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Motorcycle Helmet Impact Response: Comparison of Helmet Type and Impact Severity

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ABSTRACT

Helmets reduce the frequency and severity of head and brain injuries over a broader range of impact severities than covered by the various impact attenuation standards. Our goal was to compare, over a wide range of impact speeds, the impact attenuation performance of a number of common helmets varying from an inexpensive, non-approved beanie helmet to high-end, DOT- and Snell-approved full-face helmets. We conducted 32 single drop tests of six different helmets on a flat anvil at impact speeds of 1.2 to 10.1 m/s (energy = 3.7 to 259 J; equivalent drop heights of 7 to 518 cm). The beanie helmet reached a peak headform acceleration of 852g at 29 J and was not tested at higher energies. Three full-face and one open-face helmet responded linearly to between 290g and 345g at about 260 J, and a shorty-style helmet behaved like the full-face helmets up to 150 J, above which its acceleration rose to 663g at 242 J. Restitutions varied from 0.23 to 0.43 for the approved-helmets. Across all severities and helmets tested, the open- and full-face helmets generated the lowest headform acceleration and therefore provided the best protection against head and brain injury.

INTRODUCTION

Helmets reduce the frequency and severity of head and brain injuries resulting from motorcycle crashes (Hurt et al., 1981; Shankar et al., 1992; Rowland et al., 1996). They achieve this reduction by attenuating head acceleration and distributing the impact force over a larger area of the head. The effectiveness of helmets in mitigating injury has led to laws requiring motorcycle helmet use in many jurisdictions, and most of these laws stipulate some minimum impact performance requirement for an approved helmet. In North America, most helmets comply with standards set out by the Department of Transportation (DOT, 2001) and/or Snell Memorial Foundation (Snell, 2005). In Europe, most helmets comply with standards set out by the Economic Commission for Europe (ECE, 2002).

Approved helmets generally consist of full-face, open-face and shorty style helmets, all comprised of energy absorbing liners within a hard shell. Non-approved helmets have no or inadequate energy absorbing liners and are variously called beanies, skull caps, novelty, bogus or phoney helmets. They are estimated to make up about 10% of helmets in jurisdictions where they are illegal (Peek-Asa et al., 1999) and are potentially more common in jurisdictions where they are not illegal. Although non-approved helmets produce head injuries more than twice as frequently and severe as approved helmets (Peek-Asa et al., 1999), there are few tests quantifying their actual impact performance (Hurt et al., 1996).

Motorcycle helmets are tested most commonly under the conditions stipulated by the various helmet standards (Mitsubishi et al., 1994; Hurt et al., 1996). These conditions consist of radial helmet impacts onto variously-shaped anvils at a finite number of impact speeds. In actual crashes, however, motorcycle helmets see a broad range of impact conditions, with widely varying impact angles, impact surfaces and impact severities. Recent efforts to develop a test protocol to examine the effect of impact angle are promising (Aare and Halldin, 2003), but the impact performance of many commercially-available helmets over a wide range of impact severities in simple radial impact tests has yet to be documented. Some impact performance data for ECE-approved helmets at impact speeds from 0.5 to 10.0 m/s have been published (Schuller et al., 1993; Zellmer, 1993; Mellor and StClair, 2005), but similar data for many common helmets used in North America do not exist.

Our goal was to compare over a wide range of impact speeds the impact attenuation performance of motorcycle helmets varying from an inexpensive, non-approved beanie helmet to high-end, DOT- and Snell-approved full-face helmets. We used a radial impact test because of its simplicity and we performed our impact tests against a flat anvil because flat surfaces are the most common type of struck surface (Hurt et al., 1981; Wobrock et al., 2003).

METHODS

Six helmet models were tested (Figure 1, Table 1). All helmets had soft foam comfort liners, but only the five approved helmets also had expanded polystyrene (EPS) energy-absorbing foam liners. There was no energy-absorbing liner in the beanie (Voss Classic 45). All helmets were medium size and fit the magnesium alloy headform (ISO J, Half Magnesium K1A, Cadex Inc., Quebec, Canada). The beanie and shorty helmets were tested without their snap-on visors, and the visors for the open- and full-face helmets were cut to accommodate the ball arm (Figure 2a). The removable ear flaps of the shorty helmets remained installed for the tests (Figure 1b).

