SENSITIVITY OF MOTORCYCLE HELMET PERFORMANCE TO IMPACT VELOCITY IN THE IMPACT ATTENUATION TESTS

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ABSTRACT

The purpose of this report is to present the methodology used to determine how sensitive helmets are to impact attenuation tests on the flat anvil in the range of impact velocities 5.8 m/s to 6.2 m/s. This report is the product of a larger study, and the results presented here are preliminary. Specifically, an experiment was conducted to measure the effect on the cumulative dwell time at accelerations greater than 200g for helmets tested on a flat anvil at the extreme ends of the tolerance interval.

When likely confounding effects such as conditioning of a helmet, headform size, model of helmet, drop sequence, and location of impact on the helmet are taken into account, the difference in the values of $dwell200$ measured at the extreme ends of the velocity tolerance interval is essentially zero at a level of significance of .05. The implication is that the criterion of failing a helmet based on $dwell200$ will remain valid should the velocity at the moment of impact lie within the interval (5.8 m/s , 6.2 m/s).

INTRODUCTION

Federal Motor Vehicle Safety Standard (FMVSS) No. 218 establishes the minimum performance criteria for motorcycle helmets. Manufacturers certify that their products comply with these minimum criteria prior to importing or offering them for sale in the U.S. NHTSA enforces the standards by randomly selecting and purchasing equipment from the marketplace and testing to the requirements of FMVSS No. 218 at independent testing laboratories.

One requirement established in FMVSS No. 218 is the impact attenuation requirement. This requirement helps to ensure that helmets offer impact protection during a crash event. According to the specifications of the impact attenuation test that went into effect on October 3, 1998[1], helmets are dropped such that the minimum velocity at the moment of impact is 5.2 m/s for the hemispherical anvil and 6.0 m/s for the flat anvil. In 2008, NHTSA published a Notice of Proposed Rulemaking (NPRM) which included a provision for adding tolerances to the drop velocities specified in the standard. Many comments were received on this proposal. The most common suggestion was to limit the tolerance to $\pm 3\%$ of the nominal target velocity which would suggest a velocity range of 97% nominal to 103% nominal or 5.04 to 5.36 m/s for the hemispherical anvil and 5.82 to 6.18 m/s for the flat anvil, respectively. By means of calibration reports and experimental data, the tolerance interval of $\pm 3\%$ of the nominal target velocities was determined to be feasible, on the average, in at least 95% of impact tests.

The motorcycle helmet tolerance interval sensitivity design of experiment (DOE) was developed to provide data for measuring the effect on dwell at 200 ms when the nominal velocities at impact are 5.8 m/s and 6.2 m/s. Condition, impact site, helmet model, drop sequence, and head form size were factors that the DOE took into account. Furthermore, since the purpose of testing the helmets is to determine the sensitivity of dwell at lower and higher nominal velocities, makes and models of helmets that were tested in the 2009 compliance program and that had dwell times close to the maximum allowable by the standard were chosen as being the most likely to represent the population of problematic helmets involved in compliance testing under the new rule.

In order for a helmet to meet or exceed the minimum requirements of FMVSS No. 218, three conditions must hold true:

1. Peak accelerations shall not exceed 400g;

[1] 53 FR 11288, April 6, 1988

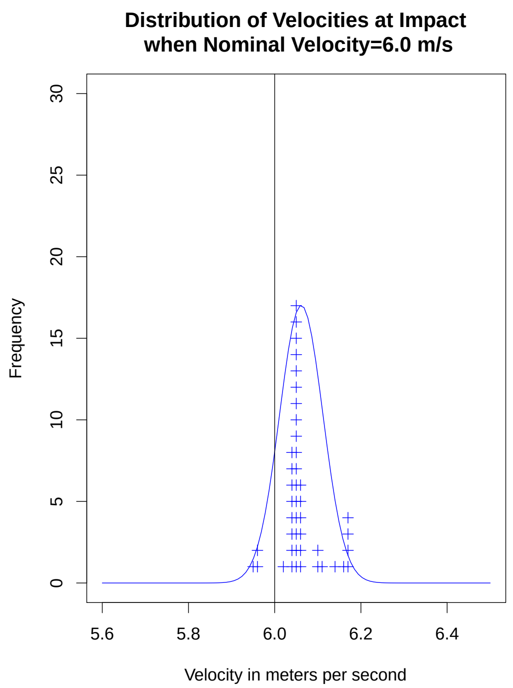

Figure 1.

