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Parameter Study of Neck Force in Restrained 3 Year Old Child Involved in Vehicle Side Impact

[1,2]Shasthri S., [3]Kausalyah V.,[1]Shah Q.H., [1]Abdullah K.A., [1]Idres M.M., [4]Wong S.V.

[1]*Faculty of Engineering, International Islamic University Malaysia, 50728 Kuala Lumpur, Malaysia.*
[2]*Faculty of Engineering, Universiti Selangor, 40000 Selangor, Malaysia.*
[2]*Faculty of Mechanical Engineering, UniversitiTeknologi Mara Malaysia (UiTM), 40000 Selangor, Malaysia.*
[4]*Malaysian Institute of Road Safety Research (MIROS), 43000 Selangor, Malaysia.*

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ABSTRACT

Child casualties and fatalities due to motor vehicle crashes are an increasing concern. In side impact crashes, the investigation of neck forces pertaining to Child Restraint System design, misuse and crash parameters are yet unexplored due to modelling constraints and experimental limitations. In this work, a three year old child seated in a Child Restraint System is subjected to lateral side impact crash. A Prescribed Structural Motion simulation method is used in which the loading pulse is obtained based on experimental data. A hybrid model comprising of multi-body ellipsoids and finite elements is developed and validated for the simulation of the lateral side impact of a HYBRID III three year old child dummy. The model is found to be computationally very economical as well as acceptably accurate. Subsequently, the model is adapted to include intrusion effects at oblique impact angles and the Design of Experiments methodology is used as a tool for this purpose. A Latin Hypercube Sampling design is used to generate the simulation runs for which a total of six parameters are considered. The simulation runs are conducted with two different impact velocities and are grouped separately. The impact velocities used are 15 km/h and 20 km/h in which the former represents the standard test impact speed. The singular and cross interactive effect of each parameter on the Neck Force of the three year old child dummy is studied. This is achieved through regression analysis where the Response Surface Method models are shown to be suitable for the mathematical modelling of the problem. Student's t test is used to conduct parameter sensitivity studies for the Neck Force response. The impact angle is revealed to be the most sensitive parameter to affect neck forces during side impact, especially for narrow impact angles ($\phi \leq 60°$). A critical range is established in which the Neck Forces are found to be highest primarily between impact angles 50° and 70°. A secondary critical range is also observed for angles below 34°. It is seen that most of the other parameters are generally found to be moderately significant only at low impact speed (15 mph).

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INTRODUCTION

Child passenger injuries due to car collisions are gaining increased attention from consumers, the industry, the research community and governments. This is due to concerns whereby motor vehicle crashes has become the leading cause of death for children in many developed countries (NHTSA, 2005; Statistics Canada, 2007). This has naturally lead to extensive studies on the safety of child passengers. Literature has shown that child anatomy and physiology (Tingvall, 1987; Yoganandan*et al*., 1999; Gotschall*et al*., 1999)necessitates a separate restraints system to be implemented during vehicle travel. Thus Child Restraint Systems or CRS were developed and have been documented under various circumstances to successfully mitigate child injury and death (Rice *et al*., 2009; Arbogast*et al*., 2004a).

Although it is well known that approximately twice as many crashes with a child fatality are frontal compared to lateral,later findings show that side impacts are nearly twice as likely to result in a child fatality as frontal impacts, regardless of restraint status or seating position [Starnes and Eigen, 2002). While most child restraints provide good protection in frontal impacts when used properly, side impact testing up to 2012 was not mandated and has not been a main design feature for most car seats and boosters. Only recently in 2014, the NHTSA National Highway Traffic Safety Administration (NHTSA) made same proposals to include side impact

Corresponding Author: Shasthri S**,** Faculty of Engineering, International Islamic University Malaysia, 50728 Kuala Lumpur, Malaysia.
E-mail:Shasthri<shasthri@yahoo.com>

testing for CRS in the Federal Motor Vehicle Safety Standards, (FMVSS).However these are far from exhaustive and remain still in the rule making stage(FMVSS, 2013).