A 6 m tall monorail and trolley assembly guided the helmets during the drop tests (Figure 2a). The headform was fastened to the trolley via a ball arm angled downwards at 25°. The helmet's strap was clamped to a surrogate chin. A uni-axial $\pm 2000g$ accelerometer (7264B-2000T, Endevco, San Juan Capistrano, CA) was fixed into the ball arm where it fastened to the headform. The total mass of this moving assembly was 5.09 kg.

Impact speed was measured with a speed trap located within 40 mm of impact and impact speed accuracy was better than ± 0.5 percent at 10 m/s. Speed trap and accelerometer signals were acquired at 100 kHz and the accelerometer data was digitally low-pass filtered at 1650 Hz using a 4th-order dual-pass Butterworth filter. Impact energy was calculated using the moving assembly mass and impact speed. Helmet mass was not included in this calculation. Rebound speed was also determined from the speed trap and restitution was calculated as the ratio of rebound speed to impact speed. Acceleration time spent above 150g and 200g was also determined.

The test setup and equipment used for these tests were based on but did not strictly comply with the requirements stipulated by the Snell standard. Each helmet was dropped once onto a flat steel anvil. The flat anvil was perpendicular to the headform trajectory and measured 30 cm x 30 cm.

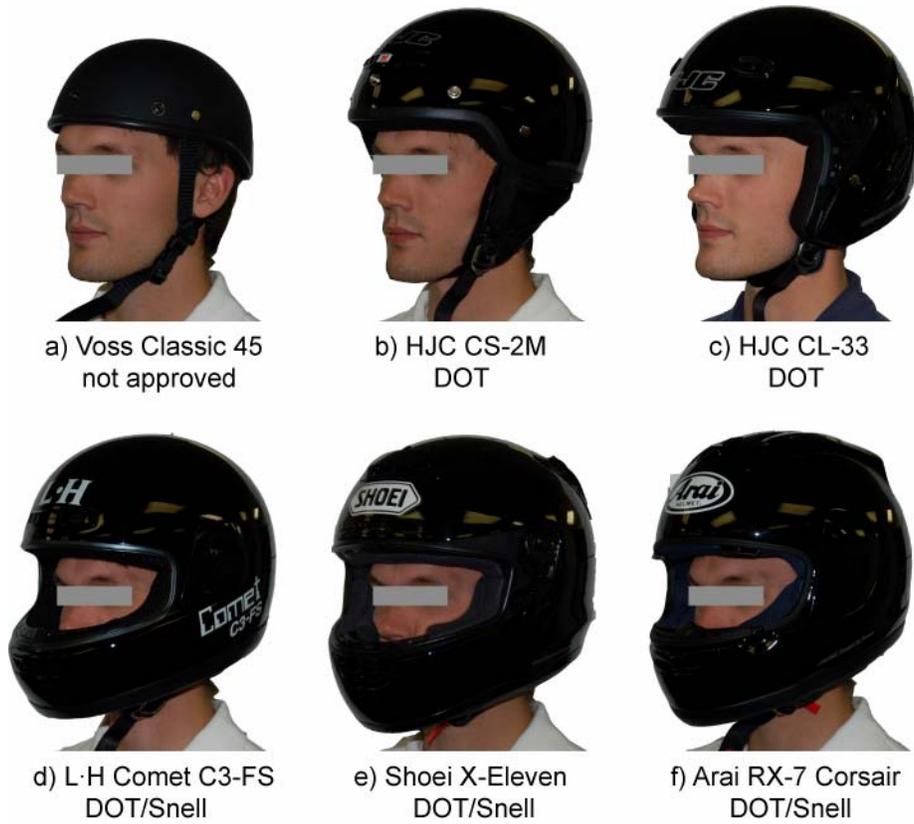


Figure 1: The Helmets Used in This Study and The Standards They Meet.

Table 1. Description of Helmets Tested. All Helmets Acquired in 2006, Except the L-H Comets, Which Were Acquired in 1995.

