

Effect of Operational Testing and Trim Manufacturing Process Variation on Head Injury Criterion in FMVSS 201 Tests

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ABSTRACT

This paper analyzes the difference in impact response of the forehead of the Hybrid III and THOR-NT dummies in free motion headform tests when a dummy strikes the interior trim of a vehicle. Hybrid III dummy head is currently used in FMVSS201 tests. THOR-NT dummy head has been in development to replace Hybrid III head. The impact response of the forehead of both the Hybrid III dummy and THOR dummy was designed to the same human surrogate data. Therefore, when the forehead of either dummy is impacted with the same initial conditions, the acceleration response and consequently the head Injury criterion (HIC) should be similar. A number of manufacturing variables can affect the impacted interior trim panels. This work evaluates the effect of process variation on the response in the form of Head Injury Criterion (HIC). To compare and contrast the response of the two dummy heads under FMVSS 201 testing, a design of experiments (DOE), that is a function of seven variables, is utilized to develop a mathematical model of the Head Impact Response. These independent parameters include five trim manufacturing process variables that relate to the interior that the dummy head hits in FMVSS 201 testing. The process variables are: mold temperature, melt temperature, packing pressure, hold pressure, and injection speed. The two operational variables considered are: free motion headform approach angle and the dummy head drop calibration. An incomplete block design approach is utilized in order to significantly reduce the number of experiments. The DOE approach determines the response in the form of the Head Impact Criterion (HIC) with respect to the seven variables at 99 % confidence level. A mathematical model is developed to optimize the response as a function of the significant

variables. The results indicate that the effects of manufacturing variables are insignificant on the response of both Hybrid III and THOR-NT dummies when interior trim panels are manufactured within the normal process. Also, the results describe the response data of both dummy heads and indicate that the Hybrid III dummy head and the THOR dummy head have significantly different response characteristics in terms of magnitude of response, variation to different input conditions, repeatability, HIC values, and acceleration time history.

KEY WORDS: NHTSA, THOR, HEAD IMPACT, DOE, BOX AND BEHNKEN, INCOMPLETE BLOCK DESIGN.

INTRODUCTION

NHTSA has directed the development of an advanced crash test dummy, denoted as THOR (Test device for Human Occupant Restraint) as shown in Figure 1, which was designed to develop and evaluate



Figure 1 THOR-NT DUMMY HEAD

vehicle occupant safety systems. THOR-NT is an advanced Anthropometrical Test Device (ATD) that is intending to simulate the kinematics of humans. It is the latest version of THOR after modifying the previous version known as “THOR Alpha” to improve its performance. The modifications of the dummy head include an integrated single skin to cover the skull and the face as compared to two skin layers for THOR alpha, improved chin anthropometrics, and improved mounting of accelerometer package that measures the force of impact [5].

This paper focuses on the effects of two operational variables; Free Motion Head-form (FMH) approach angle, and FMH drop calibration. It also assesses five trim manufacturing process variables of vehicle's upper interior trim panels on Head Impact. The five manufacturing process variables are mold temperature, melt temperature, packing pressure, hold pressure, and injection speed. The manufacturing process variable limits are kept within the normal range of the manufacturing processes. The response is determined using Head Injury Criterion (HIC) calculations. The paper evaluates the response difference between the new THOR-NT dummy head and the current Hybrid III dummy head. The current Hybrid III dummy is shown in Figure 2.



Figure 2 HYBRID III DUMMY HEAD

METHODOLOGY

Model Postulation

From literature survey, the seven investigated variables behaved exponentially in affecting outcomes in several researches. The following model is postulated to express the relationship between head injury criterion (HIC) as a response (R) and the seven investigated variables:

$$R = C \theta_M^k \theta_m^l P_p^m H_c^n P_h^o V^p \theta_a^q \tag{1}$$

The constant C, as well as, the exponents *k*, *l*, *m*, *n*, *o*, *p*, and *q* are to be estimated. Equation (1) can be expressed in logarithmic form as:

$$\ln R = \ln C + k \ln \theta_M + l \ln \theta_m + m \ln P_p + n \ln H_c + o \ln P_h + p \ln V + q \ln \theta_a \tag{2}$$

where θ_M is mold temperature (°F), θ_m is melt temperature (°F), P_p is pack pressure (psi), H_c is free motion head-form drop calibration (g), P_h is hold pressure (psi), V is injection speed (in/sec), and θ_a is free motion head-form approach angle (degree).