The side impact crash mode is shown to be a particularly harmful mode especially for children positioned in the rear struck side (Starnes and Eigen, 2002; Arbogast*et al*., 2004b).Preponderance of head injuries is largely reported to be prime cause of fatalities in CRS restrained toddlers involved in side impact crash [McCray *et al*., 2007; Arbogast*et al*., 2005). The Head Injury Criteria (HIC), an integration of the acceleration profile of the head, is commonly accepted as one method of directly assessing head injury. However, for small children, the cause of fatality may also be related to high neck loading. There has long been a concern for the possibility of the cervical spine of the child being separated due to forceson the neck. This may potentially occur when the shoulders are held back in a crash as pointed out by Weber (2000).Such an occurrence is especially possible due to the forward acceleration component present in oblique side impact. Thus, despite the preponderance of head injuries in fatality statistics, a parametric study of the effect of forces and moments experienced by the neck may well provide new insights.

Investigation of neck forces pertaining to CRS design, misuse and crash parameters is yet unexplored. The effects and relationships between the singular and cross interactive parameters, especially for oblique side impact involving intrusion are not studied(Arbogast*et al*., 2005). Reliable and realistic procedures are necessary to obtain useful insights for promoting better understanding of the side impact crash event in order to achieve greater injury mitigation. Numerical and statistical modelling are relatively inexpensive and efficient tools in this regard.

In this work, a parametric study is undertaken to study the relationship between the Neck Force (NF) of the CRS restrained dummy and the oblique side impact crash parameters involving intrusion. An attempt is made to map the parameter sensitivity both individually as well as cross interactively. A hybrid model is constructed using a combination of both Finite Elements (FE) and Multi-body ellipsoids (Mb) where a three year-old childdummy is placed inside a CRS and restrained with a harness system. A Prescribed Structural Motion (PSM) simulation of a side impact crash is carried out based on experimental data. Upon satisfactory validation, a Plan of Experiments is prepared based on the Latin Hypercube Sampling (LHS) for six parameters involving two different crash velocities.The Response Surface Method (RSM) is used to build a mathematical model for regression analysis. The maximum Neck Force (NF) value registered between the upper and lower neck of the child dummy model is defined as the response. The regression coefficients areused to assessthe Response Surface (RS) model fitness as well as to draw conclusions on the parameter sensitivity both quantitatively and qualitatively.

MATERIALS AND METHODS

Numerical Model Development:

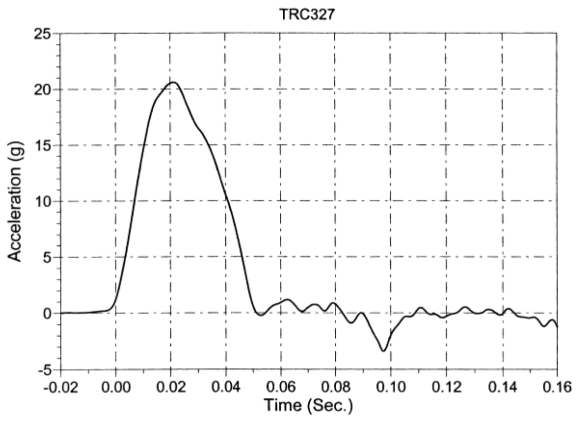

Fig. 1: Pulse TRC327 - closing speed of 15 mph.

Data from the National Highway Traffic Administration of a side impact dynamic sled test experiment (Test no 4585) is adopted to serve as baseline for the model building and subsequent validation efforts (NHTSA, 2007). In this test, a Hybrid III 3-year-old dummyis restrained in a CRS.A side rigid wall (height 762mm, breadth 810mm) is positioned 508mm from Point Z1 (location of furthest anchorage from the rigid wall) as outlined in FMVSS 213 standard(FMVSS 213, 2013). A lateral side-impact is carried out at a closing speed of 24.1 km/h (15 mph) and the acceleration pulse (pulse no TRC327) recorded is shown in Figure 1.

The numerical model developed for the simulation study is shown in Figure 2.An ellipsoid Hybrid III 3YO child dummy model is used in this study. Studies have established that the use of ellipsoid dummy modelsdrastically reduce computation time while preserving acceptable accuracy for kinematic response (Surcel and Gou, 2005). The model comprises of 28 ellipsoids while certain regions of the head is built using finite elements. It has been developed and extensively validated by TASS International (TNO, 2013).

