯80 g for 3 ms

MEDICAL COLLEGE OF WISCONSIN Department of Neurosurgery, Milwaukee, WI, USA

FMVSS	HIC	Limit	Dummy Anthropometry
201	36	1000	Adult – head-form
213	36 (8/05)	1000	3- and 6-year old
208	15	700	Adult and 6-year old
	15	570	3-year old
	15	390	12-month old
214	36	1000	Adult

MEDICAL COLLEGE OF WISCONSIN Department of Neurosurgery, Milwaukee, WI, USA

Thank you

MEDICAL COLLEGE OF WISCONSIN Department of Neurosurgery, Milwaukee, WI, USA

Criteria for Head Injury and Helmet Standards

Jim Newman
NBEC Inc.

Snell Memorial Foundation Seminar
Medical College of Wisconsin,
Milwaukee, Wisc., 6 May 2005

On the Use of the Head Injury Criterion (HIC) in Protective Headgear Evaluation

James A. Newman
Mechanical Engineering, University of Ottawa

PROCEEDINGS OF
NINETEENTH STAPP CAR CRASH CONFERENCE

November 17-19,1975
San Diego, California

Head Injury Assessment Functions.

A head injury assessment function (HIAF) is a functional relationship between the

probability/severity of brain injury

and some measurable response of the head to impact.

Premises

- Head injury caused by head impact.
- Head impact causes head motion.
- Head motion characterized by rigid body kinematics.
- Kinematics usually expressed as linear acceleration.
- Most head injury assessment functions are based upon acceleration.

Exceptions

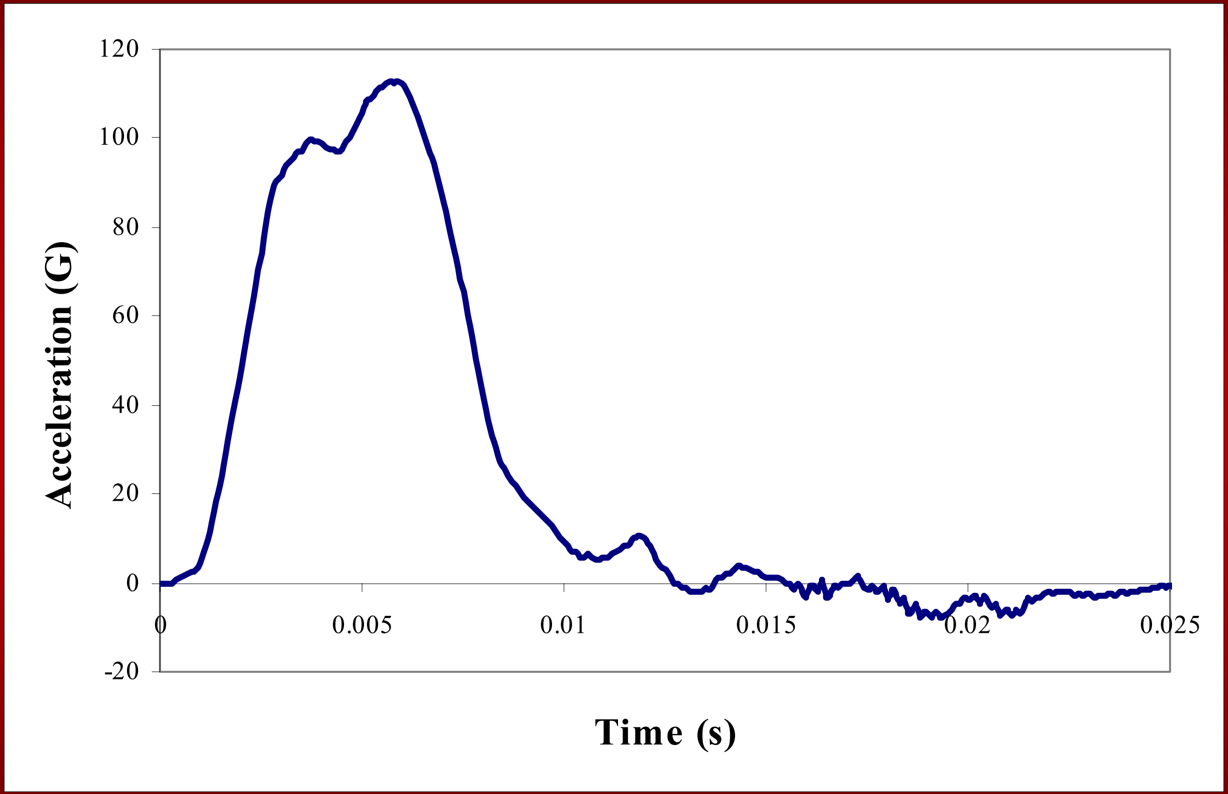
- High speed (ballistic) impact
- Low speed (crushing) loading
- Brain injury secondary to impact (e.g. swelling).
- Facial impact.
- Localized skull deformation.

