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Analysis of Helmet Impact Velocity Experimental Data and Statistical Tolerance Design

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7. Authors
Jingshu Wu,[1] Ph.D., P.E., Charles Fleming,[1] Claudia Covell[2]
1 – NCSA, 2- Enforcement of NHTSA

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16. Abstract
Helmet impact velocity experimental data is analyzed and various factors that influence the impact velocity are studied. One of the main goals of this report is to verify whether a tolerance of +/- 3 percent of mean velocity is feasible and will allow at least 95 percent of impacts to fall within the proposed impact velocity range. Statistical methods are applied to the design of impact velocity tolerances. Calibration procedures and data variances from several laboratories are also incorporated into this analysis.

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Helmet impact attenuation test, impact velocity, design of experiments, statistical tolerance analysis, General linear model, and calibration of test instruments.

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1. INTRODUCTION

The National Highway Traffic Safety Administration has the statutory authority to issue Federal Motor Vehicle Safety Standards (FMVSS) applicable to new motor vehicles and items of motor vehicle equipment, including motorcycle helmets. The law establishes a self-certification process in which the vehicle and equipment manufacturers themselves certify that their products are in compliance with all applicable FMVSS, which establish minimum criteria that the product must meet. NHTSA enforces the standards by randomly selecting and purchasing equipment from the marketplace and testing to the requirements of the standard at independent test laboratories. One such test is the motorcycle helmet impact attenuation test for the purpose of ensuring helmets to provide lower levels of energy attenuation during crashes.

The objective of this analysis is to evaluate proposed drop velocity ranges for FMVSS No. 218 motorcycle helmet impacts onto the flat and hemispherical anvil in support of NHTSA's response to comments received for the October 1, 2008, FMVSS No. 218 Notice of Proposed Rulemaking (NPRM). The impact attenuation test is specified in FMVSS No. 218 Sections S5.1 and S7.1. The nominal target velocity onto the hemispherical anvil is 5.2 meter/second and the nominal target velocity onto the flat anvil is 6.0 meter/second. The NPRM proposed the impact velocity ranges of 4.8 to 5.6 meter/second, and 5.6 to 6.0 meter/second, respectively; however, many commenters proposed alternate tolerances. The most common suggestion was to limit the tolerance to +/- 3 percent of nominal target velocity, which would suggest a velocity range of (97% nominal to 103% nominal), or 5.04 to 5.36 meter/second on the hemispherical anvil, and 5.82 to 6.18 meter/second onto the flat anvil, respectively.

One of the main interests of this analysis is to determine how many of the helmet impacts will fall within the proposed velocity range of +/- 3 percent of the nominal velocity, taking into account both uncertainty due to laboratory equipment variance (from calibration procedure and others) and all other variances (such as effects of testing different makes, helmet types, and styles of helmets at different locations that are potentially conditioned to different procedures by different technicians, etc.) as described in the NPRM. Conversely, if the alternative +/- 3 percent of nominal or mean velocity tolerance is determined not to be feasible, then the objective is to identify a tolerance range that would allow at least 95 percent of impacts to fall within the proposed velocity range. Statistical methods are applied to the design of drop velocity tolerances.

The experimental data of helmet drop tests is analyzed, and various factors that influence the drop velocity are studied in detail using statistical regression methods. Instrumental calibration procedures and data variances from several laboratories are also compared with the National Institute of Standards and Technology (NIST) standard.

2. IMPACT ATTENUATION TEST PROCEDURE

This analysis requires understanding the test procedure for the impact attenuation test specified in Section S7.1 of FMVSS No. 218. This description of the test procedure consists of only those parts relevant to this analysis.

Impact attenuation is measured by determining acceleration imparted to an instrumented test headform on which test helmets are mounted. One test series typically consists of four helmets of the same size. Each one of the four helmets is conditioned to one of four conditioning procedures: ambient, low temperature, high temperature, and water immersion. Each of the four helmets is struck a total of eight times using a monorail drop assembly test device; therefore, each test series consists of 32 total drop tests.

