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Biomedical Sciences Instrumentation

MULTIVARIATE HEAD INJURY THRESHOLD MEASURES FOR VARIOUS SIZED CHILDREN SEATED BEHIND VEHICLE SEATS IN REAR IMPACTS

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KEYWORDS

Rear-Impacts, Seat-Collapse, Children, Rear-Seated Children, Child Head-Injury, Biomechanics, Experimental Methods

ABSTRACT

Government recommendations to place children into the rear areas of motor vehicles to avoid airbag induced injuries have been complicated by the fact that most adult occupied front seats will collapse into the rear area during rear-impacts, and thus pose another potentially serious injury hazard to rear-seated children. Many variables affect whether or not a front seat occupant will collapse into the rear child, and whether that interaction could be injurious to the child. For instance, the severity of rear impact, coupled with front and rear occupant sizes (mass and stature), and the level of front seat strength, all interrelate to influence whether or not a rear seated child is likely to be impacted and possibly injured. The most common types of child injuries in these instances are head and chest injuries. In this study, a "high-low" experimental method was employed with a multi-level "factorial analysis" technique to study "multivariate" biomechanics of child head injury potential determined from rear-seated 3 and 6 year-old child surrogates in different types of vehicle bodies mounted to a sled system. The sled-buck systems were towed rearward into crushable barriers that matched the crash pulses of the vehicle types being tested. Various sizes of adult surrogates (i.e. 50 kg up to 110 kg), seated in both the "typical" low strength "single recliner" collapsing type front seat (i.e. 3.2 kN) and a much stronger "belt-integrated" seat design (i.e. up to 14.5 kN), were tested in the two different "sled body-buck" set-ups at various impact levels (i.e. 22.5 to 50 kph). One set-up used a popular minivan vehicle body with "built-in booster" seats for the 3 year-old. The other used a 4-door family sedan vehicle body with the 6 year-old in a standard rear bench seat. The parameters of the tests enabled the experimental data to be combined into polynomial "head injury" functions of the independent variables so the "likelihood" of rear child head-injury potential could be "mapped" over ranges of the key parameters. Accident cases were compared with predictions to verify the methodology.

INTRODUCTION

In order to avoid airbag hazards and fatalities to children and infants during frontal impacts, the U.S. government, among other things, recommended in the mid 1990 time frame that children be placed into the rear seating areas of motor vehicles. However, during rear impacts, most adult occupied front seats tend to collapse into the rear occupant area where the children and infants are to be located. Collapse of an adult occupied seat and occupant into the rear area presents several potential hazards and dangers to the rear seated children. These hazards include possible contact interactions that could result in head, neck, chest and other injuries to the rear occupant. Another potential hazard associated with seat collapse into a rear child is "entrapment" where the seat plastically deforms onto the legs or lower torso in such a manner as to inhibit escape in a post crash situation such as fire. Serious to fatal head injury is the most common result of front seat collapse into a rear child during rear impact. An accident data study dealing with injury to rear seated children, conducted by the Insurance Institute for Highway Safety [1], seems to corroborate the above. This study indicated that children in the rear area were *safer* for all modes of impact except for rear impact where *"in rear impacts, children seated in back had a 61 percent higher risk of fatal injury than children in the front"*. Some recent work [2-4] has investigated the rear child issue. Unfortunately, most rear-impact studies focused primarily on front occupants [5,6].

Several factors must be considered in order to evaluate the impact conditions and seat design parameters that may allow front-to-rear occupant interactions, and possibly head injury to a rear-seated child. For example, front seat rearward loading strength levels (based on tests run by the authors) exhibit a wide range of occupant load resistance (i.e. about 3 kN (675 lbs) for the single recliner types and as high as 20 kN (4,500 lbs) for a "belt-integrated" type) [2]. In addition, several other factors or variables can influence seat system performance and injury risk to both front and rear seated occupants. These include, among other things, the size and weight of the front seat occupant, and the severity or level of the rear impact (i.e. change in velocity). Each of these factors also encompasses a wide parameter range. Front occupant sizes can range from as small as a fifth percentile female of about 50 kg on up to larger adult occupants weighing more than double that amount. The size of the rear-seated child, and type of child restraint, can also affect the out come of safety system performance. Thus, the large number of variables, and the ranges of parameters within each variable, requires careful planning in order to fully evaluate safety system performance in an efficient and global manner. Traditional "one-test-at-a-time" experimental approaches are costly and only provide limited information related to a few specific test parameters. Fortunately, efficient experimental methods are available to evaluate "multivariable" effects of motor vehicle seat safety performance in relation to rear child head injury potential. Examples are presented in the following sections of the paper and correlated with actual cases cited in reference 2.