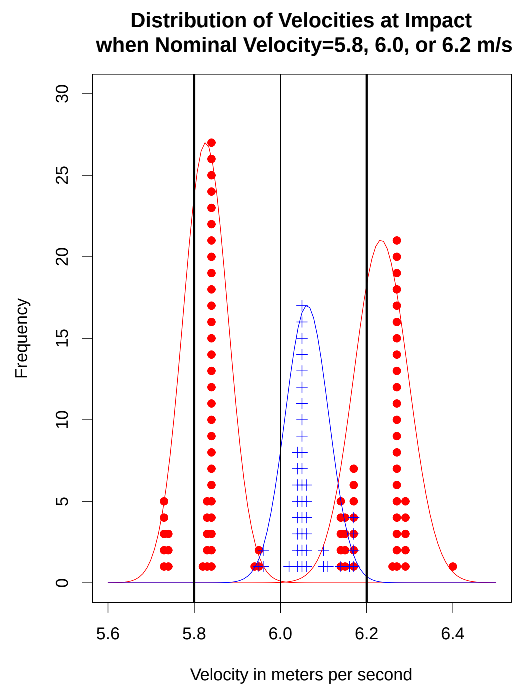

Figure 2. DOE data point=● in red; compliance test data point=$+$ in blue.

2. Accelerations in excess of 200g shall not exceed a cumulative duration of 2.0 milliseconds; and
3. Accelerations in excess of 150g shall not exceed a cumulative duration of 4.0 milliseconds.

Of these three criteria, the dwell in excess of 200g is a metric for which a test most commonly results in failure during compliance testing. We will refer to this variable as $dwell200$ in general and as $dwell200_{low}$ and $dwell200_{high}$ in regard to the nominal velocities of 5.8 m/s and 6.2 m/s, respectively, when appropriate. If the difference between $dwell200_{high}$ and $dwell200_{low}$ can be shown to be zero for all practical purposes, then we may conclude that the criterion for failing a helmet based on $dwell200$ will remain valid provided that the velocity at the moment of impact lies within the range 5.8 m/s to 6.2 m/s. To facilitate the formulation of the necessary linear models to answer that question, we will define $\Delta dwell200 = dwell200_{high} - dwell200_{low}$ and we will use it for the response variable in the models.

Impact attenuation is measured by determining acceleration imparted to an instrumented test headform on which a test helmet is mounted. In a typical test, four helmets of the same size and model are used. Each one of the four helmets is conditioned to one of the four conditioning procedures: ambient, low temperature, high temperature, and water immersion. Each of the four conditioned helmets is impacted on a flat anvil using a monorail drop assembly test device at four specific impact sites on the helmet: left, right, front, and back. For each one of these configurations of a test, the helmet is dropped twice for a total of eight times; therefore, each compliance test depends on 32 total drop tests.

Figure 1 is a plot of frequencies of velocities in which the laboratory targets a nominal velocity of 6.0 m/s. To show the variability in the data at three nominal velocities, Figure 2 was made by combining the distributions of velocities at 5.8 m/s and 6.2 m/s which were obtained from the DOE with the distribution of velocities at 6.0

m/s which were taken from actual compliance tests. The motivation for adopting the concept of a tolerance interval on velocity is reflected in the bell shaped distribution of velocities. This variability in measured velocities at the moment of impact about the nominal velocities underscores the concern that the criterion for failing a helmet based on $dwell200$ might be different at one end of the tolerance interval than at the other end. That is, if the hypothesis that $dwell200_{low} = dwell200_{high}$ cannot be rejected, then we may conclude that the criterion for failure based on $dwell200$ will be valid provided that the velocity at impact lies within the interval (5.8 m/s , 6.2 m/s).