To accomplish the eight drop tests per helmet, the person conducting the test (hereafter called the technician) selects four locations on the shell of the helmet and places the ambient conditioned helmet onto the instrumented test headform, which is mounted to the monorail drop assembly. The helmeted headform is aligned so that the first impact location will fall onto the hemispherical anvil.

The helmet impact velocity is determined by the drop height by the following Eq. (1):

$$\text{Impact Velocity (meter/second)} = \sqrt{2gh} \qquad \text{Eq. (1)}$$

Where "g" is gravity acceleration constant (9.81 meter/second^2), and "h" is the drop height (meter).

The helmet is raised to a height approximately 54.5 inches (1.38 meter) from the anvil and allowed to freely drop. The drop height of 54.5 inches (1.38 meter) allows a theoretical impact velocity of 5.2 meter/second from Eq. (1). The velocity is measured at the point when the helmet hits the anvil, and the test data is recorded. The technician raises the helmet and drops it for a second time onto the same location. The helmets conditioned to the low temperature, high temperature, and water-immersed procedures are tested at the same location. The ambient helmet is again placed onto the headform and the headform is realigned to allow impacts at the second location. Again, the helmet is tested with two successive drops at this location and then the other three helmets are tested. The third location is tested similarly. However, the hemispherical anvil is changed to a flat anvil and the drop height is increased to 72 inches (1.83 meter), which results in a theoretical impact velocity of 6.0 meter/second. Testing continues in this order until 32 total drop tests using all four helmets have been completed.

The above test procedure, at each of two test laboratories, can be illustrated by the following flow chart (**Figure 1**). The two laboratories are kept anonymous, simply designated as "Lab A" and "Lab B."

The results, from an in depth statistical analysis, are presented below as Figure 1.

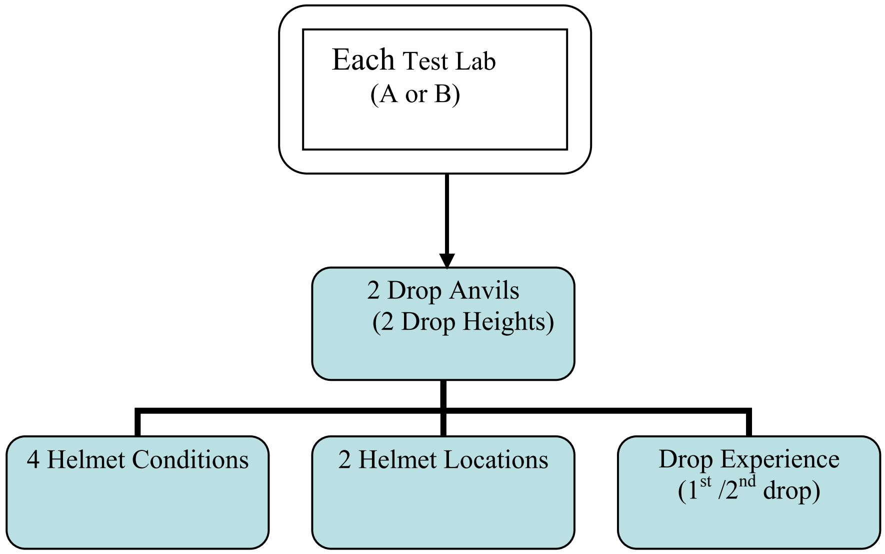

Figure 1: Helmet Drop Test Procedure

Understanding this test procedure allowed the following factors to be considered (see Figure 1):

- Does one laboratory more closely achieve the target velocity than another laboratory?

- Is the target velocity for either anvil (hemispherical or flat, that is determined by drop height) easier to achieve than the other anvil?

- Is the helmet conditioning procedure a factor in achieving target velocity?

- Does the location of the impact influence the ability of the technician to achieve the target velocity?

- Is drop experience (first and second drop) a factor in achieving a target velocity?

These factors are considered as well as the feasibility of achieving the alternative proposed impact velocity ranges for each of the test anvils as described below using statistical tools.

