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# Vehicle Profile Optimization using Central Composite Design for Pedestrian Injury Mitigation

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

[1] Department of Mechanical Engineering, Faculty of Engineering, International Islamic University Malaysia, Jalan Gombak, 50728 Kuala Lumpur, Malaysia
[2] Faculty of Mechanical Engineering, University Technology of MARA, 40450 Shah Alam, Selangor, Malaysia
[3] Department of Mechanical Engineering, Faculty of Engineering, University Selangor, 40000, Shah Alam, Malaysia
[4] Malaysian Institute of Road Safety Research (MIROS), Lot 125-135, Jalan TKS 1, Taman Kajang Sentral, 43000 Kajang, Selangor Darul Ehsan, Malaysia

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**Abstract:** Pedestrian injury poses a significant problem throughout the world. Pedestrians contribute to the second largest category of motor vehicle deaths accounting for about 13% of fatalities, after occupant injuries. Therefore is vital to design pedestrian friendly vehicles to mitigate injuries and fatalities. A statistical methodology employing the Design of Experiments (DoE) is adopted in this work to obtain the optimum design parameters for the vehicle front end geometry. The work studies the feasibility of the use of Central Composite Designs (CCD) between a Circumscribed design (CCC) and a Faced design (CCF). A total of 100 simulation runs are performed and the response is tabulated. Multi linear regression analysis is performed following which, quadratic programming is used to carry out the optimization task using the Response Surface models obtained. It is concluded that the CCC offers a better prediction for the optimum values in comparison to the CCF design. The SSR value for the CCC design offers a better fit for the model yielding the value of 2.68 which is lesser than CCF's value of 2.87. In addition, the practical error margin between the predicted CCC designs and observed experimental values are 43.68 for CCC and 187.66 for CCF respectively, thus affirming the conclusion made.

**Keywords:** Design of Experiments, Faced and Circumscribed Design, Vehicle Front End Profile, Optimization, Pedestrian Head Injury Mitigation

## 1 Introduction

Pedestrians are extremely vulnerable road users who are at high injury risk in road traffic accidents with motor vehicles. These pedestrian injuries pose a significant problem throughout the world. In 2010, 4,280 pedestrians were killed in traffic crashes in the United States, and another 70,000 were injured [1]. This averages to one crash-related pedestrian death every 2 hours, and a pedestrian injury every 8 minutes [1]. Pedestrians are 1.5 times more likely than passenger vehicle occupants to be killed in a car crash on each trip [2]. In Malaysia, the police statistics reveals that on average, 562 pedestrians are killed annually, mostly in urban areas in the past three years [3]. Pedestrians are more likely to be struck by a car than any other vehicle. Mitigation efforts have been long undertaken with the hopes of reducing these statistics but have failed to address the underlying issue. Isolation techniques such as pedestrian bridges, road infrastructure, public education and traffic regulation have contributed in reducing the number of pedestrian vehicle collision [4], but have not been able to mitigate injury in the occurrence of a collision.

This calls for the need of a more design inherent approach by which the pedestrian protection provided is built in to the vehicle design. Advances have been made by vehicle manufacturers to address this issue with respect to the design of the vehicle, but the complex nature of the pedestrian accident scenario has resulted in difficulties in optimizing the design [5]. The shape of the vehicle front end has shown to contribute as the leading factor in determining the pedestrian kinematics, which in turn affects the injury outcome, primarily that of the head [6]. This study uses a statistical optimization method to

* Corresponding author e-mail: kausalyah@hotmail.com

obtain the optimum vehicle design parameters for the vehicle front end profile for the purpose of mitigating the head injury in a pedestrian-vehicle related crash scenario. The Design of Experiments (DOE) approach is taken to generate the plan of experiment. The differences between the Central Composite Design Faced (CCF) and Circumscribed (CCC) are analyzed here.

## 2 Simulation Model and Set Up

A simplified vehicle front end model is used to simulate the impact of a vehicle to an adult pedestrian. The design and development of the simplified vehicle model consist of a series of non-iterative and iterative steps. An extensive validation is carried out for the model and the results as well as the model development details are presented in Kausalyah et al. [7]. The simplified vehicle model (Figure 1(b)) is made to collide with the adult pedestrian at speed of 40km/h [4,8,9]. MADYMO v7.4.1 by TASS BV is used for the simulations. The pedestrian is impacted on the right side at the centreline of the vehicle as shown in Figure 1(c). Acceleration due to gravity is applied universally to all models and an additional horizontal constant deceleration of $5m/s^2$ is given to the vehicle to simulate braking. The TNO's (TASS Netherlands) adult $50^{th}$ percentile male pedestrian ellipsoid human body dummy is chosen for this study (Figure 1(a)). This dummy is made to represent the adult population of the sample. These dummy models have been extensively validated by TNO using cadavers, both by blunt impact tests on body segments and full body car-pedestrian tests [10].