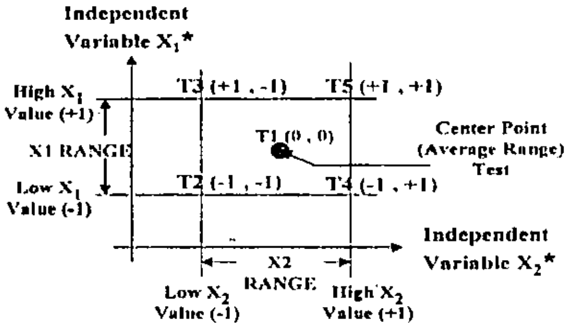
MULTIVARIATE EXPERIMENTAL / ANALYTICAL METHODS

Efficient experimental design and "multi-variable" analysis methods have been available since as far back as the 1940 time frame [7]. For instance, in the "Plackett-Burman" screening method only 12 tests are required to screen up to six variables and determine the ranking or level of importance of the variables tested [7]. Once the two or 3 most important variables have been identified by these screening methods, these primary variables can then be more efficiently evaluated by methods such as the "Box-Behnken" or "factorial" method [8]. In these latter methods, only a relative few tests are required to establish mathematical interrelationships of the variables and measured output responses, such as child head injury potential. The mathematical interrelationships of the variables are expressed in a polynomial format that presents the desired output (i.e. child head injury potential in this study) as a function of the many variables. The polynomial output of test results also allows for interpolation and extrapolation to study output responses at levels of parameters not tested. Thus, these techniques are "test efficient". In addition, rather than crashing several expensive vehicles to obtain the data for each test, a "single vehicle body" is mounted to a sled test apparatus. Thus, the sled-buck system requires only one vehicle body that can be reused for each test by simply replacing only the damaged test articles (i.e. usually just the front seats). The sled-buck is then towed rearward into a crushable barrier that simulates the actual vehicle rear impact crash pulse. This provides a "cost effective" means for gathering relevant measures.

The "2-level factorial method" is the experimental approach used in this study. The authors also used the "2-level factorial method" in a prior study [3] to examine the rear impact seat system performance of a common type of "single recliner (SR)" front seat as it related to the head injury of a 3 year-old child surrogate in a "built-in child booster seat". This child was located behind a typical SR collapsing front seat of a popular minivan. Only 5 tests were required to quantify front seat performance, and the head injury potential of a rear seated 3-year old child, as a function of two variables: rear-impact severity (i.e. variable X1); and size of front seat occupants (i.e. variable X2). Figure 1 illustrates the matrix of tests "T" and level of variables examined in reference 3, and the general form of "response" polynomial "Y". Note also that the actual high-low values of the variables are represented as non-dimensional +/- 1 units.

Independent Variable X1 = Impact Severity Defined by Delta Velocity Levels of :
Low = 13.5 mph (22.5 kph);
Ave. = 19.5 mph (32.5 kph);
High= 25.5 mph (42.5 kph).

Independent Variable X2 = Front Adult Weight (Seated in SR Collapsing Seat):
Low = 110 lbs (50 kg);
Ave. = 175 lbs (80 kg);
High= 240 lbs (110 kg).



$$\boxed{Y(\text{Child HIC}) = A_0 + A_1X_1 + A_2X_2 + A_{12}X_1X_2}$$

Figure 1 - Example of the Test Configurations for a 2-Level Factorial Test Series with Two Primary Variables X1 and X2

The independent variables X1 and X2 are non-dimensionalized in the response polynomial "Y" by equation 1 so that the maximum, minimum and average values are represented as +1, –1, and 0, respectively. Any values between or beyond the maximum and minimum are also scaled by equation 1. For instance, a 65 kg occupant weight would be represented by a dimensionless X2 value of "-0.5".

Xi (non-dimensional) = {Xi(actual) – (Xi(actual hi) + Xi(actual lo))/2} / {(Xi(actual hi) – Xi(actual lo))/2} (eq#1)

The minimum number of tests "T" required for "X" independent variables in the "two-level" (High-Low) factorial method for development of the "response" polynomial "Y" is $T = 2^X$. The statistical significance of the polynomial factors can be evaluated by running random repeats of each of the five configurations shown above in figure 1. Details of the statistical aspects are covered in reference 8.