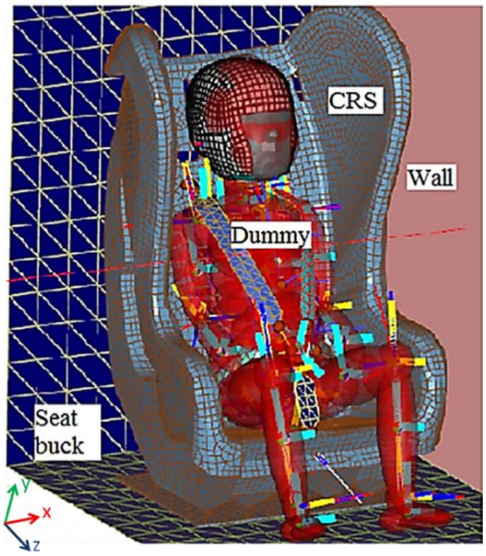

Fig. 2: PSM numerical model.

The R44-standard compliant CRS is modelled using shell elements with a specified thickness of 4 mm. 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, 0.842GPa and 0.3 whereas the yield and the ultimate tensile strengths are set as 8.76 MPa and 18.76 MPa respectively(NHTSA, 2007; Kapoor*et al*., 2008; Wang *et al*., 2007). A foam insert comprising of solid elements is also modelled as shown in Fig. 2. This is placed at the side wings of the CRS to absorb head impact. A highly compressible low-density foam material model (ρ = 50.2 kgm-^{3}, E = 5.463 MPa) is used (Kapoor*et al*., 2008; Wang *et al*., 2007). The CRS is constrained at base anchorage points on a ECE R.44 test bench using fixed cross bars.

The five-point harness system of the CRS is modelledpredominantly using 1 mm thick membrane elements (ρ = 890.6 kgm-^{3}, E = 2.068 GPa, μ = 0.3) (Kapoor*et al*., 2008; Wang *et al*., 2007). 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 is provided for both belt types (Kapoor*et al*., 2008; Wang *et al*., 2007, TNO, 2013). No slack is allowed for the belt fitting as per conditions in Test 4585.

Both dummy and CRS are subjected to gravitational loading as well as acceleration pulse TRC327 to simulate lateral side-impact. Dynamic simulation time is set to terminate after 125ms. Convergence study is carried out during the trial runs and a good trade-off between model cost and accuracy is achieved with an element count of 24,320. All simulations are performed using MADYMO 7.4.1 by TASS on aLenovo Thinkpad T430 (Intel 2.9 GHz quad core processor, 16GB RAM).

Validation:

The Hybrid model simulation results are benchmarked against experimental values and simulation results obtained by Kapoor*et al*. (2008) and Wang *et al*., (2007). The benchmarked studies involved a PSM FE simulation based on the same experiment (Test 4585) with similar boundary conditions and properties. This simulation was reported to have taken about 16 hours, run from a dual core 2.6 GHz AMD Athlon processor with 2GB of RAM. A full vehicle analysis (FVA) would typically take many times that amount of time. In contrast, the computation time to run the analysis in this study using the Hybrid model took only 20 minutes. Despite the differences in computer systems used in the two simulations, a general conclusion may be reasonably drawn that the method presented here is able to save considerably more processing time. Furthermore, the body-segment acceleration, force and moment plots depicted in Figure 3 show that an overall good match is obtained between the experimental values and the results obtained in this study.

Oblique Impact Model with Intrusion:

To study the effect of angular direction of bullet vehicle impact, the lateral pulse direction is rotated towards the bullet vehicle's Principle Degree of Freedom (PDOF) lead angle ϕ. Figure 4 depicts a schematic diagram of the struck vehicle and the bullet vehicle, where **R** is the orientated initial pulse data set. **R** is then separated into its axial components where **X** = **R**sinϕ and **Z** = **R**cosϕ. Thus a two dimensional pulse data set which includes the lateral component **X** as well as the forward component **Z** is created. By asserting both these pulse loads upon the

CRS and the child dummy, it is assumed that an oblique impact for a given value of ϕ can be simulated adequately.