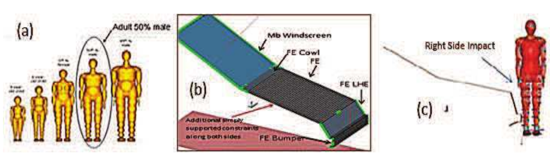


**Fig. 1:** (a) Full Range of TNO's human models (Multi body ellipsoid dummies) (b) Front End vehicle model parts and nodal constraints (c) Impact position of vehicle to pedestrian dummy.

## 3 Design of Experiment

### 3.1 Design Parameters and Injury Criteria

With reference to the literature, seven design parameters, controlling the shape of the vehicle front is selected to generate the different front end geometries within the design space [5,8]. They are the bumper lead (BL), bumper centre height (BCH), hood leading edge (HLE), hood length (HL), hood edge height (HEH), windshield angle (WS$\alpha$) and hood angle (H$\alpha$). The Head Injury Criteria, HIC15 which has a safety threshold of $\leqslant 1000$ is used for the evaluation of the injury [11,12]. The resultant head acceleration (Eq 1) is used in calculating the HIC, as presented in Equation 2, where x,y and z axes are the local coordinate system located at the head of the dummy [11].

$$a_{resultant} = \sqrt{a_x^2 + a_y^2 + a_z^2} \tag{1}$$

$$HIC = \left\{ \left[ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} (t_2 - t_1) \right\}_{max} \tag{2}$$

### 3.2 Central Composite Design (CCD)

A central composite design is an experimental design, useful in Response Surface Methodology (RSM), for building a second order (quadratic) model for the response variable without needing to use a complete three-level factorial experiment [13]. It contains an imbedded factorial or fractional factorial design with center points that is augmented with a group of 'star points' that allow estimation of curvature [13]. The values of axial or star points should be selected with consideration of the rotability of a central composite design (Figure 2).

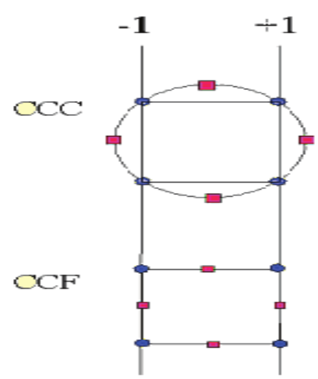


**Fig. 2:** A Comparison of CCC and CCF Designs

CCC designs are the original form of the central composite design (graphical representation in Figure 3). The star points are at some distance from the center based on the properties desired for the design and the number of factors in the design [14]. The star points establish new extremes for the low and high settings for all factors. For the CCF, the star points are at the center of each face of the factorial space, so $\alpha = \pm 1$. This variety requires 3 levels of each factor [14].

Central Composite Designs are commonly preffered as it is very flexible and can be run sequentially, thus it facilitates the modelling process. The availability of several varieties of CCDs enables their use under different experimental regions of interest and operability.The cube and centre points serves as a preliminary stage where a first-order model could be constructed but still provide evidence regarding the importance of a second order contribution. For a more detailed analysis, axial points of the design are built up into the central composite design to fit a second degree model. Thus, the CCD allows for efficient estimation of the quadratic terms in the second-order model. It also proves to be very effcient in providing information on experiment variable effects and overall experimental error in a minimum number of required runs and is able to efficiently screen out the vital parameters from a large number of factors. The Central Composite Design and polynomial metamodels have been successfully adopted in studying crash related researches in the past [14,16,17].

The CCD applied in this present study consists of 64 (2n-1) factorial runs ( coded to the usual + notatation), 14 axial runs and 22 centre runs.

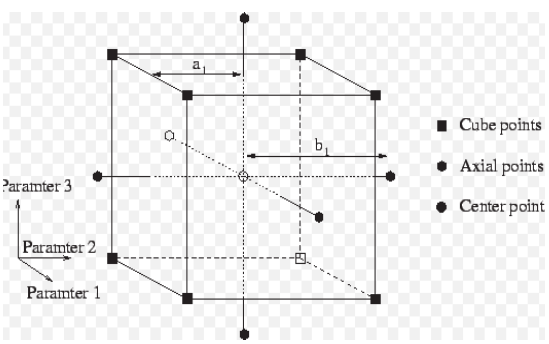


**Fig. 3:** A Graphical Representation of the Central Composite Design with Three Factors (k=3)

Minimal modification on one of the axial value for the CCC design is undertaken to avoid design unfeasibility and to maintain the general shape of the vehicle profile. The optimization process essentially involves three main steps: (1) performing the statistically designed experiments, (2) estimating the coefficients in the mathematical model, and (3) predicting the response and checking the adequacy of the model [15]. The MATLAB v7.11.0 is used for optimization process.