Two Level Factorial Approach for a "2-Variable" Head Injury Threshold Analysis of a 6 Year-old

The current study presents the results of a two variable analysis (i.e. impact severity and front occupant size) for a six year-old child surrogate seated behind a SR collapsing seat (i.e. 3.2kN strength) of a standard "family" 4-door sedan, and using the available rear lap-shoulder restraint. This case included a repeat test to demonstrate repeatability of occupant-to-occupant head contact and level of injury prediction. In addition, a severe 50 kph test was also run to allow side-by-side comparison of the difference in response of an average size front surrogate seated in the typical "single recliner" collapsing type seat versus a stronger "belt-integrated" retrofit seat. Figure 2 shows a scene at impact for this last test condition. In all tests, the front seats were placed approximately ¾ back from full forward, with the seatbacks 20 degrees from vertical. All surrogates were fully restrained and in normal seated positions.

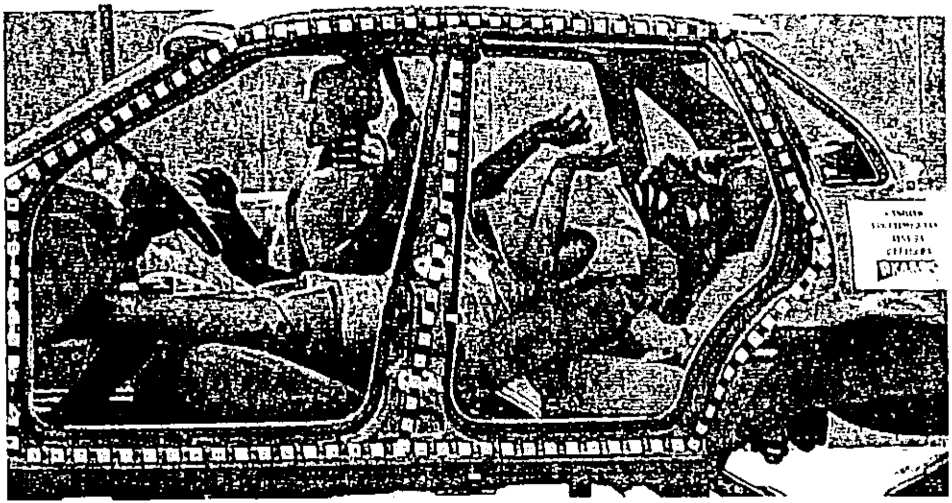


Figure 2 – Comparison of Strong and Weak Seat Average Adult Interactions with Rear 6 Year-old Surrogates at 50 kph

Table 1 summarizes the levels of the "independent variable" parameters for each test of the rear seated six-year-old Hybrid-III child surrogate study for 2 variables. Also included in the table 1 is the resultant "dependent variable" child HIC (15 ms Criteria) calculated from the measured child head accelerations.

Table-1 Test Data and Child "HIC" Results for Six Year-old "2-Variable" Study

Test Number	Independent Variable – X1 (Speed Delta)	Independent Variable – X2 (Front Occupant Weight / Seat Type)		Resultant Variable (6 Year-old Child HIC)	
		Driver	Right Front	Left Rear	Right Rear
1	50.0 kph	73 kg / SR	73 kg / BIS	2,032.1	48.1
2	25.0 kph	110 kg / SR	50 kg / SR	135.8	22.6
3	50.0 kph	110 kg / SR	50 kg / SR	4,379.4	70.2
4 (repeat of 3)	50.0 kph	110 kg / SR	50 kg / SR	7,004.7	66.6
5	37.5 kph	110 kg / SR	73 kg / SR	3,412.6	1,572.9

*** NOTE: SR indicates single recliner collapsing seat and "BIS" indicates stronger belt-integrated seat.**

With regard to the 1st test, it is interesting to note that the 6 year-old child surrogate seated behind the collapsing driver SR seat received a fatally high HIC level of 2,032.1 whereas the child behind the "stronger" BIS seat only experienced a non-injury threatening HIC of 48.1. Also note, the 4th test is a repeat of the 3rd and the mean value of "child HIC" associated with these 2 tests is 5,692.1 +/- 23.1%.