For each condition and for each location of impact on the helmet, a helmet is dropped twice. Although the structural properties of a helmet change after the first impact, the helmet is required to comply with the FMVSS even on the second impact.

A plot of dwell at 200g with respect to the order of drop sequence is given in Figure 3. We clearly see in this figure that $dwell200_{2^{nd}\text{ impact}} \geq dwell200_{1^{st}\text{ impact}}$, regardless of impact site on the helmet. The points marked by a solid dot represent $dwell200$ corresponding to a left-right impact locations on the helmet whereas those points that are marked by a $+$ symbol represent $dwell200$ corresponding to a front-back impact locations.

Figure 3 reveals that the sequence of impact does affect $dwell200$ in that $dwell200_{2^{nd}\text{ impact}} \geq dwell200_{1^{st}\text{ impact}}$ with a p-value of 1.785e-08 based on a paired difference test. On the other hand, when considering the difference in $dwell200$ with respect to the same drop sequence, it can be shown that $\Delta dwell200_{1^{st}\text{ impact, left-right}}$ is no different than $\Delta dwell200_{2^{nd}\text{ impact, left-right}}$ as well as $\Delta dwell200_{1^{st}\text{ impact, front-back}}$ is no different than $\Delta dwell200_{2^{nd}\text{ impact, front-back}}$ at p-values of 0.3135 and 0.1915 respectively based on paired difference tests. Consequently, given the same impact site on the helmet, the same helmet conditioning, and the same drop sequence, $dwell200$ produced at a nominal velocity of 5.8 m/s is statistically the same as $dwell200$ produced at 6.2 m/s.

There are two parts to the DOE. The first part is a complete 4x3x2x2 replicated factorial design. In this design, four conditions were applied to three models of helmet. For each model and condition, a helmet was dropped such that a helmet would land at the same impact site two times for the same nominal impact velocity. Although there are four specified impact sites on a helmet, the left and right ones were treated as one and the same in the analysis and the front and back impact sites were treated as one. In summary, for each combination of three helmet models and four conditions, a helmet mounted to a medium head form was dropped two times onto a flat anvil at two equivalent impact sites on a helmet at the high nominal velocity, and similarly another helmet was dropped at the low nominal velocity for a total combination of 96 tests. That is, 4 conditions, 3 models, 2 locations, 2 nominal velocities, and replicated twice constituted the first part of the DOE. The purpose of this first part of the DOE is to test whether or not condition, model, impact site of the helmet, and drop sequence could be significant effects in determining $\Delta dwell200$.

According to the DOE test protocol, the laboratory was instructed to conduct a test such that the velocity at the moment of impact would be 5.8 m/s for the low nominal velocity and 6.2 m/s for the high nominal velocity. Nevertheless, we see in Figure 2 the bell shaped distributions

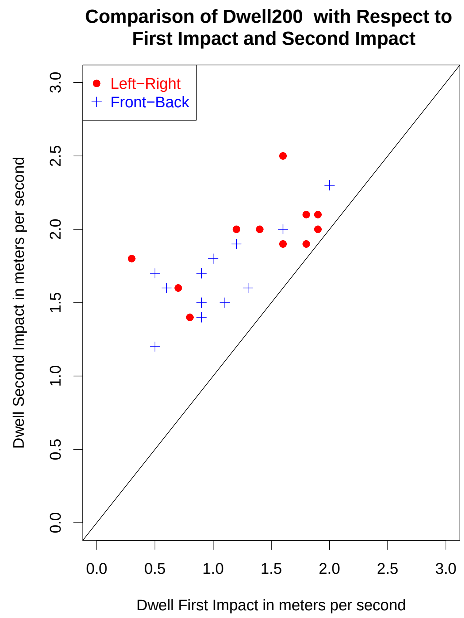

Figure 3.