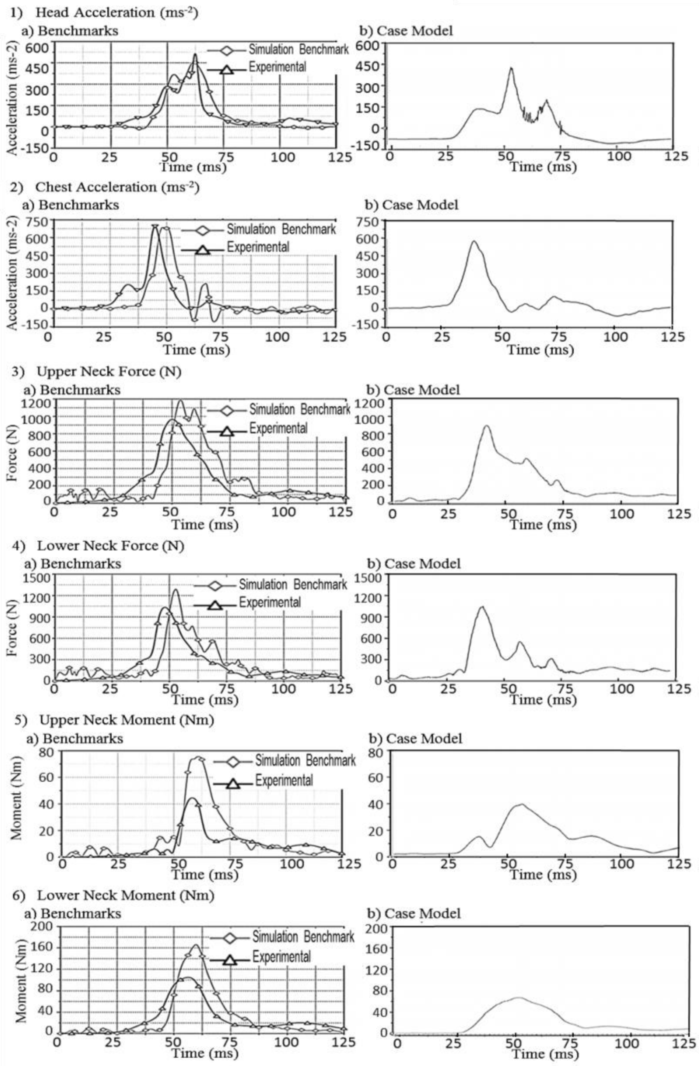

Fig. 3: A comparison of body-segment response vs time plots against benchmarks.

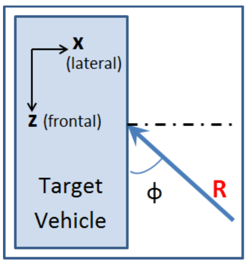

Fig. 4: Schematic diagram illustrating oblique side impact on struck vehicle.

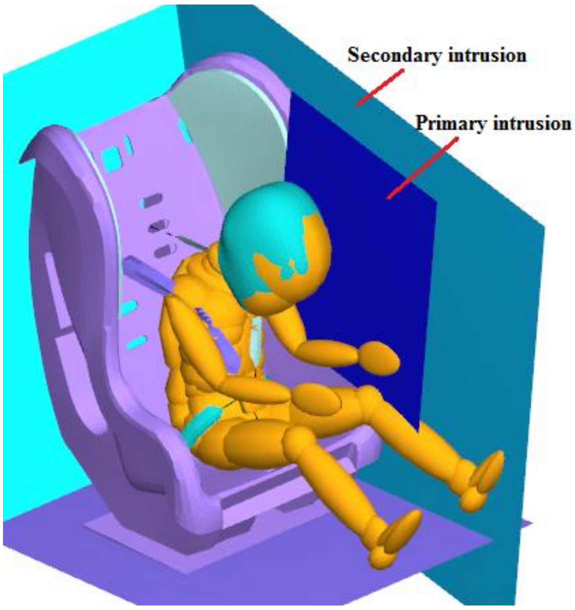

Fig. 5: Oblique side impact PSM simulation.

Extreme intrusions have been reported with values of 570mm to 620mm [Anderson *et al*., 2011). These certainly result in fatalities and the conditions for mitigation are too stringent for any CRS manufacturer to comply. A more practical approach of considering moderate intrusion conditions as outlined by the ECE R95 regulation may be acceptable and is considered in this study(ECE R95; Heiko*et al*., 2007). An intrusion of 280 mm is considered in this study and this is achieved by means of introducing rigid static planar-surfaces as shown in Figure 5. The secondary intrusion plane (130 mm intrusion) has contact defined against the CRS as well as the child dummy where else for the primary intrusion plane, only the head is allowed 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.