Linear Kinematic Head Injury Assessment Functions

- **Maximum translational acceleration.**
- Average acceleration plus time duration.
- Gadd Severity Index - GSI.
- Versace “Correction”.
- “Head Injury Criterion” - HIC.

Helmet Impact Test Setup

Headform Acceleration Response



Maximum translational acceleration.

$$a_m < N$$

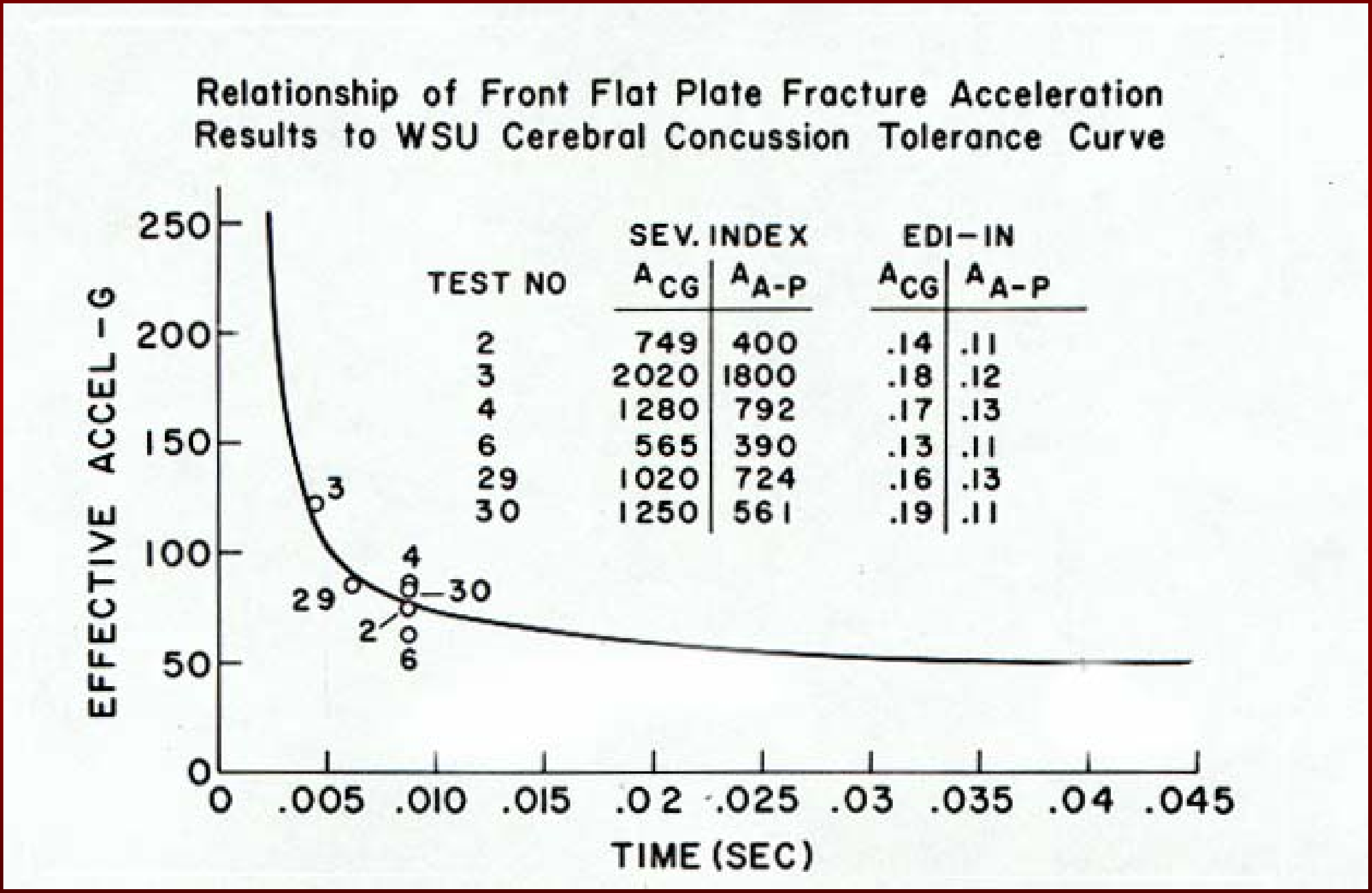
where a_m is the maximum value of the resultant head (c of g) linear accl'n.