Table 1. Levels of Factors

Location of Impact Site	Condition	Model	Nominal Velocity Velocity	Drop Sequence
Left-Right	Ambient	1	High	First
Front-Back	Hot	2	Low	Second
	Cold	3		
	Wet			

Table 2. ANOVA Table for the Complete Paired Difference Design of Part One for $dwell200$

Source	df	Sum of Squares	Mean Sum of Squares	F Test Statistic	p-value
Condition	3	1.2010	0.40034	1.2029	0.3218
Model	2	0.8267	0.41335	1.2419	0.3003
Impact Site	1	0.0031	0.00306	0.0092	0.9242
Drop Sequence	1	0.0704	0.07043	0.2116	0.6481
Residuals	38	12.6475	0.33283		

of velocities around the nominal velocities located at the extreme limits of the proposed tolerance interval. They are similar to the distribution of velocities drawn in blue which were obtained from the 2009 compliance program for which the nominal velocity is 6.0 m/s.

FIRST PART OF THE DOE

A simple paired difference test would have been appropriate to study the sensitivity of dwell according the low and the high nominal velocity, if confounding factors like the model of the helmet, condition of the helmet, and location of impact did not exist. The first part of the DOE was formulated to assess the importance of these confounding factors. If the confounding factors did not exist, the linear model for a paired difference test would be given by equation (1)

$$\Delta dwell200 = \mu_d + \epsilon \text{ where } \epsilon \sim N(0, \sigma^2) \qquad (1).$$

where the resulting analysis of variance would then be used to test the hypothesis

$$H_0 : dwell200_{high} - dwell200_{low} = \mu_d = 0$$
$$\text{vs } H_1 : dwell200_{high} - dwell200_{low} = \mu_d \neq 0$$

at $\alpha = .05$. However, in the presence of the confounding factors, a more complete model is needed, and it is given by equation (2). Based on this model, it was determined that condition, impact site, and model are not significant factors when tests of the helmets are paired according to low and high nominal velocities. The response variable which appears in the model is $\Delta dwell200 = dwell200_{high} - dwell200_{low}$.

Table 1 shows the levels for the linear model given by equation (2).

$$\Delta dwell200_{ijkln} = \mu_d + location_i + model_j + condition_k + drop_l + \epsilon_{ijkln} \quad (2).$$

where $\epsilon_{ijkn} \sim N(0, \sigma^2)$, i=1,2, j=1,2,3, k=1,2,3,4, l=1,2, n=1,2, and μ_d is an overall constant which we hope to show is for all practical purposes equal to 0.

The corresponding analysis of variance (ANOVA) table is given in Table 2. We see from Table 2 that condition,

Table 3. ANOVA Table for the Effect of Headform Size on $\Delta dwell200$

Source	df	Sum of Squares	Mean Sum of Squares	F Test Statistic	p-value
Constant	1	0.9309	0.93091	2.3710	0.1311
Headform Size	1	0.1591	0.15909	0.4052	0.5279
Residuals	42	16.4900	0.39262		

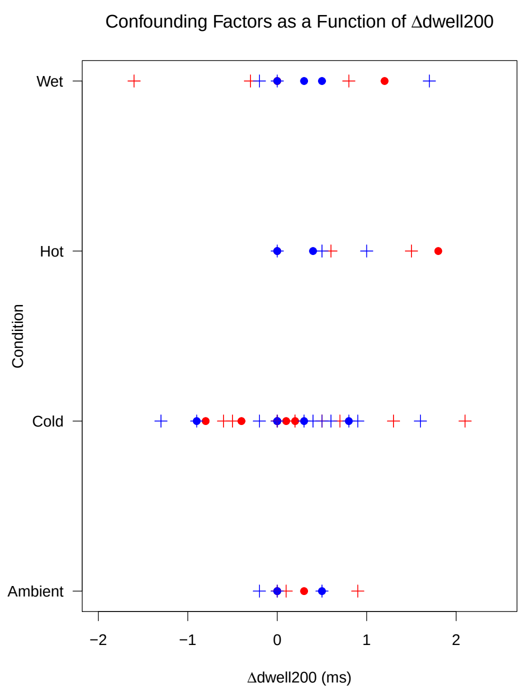

Figure 4. First Impact=●; Second Impact=+; Left-Right Site Impacts=Red; Front-Back Site Impacts=Blue

model, left-right locations, front-back locations, and drop sequence are not significant effects on the paired differences in $dwell200$, and this observation agrees with the plot of the data given in Figure 4. Consequently, left-right and front-back impact locations, the cold ambient condition, both drop sequences, and all eleven models of helmets were used to study the effect on $dwell200$ of targeting impact velocities at the high and low nominal velocities as discussed in the second part of the DOE.