3. METHODS

3.1 General Linear Model for Experimental Data

Design of experiments (DOE) is a process of determining the variations of the interest variables (such as helmet impact velocity of this project), and reasoning about these variables based on the randomization, comparison, replication, blocking, orthogonality, and factorial effects.[2] The analysis of DOE is built on the foundation of the analysis of variance (ANOVA). ANOVA is a collection of models in which the observed variance is partitioned into components due to different factors, and those factors are then estimated and tested against certain hypothesis. Helped by the ideas of advanced algebra and ordinary least squares (OLS), the general linear model (GLM), that including ANOVA, is a comprehensive method to analyze the experimental data.

Under the GLM, the measured helmet drop velocity can be expressed by the following equation:

$$Impact\ Velocity = \mu + \alpha + \beta + \lambda + \delta + \eta + \varepsilon \qquad \text{Eq. (2)}$$

Where μ is the overall velocity mean, α is the effect from drop contact "anvil" type (flat or hemispherical surfaces that are determined by drop heights), ß is the "lab" effect on velocity (Lab A or Lab B), λ is a "condition" effect on impact velocity (four helmet conditions), δ refers to the helmet location (two locations per anvil). Furthermore, we also consider the difference of first drop and second drop of the same location, using "drop experience," or, η, as one extra variable, and ε is random error with an assumed zero mean and variance.[3]

This statistical method will explore the following:

1) Find out the effects on impact velocity from various helmet test conditions, laboratories, contact anvils (drop heights), impact locations and effect of "drop experience,"

2) Compare the velocity mean differences and verify if these comparisons are significant, and

3) Explore the velocity ranges and various confidence intervals (CI), such as common 95 percent CI and 99 percent CI.

3.2 Statistical Consideration of Tolerance Design

In engineering and manufacturing, it is not realistic to manufacture a part with a perfect dimension size, but it is common that a part dimension size has a mean value with a small tolerance. As one analogy and simplest example of tolerance here, a steel shaft diameter has a mean (or nominal) of **μ** =12 mm, with a tolerance of (+/- 0.015 mm), and this implies that the shaft diameter range of (11.985 to 12.015 mm) is acceptable[4] [5] (see **Figure 2**). This same idea also applies to impact velocity that may have a small variation around its mean value.

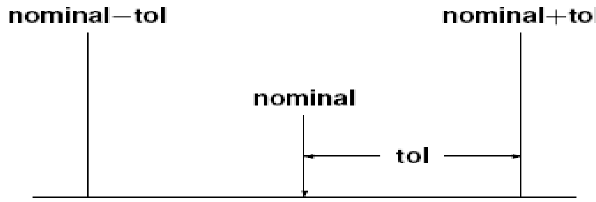

Figure 2: Tolerance and Nominal

Figure 3 further explains the statistical consideration of tolerance design – if the set of experimental data is large enough, and if it follows the Gaussian distribution curve around the mean value of μ with a standard deviation value of σ, then the interval [μ - 3 σ , μ +3 σ] will cover approximately 99.7 percent of the test data.[24] Here, 3 σ can be regarded as the absolute value of a statistical tolerance, which is a common engineering practice and is shown as Figure 3 (the percentage numbers of Figure 3 are approximate).

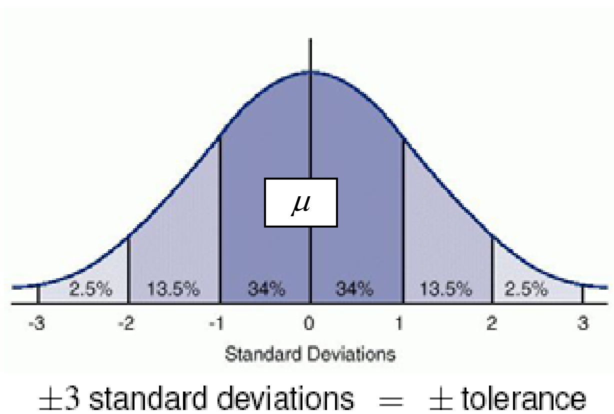

Figure 3: Gaussian Curve used for Statistical Tolerance Design

Or, equivalently, standard deviation, σ = 1/3*(Tolerance), and hence,

$$\text{Tolerance Interval} = [\, \mu - 3\sigma ,\ \mu + 3\sigma \,] \qquad \text{Eq. (3)}$$

