



## A PARAMETRIC STUDY OF NECK MOMENT RESPONSE IN A 3 YEAR OLD CHILD SUBJECTED TO OBLIQUE SIDE IMPACT

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### ABSTRACT

The effect and interactions of various parameters on the Neck Moment experienced by a three year old child during side impact is investigated using a pre-validated numerical model. The simulation involves a HYBRID III 3-year old child Anthropometric Test Device (ATD) model restrained in a Child Restraint System. The numerical model assembly is comprised of a combination of both Finite Elements (FE) and Multi-body ellipsoids (Mb). It is subjected to lateral and oblique side impact crash using the Prescribed Structural Motion method. The model is adapted to investigate the effect of intrusion and oblique impacting angles. The Latin Hypercube Sampling (LHS) design is adopted for the Plan of Experiments in which six parameters are subjected to two different impact velocities. Statistical methods are employed in which both quantitative and qualitative parametric studies are carried out. The study indicates greater parametric significance at high impact speed and at wide impact angles ( $\phi \geq 60^\circ$ ). The impact angle parameter is largely shown to be the most significant parameter in affecting the Neck Moment response. The impact angle parameter trend is found to be very similar for both impact speeds. A relatively safe region is found to exist between impact angles  $45^\circ$  and  $65^\circ$ .

**Keywords:** oblique side-impact, neck moment, child restraint system, parameter sensitivity.

### INTRODUCTION

Motor Vehicle Crash (MVC) injuries sustained by the pediatric population are rapidly attracting increasing attention from all corners. This is timely as it comes amidst concerns whereby traffic injuries are fast becoming the leading cause of death for children (NHTSA, 2005), Stats Canada, 2003). A properly used Child Restraint System (CRS) provides a good measure of protection for frontal impacts (Rice *et al.*, 2009). However, regardless of restraint status or seating position, the likelihood of a child fatality is almost doubled in side impact crashes compared to the more frequently occurring frontal impact (Starnes and Eigen, 2002), (PCPS, 2008). Currently, we find that side impact testing is largely not mandatory and proposals to remedy this design oversight is still in its infancy (FMVSS, 2013).

The kinematics of side impact crash relies upon both the Principle Direction of Force (PDOF) impacting angle as well as the pulse magnitude caused by the impacting bullet vehicle. Scrutiny of accident databases shows that oblique crashes comprising of PDOF  $60^\circ$  to  $75^\circ$  seem to account for three fourth of all side impact crashes (Anderson *et al.* 2011), (McCray *et al.* 2007).

Additionally, literature shows that most of the higher injury severity cases recorded is due to the effect of intrusion (Arbogast *et al.* 2002), (Brown *et al.* 2005), (Howard *et al.* 2004). The general maximum intrusion depth accepted by the ECE regulation is between 170 mm to 280 mm with the former value associated more to newer cars (ECE, 95).

Besides these, other factors traditionally associated with frontal impact may also require investigation. In this regard, Chouinard points out that unsuitable restraints

classified as CRS misuse, play a major role (Chouinard and Huxley, 2005), (Weber, 2000). Of these, the presence of shoulder harness slack is noted to be a major contributing factor (Decina and Knoebel, 1996), (JAF, 2009).

Generally, head injuries are largely reported to be the prime cause of fatalities in CRS restrained toddlers involved in side impact crash (Arbogast *et al.* 2004), (McCray *et al.* 2007), (Arbogast *et al.* 2005). However, for small children, the cause of fatality may also be related to high neck loading (Weber, 2000). There has long been a concern for the possibility of the cervical spine of the child being separated due to forces on the neck. This may potentially occur when the shoulders are held back in a crash. 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. In this regard, numerical and statistical modelling offer reliable procedures which are relatively inexpensive and efficient.

In this work, a parametric study is undertaken to study the relationship between the Neck Moment (NM) of the CRS restrained dummy and the oblique side impact crash parameters involving intrusion.