Make and Model	Type	MSRP*	Mass (g)	Approved by
Voss Classic 45	Beanie	~\$50	390	None
HJC CS-2M	Shorty	~\$65	980	DOT
HJC CL-33	Open-face	~\$100	1074	DOT
L-H Comet C3-FS	Full-face	~\$100	1613	DOT, Snell
Shoei X-Eleven	Full-face	~\$600	1424	DOT, Snell
Arai RX-7 Corsair	Full-face	~\$600	1423	DOT, Snell

* Manufacturer's suggested retail price, US\$

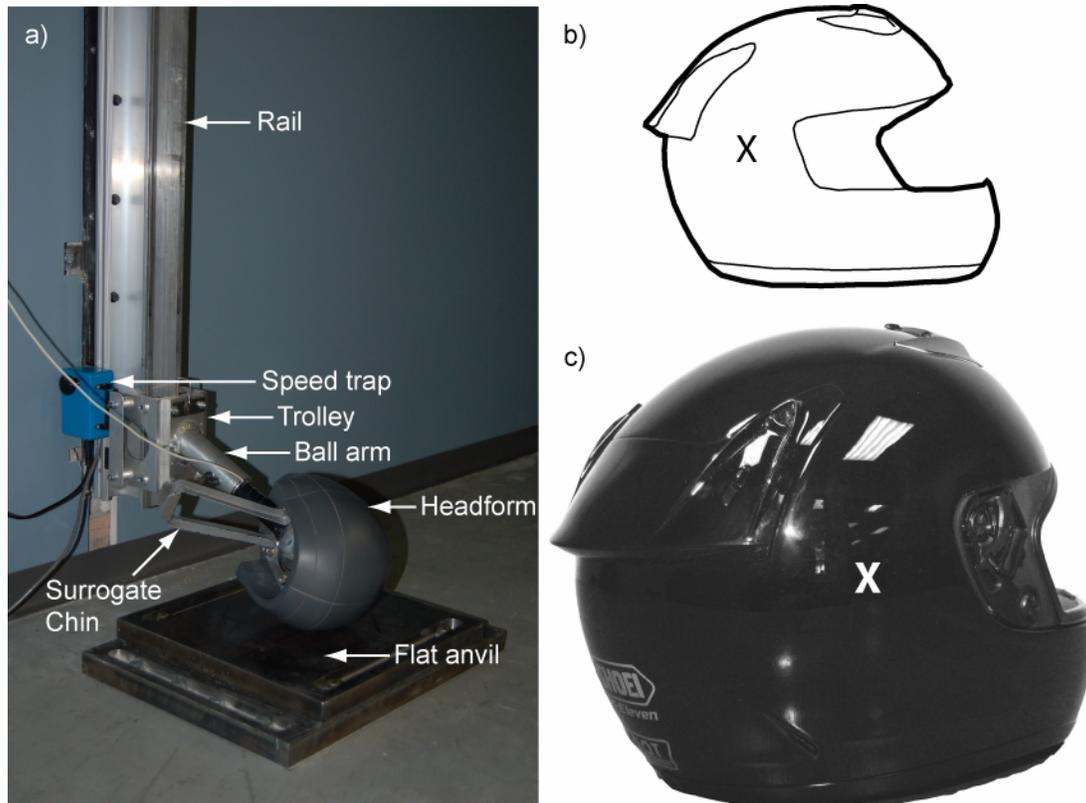


Figure 2: a) Test Setup, b) Lateral Schematic of The Shoei Helmet, and c) ¾ View of The Shoei Helmet. The X's Depict The Right Side Impact Location of Most Tests.

Thirty-two drop tests were conducted with the right side of the helmet (X in Figures 2b and 2c) striking the flat steel plate anvil at impact energies between 3.7 and 259 J. To ensure consistent helmet positioning, the helmet positioning index was measured before each impact (Snell, 2005).

RESULTS

For the right side impacts onto the flat anvil, all helmets showed increasing peak headform acceleration with increasing impact energy (Figures 3a-f). All three full-face helmets and the HJC open-face helmet behaved similarly—and essentially linearly—up to peak headform accelerations of between 290g and 345g at about 260 J of impact energy (Figures 3a and 3f). The HJC shorty helmet behaved similar to the full-face helmets up to 150 J, above which the peak headform acceleration increased steeply to 663g at 242 J (Figures 3b and 3d). The beanie helmet response was also linear, but reached a peak headform acceleration of 852g at only 29 J (Figures 3b and 3c).