Equation (2) can be expressed by:

$$\hat{y} = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_6 x_6 + b_7 x_7 \tag{3}$$

where $\hat{y}$ is the logarithmic value of the predicted head injury criterion, $x_0 = 1$, b_0 is an estimate of $\ln C$, b_1 through b_7 are estimates of the coefficients *k* through *q* respectively, while x_1 through x_7 are the coding of the seven investigated variables as shown in Equations 1A to 7A in Appendix A. Equation (3) may be extended to include the second-order model. Second-order model includes seven squared terms (one for each of the seven variables), and 21 interaction terms, which are the interaction of each variable with all other variables. Equation (3) can be written in the following form [6]:

$$\begin{aligned} \hat{y} = & b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_6 x_6 + b_7 x_7 + \\ & b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{44} x_4^2 + b_{55} x_5^2 + b_{66} x_6^2 + b_{77} x_7^2 + \\ & b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{14} x_1 x_4 + b_{15} x_1 x_5 + b_{16} x_1 x_6 + \\ & b_{17} x_1 x_7 + b_{23} x_2 x_3 + b_{24} x_2 x_4 + b_{25} x_2 x_5 + b_{26} x_2 x_6 + b_{27} x_2 x_7 + \\ & b_{34} x_3 x_4 + b_{35} x_3 x_5 + b_{36} x_3 x_6 + b_{37} x_3 x_7 + b_{45} x_4 x_5 + b_{46} x_4 x_6 + \\ & b_{47} x_4 x_7 + b_{56} x_5 x_6 + b_{57} x_5 x_7 + b_{67} x_6 x_7 \end{aligned} \tag{4}$$

Table I lists the variables and their coded levels. The actual experimental approach angles were -15, -10, and 0. The logarithmic calculations can not be obtained for the approach angles in negative values using Equation (7A) in Appendix A. Therefore, 20 degrees were added to each angle as listed in Table I under FMH approach angle column.

TABLE I
LEVELS AND CODING OF INDEPENDENT VARIABLES

Independent Variable	Mold Temp. (°F)	Melt Temp. (°F)	Packing Pressure (psi)	Head Drop Calibration (g)	Hold Pressure (psi)	Injection Speed (in/sec)	FMH Approach Angle (degree)
	θ_M	θ_m	P_p	H_c	P_h	V	θ_a
Code	x_1	x_2	x_3	x_4	x_5	x_6	x_7
-1	75.2	425	160	237 THOR	450	1.6	5
0	95	449.3	200	253 Hybrid III	493	2	10
+1	120	475	250	267 Hybrid III	540	2.5	20

Design of Experiments

An incomplete block design, which was effectively utilized by Taraman [6], is used in this paper as shown in Appendix B [1]. This design was developed by Box and Behnken [1], and chosen to investigate the effects of the seven variables, at three levels each, on HIC with limited number of experiments. This design of experiments requires only 62 experiments versus 2187 experiments, which would have been required to investigate these seven variables by the traditional one-variable-at-a time method. The generated design of 62 experiments provides estimates of the 36 parameters of the second-order model given by Equation (4). The experiments were conducted in two blocks. Each block has 28 experiments, and one experiment conducted six times (three in each block) at the center levels of all investigated variables [1, 6]. The two blocks are shown in Appendices C and D. From Appendices C and D, THOR dummy head is used for 12 experiments only (6 in each of the two blocks), since its head drop calibration (237) is coded (-1) as shown in table I. Hybrid III dummy head at coded level (+1) is also used for 12 experiments. Hybrid III dummy head with the center level ($x = 0$) is used the remaining 38 experiments.

Experimental Setup

The tests were performed on a component-level test fixture using a retrofitted BIW aperture. Epoxy filler was applied into the BIW pillar to stiffen it to withstand multiple impacts. The interior trim panel material was EXXON 8023 mid-impact Polypropylene. Parts were molded by VAN DORN DEMAC 880 ton hydraulic clamp injection molding machine. The head drop calibration was measured for all dummy heads.