According to the NHTSA, for side impact testing, no consensus is made on an appropriate child test dummy and the associated neck injury criteria (NHTSA, 2002). However, the Neck Injury Criteria (N_{ij}) is commonly used and the proposed limit set by the NHTSA is unity (Eppinger*et al*., 1999). It is determined using equation (1):

$$N_{ij} = \left(\frac{F_z}{F_{zc}}\right) + \left(\frac{M_Y}{M_{YC}}\right) \quad (1)$$

Where F_z is the vertical shear force experienced by the neck. A critical value $F_{zc}$of 2340 N and 2120 N is assigned in tension and compression respectively. M_y isthe extension and flexion moments of the neck along the lateral direction. The critical values M_{yc} used are 68 Nm and 27 Nm in flexion and extension respectively (Rockwell, 2003).

Statistical Model Development:

Figure 6 illustrates the parameters selected for the sensitivity study. Table 1 shows organization of the DoE as well as the upper and lower bounds considered for each parameter adopted from standards (FMVSS 213, 2013; NHTSA, 2002). To further increase the sensitivity of the study, the PDOF impact angle (ϕ) is divided into two groups, namely PDOF A ($60° \leq \phi \leq 90°$) and PDOF B ($30° \leq \phi \leq 60°$). The first caters for a wide PDOF angle ($\phi \geq 60°$) impact approach while the later represents a narrow impact approach ($\phi \leq 60°$). Two standard impact velocities, 15 mph Pulse TRC327 and 20 mph PulseTRC595 (Figure 7) (Heiko*et al*., 2007) are investigated here and therefore, each aforementioned group is further divided. Thus in total, four DoE groups are created, all of which mapping a total of 160 simulation runs. The ensuing Neck Force response plots generated by MADYMO are recorded. The occurrence of impact, head excursion and intrusion contact are also noted for reference.

Results:

The Students T test is used here to identify the major contributing single parameters and cross interaction parameters, as well as to assess their respective parametric significance. The models are organized primarily following the PDOF groups and secondarily with respect to the pulse loads as shown in Table 3, and the respective models' T test statistics are compiled therein. The ordering is arranged in this manner so as to facilitate the identification of possible trends in the data. Figure 8 depicts the data distribution and pattern of the t statistic values for each model in graphical form.

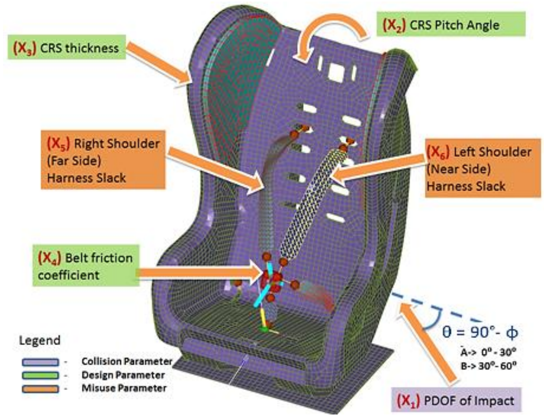

Fig. 6: CRS parameters considered for oblique side impact.

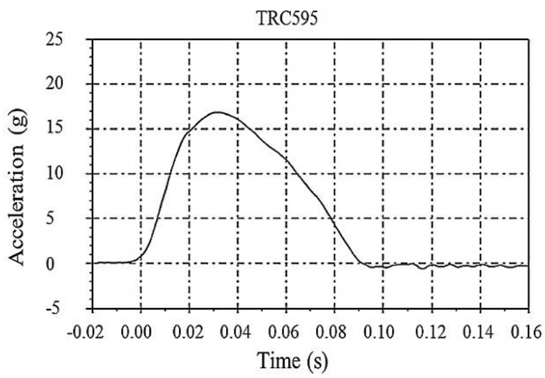

Fig. 7: Pulse TRC595 – closing speed of 20 mph.

Table 1: DOE Grouping and parameter bounds.