Restitution averaged 0.34 ± 0.04 (range 0.23 to 0.42) for all of the approved helmets in the flat anvil tests (Figure 3h). Above 90 J, restitution was always greater than 0.30. The beanie helmet did not rebound enough to retrigger the speed sensor, but based on high speed video data had a restitution between 0.14 and 0.24. All approved helmets remained above 150g for less than 4 ms and 200 g for less than 2 ms at impact energies of 120 J or less (Figure 3h).

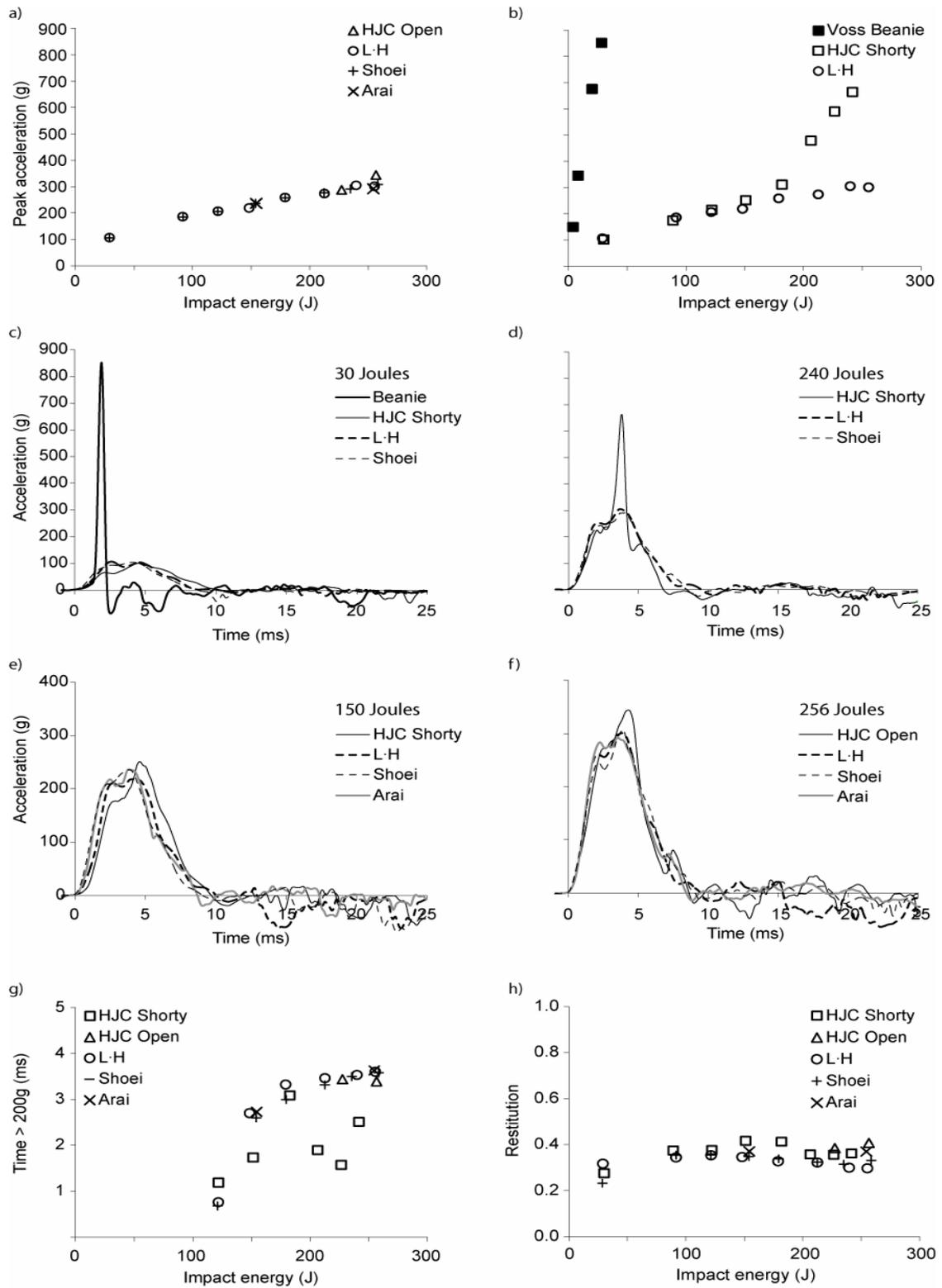


Figure 3: Right Side Impacts Onto The Flat Anvil. a) and b) Summary Of Peak Acceleration vs. Impact Energy Data; c) through f) Show Acceleration vs. Time For 30, 240, 150 And 256 J, respectively; g) Time Acceleration Exceeded 200g vs. Impact Energy; and h) Restitution vs. Impact Energy.