- Snell standards

Linear Kinematic Head Injury Assessment Functions

- Maximum translational acceleration.
- **Average acceleration plus time duration.**

Wayne State Concussion Tolerance Curve



Average acceleration and time duration.

$$\overline{a}^{2.5}T < 1{,}000$$

Never ever used to assess head impact severity or head protection systems.

Linear Kinematic Head Injury Assessment Functions

- Maximum translational acceleration.
- Average acceleration plus time duration.
- **Gadd Severity Index.**

Gadd Severity Index (1966).

$$\bar{a}^{2.5} T < 1{,}000$$

$$\int_T a^{2.5}\, dt < 1{,}000$$

- NOCSAE football helmet standard.

Linear Kinematic Head Injury Assessment Functions

- Maximum Translational Acceleration.
- Average acceleration plus time duration.
- Gadd Severity Index - GSI.
- Versace “Correction”.

Versace "Correction". (1971)

$$\bar{a}^{2.5} T < 1{,}000$$

$$[1/T \int_T a(t)dt]^{2.5} T < 1{,}000$$

If he'd only left it alone…………

Linear Kinematic Head Injury Assessment Functions

- Maximum translational acceleration.
- Maximum acceleration plus dwell times.
- Gadd Severity Index – GSI.
- Versace Correction.
- **“Head Injury Criterion” - HIC.**

“Head Injury Criterion” - HIC.