	GROUP			
Attributes	15 PDOF A	15 PDOF B	20 PDOF A	20 PDOF B
X_1 (90°-ϕ) (degrees)	$0^0 \leq X_1 \leq 30^0$	$30^0 \leq X_1 \leq 60^0$	$0^0 \leq X_1 \leq 30^0$	$30^0 \leq X_1 \leq 60^0$
X_2 (degrees)	$8^0 \leq X_1 \leq 24^0$			
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)	$0 \leq X_1 \leq 5$			
Load Pulse	15 mph (TRC327)		20 mph (TRC595)	

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. Table 2 shows the statistical diagnostics obtained for all four models. From the regression coefficients, a good fitness is indicated for all the models. The model errors are acceptably low as indicated by the small RMSE values. The R^2 and R^2 adjusted (R^2 Adj.) values substantiate this conclusion as well as providing 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 as indicated by the low p values.

Table 2: Model Fitness Diagnostic statistics (Neck Force).

RSM MODELS	Model Fitness Statistics				
	Fisher Test		R^2	R^2 Adj.	RMSE
	F statistic[1]	p value			
1) 15 PDOF A	26.588	9.890E-14	0.9625	0.9263	0.022
2) 20 PDOF A	37.965	9.022E-16	0.9734	0.9478	0.046
3) 15 PDOF B	21.084	1.982E-12	0.9531	0.9079	0.013
4) 20 PDOF B	16.743	3.669E-11	0.9417	0.8854	0.008

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Where F statistic > 1.92 to satisfy Null hypothesis requirement. Value of f = 1.92 is obtained from the Murdoch & Barnestable by matching regression coefficients

Table 3: t test and significance p of parameters for Neck Force response.

Significant Parameters*	15 PDOF A		20 PDOF A		15 PDOF B		20 PDOF B	
	t	p	t	p	t	p	t	p
X_1	-3.5991	0.0012			-11.7393	2.50E-12	-10.1503	6.29E-11
X_2	-2.0663	0.0482						
X_3			2.3947	0.0236	2.5018	0.0185	2.2480	0.0326
X_4					3.3664	0.0022		
X_1X_3	3.2253	0.0032						
X_1X_4					-4.3805	0.0002		
X_1X_5	2.4770	0.0196						
X_2X_3					-3.7246	0.0009		
X_3X_4	-2.2570	0.0320						
X_3X_6	-2.1605	0.0394						
X_4X_5					2.4902	0.0190	2.1365	0.0415
X_5X_6	-2.0088	0.0493			-2.6770	0.0123	-3.8399	0.0006
X_1^2					10.1496	6.93E-11	7.8570	1.47E-8
X_2^2	2.4509	0.0208						
X_4^2					-2.9130	0.0070		
X_5^2								
X_6^2					2.6618	0.0127		

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

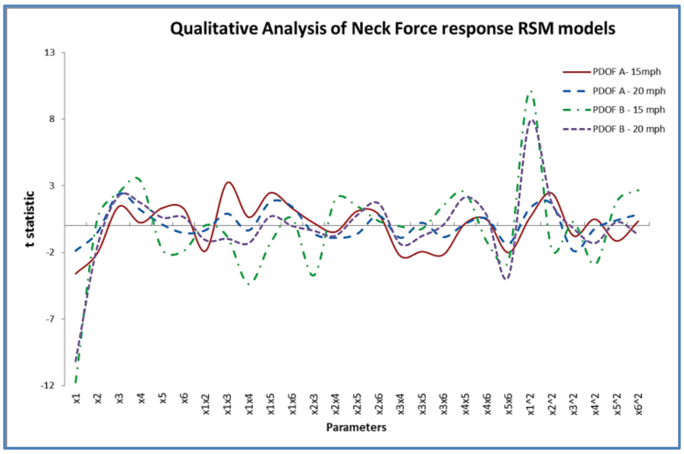

Fig. 8: Qualitative analysis of Neck Force response for RS models.

In general, an expected progression of the NF is seen for the individual parameters. This is discerned from the t statistics of the singular parameters X_1 to X_6. A positive value of the t statistic indicates that the parameter contributes to the increase of the response NF and vice versa, whilst the magnitude suggests the comparative degree of that contribution. The p values further validate the significance of the parameters contribution to the NF. The sensitivity of the parameters individually or cross interactively with each other is ascertained in this manner for each model as well as collectively for the NF response.