## METHODOLOGY

### Numerical model

A numerical model is developed and validated based on a side impact dynamic sled test experiment (Test no 4585) carried out by the National Highway Traffic Safety Administration (NHTSA) (FMVSS, 2013), (NHSTA, 2007). The test is FMVSS 213 compliant and it is generally accepted as the industrial standard in assessing the side impact safety of three year old children in a CRS for the standard impact speed of 24.1 km/h (15 mph) (FMVSS, 2013). In this test, a Hybrid III 3-year-old dummy is restrained in a CRS and it is subjected to a lateral side-impact. A numerical hybrid model comprising of Finite Elements (FE) as well as Multi-body ellipsoids (Mb) is developed for the simulation, as shown in Figure-1. A numerical model of a HYBRID III three year-old child ATD by TASS International, is positioned to be seated inside a FE CRS model (TNOa, 2013). A harness system is used to simulate the restraints upon the dummy (Kapoor *et al.*2008),(Wang *et al.*2007),(TNOb,2013). A Prescribed Structural Motion (PSM) simulation is carried out in which the Pulse obtained from Test 4584 is used as the boundary condition on the CRS and the ATD. This is done in order to simulate the bullet vehicle impact upon the struck vehicle. A detailed account of the numerical model development is reported in our previous work (Shasthri *et al.*2014). The entire numerical model assembly has been previously validated and it has been shown to be both accurate as well as computationally economical with each run typically taking only 20 minutes on a Lenovo Thinkpad T430 (Intel 2.9 GHz quad core processor, 16GB RAM) (Shasthri *et al.*2014). MADYMO 7.4.1 by TASS is used to carry out all simulation work.

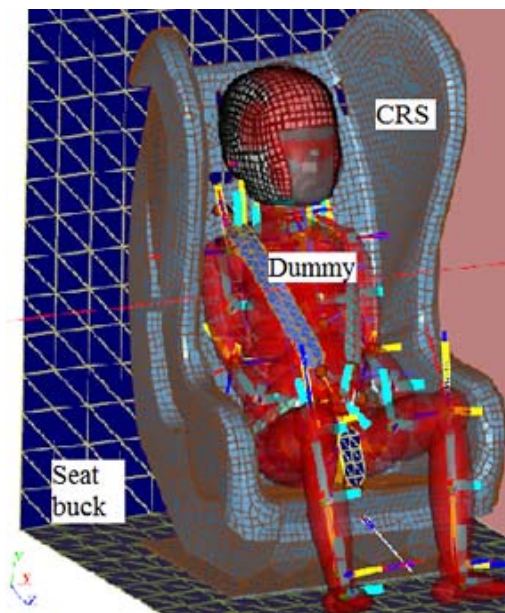


Figure-1. PSM numerical model.

### Consideration for oblique impact

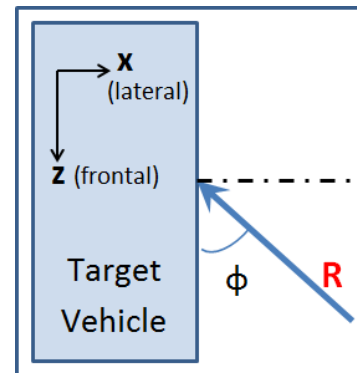


Figure-2. Schematic diagram illustrating oblique side impact on struck.

In order to consider the effect of the bullet vehicle impact angle, the pulse data  $R$  which are obtained from lateral impact, is rotated to reflect the required bullet vehicle's Principle Direction of Force (PDOF) lead angle  $\phi$ , shown schematically in Figure-2. This rotated pulse data  $R$  is then split into its  $x$  and  $z$  axis components where  $X = R \sin \phi$  and  $Z = R \cos \phi$ . In this way, both the lateral pulse component  $X$  and the forward pulse component  $Z$  is created. These two separated pulse loads are asserted upon both the CRS and the ATD. By such contrivance it becomes possible to adequately simulate oblique impact at any PDOF angle  $\phi$ .

