Research Article

Neck Moment Characterization of Restrained Child Occupant at Realistic Nontest Standard Higher Impact Speed of 32.2 km/h

**S. Shasthri,^{1,2} V. Kausalyah,³ Qasim H. Shah,¹ Kassim A. Abdullah,¹
Moumen M. Idres,¹ and S. V. Wong⁴**

¹ Faculty of Engineering, International Islamic University Malaysia, 50728 Kuala Lumpur, Malaysia

² Faculty of Engineering, Universiti Selangor, 40000 Selangor, Malaysia

³ Faculty of Engineering, Universiti Teknologi Mara, 40000 Selangor, Malaysia

⁴ Malaysian Institute of Road Safety Research (MIROS), 43000 Selangor, Malaysia

Correspondence should be addressed to S. Shasthri; shasthri@yahoo.com

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The effects of bullet vehicle crash impact angle, child restraint system design, and restraint harness slack at side impact speed of 32.2 km/h (20 mph) on moments sustained at the neck by a three-year-old child are investigated. Mathematical models are built using the response surface method based on simulation results whereby good fitness is achieved. The singular and cross interactive effect of each predictor on the neck moment are analyzed. The number of significant parameters affecting the neck moment is shown to be the largest for wide impact angles ($\phi \geq 60^\circ$) and the impact angle parameter is largely revealed to be the most sensitive. An ideal safe range for low neck moment has been established to be within ϕ angles 45° and 65° . It is further shown that the nature of all parameters effect on the neck moment is highly dependent on the impact angle range.

1. Introduction

It has been shown over the last two decades that vehicle crashes have become the leading cause of death for children in many developed countries [1–4]. The side impact crash mode especially is shown to be a particularly harmful mode [5, 6]. Many factors contribute to this scenario, one of which is the presence of shoulder harness slack [3, 6, 7]. Another is due to the kinematics of side impact crash which depends upon both the magnitude of the impulse from the bullet vehicle and its principle direction of force (PDOF) impacting angle [8]. In addition, it has been shown that the head contact with intruding door due to the bullet vehicle plays a pivotal role and has to be considered in addressing any mitigation efforts [9, 10].

Although head injuries are largely reported to be prime cause of fatalities in child restraint system (CRS) restrained toddlers involved in side impact crash [3, 4, 10, 11], there is sufficient cause for concern where the fatality may also be related to high neck loading [12]. Investigation of neck

moments pertaining to CRS design, misuse, and crash parameters is yet unexplored due to insufficient accident data and costly full vehicle analysis simulations. Thus, the effects and relationships between the singular and cross interactive parameters, especially for oblique side impact involving intrusion, are not studied [10]. Insights obtained from such a work would serve to promote better understanding of the side impact crash event in order to achieve greater injury mitigation.

In this work, a study is undertaken to characterize the neck moment (NM) of a CRS restrained 3-year-old child occupant involved in lateral and oblique side impact, with respect to identified relevant crash parameters. A prescribed structural motion (PSM) simulation is carried out where a prevalidated Hybrid model consisting of both finite elements (FE) and multibodies (Mb) is subjected to a pulse, which represents the bullet vehicle kinematic impact load. The methodology allows for significant savings in computational cost while preserving the required accuracy. The commercially available MADYMO 7.4.1 by TASS is used for the

FIGURE 1: Oblique side impact PSM simulation.

FIGURE 2: CRS parameters considered for oblique side impact.

simulation due to its capability to handle both FE and MB. A design of experiments (DoE) using the Latin hypercube sampling (LHS) is employed to build mathematical models using the response surface method (RSM). Statistical methods are used to map the parameter sensitivity upon the NM both individually and cross interactively. Statistical modelling and analysis are conducted using MATLAB 2013a. The present work reports data corresponding to a bullet vehicle impact speed of 32.2 km/h (20 mph) based on the TRC

595 pulse which is relatively higher compared to the standard manufacturer-friendly test impact speed of 24.4 km/h (15 mph) [13]. The selected velocity is considered to be a more realistic estimation of the crash event.

2. Numerical Modelling

An R44-standard compliant CRS is modelled using shell elements with a specified thickness of 4 mm. LS-PrePost 4.1 by

FIGURE 3: Effect of impact angle parameter X_1 on neck moment.

FIGURE 4: Qualitative analysis of neck moment response for RS models.

Livermore Software Technology Corporation is used for the FE model mesh generation. The material property is defined as polypropylene. The density (ρ), Young's modulus (E), and Poisson's ratio (μ) are specified, respectively, as 800 kgm^{-3} , 0.842 GPa , and 0.3 whereas the yield and the ultimate tensile strengths are set as 8.76 MPa and 18.76 MPa , respectively [14–16]. A foam insert comprising solid elements is also modelled as shown in Figure 1. This is placed at the side wings of the CRS to absorb head impact. A highly compressible low-density foam material model ($\rho = 50.2 \text{ kgm}^{-3}$, $E = 5.463 \text{ MPa}$) is used [7, 16]. The CRS is constrained at base anchorage points on a ECE R.44 test bench using fixed cross bars. The boundary conditions and simulations are done in MADYMO 7.4.1.