Discussion:

From a cursory view of Table 3, a trend is apparent,where for increasing impact speed from 15 mph to 20 mph, the number of significant parameters appear to dwindle. This is observed for both PDOF groups although PDOF B is shown to register sensitivity for more parameters.The PDOF B model for 15 mph impact speed shows the highest number of parameters (10 parameters) influencing the NF and this is followed closely (8 parameters) by the PDOF A group of the same impact speed. Except for X_1 and the cross interactive parameter X_5X_6, an agreement is not seen between the two groups in terms of parameter significance. These cursory observations present two conclusions. The first is that the NF injury response isgenerally shown to be less affected by the parameters for higher impact speeds especially for wide PDOF angles ($\phi \geq 60°$). Secondly, the NF response indicates much more relevancy for narrow PDOF angles ($\phi \leq 60°$).

A further scrutiny of the data reveals the PDOF impact angle ϕ (X_1) to be the most sensitive parameter for all cases except for the group 20 PDOF A. The parameter relatively shows very high significance for narrow PDOF angles ($\phi \leq 60°$). This is notably seen by the very small p values of 2.50E-12 and 6.29E-11 respectively in groups

15 PDOF B and 20 PDOF B. This implies that compared to other parameters, the PDOF impact angle ϕ (X_1) largely affects the value of the Neck Force in a crash. However an exception presents itself for the case of wide PDOF impact angles ($\phi \geq 60°$). The group 15 PDOF A shows that although X_1 remains still the most sensitive parameter, nevertheless, relative to other parameters, the significance is only moderate ($p = 0.0012$). Furthermore the parameter reduces to non-significance for the same impact angle group subjected to higher impact speed (20 PDOF A).

Cross interactively, X_1 registers no significance except for the 15 PDOF A group. A moderate X_1 interaction is seen here with X_3 ($t = 3.2253$, $p = 0.0032$) and X_5 ($t = 2.4770$, $p = 0.0196$). From this, it maygenerally be assumed that all other parameters are independent of the PDOF impact angle (X_1) in influencing the magnitude of the Neck Force during side impact crash.

Figure 9 shows NFresponse for the full range of X_1values encompassing both PDOF A and B groups. A close trend is observed between the two impact speeds 15 mph and 20 mph with the latter registering somewhat higher values. Between PDOF ϕ angles 50° and 70°, neck forces rise above 900 N and a relatively higher trend deviation (approximately 15%) is noted between the two impact speeds. The values seem to peak between φ angles 55° and 65° with NF value above 1000 N. For narrow angles less than 34°, a rise in neck forces is also indicated and may be attributed to the rising magnitude of the frontal component of the impact pulse.

The X_2(CRS pitch angle) parameter is found to be sensitive only for the lower impact speed 15 mph. It is singularly of moderate significance for wide PDOF impact angles ($\phi \geq 60°$) while a strong cross interactive significance with X_3 is observedfor narrow PDOF impact angles ($\phi \leq 60°$). It is seen here that for either case, a reduction of the parameter contributes to an increase in neck force.

The CRS shell thickness parameter X_3 is found to be generally significant either individually or cross interactively across the groups. In fact for the 20 PDOF A group, it is the only significant parameter. Singularly,$X_3$is proportionately significant i.e., NF increases with X_3, for all groups except for 15 PDOF A.For the 20 PDOF B, it is the only other significant singular parameter after X_1. Cross interactively, it is found to be significant only for lower impact speed 15 mph. However a dissimilar trend is seen between PDOF group A and B. The former registers significance with X_1, X_4 and X_6 while the latter is only cross interactive with X_2.Except for X_3X_1, all cross interactions are found to be inversely proportionate to neck force (neck force reduces with positive X_3 increments).