The standard deviation in Eq. (3), σ, is the "pooled standard deviation" or "total standard deviation," σ_{total} , of considering human test errors while performing the experiments, σ_{test}, and instrumental errors from different labs, σ_{lab}, which is described by Eq. (4) as following root sum square (RSS) method, if human test errors and instrumental errors are assumed to be reasonably independent to each other;[24]

$$\sigma_{total} = \sqrt{(\sigma_{test}^2 + \sigma_{lab}^2)} \qquad \text{Eq. (4)}$$

4. RESULTS

4.1 Descriptive Tables of Helmet Impact Velocities

Two test laboratories under contract to NHTSA during fiscal years 2007 and 2008, Lab A and Lab B, performed the helmet drop tests. Lab A performed 1,280 drops using 38 helmets, and Lab B performed 1,216 drops using 39 helmets. Figure 1 illustrates test procedure at either Lab A or Lab B; the helmets are dropped onto two different anvils (or drop surfaces /drop heights), struck at two helmet locations for each anvil, and two drops at each location (assume first drop as "not-experienced" and second drop as "experienced"). Furthermore, the helmets are with four different test conditions (low temperature, high temperature, and water-immersed). The appendix in Section 8 provides partial drop data samples onto two anvils.

The descriptive statistical results of impact velocities of combined two laboratories are listed as **Table 1**. The helmets are dropped onto two different surfaces, and the test results indicate that they have relatively small standard deviations due to test protocol and procedure by test technicians, σ_{test}, and the ratio of standard deviation over the mean (coefficient of variation, or CV) is also small. The range of "mean +/- 3 percent mean" is wider than the range of 95 percent confidence interval.

Table 1: Velocity 95 percent CI and a Range of "Mean +/- 3 Percent Mean"

Drop Anvil	Mean μ	Standard Deviation σ_{test}	CV= $(\sigma_{test}/\mu)100\%$	95%CI, μ +/-(2 σ_{test})	μ +/- (3% μ)
Hemis-pherical	5.23	0.045	0.86%	[5.14 – 5.32]	[5.07 – 5.39]
Flat	6.00	0.048	0.80%	[5.90 – 6.10]	[5.82 – 6.18]

Table 2 provides the velocity results of experimental data, per drop anvil, from two different labs, and it indicates that the result from Lab A has a smaller deviation for both anvils.

Table 2: Impact Velocity Test Data by Laboratory

Drop Anvil	Lab	Mean μ	Standard dev. σ_{test}	Minimum	Maximum
Hemispherical	A	5.21	0.036	5.06	5.29
	B	5.25	0.046	5.11	5.37
Flat	A	5.99	0.036	5.87	6.08
	B	6.00	0.057	5.82	6.16

4.2 Impact Velocity Regression Results of General Linear Model

The results from the GLM, as Eq. (2), indicate either a statistically significant or non-significant contribution to the variance in the dependent variable, impact velocity, from each independent variable, such as helmet location or test condition. The traditional p-value of 0.05 is used as the threshold of statistical significance. For example, if a p-value of 0.20 is obtained for the variable "condition," this implies that changes in condition do not result in statistically significant changes in drop velocity.

Table 3: GLM Regression Results of Impact Velocity Data

Source	p-value	Comments
Anvil (height)	<0.0001	Statistically significantly different
Lab	<0.0001	Statistically significantly different
Experience	0.2123	Not statistically significantly different
Location	0.7412	Not statistically significantly different
Condition	0.3757	Not statistically significantly different

Table 3 indicates that "anvil (drop height)" and "lab" are two statistically significant factors (with p-values far under 0.05) that influence the impact velocity, while "condition', "location," and "drop experience" (or first and second drop) are not significant factors with p-values much larger than 5 percent.