### Consideration for intrusion effect

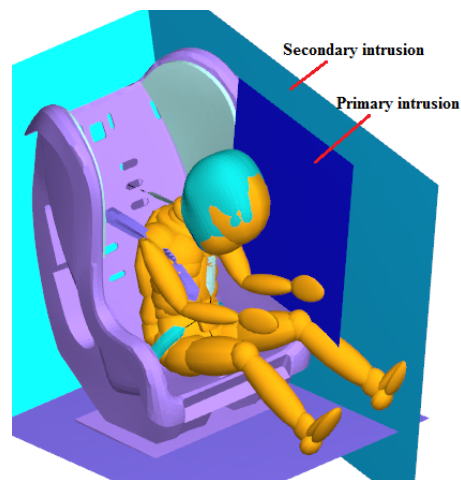


Figure-3. Oblique side impact PSM simulation.

Intrusion distance of 280 mm, as outlined by the ECE R95 regulation is adopted in this work (ECE, 95),(Heiko *et al.*2007). A primary rigid static planar-surface is introduced in the numerical model as depicted in Figure-3. The model is configured thus so that it can simulate the worst-case scenario in a medium intrusion side impact event i.e. the head is free to hit the hardest part



of the intrusion, at the earliest moment of time. A secondary intrusion plane (intrusion distance of 130 mm) which represents the door prior to impact is also created to serve as a reference. Contact definition for the primary intrusion plane is set against the CRS as well as the entire ATD.

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 ( $N_{ij}$ ), equation 1, is commonly used, and the proposed limit set by the NHTSA does not exceed 1 (Eppinger *et al.* 1999).

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

Where  $F_z$  is the axial force experienced by the neck. A critical value  $F_{zc}$  of 2340 N and 2120 N is assigned in tension and compression respectively.  $M_y$  is the 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).

### Design of experiments (DoE)

A Plan of Experiments is prepared based on the Latin Hypercube Sampling (LHS) for six parameters involving two different crash velocities. Figure-4 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,2013),(NHTSA,2002). To further increase the sensitivity of the study, the PDOF impact angle ( $\phi$ ) 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 later represents a narrow impact approach ( $\phi \leq 60^\circ$ ). Two standard impact velocities, 15 mph (24.1 km/h) Pulse TRC327 and 20 mph (32.2 km/h) PulseTRC595, shown respectively in Figure-5 and Figure-6, are investigated here and therefore, each group is further subdivided (FMVSS,2013),(Heiko *et al.* 2007). In this way, four DoE groups comprising of 160 simulation runs are created in total. The ensuing Neck Moment response plots generated by MADYMO are recorded.

### Response surface method (RSM)

The quadratic polynomial Response Surface Method (RSM) is used to model the problem and parameter sensitivity is determined by means of Multinomial Regression. The maximum Neck Moment (NM) value registered between the upper and lower neck of the child dummy model is defined as the response. This response data is converted to logarithmic values of base 10 and submitted for regression analysis. The regression coefficients are used to assess the Response Surface (RS) model fitness as well as to draw conclusions on the parameter sensitivity both quantitatively and qualitatively.



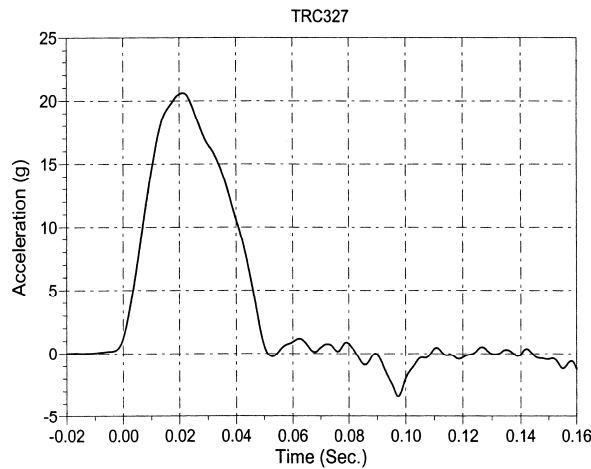
Figure-4. CRS parameters considered for oblique side impact.