$$\left[1/(t_2 - t_1)\int_{t_1}^{t_2} a(t)dt\right]^{2.5}(t_2 - t_1) < 1{,}000$$

FMVSS 208 - occupant protection

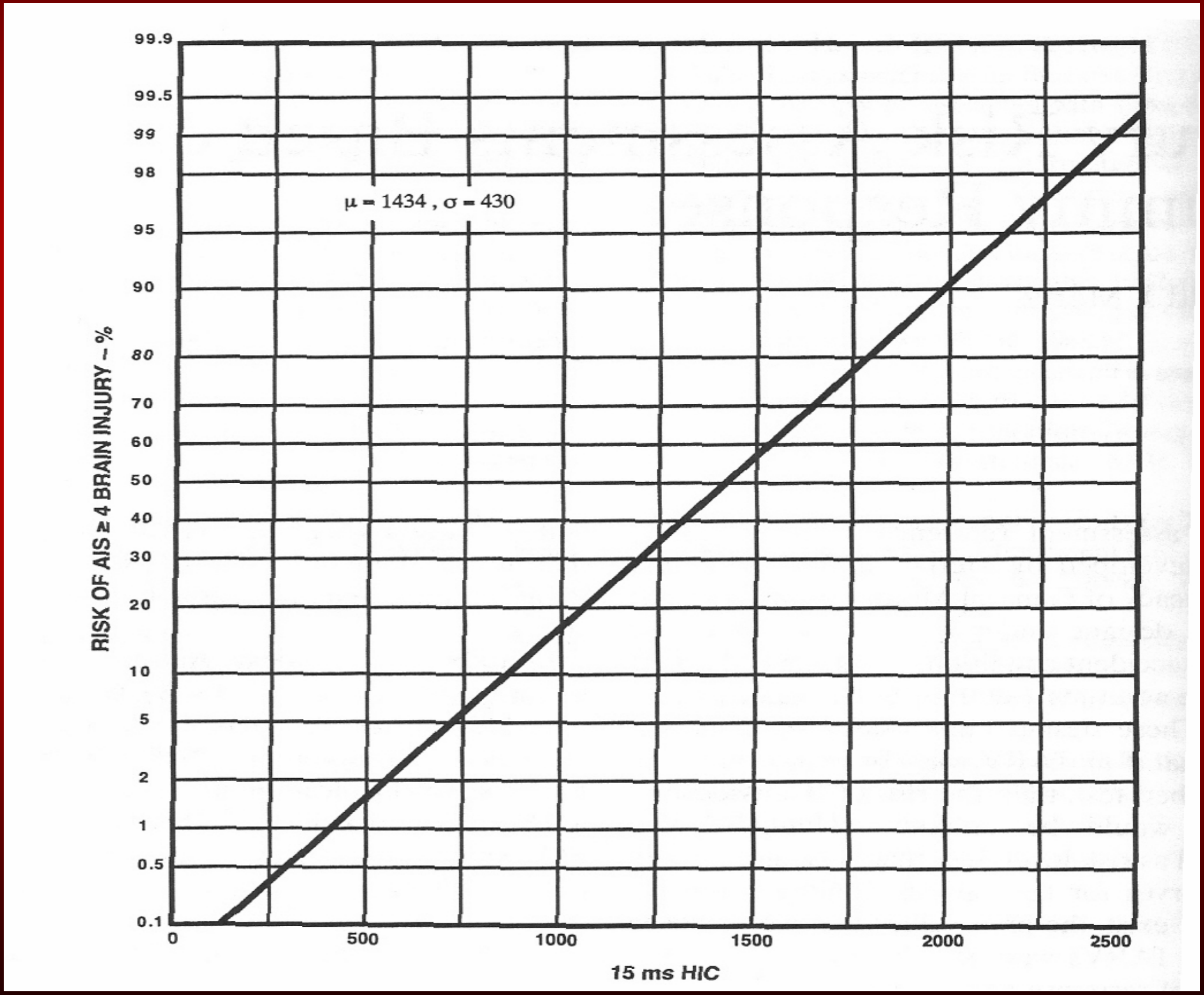
What’s wrong with HIC?

1. Introduced by NHTSA without peer review.
2. Assigns attributes to a(t) based on a_{ave}
3. Provides “unsafe pulse” within a “safe” pulse.
4. Has nonsensical units.
5. Takes no consideration of
   1. *Injury type.*
   2. *Rotation.*
   3. *Direction.*
   4. *Mass.*