4.3 Deviations From Both Laboratory Instrument and Experimental Test Procedure

This analysis has taken into account the deviations from laboratory instrument calibration, σ_{lab}, as well as experimental test protocol and procedures performed by technicians as shown in Tables 1, σ_{test}. Every year the test equipment at each lab is calibrated to the NIST standards. Records from test labs showing the calibration traceability to the NIST are maintained for all measuring and test equipment. Higher order standards are produced by institutes or international organizations with responsibility for metrological traceability.

Based on the RSS method as Eq. (4), the total standard deviations of the velocities when taking into account of labs (see Appendix of Section 7 for the calculation details of lab deviation, σ_{lab}) and experimental test procedure in Table 1, σ_{test}, are estimated as follows:[4 6]

Hemispherical Anvil: $\sigma_{total} = \sqrt{(\sigma_{test}^2 + \sigma_{lab}^2)} = \sqrt{(0.045^2 + 0.017^2)} = 0.048$

Flat Anvil: $\sigma_{total} = \sqrt{(\sigma_{test}^2 + \sigma_{lab}^2)} = \sqrt{(0.048^2 + 0.020^2)} = 0.052$

Where σ_{lab} is the result of focusing only on the instrumental errors and calibrations against NIST standard, and is independent from the test procedure error, σ_{test}, and Section 7 provides more details.

The following **Table 4** provides the drop velocity ranges with 95 percent CI, 99% CI, and the range of "velocity mean +/- 3% velocity mean." It can be seen that both 95 percent CI and 99 percent CI are within the range of "velocity mean +/- 3 percent velocity mean." Graphical displays of the same results are shown by **Figures 4 and 5**.

Table 4: Velocity Tolerances Considering the Combined Data Deviations

Drop anvil	mean, μ	σ test	σ lab	σ total	95% CI: μ+/2σ total	99% CI: μ+/-3σ total	μ+/- 3% μ
Hemis-pherical	5.20	0.045	0.017	0.048	5.10 – 5.30	5.06 - 5.34	5.04 - 5.36
Flat	6.00	0.048	0.020	0.052	5.90 – 6.10	5.84 - 6.16	5.82 - 6.18