### RESULTS

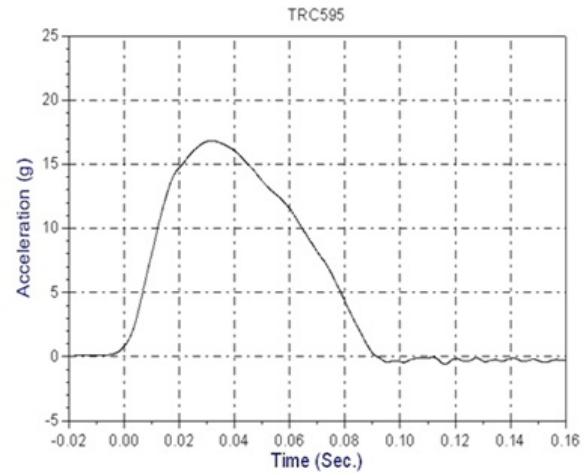
The statistical diagnostics for the four RS models are presented in Table-2. The regression coefficients for all four models indicate good fitness criteria. The small RMSE values show that modelling errors are low. More importantly, values close to the value of one are observed for the  $R^2$  and  $R^2$  adjusted ( $R^2$  Adj.) statistics. Additionally, the Fisher (F) test is performed and the resulting favourable F and p statistics serve as additional corroboration of the statistic suitability of the models.

Having established the validity of the RS models in suitably describing the injury responses, parametric study is carried out by means of the Students (t) test. In this way, the significant contributing singular as well as cross interactive parameters are identified. A quantitative and qualitative assessment of their respective significance is tabulated. 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. A positive value t statistic is indicative of an increasing response (NM in this case) due to the associated parameter whilst a negative value represents a decreasing response. The degree of contribution is represented by the magnitude of the t statistic. The p values which represent the confidence interval (CI) reflect the reliability of the t statistic value. Together, the t statistic and its p value indicate the significance of the parameter's contribution to the NM injury response.





**Figure-5.** Pulse TRC327 - closing speed of 24.2 km/h (15 mph)[10].



**Figure-6.** Pulse TRC595 - closing speed of 32.2 km/h (20 mph)[29].

**Table-1.** DoE grouping and parameter bounds.

| Attributes                                | GROUP                            |                                   |                                  |                                   |
|-------------------------------------------|----------------------------------|-----------------------------------|----------------------------------|-----------------------------------|
|                                           | 15 PDOF A                        | 15 PDOF B                         | 20 PDOF A                        | 20 PDOF B                         |
| $X_1 (90^\circ - \phi) \text{ (degrees)}$ | $0^\circ \leq X_1 \leq 30^\circ$ | $30^\circ \leq X_1 \leq 60^\circ$ | $0^\circ \leq X_1 \leq 30^\circ$ | $30^\circ \leq X_1 \leq 60^\circ$ |
| $X_2 \text{ (degrees)}$                   | $8^\circ \leq X_1 \leq 24^\circ$ |                                   |                                  |                                   |
| $X_3 \text{ (mm)}$                        | $3.5 \leq X_1 \leq 5.5$          |                                   |                                  |                                   |
| $X_4 \text{ (value)}$                     | $0.25 \leq X_1 \leq 0.35$        |                                   |                                  |                                   |
| $X_5 \text{ (cm)}$                        | $0 \leq X_1 \leq 5$              |                                   |                                  |                                   |
| $X_6 \text{ (cm)}$                        | $0 \leq X_1 \leq 5$              |                                   |                                  |                                   |
| Pulse                                     | 15 mph (TRC327)                  |                                   | 20 mph (TRC595)                  |                                   |