The test device used was MTS model 314.51 configured with control console with rack-mounted PC and free-standing monitor and keyboard. The device included mechanical components such as positioner with velocity generator. Each trim panel was impacted at a selected point which is the target point for the entire testing event, as specified in the Laboratory test procedure TP201U-01 for FMVSS 201 Occupant Protection in Interior [2]. The dummy head approach angle was adjusted by setting the angles on the impact testing machine as required for the experiments identified in Appendices C and D. The dummy head with the specified angle for a required test is moved toward the trim panel until the dummy's head impact zone is in contact with the target point on the trim panel, and then moved back to a distance as specified in the test procedure. The horizontal rotation of the FHM is kept constant for all experiments, which allows the lip or chin of the FMH to contact the trim component when impacted. Figure 3 shows FMH mounted on the testing device with approach angle θ_a equals to -10 degrees. θ_a is a vertical angle adjusted up and down for the other angles to be tested (-15 and 0 degree). Equation (7A) in appendix A can not be used with real numbers with a

negative term in it. Therefore, a 20 is added to all angles to enable using the DOE model. Hence, the angles in the DOE (5, 10, & 20) represent the setup angles of -15 , -10 , & 0 respectively, which are within the approach angle range per FMVSS 201 test procedure. This should not effect the analysis since it was conducted using the coded values (-1 , 0 , and 1). θ_a equals to -10 degrees is the baseline angle.

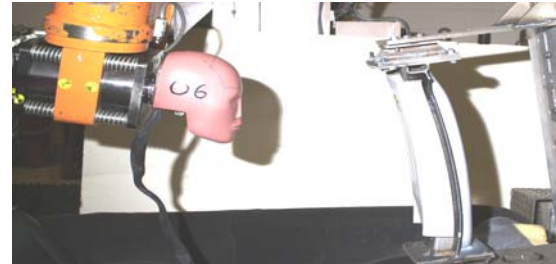


Figure 3 FMH testing device

Analysis Method

MINITAB® software version 14 [3] was utilized to perform analysis of variance (ANOVA) to evaluate the significance of the seven variables and their interactions. In addition, Response Surface Methodology (RSM) was utilized to search for the optimum region for all variables and their best fit. The purpose of ANOVA is to determine which variables and interactions affect the head injury criterion (HIC) significantly, and to develop an empirical model that predicts the HIC value for any variable settings. A regression equation describes the response (R) as a function of the predicted variables can be written as:

$$\hat{y} = f(x_i) + \varepsilon \quad (5)$$

where $\hat{y}$ is the logarithmic value of the response (R), x_i is a coded variable for the investigated variable, and ε is the error. The parameters of the first and second orders for each of the variables were estimated using the least square method. This method minimizes the sum of the squared distances between the points and the fitted line. By using the mean square for each variable versus the mean square for error, the F-test is performed to determine the statistical significance. Then, the model is modified by dropping all insignificant terms and/or variables. Model terms with (Prob>F) less than the confidence level (α) are considered significant, and therefore they are kept in the model. α equals to 0.05 by default in MINITAB® software. α was chosen to be equal to 0.01 for more accuracy.

RESEARCH RESULTS AND ANALYSIS

Data Analysis

An analysis of variance was performed based on the

output data as shown in Appendix E under the response column. The response is HIC in a logarithmic value. The results are displayed in Table II. Table II shows the P value that indicates the significance levels of all terms (linear, quadratic, and interaction) as relationships to the response. The P value tests the relationship of the variable and the response. If the P value is smaller than α , then the term is considered significant. The pre-selected confidence level (α) of 0.01, which represents a 99% confidence level, was chosen for this analysis. The P values for the linear and quadratic terms are less than 0.01, which indicate that they should be kept in the model, while the P value for the interaction terms is large (0.882), and therefore the interaction terms are to be removed from the model accordingly. Similarly, the insignificant blocks effect with P value of 0.017 is to be removed.

TABLE II
ANALYSIS OF VARIANCE FOR LN HIC

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Blocks	1	0.03217	0.03217	0.032174	6.58	0.017
Regression	35	2.22068	2.22068	0.063448	12.98	0.000
Linear	7	1.83025	1.83025	0.261464	53.50	0.000
Square	7	0.32900	0.32900	0.046999	9.62	0.000
Interaction	21	0.06143	0.06143	0.002925	0.60	0.882
Residual Error	25	0.12217	0.12217	0.004887		
Lack-of-Fit	21	0.11949	0.11949	0.005690	8.47	0.025
Pure Error	4	0.00269	0.00269	0.000672		
Total	61	2.37503				

The results seem to indicate that the first-order (linear) and second-order (square) terms are significant at $\alpha = 0.01$ confidence level, where the F values of 53.50 and 9.62 respectively are greater than $F_{7,25,0.99} = 3.46$. However, the interaction terms are not significant since the F value obtained (0.60) is less than $F_{21,25,0.99}$ (2.70). Also, the block effect is not significant either, since the F value obtained (6.58) is less than $F_{1,25,0.99}$ (7.77). The F value for the lack-of-fit is 8.47 (Table II), which is less than $F_{21,4,0.99}$ (14.00). The F value and P value for the lack-of-fit indicate that it is insignificant.