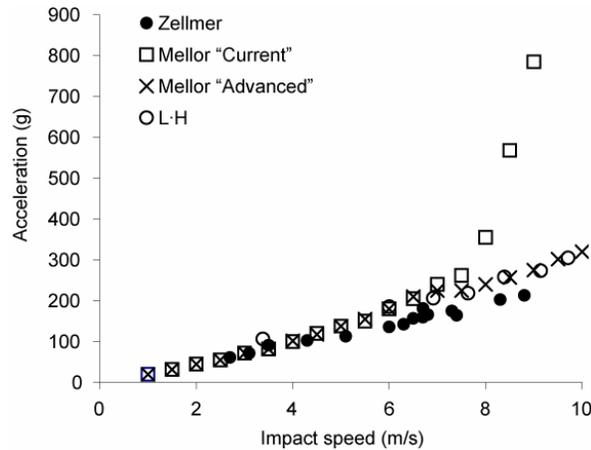


Figure 4: Comparison Of The ECE Helmet Data (Zellmer, 1993; Mellor And StClair, 2005) Against Our L-H Helmet Data. [The “Current” Helmet Is An ECE Approved Helmet; The “Advanced” Helmet Is One Developed By Mellor And StClair (2005).]

DISCUSSION

In this descriptive study, we quantified the impact performance of some common helmets over a range of impact severities. Although the number and type of tests conducted on each helmet did not strictly adhere to the requirements set out by either the DOT or Snell standards, the acceleration responses measured suggest that the approved helmets would comply with the standards they claimed to meet.

As expected, the beanie (Voss Classic 45), clearly marked as a novelty item and not claiming to meet any helmet standards, performed poorly. We did not plan to conduct tests below 30 J; however, after the beanie’s first test produced a peak acceleration of 852g, we decreased rather than increased impact severity to quantify this helmet’s performance. Even at 3.7 J—equivalent to an impact speed of 1.2 m/s and a drop height of only 7 cm—the beanie produced a peak headform acceleration of 150g. Linearly extrapolating these findings suggest that this beanie would exceed 2500g at 90 J—considerably worse than other “bogus” helmets that reached 1100 to 1700g during DOT testing (Hurt et al., 1993).

The steep increase in peak acceleration of the shorty helmet (HJC CS-2M) above 180 J (8.4 m/s, Figure 3b) occurred on the second of two peaks making up its acceleration response (Figure 3d). This acceleration response pattern suggests a transition to a stiffer response as the energy liner “bottomed out.” Similar bottoming-out behavior has been previously observed between 7 and 8 m/s in ECE-approved helmets (Schuller et al., 1993; Mellor and StClair, 2005). This bottoming-out behavior was not observed in the other approved helmets we tested, and may prevent the shorty helmet from meeting the double impact requirement of the Snell standard (Snell, 2005).

Although the remaining open- and full-face helmets behaved essentially linearly up to 256 J (10 m/s), these helmets are also expected to show a bottoming-out response at some impact level. The HJC CL-33 (open-face) and perhaps the Shoeni X-Eleven may be starting to show this bottoming-out response in their accelerometer traces at 256 J (compare their response in Figure 3f with the HJC response at 150 J in Figure 3d). Further work at impact severities above 256 J is necessary to confirm the level this bottoming-out response occurs in the open- and full-face helmets tested.

There remains some debate in the popular and scientific literature regarding which standard—DOT or Snell—produces “better” helmets (Ford, 2005; Thom, 2006). The helmets tested showed essentially no difference in peak acceleration responses between the DOT-only and the DOT+Snell helmets in the sub 150 J range relevant to both standards. While a helmet could conceivably be designed to trade off poorer performance above 150 J for better performance below 150 J (Schuller et al., 1993), this was not the case for either the shorty helmet tested or an ECE-approved helmet tested by Mellor and StClair (2005) (Figure 4).