From a cursory view of Table-3, the PDOF A groups are shown to obviously register more number of significant parameters than the PDOF B groups. This shows that the Neck Moment 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  $\phi \geq 60^\circ$ . At higher speed of 32.2 km/h (20 mph), the number of significant parameters jumps from six to nine. This suggests that higher impact speed invites greater parametric significance for wide PDOF impact angles ( $\phi \geq 60^\circ$ ). In contrast, the PDOF B groups show only three parameters of significance irrespective of speed. Qualitatively, the sensitivity trend seems to increase with higher impact speed for wide PDOF impact angles while an opposite trend is mildly indicated for narrow PDOF impact angles.

## DISCUSSION

The results of the study are useful in characterizing how each of the six parameters contributes to the NM response in a three year old child during side impact crash. Previously, while it is known that each of these parameters are a factor in injuries sustained during side impact crash,

the degree of its impact as well as its nature has not been studied. A study of the statistics and trends obtained in this work bridge this gap. The role of each parameter is discussed summarily in the following.

### PDOF impact angle parameter ( $X_1$ )

From the results, the study shows that the PDOF impact angle  $\phi$  ( $X_1$ ) is marginally the most sensitive parameter and therefore the most dominant one. The impact angle parameter ( $X_1$ ) not only largely affects the NM response on its own (singularly), but also seems to influence all other parameters (interactively) except for harness friction parameter ( $X_4$ ).

The t tests show that higher NM is likely to occur at wide PDOF impact angles ( $\phi \geq 60^\circ$ ) compared to narrow impact angles ( $\phi \leq 60^\circ$ ). The severity of NM related injury for both impact angles is seen to concomitantly increase with escalating impact speed. For a deeper scrutiny, Figure-7 is plotted which shows the NM response for the full range of  $X_1$  values encompassing both impact angle groups (PDOF A and B). A close trend is observed between the two impact speeds 24.1 km/h (15 mph) and 32.3km/h (20 mph) with the latter registering somewhat higher values especially for  $\phi < 42^\circ$ . The



values seem to peak at 30° with approximately 70 Nm. A favourable low Neck Moment of 50 Nm and below is indicated between PDOF  $\phi$  angles 45° and 65°. Therefore, it is recommended that mitigation efforts work towards

confining the impact angle to be between 45° and 65° for lower severity of NM induced injuries.