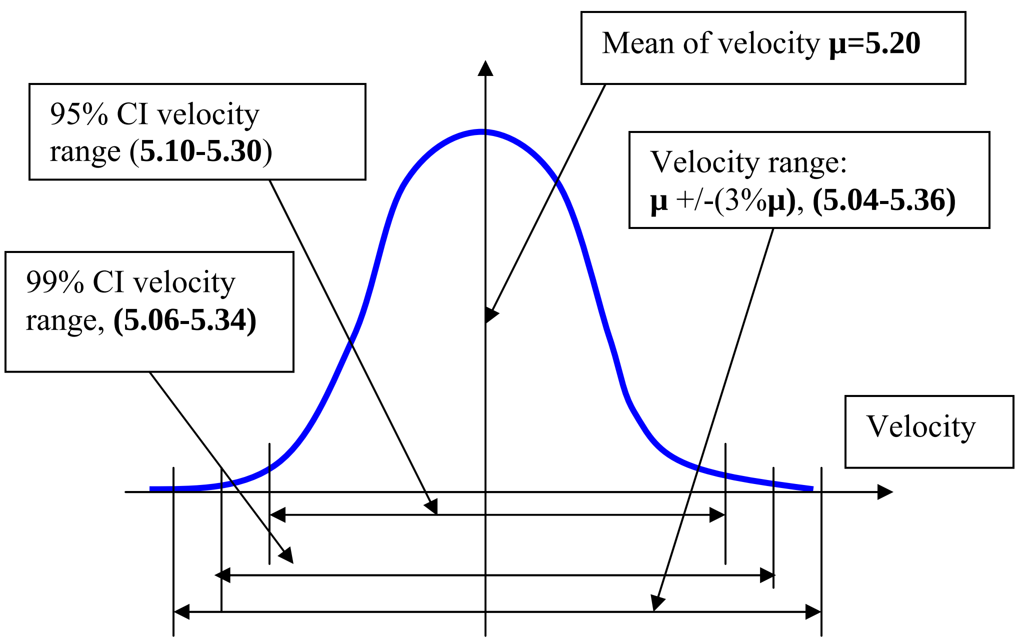

Figure 4: Velocity Ranges During Impacts Onto the Hemispherical Anvil

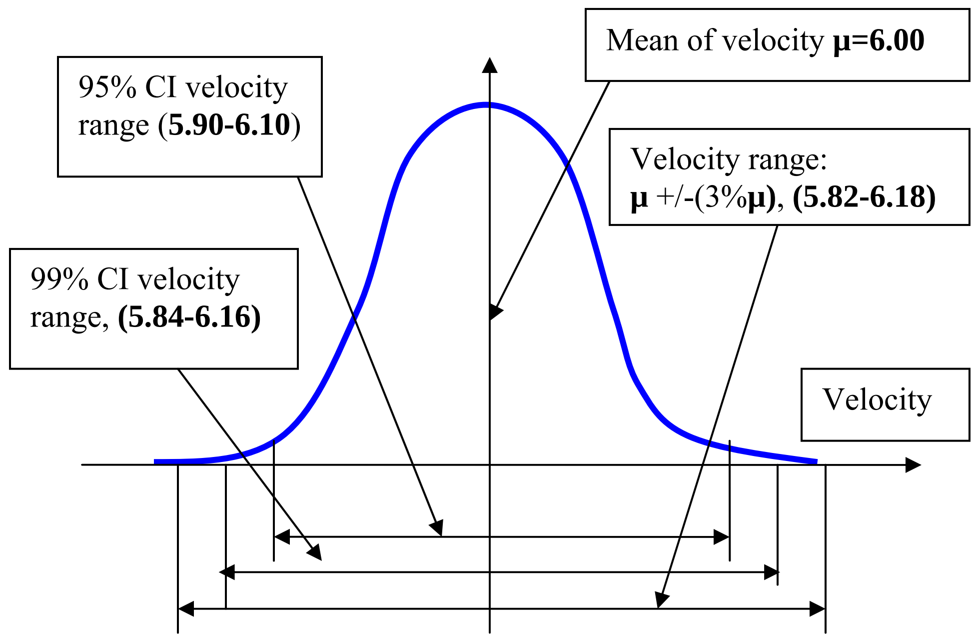

Figure 5: Velocity Ranges During Impacts Onto the Flat Anvil

5. CONCLUSIONS

- Experimental data of drop tests indicate that two factors are statistically significant in influencing impact velocities, the laboratory at which the test was conducted, and the drop height for each anvil. Conversely, test conditions, helmet locations, and drop experience are not statistically significant factors in influencing impact velocities.

- The experimental design data variances are from both test procedures used by test technicians and laboratory instruments, and the combined variances are used to design the velocity tolerance ranges.

- All test laboratories have satisfactory calibration standards comparable with the NIST standard. Lab A has a slightly smaller impact velocity deviation compared with Lab B, and both are satisfactory.

- It is determined that on average more than 99 percent of impacts will fall within the impact velocity range, if the +/-3 percent nominal tolerance range is adopted, and the velocity interval of 97 percent nominal to 103 percent nominal is acceptable.

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7. APPENDIX A: INSTRUMENTAL VARIABILITY AND BIAS

According to the certificates of calibration, each instrument not only produces variable measurements of the velocities, but the measurements which it produces might be biased with respect to the NIST standards. The average relative bias of drop velocity based on five calibration certificates is as follows:

$$bias = \sum_{i=1toN} \frac{(V_{lab} - V_{NIST})}{V_{NIST}} \qquad \text{Eq.(5)}$$

With a sample bias standard deviation of

$$\sigma_{\text{bias}} = \sqrt{\frac{\sum \{ \frac{V_{lab} - V_{NIST}}{V_{NIST}} - bias_{mean} \}^2}{n_{obs} - 1}} \qquad \text{Eq. (6)}$$

Where "n_{obs}" is the number of comparisons observed between laboratory test data and NIST standard data for each lab, and "V_{lab}" stands for drop velocity measured by labs and "V_{NIST}" Velocity measured by NIST.