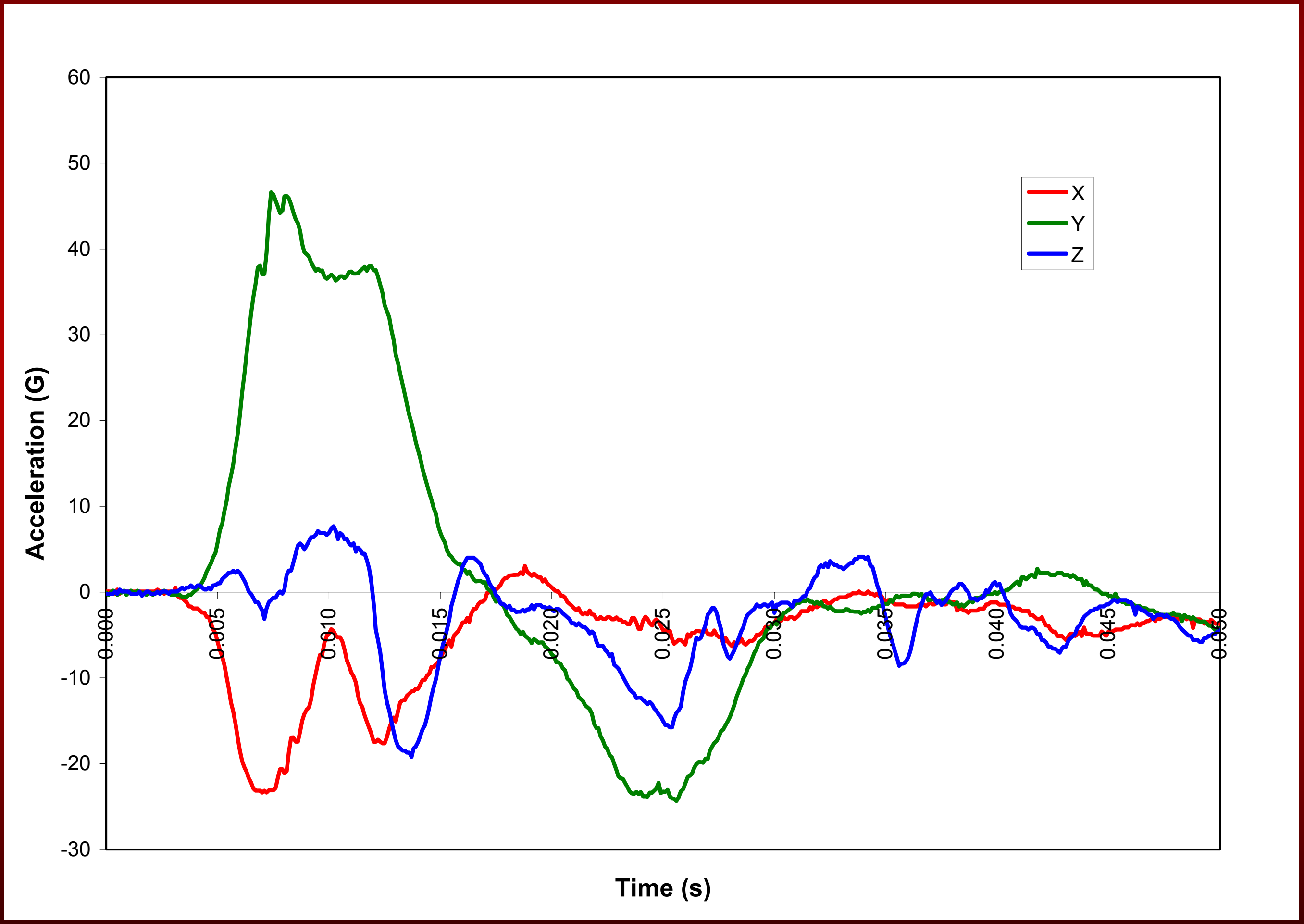
What’s right with HIC?

1. It contains a_{max}.
2. It correlates better than a_{max} because it introduces part of the “time duration” factor.
3. Risk curves have been developed.