**Table-2.** Model fitness diagnostic statistics (Neck Moment).

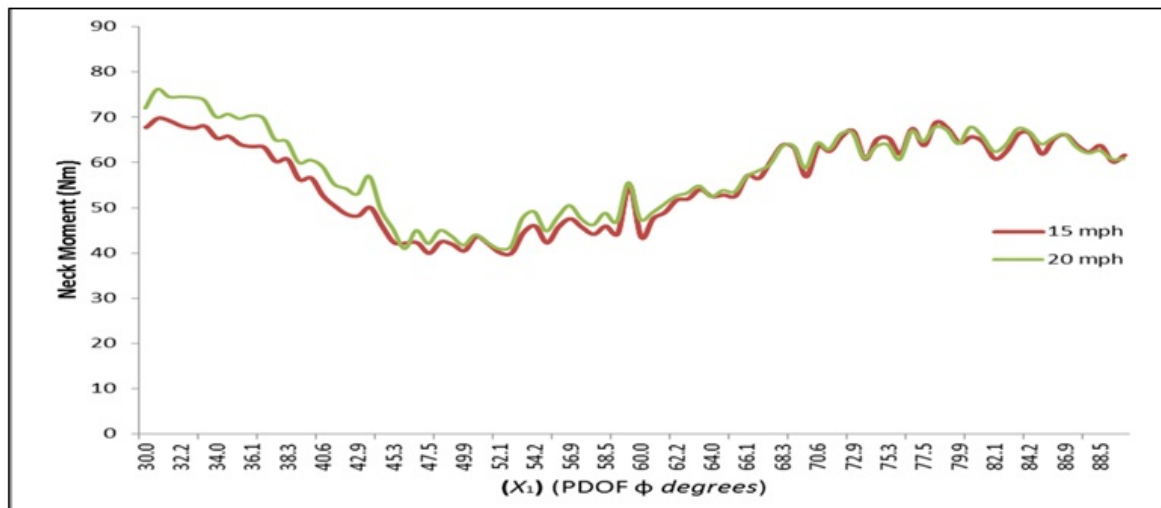
| RSM MODELS   | Model Fitness Statistics |           |                |                     |       |
|--------------|--------------------------|-----------|----------------|---------------------|-------|
|              | Fisher Test              |           | R <sup>2</sup> | R <sup>2</sup> Adj. | RMSE  |
|              | F statistic <sup>1</sup> | p value   |                |                     |       |
| 1) 15 PDOF A | 73.545                   | 4.787E-11 | 0.9930         | 0.9795              | 0.004 |
| 2) 20 PDOF A | 143.011                  | 4.841E-13 | 0.9964         | 0.9894              | 0.006 |
| 3) 15 PDOF B | 29.263                   | 2.5109E-8 | 0.9826         | 0.9490              | 0.025 |
| 4) 20 PDOF B | 18.409                   | 5.3650E-7 | 0.9726         | 0.9198              | 0.015 |

<sup>1</sup> Where F statistic > 2.08 for statistical relevance. Value is obtained from the Murdoch and Barnes table

**Table-3.** t test and significance p of parameters for neck moment response.

| Significant Parameters* | 15 PDOF A |        | 20 PDOF A |         | 15 PDOF B |         | 20 PDOF B |         |
|-------------------------|-----------|--------|-----------|---------|-----------|---------|-----------|---------|
|                         | t         | p      | t         | p       | t         | p       | t         | p       |
| $X_1$                   | 4.5150    | 0.0005 | 7.6795    | 2.20E-6 | -3.8615   | 0.0017  | -2.7923   | 0.0144  |
| $X_2$                   |           |        | 2.4049    | 0.0306  |           |         |           |         |
| $X_1X_2$                | 2.5775    | 0.0219 | 3.6455    | 0.0026  |           |         |           |         |
| $X_1X_3$                |           |        | -2.5905   | 0.0214  |           |         |           |         |
| $X_1X_5$                |           |        |           |         | -3.1269   | 0.0074  | -2.8355   | 0.0132  |
| $X_1X_6$                |           |        |           |         | -2.7876   | 0.0145  | -2.1828   | 0.0466  |
| $X_2X_5$                |           |        | -2.8776   | 0.0122  |           |         |           |         |
| $X_2X_6$                | -2.1478   | 0.0497 |           |         |           |         |           |         |
| $X_3X_4$                | 2.3885    | 0.0316 | 3.3560    | 0.0047  |           |         |           |         |
| $X_3X_5$                | 2.2547    | 0.0407 | 2.9570    | 0.0104  |           |         |           |         |
| $X_3X_6$                |           |        | 2.4350    | 0.0289  |           |         |           |         |
| $X_5X_6$                | 2.5656    | 0.0224 | 2.4276    | 0.0293  |           |         |           |         |
| $X_1^2$                 |           |        | -10.0325  | 8.97E-8 | 7.9792    | 1.41E-6 | 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