It is important to ensure that the (LN HIC) output data is distributed normally. Figure 4 shows the normal plot and the residuals versus their expected values. If

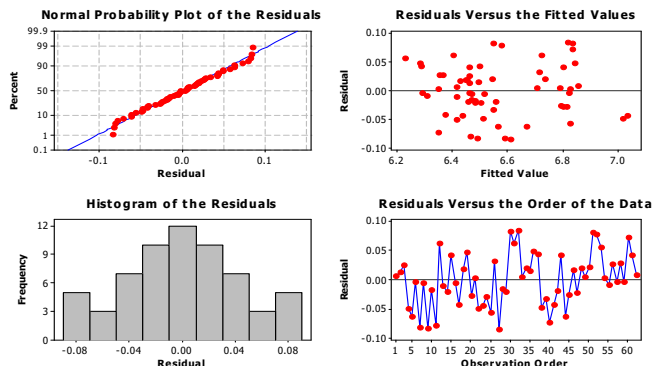


Figure 4 NORMAL AND RESIDUAL PLOTS FOR LN HIC

the residuals from the analysis are normally distributed, the normal probability plot of the residuals should follow a straight line. Results in Figure 4 show that residuals do not deviate substantially from a normal distribution. The curls at the two tails of the line represent the outliers in the model. These outliers are observed to be insignificant, and therefore kept in the model, based on how they would affect the model if they were to be removed. The residual versus fitted value plot shows scattered observations. The fitted or the predicted response is the mean response with the given value of the coded variables. The fitted value is computed using the regression equation, and it is in logarithmic transformation of the actual value. The residual is the observed value minus the predicted one. The residuals-versus-order plots the residuals in the order of the corresponding observations. The residuals in the plot are shown in a random pattern around the centerline. The residuals data is displayed in Appendix E.

Figure 5 shows the main effects plot for all variables and compares the changes in the level means to evaluate which variable influences the HIC the most. MINITAB® creates the main effects plot by plotting the response mean for each variable level. A line is connecting the mean values for the three levels of each variable. If the line is horizontal, there is no main effect of the variable; the HIC mean is the same for all levels of the variables. If the line is not horizontal, there is a main effect; different variable levels may affect the response differently. Figure 5 clearly indicates that the only two significant variables are the head drop calibration (H_C), and approach angle (θ_a). Packing pressure and injection speed show a slight effect on HIC. The variation in the HIC due to packing pressure and injection speed is within approximately 5%, which would be considered a component of the experimental error.

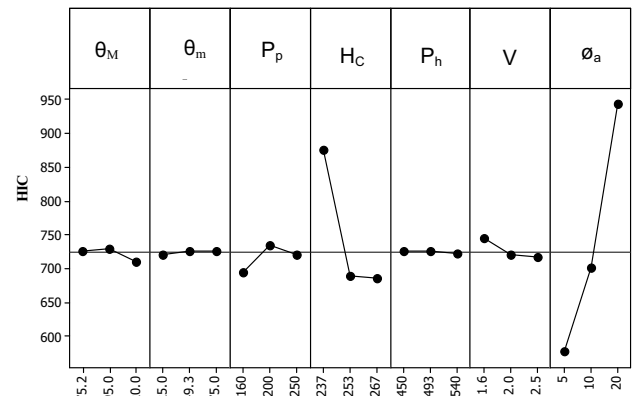


Figure 5 MAIN EFFECTS PLOT FOR ALL VARIABLES

Appendix F displays the estimated regression coefficients for HIC. It shows the calculated R^2 and adjusted R^2 , which represent the proportion of variation in the response that is explained by the model. R^2 describes the amount of variation in the observed responses. For the HIC, 94.9% of the variation in response is explained by model. Adjusted R^2 (87.4%) is