SECOND PART OF THE DOE

The knowledge that the effects of location of impact on a helmet and of the helmet's condition do not have an important effect on $\Delta dwell200$ is utilized to economize on the size of the second part of the DOE. By taking advantage of that knowledge, only the cold condition was chosen out of the four possible conditions. Based on past experience in compliance testing, the cold condition presents a more severe test case in some instances. Two headform sizes, medium and large, were used to accommodate eleven models of helmets. The high and low nominal velocities were paired according to left-right and front-back impact locations. By having accounted for possible confounding factors of location of impact, condition, drop sequence, and model, 44 paired tests were were conducted in the second part of the DOE for the purpose of testing the hypothesis that $dwell200_{low} = dwell200_{high}$. In this part of the DOE, impacts at low and high nominal velocities with eleven models of helmet, at left-right and front-back impact locations, for two drops, and at the cold condition were used for conducting a total of 88 drops to produce 44 paired differences in $dwell200$.

Before proceeding, it is necessary to determine if the effect of headform size which was introduced to accommodate different sizes among the eleven models of helmets might be a significant confounding factor. The linear model which applies to this question is

$$\Delta dwell200 = \mu_d + headform + \epsilon \qquad (3).$$

where $\epsilon \sim N(0, \sigma^2)$ and where $\Delta dwell200 = dwell200_{high} - dwell200_{low}$, headform=medium, large, and μ_d is an overall constant.

The resulting analysis of variance table, Table 3, shows that headform size is not a significant factor at a level of significance of $\alpha = .05$ with respect to a paired differ-

Table 4. ANOVA Table for Paired Difference Model in the Presence of All Possible Confounding Factors for $\Delta dwell200$

Source	df	Sum of Squares	Mean Sum of Squares	F Test Statistic	p-value
Constant	1	0.9309	0.93091	2.4043	0.1283
Residuals	43	16.6491	0.38719		

ence design, that is, given all factors being equal excluding drop velocity, headform size is not a significant factor in explaining $\Delta dwell200$. The benefit of using a paired difference approach which was adopted for the basis of the DOE relies on the idea that confounding factors are subtracted out of the analysis. Within a confounding factor like headform size, the difference in dwell at the low nominal velocity and at the high nominal velocity is essentially zero.

Having shown that the confounding effects of headform size, impact location, condition, drop sequence, and model are not important in affecting $\Delta dwell200$, they will be removed from the model, so that we come full circle to equation (1).

$$\Delta dwell200 = \mu_d + \epsilon$$

where ϵ_i, $\Delta dwell$, and μ_d are defined as before. The corresponding ANOVA is given in Table 4, and based on it, we cannot reject the null hypothesis in favor of the alternative,

$$H_0 : \mu_d = 0 \text{ vs } H_1 : \mu_d \neq 0$$

at a level of significance of $\alpha = .05$, that is, $dwell200_{low}$ and $dwell200_{high}$ are not significantly different. The p-value which is reported in Table 4 is exactly the same p-value which would have been obtained from conducting a classical paired difference test.

CONCLUSION

Based on the factorial design of a paired difference experiment, we are able to show that $dwell200$ of a helmet impacted on a flat anvil at a nominal velocity of 5.8 m/s is statistically the same as the $dwell200$ of a helmet tested at 6.2 m/s given the same condition, head form size, model, drop sequence, and location of impact. Therefore, we may conclude that the criterion for failure based on $dwell200$ will be robust, when the velocity at impact lies within range 5.8 m/s to 6.2 m/s.