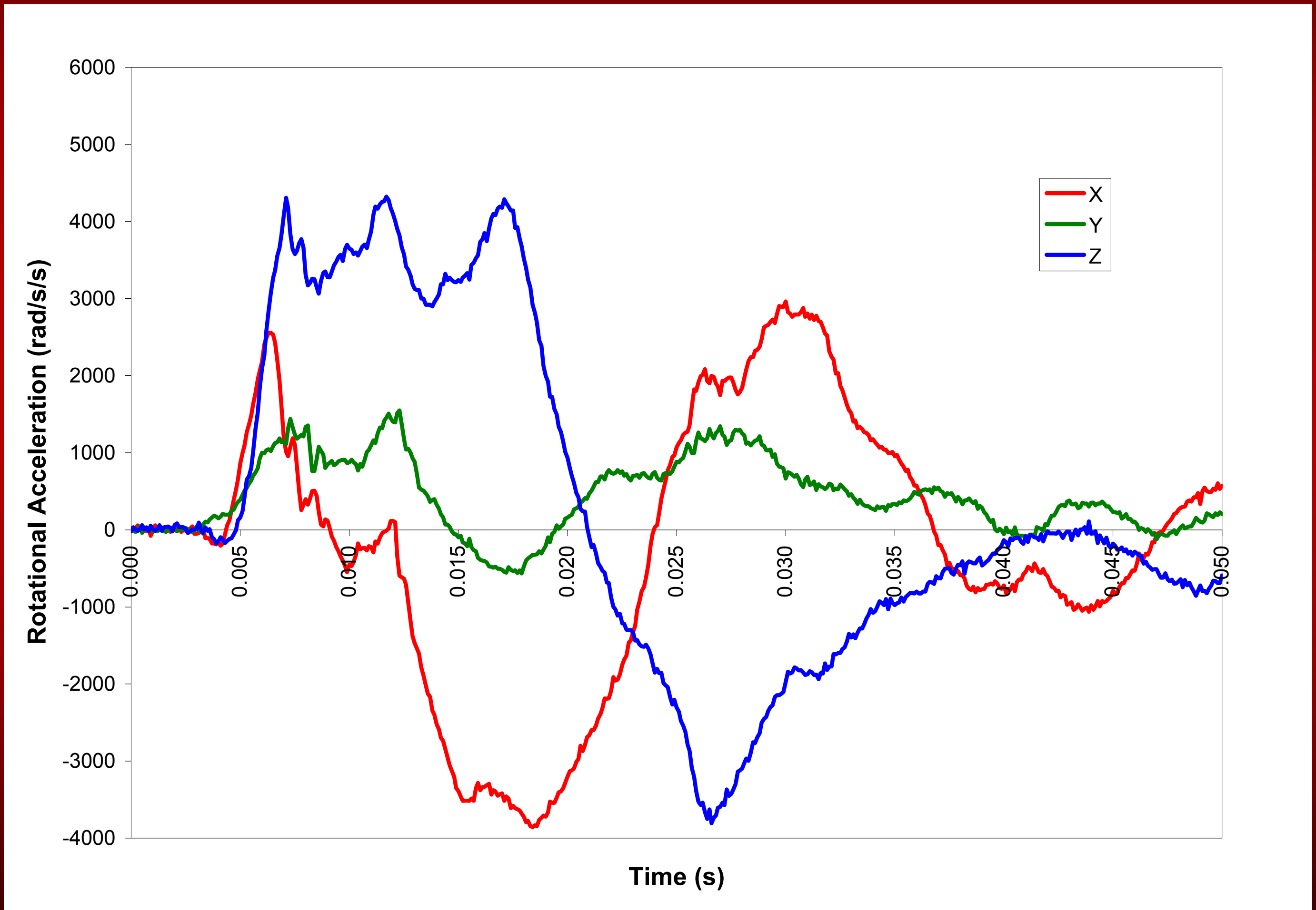
HIC Brain Injury Risk Curve (Mertz)



Linear Headform Response



Rotational Headform Response



Appendix 9—Relevant Papers

Anthropometry and Mass Distribution for Human Analogues, Volume I: Military Male Aviators, Harry G. Armstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio 45433-6573 AAMRL-TR-88-010, Naval Aerospace Medical Research Laboratory, Pensacola, Florida 32508-5700, NAERL-1334, Naval Air Development Center, Warminister, Pennsylvania 18940-5000 NADC-88036-60, Naval Biodynamics Laboratory, New Orleans, Louisiana 70189-0407, NBDL 87R003, U.S. Air Force School of Aerospace Medicine, Brooks Air Force Base, Texas 78235-5301, USAFSAM-TR-88-6, U.S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama 36362-5292, USAARL Report No. 88-5, March 1988.

ECE22rv4 Helmet Standard (Regulation No. 22: Uniform Provisions Concerning the Approval of Protective Helmets and of Their Visors for Drivers and Passengers of Motor Cycles and Mopeds.)

Aare M, Kleiven S, Halldin P. Injury Criteria for Oblique Helmet Impacts. In: *IRCOBI Conference – Lisbon (Portugal),* September 2003. Division of Neuronic Engineering, CTV – Centre for Technology within Health Care, Royal Institute of Technology and Karolinska Institute, Stockholm, Sweden.