The harness coefficient of friction parameter X_4 indicates a moderately large sensitivity for the group 15 PDOF B. It registers the only singular significance across the groups. Cross interactions for the groups are present with X_1 and X_5. The former is inversely proportionate with greater significance ($t= -4.3805$, $p = 0.0002$) while the later affects the NF positively in a moderate way ($t = 2.4902$, $p = 0.0190$). Across the groups, cross interaction is minimal with X_3X_4 and X_4X_5 being notable for groups 15 PDOF A and 20 PDOF B respectively, while none are significant for group 20 PDOF A. A general conclusion is that the X_4 parameter only affects neck force moderately for lower impact speeds (15 mph) with narrow impact angles ($\phi \leq 60°$).

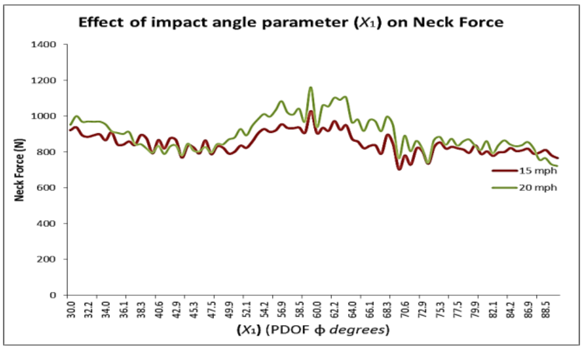

Fig. 9: Effect of impact angle parameter X_1 on Neck Force.

The misuse parametersX_5 (far side harness slack)and X_6 (near side harness slack) are shown to be singularly insignificant for the determination of neck forces in side impact crash. However, cross interactively, a moderate effect on the neck force is observed especially for low impact speed with wide PDOF angle ($\phi \geq 60°$). The interaction parameters for this group are X_1X_5, X_3X_6 and X_5X_6. This last interaction is notably present in all other groups except for the 20 PDOF A group. It is shown to affect the neck force inversely. The sensitivity of the X_5X_6 parameter is seen to be greater for narrow PDOF impact angles especially for higher impact speed 20 mph.

Finally, a study of Figure 8 shows that for some parameters, an opposite effect to the NF response is noted for the PDOF groups i.e., NF is reduced rather than increased for the same parameters in different PDOF groups. This is noted for the single parameter X_5 and its quadratic pair, while cross interaction parameters includeX_1X_3,X_1X_4,X_1X_5, X_2X_3,X_2X_4, X_2X_5, and X_3X_6.

Conclusions:

APSMsimulation Hybrid Model of a three year old child tethered in a CRS and subjected to lateral side impact is developed and validated. The model is shown to be acceptable for common standard injury responses as well as being greatly economical in terms of computational processing time.DoE using LHS design is used to construct mathematical models for regression analysis. Despite non linearity of design problem, models generated using quadratic RSM are shown to have good fitness.Student's t test is used to study singular and cross interactive parameter sensitivity. Acceptable values of the t statistic and its significance p are obtained and reported.The significance of identified common crash parameters in side impacts are, for the first time, quantified.

Qualitative categorization is performed and a number of conclusions are ascertained. Firstly, the number of significant parameters affecting the neck force is found to be largest at low impact speeds (15 mph). This indicates that parameter effects on Neck Force during side impact become less meaningful at higher impact speeds. Secondly, greater parameter significance is seen for narrow impact angles($\phi \leq 60°$).Thirdly and most importantly, The PDOF angle parameter X_1shows a close trend for both impact speeds 15 mph and 20 mph and it is revealed to be the most sensitive parameter to affect NF. This is again especially so for narrow PDOF angles ($\phi \leq 60°$) and the critical range is found primarily to be between ϕ angle 50° and 70°. A secondary critical range is observed for angles below 34°. Fourthly, most of the other parameters are generally found to be moderately significant only at low impact speed (15 mph), of which the CRS shell thickness is seen to have a broad moderate significance across the PDOF angles and impact speeds. Cross interaction between the two harness slack parameters X_5X_6 is seen to have a notable effect only for higher speed (20 mph), especially for narrow PDOF angles ($\phi \leq 60°$). Individually and otherwise the parameters prove to be insignificant with respect to NF.

Finally, the workdemonstrates a necessity for further study and experimental testing in consideration of the relationships that is parametrically shown to exist between CRS design, harness slack and PDOF impact angle of bullet vehicle with regards to neck forces in a 3 year old child.The findings of this study will be useful as a reference in the development of newer test procedures and safety standards in addressing safety concerns in oblique side impact crash.

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