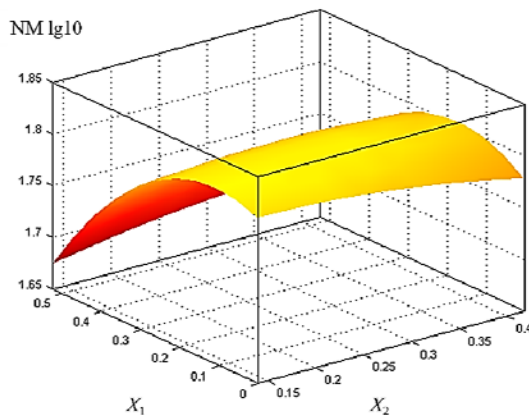


**Figure-7.** Effect of impact angle parameter  $X_1$  on neck moment.



### CRS pitch angle parameter ( $X_2$ )

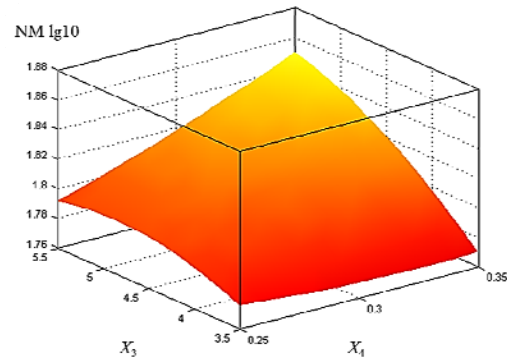
The study shows that, singularly, the CRS pitch angle parameter ( $X_2$ ) only moderately contributes to the NM injury response, and this is seen only at wide PDOF impact angles ( $\phi \geq 60^\circ$ ) at higher impact speed of 32.2 km/h (20 mph). However, under these conditions, the significant cross interactive t statistic  $X_1X_2$  in Table-3 shows that the PDOF impact angle  $X_1$  very much influences the CRS pitch angle parameter  $X_2$ . The trend of this relationship is shown in the  $X_1X_2$  cross-interaction response surface plot in Figure-8. From these results, it can be summarized that specifying a higher CRS pitch angle ( $X_2$ ) may be beneficial in marginally reducing the NM injury response particularly for higher impact speeds involved in PDOF impact angles of  $60^\circ$  and greater. At low impact speeds and at narrow PDOF impact angles, the  $X_2$  parameter effects are expected to be negligible.



**Figure-8.**  $X_1X_2$  vs NM response surface plot for PDOF A at 32.2 km/h (20 mph).

### CRS shell thickness parameter ( $X_3$ )

From the results of the study, the CRS shell thickness parameter  $X_3$  does not bear any significance whatsoever at narrow impact angles (PDOF B). At wide PDOF impact angles, the parameter by itself (singularly) does not seem to affect the NM injury response. However, cross interactively, a number of parameters are indicated. Four interactions ( $X_1X_3$ ,  $X_3X_6$ ,  $X_3X_4$ ,  $X_3X_5$ ) are found for 32.2 km/h (20 mph) impact speed, while only the last two interactions are seen for 24.1 km/h (15 mph). This suggests that while the parameter  $X_3$  does not directly affect the NM injury response, it seems to do so in an indirect manner by influencing the other parameters noted. However these effects are relatively small except for the  $X_3X_4$  cross-interaction parameter. For the latter, the relationship between the two parameters can be seen in Figure-9, where a thinner shell thickness ( $X_3$ ) together with higher harness friction ( $X_4$ ) seems to indicate lower NM injury response. This may be considered as a design guideline in efforts to lower NM injury response at wide PDOF impact angles.



**Figure-9.**  $X_3X_4$  vs NM response surface plot for PDOF A at 32.2 km/h (20 mph).

### Harness friction parameter ( $X_4$ )

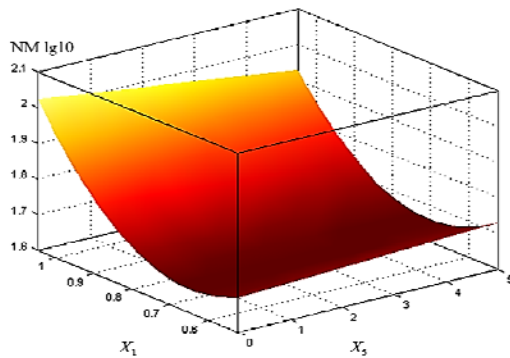
The harness coefficient of friction parameter  $X_4$  indicates the least sensitivity in this study. No singular significance is noted for any group. Cross-interactively, other than the single occurrence of a cross interaction with  $X_3$  (as was discussed in 4.3), no other occurrence is found significant.