Since there are six sets of calibration certificates from three different laboratories, six different bias deviations, σ_1, σ_2, …, σ_6, (i.e., 0.56%, 0.39%, 0.09%, 0.08%, 0.25%, and 0.35%) from six lab tests, respectively, can be obtained using same equations as Eq. (5) and Eq.(6), and the following σ_{lab} is the average of pooled , or total laboratory bias standard deviations by considering all six certificates, and this average deviation is used in Eq. (4) calculation of Section 4.3:

$$\sigma_{lab} = \sqrt{(\sigma_1^2 + \sigma_2^2 + ... + \sigma_6^2)/6} \; = 0.334\% \; \mu$$

Where μ is the velocity mean, thus, the average standard deviations of the velocity for each of the two anvils are the following:

Hemispherical Anvil: σ_{lab} =0.00334(5.2 meter/second) =0.017meter/second
Flat Anvil: σ_{lab} = 0.00334(6.00 meter/second) =0.020 meter/second

Furthermore, it is important to find out whether any significant difference between the laboratory results with NIST result occurs. The null hypothesis of no significant difference is tested against the alternative, based on five lab calibration certificates:

H_0: relative bias =0 vs. H_1: relative bias not = 0

The statistical significance level is 5 percent, and the t-test statistic of 0.409 is associated with a p-value of 0.703, or 70 percent (much larger than marginal value of 0.05 or 5%). Hence, there is no significant difference between lab results and the NIST standard.

8. APPENDIX B: PARTIAL DROP VELOCITY DATA

Table 5: Partial Drop Velocity Data Onto Hemispherical Anvil

Helmet Condition	Location1 Drop1	Location1 Drop2	Location2 Drop1	Location2 Drop2
Water Immersed	5.17	5.17	5.2	5.19
High Temp	5.17	5.15	5.2	5.22
Ambient	5.23	5.16	5.2	5.2
Low Temp	5.17	5.17	5.22	5.19
Low Temp	5.16	5.17	5.18	5.2
Water Immersed	5.15	5.15	5.18	5.19
Ambient	5.1	5.16	5.19	5.18
High Temp	5.15	5.16	5.18	5.19
Ambient	5.1	5.15	5.18	5.19
Low Temp	5.16	5.17	5.2	5.18
High Temp	5.17	5.17	5.19	5.19
Water Immersed	5.16	5.16	5.19	5.2
Low Temp	5.17	5.15	5.18	5.16
Ambient	5.16	5.15	5.17	5.18
Water Immersed	5.16	5.16	5.17	5.16
High Temp	5.16	5.16	5.19	5.18

Table 6: Partial Drop Velocity Data Onto Flat Anvil

Helmet Condition	Location1 Drop1	Location1 Drop2	Location2 Drop1	Location2 Drop2
Water Immersed	5.98	5.99	5.98	5.92
High Temp	5.98	5.99	5.96	5.98
Ambient	6.02	5.99	5.98	5.98
Low Temp	5.99	6	5.98	5.98
Low Temp	5.96	5.96	5.93	5.91
Water Immersed	5.98	5.95	5.93	5.93
Ambient	5.96	5.96	5.93	5.93
High Temp	5.96	5.96	5.93	5.93
Ambient	6	6	5.98	5.98
Low Temp	6	6.02	5.98	5.98
High Temp	6	6.02	5.98	5.98
Water Immersed	6	6	5.98	5.99
Low Temp	5.92	5.91	5.87	5.92
Ambient	5.93	5.92	5.93	5.92
Water Immersed	5.91	5.91	5.91	5.93
High Temp	5.92	5.91	5.93	5.93

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