The five-point harness system of the CRS is modelled predominantly using 1 mm thick membrane elements ($\rho = 890.6 \text{ kgm}^{-3}$, $E = 2.068 \text{ GPa}$, and $\mu = 0.3$). However, to reduce computation time, the FE belts are connected at both ends to the anchor point using rigid bodies. Loading and unloading

data with hysteresis are provided for both belt types [7, 16, 17]. No slack is allowed for the belt fitting [14].

An intrusion of 280 mm is considered [13, 18] and this is achieved by means of introducing rigid static planar-surfaces as shown in Figure 1. The secondary intrusion plane (130 mm intrusion) has contact defined against the CRS as well as the child dummy whereas for the primary intrusion plane, only the head is allowed to contact with it. This arrangement is assumed to cater for the worst case scenario of the intrusion whereby the head is free to strike the hardest part of the intruding door, at the earliest moment of time.

A commercially available ellipsoid Hybrid III 3YO child dummy model is used in this work [17]. Both dummy and CRS are subjected to gravitational loading as well as acceleration pulse to simulate lateral side impact. Dynamic simulation time is set to terminate after 125 ms . Convergence study is carried out during the trial runs and a good tradeoff between model cost and accuracy is achieved with an element count of $24,320$. The entire model assembly has been previously validated and it has been shown to be both accurate and

FIGURE 5: NM significant singular parameter response line plots.

computationally economical with each run typically taking only 20 minutes [19].

3. Statistical Modeling

Figure 2 illustrates the parameters selected for the sensitivity study and Table 1 shows organization of the DoE as well as the upper and lower bounds considered for each parameter adopted from standards [20, 21]. To further increase the sensitivity of the study, the PDOF impact angle (ϕ) is divided

into two groups, namely, PDOF A ($60^\circ \leq \phi \leq 90^\circ$) and PDOF B ($30^\circ \leq \phi \leq 60^\circ$). The first caters for a wide PDOF angle ($\phi \geq 60^\circ$) impact approach while the latter represents a narrow impact approach ($\phi \leq 60^\circ$). The ensuing NM response plots generated by MADYMO are recorded. Multinomial regression is used as a method to determine parameter sensitivity and hence a quadratic response surface method (RSM) is used to model the problem. The response data is converted to logarithmic values of base 10 and submitted for regression analysis.

FIGURE 6: NM significant X_1 cross interactive parameter response surface plots.

TABLE 1: DOE grouping and parameter bounds.

Attributes	Group	
	PDOF A	PDOF B
$X_1(90^\circ - \phi)$ (degrees)	$0^\circ \leq X_1 \leq 30^\circ$	$30^\circ \leq X_1 \leq 60^\circ$
X_2 (degrees)	$8^\circ \leq X_1 \leq 24^\circ$	
X_3 (mm)	$3.5 \leq X_1 \leq 5.5$	
X_4 (value)	$0.25 \leq X_1 \leq 0.35$	
X_5 (cm)	$0 \leq X_1 \leq 5$	
X_6 (cm)	$0 \leq X_1 \leq 5$	
Pulse	32.2 km/h (TRC595)	

4. Results and Discussion

From the DoE tabulations, the full range of X_1 values encompassing both PDOF A and B groups against the NM response is plotted as shown in Figure 3. The values seem to peak at 30° with approximately 75 Nm. A favourable low neck moment of 50 Nm and below seems to be indicated

between PDOF ϕ angles 45° and 62° . The NM severity range (approximately above 60 Nm) is indicated for PDOF impact angles to be less than 40° and greater than 66° .

Table 2 shows the statistical diagnostics obtained for all four models. From the regression coefficients, good fitness is indicated for all the models where the model errors are shown to be low as given by the small RMSE values. The R^2 and R^2 adjusted (R^2 Adj.) values substantiate this conclusion and provide a good indication of the model fitness with all values approaching unity. Additionally, results from the Fisher (F) test reconfirm that the RSM models are statistically acceptable and this is supported by the low associated P values.

Student's t -test is used to identify the major contributing single parameters and cross interaction parameters as well as assess their respective parametric significance. Figure 4 depicts the full data distribution and pattern of the t statistic values for each model in graphical form while Table 3 shows the t statistics for only the significant parameters identified. A quick glance reveals that the PDOF A groups obviously register more numbers of significant parameters than the

FIGURE 7: NM other significant cross interactive parameter response surface plots.

TABLE 2: Model fitness diagnostic statistics.

RSM models	Fisher test		Model fitness statistics		
	<i>F</i> statistic	<i>P</i> value	R^2	R^2 Adj.	RMSE
PDOF A	143.011	$4.841E - 13$	0.9964	0.9894	0.006
PDOF B	18.409	$5.3650E - 7$	0.9726	0.9198	0.015

Note: Only parameters having *P* value of less than 0.05 are included in the table.