Table-2 Factorial (high-low) Computation Matrix for 6 Yr-old, 2-Variable, Polynomial HIC Function

COMPUTATION TEST CONFIGURATIONS	A0	A1	A2	A12	Child (6 yr-old) HIC RESULTS
1A (Test #2 right Side)	+	-	-	+	22.6
2A (Test #3 & 4 rt. side ave.)	+	+	-	-	68.4 (Tests 3 & 4 ave.)
3A (Test #2 driver side)	+	-	+	-	135.8
4A (Test #3 & 4 dr. side ave.)	+	+	+	+	5,692.1 (Tests 3 & 4 ave.)
Σ (COLUMN SUM) =	5,918.9	5,602.1	5,736.9	5,510.5	
Ai (Σ ÷ by # of TESTS) =	1,479.7	1,400.5	1,434.2	1,377.6	

Table 2 shows the "high-low" "factorial matrix" used to calculate the head injury response polynomial "Y (Child-6 HIC)" for the six year-old child. The polynomial coefficients in a given column are calculated by simply multiplying the "result" column HIC value in a given row by the appropriate "plus" or "minus" sign of that row, under a desired "coefficient" column, and then summing the values in that column. Finally, divide the sum by the number of "hi-lo" test configurations (i.e. 4 in this example) and the result yields the polynomial coefficient. Thus, the 6 year-old Child Head-Injury-Criteria HIC polynomial for a "typical" SR type front seat is given in dimensionless form, for 2 variables as:

$$Y\ (\text{Child-6 HIC}) = 1{,}479.7 + 1{,}400.5*X1 + 1{,}434.2*X2 + 1{,}377.6*X1*X2 \qquad (\text{eq\#2})$$

Two Level Factorial Approach for a "3-Variable" Head Injury Threshold Analysis of a 3 Year-old

The current work also expands the prior reference 3 study for a 3 year-old in a minivan booster seat to include a 3rd variable of seat strength (i.e. variable X3). Tables 3 and 4 give the test configurations, parameter ranges, computation matrix, and resultant HIC data for the updated 3 Year-old head injury study. Reference 3 only examined collapsing SR seat HIC levels. This study now includes BIS seat data.

Table-3 Test Configurations, Levels of 3 Variables, and Child "HIC" Results for 3 Year-old Study

Test Configurations	Indep. Variable X1 (Speed Change)	Indep. Variable X2 (Occupant Weight)	Indep. Variable X3 (Seat Type-Strength)	Resultant HIC (3 Year-old Child)
1B	32.5 kph	80 kg	SR – 3.2 kN	1,903.6
2B	22.5 kph	50 kg	SR – 3.2 kN	47.4
3B	42.5 kph	50 kg	SR – 3.2 kN	178.3
4B	22.5 kph	110 kg	SR – 3.2 kN	2,335.2
5B	42.5 kph	110 kg	SR – 3.2 kN	8,515.9
6B	22.5 kph	50 kg	BIS – 14.7 kN	48.7
7B	42.5 kph	50 kg	BIS – 14.7 kN	100.2
8B	22.5 kph	110 kg	BIS – 14.7 kN	66.8
9B	42.5 kph	110 kg	BIS – 14.7 kN	100.2

Table-4 Factorial (high-low) Computation Matrix for 3 Yr-old, 3-Variable, Polynomial HIC Function

Configuration #	A0	A1	A2	A3	A12	A13	A23	A123	Child HIC Results
2B	+	-	-	-	+	+	+	-	47.2
3B	+	+	-	-	-	-	+	+	178.3
4B	+	-	+	-	-	+	-	+	2,335.2
5B	+	+	+	-	+	-	-	-	8,515.9
6B	+	-	-	+	+	-	-	+	48.7
7B	+	+	-	+	-	+	-	-	100.2
8B	+	-	+	+	-	-	+	-	66.8
9B	+	+	+	+	+	+	+	+	100.2
Ai (Σ / 8) =	1,424.1	799.6	1,330.4	-1,345.1	754.0	-778.3	-1,325.9	-758.5	

The 3-year-old Child HIC polynomial "Y" (Child-3 HIC)" for 3 variables is calculated from Table 4 as:

$$\begin{aligned} Y\ (\text{Child-3 HIC}) = {} & 1{,}424.1 + 799.6*X1 + 1{,}330.4*X2 - 1{,}345.1*X3 + 754*X1*X2 \\ & - 778.3*X1*X3 - 1{,}325.9*X2*X3 - 758.5*X1*X2*X3 \qquad (\text{eq\#3}) \end{aligned}$$

RESULTS AND DISCUSSION

Equation 3 allows for a study of the 3-year-old child HIC as a function of 3 variables, including front seat strength X3. The comparison of tests 5B and 9B HIC results show a dramatic reduction in HIC level with the BIS seat. Setting X3 to a –1 value (i.e. the same as a SR collapsing seat of 3.2 kN strength) allows for comparison of the 3 and 6 year-old child head injury levels, as well as comparison with actual cases using a similar type of SR seat as described in reference 2. A 700 HIC level has been suggested as the appropriate head-injury level for a 6-year-old child and this level is used for both the 3 and 6 year-old in this study. Figure 3 shows the 700 level HIC curves generated from equations 2 and 3. Both curves correlate well with actual accident cases [2] and seem to validate the multi-variate methodology. Differences in the levels of the 2 curves, however, are due to "biofidelic" differences of the 3 and 6 year-old surrogates (i.e. seated size, stiffness, joint characteristics, etc.) and is the subject of future study.