Gadd CW. Use of Weighted-impulse Criterion for Estimating Injury Hazard. In: *Proceedings of the Tenth Stapp Car Crash Conference*. Society of Automotive Engineers, Inc., New York, 1966.

Gadd CW. Tolerable Severity Index in Whole-Head, Nonmechanical Impact. In: *Proceedings of the 15th Stapp Car Crash Conference.* Society of Automotive Engineers, Inc., New York, 1972.

Hodgson VR, Impact, Skid and Retention Tests on a Representative Group of Bicycle Helmets to Determine Their Head-Neck Protective Characteristics. Department of Neurosurgery, Wayne State University Detroit, Michigan. February, 1990.

Hodgson VR. Skid Tests on a Select Group of Bicycle Helmets to Determine Their Head-Neck Protective Characteristics. Department of Neurosurgery Wayne State University, Detroit, Michigan. 1991.

King AI, Yang KH, Zhang LY, Hardy W, Viano DC. Is Head Injury Caused by Linear of Angular Acceleration? In: *IRCOBI Conference – Lisbon (Portugal),* September 2003.

McIntosh AS, McCrory P. Impact Energy Attenuation Performance of Football Headgear. In: *British journal of Sports Medicine*. 2000; Vol. 34:337–341 337.

Mertz HJ, Prasad P, Irwin AL. Injury Risk Curves for Children and Adults in Frontal and Rear Collisions. In: *Proceedings of the 41st Stapp Car Crash Conference*. Society of Automotive Engineers, Inc. New York, 1997.

Mertz HJ. Injury Risk Assessments Based on Dummy Responses. In: *Accidental Inju ry*, New York, Spring-Verlag: 89-102, 2002.

Newman JA. Biomechanics of Head Trauma: Head Protection. In: *Accidental Injury*, New York, Spring-Verlag: 303-323, 2002
.
Newman JA, Schewchenko N, Welbourne E. A Proposed New Biomechanical Head Injury Assessment Function – The Maximum Power Index. In: *Proceeding of the 44th Stapp Car Crash Conference.* Society of Automotive Engineers, Inc. New York, 2000.

Prasad P. Biomechanical Basis for Injury Criteria Used in Crashworthiness Regulations. In: *IRCOBI Conference – Sitges (Spain)*, September 1999.

Richter M, Otte D, Lehmann U, Chinn B, Schuller E, Doyle D, Sturrock K, Krettek C, FRACS. Head Injury Mechanisms in Helmet-Protected Motorcyclists: Prospective Multicenter Study. In: *The Journal of Trauma*, 2001. Vol. 51:949 –958.

Snell M2005 Standard for Motorcycling Helmet. Snell Memorial Foundation, Inc., North Highlands, CA, 2005.

Thom D. Peak D and HIC Data for MCW. Collision and Injury Dynamics, Inc. 149 Sheldon Street, El Segundo, CA 90245. May 2005.

Thom DR, Hurt, Jr. HH. Conflict of Contemporary Motorcycle Helmet Standards. In: *The 36th Annual Proceedings of Association for the Advancement of Automotive Medicine*, October 5-7, 1992, Portland, OR. pp. 163-174.

Thom DR, Hurt, Jr. HH, Smith TA, Ouellet JT. Feasibility Study of Upgrading FMVSS No.218, Motorcycle Helmets. Final Report: Contract DTNH22-97-P-02001. U.S. Dept. of Transportation, National Highway Traffic Safety Administration, 400 7th St. S.W. Washington, DC 20590. 1997.

VINCZE-PAP, Sandor and AFRA, Zsombor. Comparative Impact Tests on Helmets. (http://www.autokut.hu/au_varsohelmet.htm) 2/9/2005.

Versace J. A Review of the Severity Index. In: *Proceeding of the 15th Stapp Car Crash Conference*. Society of Automotive Engineers, Inc. New York, 1972. pp.771-796.

Yoganandan N, Pintar FA, Zhang J, Gennarelli TA, Beuses N. Biomechanical Aspect of Blunt and Penetrating Head Injuries. In: *IUTAM Symposium on: Biomechanics of Impact: from fundamental insights to applications, July 11-15, 2005, Dublin, Ireland*, 173-184.