PDOF B groups. This shows that the NM of the restrained 3-year-old child during side impact is very much affected by the designated parameters both individually and cross interactively for wide PDOF impact angles of $\phi \geq 60^\circ$.

A scrutiny of Table 3 and Figure 4 reveal the PDOF impact angle ϕ (X_1) to be the most sensitive parameter for all cases, both singularly and cross interactively. Singularly, the significance is found to be especially pronounced for wide PDOF impact angles ($\phi \geq 60^\circ$) where the *P* value is shown to be relatively very small ($t = 7.6795$, $p = 2.20E - 6$). It is interesting to note that, contrary to PDOF A, values for PDOF B ($\phi \leq 60^\circ$) are negative indicating that increase in X_1 serves only to reduce NM. The response surface line plots for X_1 with respect to NM for both impact angle groups are shown in Figure 5.

Cross interactively, the parameters X_1X_5 and X_1X_6 register moderate significance for PDOF B although this observation is not seen to hold for wider impact angles (PDOF A). For the later impact angle group, X_1 interaction is notable with X_2 and X_3 . No interaction with parameter X_4 is seen for any of the models. The response surface plots for these significant interactions with X_1 are depicted in Figure 6.

The CRS pitch angle parameter (X_2) is found to be sensitive only for wide PDOF impact angles ($\phi \geq 60^\circ$) (Figure 5(c)). Cross interactivity of the parameter with X_1 (Figure 6(a)) as well as with X_5 is observed (Figure 7(a)). The CRS shell thickness parameter X_3 is also found to be significant only cross interactively and that too only for wide PDOF impact angles (PDOF A). Four interactions, X_1X_3 , X_3X_4 , X_3X_5 , and X_3X_6 , are seen of which the response surface plots for the last three are given in Figures 7(b), 7(c), and 7(d), respectively. Except for the first interaction (Figure 6(b)), the other three are shown to have a positive effect on neck moment.

The harness coefficient of friction parameter X_4 indicates the least sensitivity in this study with only a single positive cross interaction with X_3 (Figure 7(c)) seen for PDOF A. The misuse parameter X_5 (far side harness slack) is found to be singularly insignificant for the determination of neck moment in side impact crash. However, cross interactively, three observations (X_2X_5 , X_3X_5 , and X_5X_6) of moderate significance are noted for PDOF A. The response surface plots are given in Figures 7(a), 7(c), and 7(e), respectively. Similar to X_5 , the X_6 parameter (near side harness slack) has no singular significance but retains some cross interactivity across the models. The PDOF B group has only one cross interaction parameter, X_1X_6 (Figure 6(a)), while PDOF A reveals two observations X_3X_6 (Figure 7(d)) and X_5X_6 (Figure 7(e)), all of moderate significance.

TABLE 3: Student's *t*-test and significance *P* of parameters for NM response.

Significant parameters*	20 PDOF A		20 PDOF B	
	<i>t</i>	<i>P</i>	<i>t</i>	<i>P</i>
X_1	7.6795	2.20E - 6	-2.7923	0.0144
X_2	2.4049	0.0306		
X_1X_2	3.6455	0.0026		
X_1X_3	-2.5905	0.0214		
X_1X_5			-2.8355	0.0132
X_1X_6			-2.1828	0.0466
X_2X_5	-2.8776	0.0122		
X_2X_6				
X_3X_4	3.3560	0.0047		
X_3X_5	2.9570	0.0104		
X_3X_6	2.4350	0.0289		
X_5X_6	2.4276	0.0293		
X_1^2	-10.0325	$8.97E - 8$	6.7638	$9.11E - 6$
X_5^2	2.1956	0.0455		

* Only parameters having *P* value of less than 0.05 are included in the table.

Note. Values of high statistical significance ($P < 0.01$) are bold.

5. Conclusions

Response surface models have been generated using LHS design and have been shown to have good fitness. Parametric behaviour affecting neck moments during side impact crash affecting restrained child, which is previously unavailable, is captured. The singular and cross interactive parameter sensitivity for neck moments in a 3-year-old child involved in realistic intrusive side impact speed of 32.2 km/h is studied and acceptable values of the *t* statistic and its significance *P* are obtained and reported.

The number of significant parameters affecting the neck moment is shown to be the largest for wide impact angles ($\phi \geq 60^\circ$) and the PDOF angle X_1 is largely revealed to be the most sensitive parameter. An ideal safe range for low NM has been established to be within ϕ angles 45° and 65° . It is reported that X_1 has an increasing effect on NM at wide impact angles but, for narrow impact angles, the opposite holds true. The other parameters are generally found to be moderately significant only for wide PDOF impact angles. It has been shown that the harness friction coefficient (X_4) has relatively very little effect on NM.

The nature of all parameters effect on the NM (of weather increasing or decreasing) is shown to be highly dependent on the impact angle range. Thus, it is understood that oblique

side impact with intrusion affects the neck moment very differently compared to purely lateral crash.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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