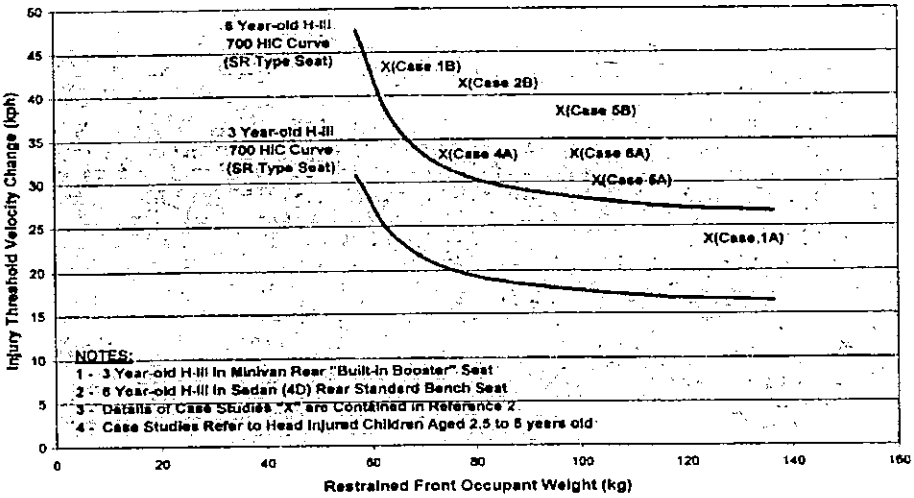


Figure 3 – Comparison of 3-Year-Old & 6-Year-Old 700 HIC Curves, in SR Collapsing Seats, with Actual Cases

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CASE REVIEW

06-026

LUSK VS. GM

DAVID BRIGHT
WATTS LAW FIRM
555 NORTH CARANCAHUA
TOWER II BLDG.
SUITE 1400
CORPUS CHRISTI, TEXAS 78478
361-877-0500
361-887-0055 FAX

INV. JENICA HENSON

SUB #1: LONNIE LUSK
W/M AGE: 50
HT: 5 ft. 9 in. WT: 260 LBS.
POSITION: #3 (RESTRAINED)
INJURIES: C6 QUADRIPLEGIA

SUB #2: KEISHA HIGGINS
W/F AGE: 13
HT: 5 ft. 2 in. WT: 81.8 kg
POS: #6 (RESTRAINED- EJECTED)
INJURIES: CLOSED HEAD INJ./SKULL FX

DATE OF INC: 11-6-05
VEH: 2002 CHEV. TRAILBLAZER
TYPE ACCIDENT: T BONE THEN ROLLOVER
DELTA V:
PDOF:
OF ROLLS:
SIDE LEADING:
SPEED AT ROLL:

<u>INITIAL ITEMS PROVIDED FOR REVIEW UNDER CLD 2-16-06:</u>

1) ALABAMA UNIFORM TRAFFIC ACCIDENT REPORT
2) COLOR LASER COPIES OF PHOTOGRAPHS OF VEHICLE.
3) COLOR LASER COPIES OF PHOTOGRAPHS OF THE OTHER VEHICLE INVOLVED IN ACCIDENT AND ACCIDENT SITE (POST ACCIDENT)
4) HUNTSVILLE HOSPITAL RECORDS FOR LONNIE LUSK.
5) BAPTIST MEDICAL-DEKALB CENTER RECORDS FOR LONNIE LUSK.
6) DEKALB AMBULANCE SERVICE RECORD FOR LONNIE LUSK.
7) MEDFLIGHT RECORD FOR LONNIE LUSK.
8) HUNTSVILLE HOSPITAL RECORDS FOR KEISHA NICOLE HIGGINS.
9) DEKALB AMBULANCE SERVICE RECORD FOR KEISHA NICOLE HIGGINS.
10) MEDFLIGHT RECORDS FOR KEISHA NICOLE HIGGINS.
11) EDR REPORT
12) MULTIPLE COLOR LASER COPIES OF PHOTOGRAPHS OF THE SUBJECT VEHICLE.