### Shoulder harness slack parameters ( $X_5$ and $X_6$ )

The results indicate that the harness slack parameters,  $X_5$  (far side harness slack) and  $X_6$  (near side harness slack), do not directly influence the NM injury response, as seen in the absence of singular statistical significance. However, they do seem to some extent influence all other parameters except for the friction coefficient parameter  $X_4$  as seen by the numerous cross-interaction parameters.

Two interactions are of particular note namely with CRS pitch angle  $X_2$  and PDOF impact angle  $X_1$ . For the former, the presence of slack at the far side shoulder harness ( $X_5$ ) seems to some degree influence the NM injury response at wide impact angles although at narrow impact angles, it is the near side harness slack ( $X_6$ ) instead which is prominent. However, the effects are mild and are not scrutinized in this study.

For the interaction with the PDOF impact angle  $X_1$ , the effects are only notable at narrow impact angles ( $\phi \leq 60^\circ$ ). However, between the two shoulder harness slack parameters, the far side parameter ( $X_5$ ) is shown to be highly significant at low impact speed. The nature of this  $X_1X_5$  cross interaction relationship at 24.1 km/h (15 mph), with respect to the NM injury response is shown in the Response Surface plot in Figure-10. It suggests that at narrow impact angles ( $\phi \leq 60^\circ$ ), the presence of slack at the far side shoulder harness seems to have a lowering effect to the NM injury response. However, at higher impact speed, the positive effect of the far side harness slack becomes negligible. Since CRS are meant to mainly offer protection at relatively low impact speeds, therefore, this observation may be of practical use in its design.



**Figure-10.**  $X_1X_5$  vs NM response surface plot for PDOF B at 24.1 km/h

## CONCLUSIONS

DoE using LHS design is used to construct mathematical models for regression analysis based on a pre-validated PSM simulation Hybrid Model of a three year old child tethered in a CRS and subjected to lateral side impact. Despite non linearity of design problem, models generated using quadratic RSM are shown to have good fitness. Student's t test is used to map and study singular and cross interactive parameter sensitivity. The nature of each singular parameter as well as its influence on other parameters with respect to affecting NM injury response is characterized. By these statistical and simulation methods, it has become possible to conduct an efficient virtual parametric study in order to narrow the scope for future research involving real experimental crash.

It is found that oblique side impact affects the Neck Moment very differently compared to purely lateral crash. The PDOF impact angle  $\phi$  is clearly indicated to be the most prominent parameter to affect NM injury response. Its presence has also been shown to influence other parameters. The study finds that a PDOF impact angle corridor of  $45^\circ$  to  $65^\circ$  is recommended for minimal NM induced injuries. It also shows that specifying a higher CRS pitch angle is marginally beneficial for reducing the NM injury response particularly at higher impact speeds involving wide impact angles. For narrow impact angles, the presence of shoulder harness slack particularly at the far side is found helpful in achieving lower NM induced injuries. Lastly, the harness friction coefficient is shown to have relatively very little effect on the NM injury response.

The findings here show the relevancy of various injury parameters in attenuating critical injury during side impacts. In addition, the study indicates safety thresholds as well as critical regions which will serve useful in the design of CRS as well as the vehicle interior. The results will also be useful as reference in the development of newer test procedures and safety standards in addressing child safety concerns in oblique side impact crashes. The findings demonstrate a necessity for refined experimental testing to validate the outcomes of this study.

## ACKNOWLEDGEMENTS

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