The “advanced protective helmet” developed by Mellor and StClair (2005) also did not exploit this phenomenon, but rather yielded a helmet with a radial impact response similar to the commercially-available full-face helmets we tested (Figure 4).

The three distinct response patterns observed between the beanie, shorty and open/full-face helmets cannot be extrapolated to all beanie, shorty and open/full-face helmets. Others have shown variability between similar styles of helmets at isolated test energies (Hurt et al., 1996; Thom 2006) and therefore we expect similar variability over the wider range of impact speeds used here. This study was also limited to the linear kinematic responses produced by radial impacts of the side of the helmet onto a flat anvil. As a result, these data should be applied cautiously to the many actual helmet impacts that differ from our experimental conditions.

CONCLUSIONS

We have described the impact attenuation response of several commonly available helmets over a wide range of impact severities. Based on these data, beanie helmets provide scant protection against head injury. The approved helmets behaved similarly at impact severities below 150 J, but diverged above this impact level. Across all severities and helmets tested, the open- and full-face helmets generated the lowest headform acceleration and therefore the best protection against head and brain injury.

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DISCUSSION

PAPER: **Motorcycle Helmet Impact Response: Comparison of Helmet Type and Impact Severity.**

PRESENTER: *Alisa L. DeMarco, MEA Forensic Engineers & Scientists, CA*

QUESTION: *Guy Nusholtz, Daimler Chrysler*

It's an interesting study, but the joule levels you're getting are extraordinarily high. I think it's primarily because you're testing them against a flat impact. These helmets that you test will not take 250 joules at a single impact against the hemi-anvils. The best you're gonna get is probably about 180, maybe 190 joules. The high standard in the world is the FIA Super-helmet standard, which is going online fairly soon, and that's gonna be for single impact somewhere around 220 joules against a hemi-anvil. So in the comparison testing if you don't use the hemi-anvil, you're only testing a very limited circumstance under which these helmets are tested. So, you have to be somewhat careful in extending this information in a general way because these helmets are designed to optimize between two extreme conditions of impact: One is a flat anvil and one is a hemi, which is 1.9 inch radius of curvature impact. So, it would be interesting if you would redo the experiments against the hemi-anvil.

ANSWER: Thank you. What we're doing here is mostly a comparison of the beanie helmet to the other helmets, and that's why we chose to do them all on one anvil. We have conducted some preliminary tests on an edge anvil and we just haven't finished compiling that data yet; but something that we are considering is the other anvil approach.

Q: *Hans Delye, Catholic University of Leuven, Belgium*

Did you look at the damage that the helmets showed after the impact so you can compare those?

A: Yes, that's actually the second phase of our study is to look at the damage sustained by each one of the helmets at the different impact energies and try to come up with a correlation between the damage sustained by the helmet and the impact severity. In that way, we're hoping that we can look at a damaged helmet and understand the type of acceleration that the person would have been exposed to for that particular impact.

Q: One of the reasons I question that is because our research center is interested in bicycle helmets, which are more or less a beanie helmet with some liner to get some energy absorbed. But, I wondered if the beanie helmet did so bad in the test. Did you actually see beanie helmet, like, tearing apart with sharp edges into the inside or something like that?

A: Interesting enough: With the beanie helmet, we did not see any sort of tearing apart damage at all. We could see a minor flat spot where the impact occurred and just basically disruption to the shining of paint, but that was basically it.

Q: Thank you.

A: You're welcome.

Q: *Erik Takhoumts, National Highway Traffic Safety Administration*

I'll ask, also, a question, if I may. You pointed out one of the impacts, which is 400 g's, but there are two more, which is 200 g's in 4 milliseconds and 150 g's in 2 milliseconds. So, have you looked at those, as well, in your comparison study?

A: We've collected the data and we've analyzed it in that way. It appears that all the helmets that we tested, if they said they met the standards, they did.

Q: Okay. Are you planning to look at European regulations also?

A: No, we're not planning to look at that. We're not really trying to certify any of these helmets. We're more trying to compare them to each other and see how they perform. We're not interested in any

particular standard. We just kind of used the Snell and DOT standards as a loose guideline as to how we were going to set up our tests.

Q: Thank you.

A: You're welcome.

Q: Thank you, Alisa.