An empirical model is developed to correlate the response to the crash analysis and is based on the second order quadratic model for obtaining the Head Injury Criteria (HIC) as given in Equation 3,

$$Y(HIC) = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_i i X_i^2 + \sum_{i=1}^{n} \sum_{j>1}^{n} \beta_{ij} X_i X_j + \varepsilon \tag{3}$$

where $Y(HIC)$ is the predicted response, $\beta_0$ is the constant coefficient, $\beta_i$ is the linear coefficient, $\beta_{ij}$ is the interaction coefficient, $\beta_{ii}$ is the quadratic coefficient and $X_i$, $X_j$ are the coded values.

## 4 Result and Discussion

Table 1 above present the range and levels for both the CCF and CCC designs respectively. Figure 4 illustrates the vehicle front end profile with the respective parameters.

Table 3 shows the responses for the 14 axial values of the CCF abd CCC designs. The responses generated for the first 64 runs and 22 centre runs are similar for both the designs. It can be seen from the table that the HIC values generated through the simulation shows some notable differences between the CCF and CCC designs in some of the runs. This is attributed to the parameter influences on the various profiles generated. As presented in the illustration in Figure 2, the maximum $\alpha$ value for the CCF will be -1/1 and for the CCC -2.828/2.828 (for 7 parameters). The logarithm function is applied to the values of HIC obtained to reduce the difference of margin amidst the values.

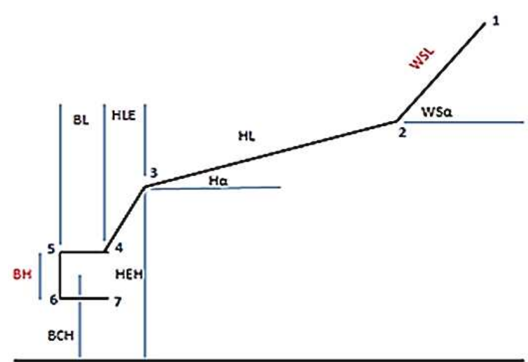


**Fig. 4:** Vehicle Front End Profile

## 5 ANOVA

Table 3 presents the ANOVA for the CCF and CCC designs respectively. The Analysis of Variance (ANOVA) is used to evaluate the statistical significance of the constructed model. The mean square error obtained for both the design is small and in the acceptable range. The

**Table 1:** Design Parameters

| | The $\alpha$ coded values and the actual values for CCF and CCC designs | | | | |
|---|---|---|---|---|---|
| Design Parameters | **-2.828** | **-1** | **0** | **1** | **2.828** |
| $X_1$ (WS$\alpha$) | 18.95 | 29.00 | 34.50 | 40.00 | 50.05 |
| $X_2$ (BL) | -35.70 | 10.00 | 35.00 | 60.00 | 105.70 |
| $X_3$ (BCH) | 360.97 | 435.00 | 475.50 | 516.00 | 590.03 |
| $X_4$ (HLE) | -41.40 | 50.00 | 100.00 | 150.00 | 241.40 |
| $X_5$ (HL) | 118.59 | 635.00 | 917.50 | 1200.00 | 1716.41 |
| $X_6$ (H$\alpha$) | 4.60 | 11.00 | 14.50 | 18.00 | 24.40 |
| $X_7$ (HEH) | 314.56 | 565.00 | 702.00 | 839.00 | 1089.44 |

**Table 2:** Design Matrix and Responses of the HIC for the Axial Values

| Exp No | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_7$ | CCF(HIC) | CCF(log 100) | CCC(HIC) | CCC(log 100) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 65 | $-\alpha$ | 0 | 0 | 0 | 0 | 0 | 0 | 144.68 | 1.080204 | 240.77 | 1.1908 |
| 66 | $\alpha$ | 0 | 0 | 0 | 0 | 0 | 0 | 231.06 | 1.181862 | 236.09 | 1.18654 |
| 67 | 0 | $-\alpha$ | 0 | 0 | 0 | 0 | 0 | 489.42 | 1.344841 | 500.58 | 1.34974 |
| 68 | 0 | $\alpha$ | 0 | 0 | 0 | 0 | 0 | 195.34 | 1.145396 | 1001.9 | 1.50041 |
| 69 | 0 | 0 | $-\alpha$ | 0 | 0 | 0 | 0 | 192.74 | 1.142486 | 169.64 | 1.11476 |
| 70 | 0 | 0 | $\alpha$ | 0 | 0 | 0 | 0 | 306.27 | 1.243052 | 312.08 | 1.24713 |
| 71 | 0 | 0 | 0 | $-\alpha$ | 0 | 0 | 0 | 206.5 | 1.15746 | 180.13 | 1.12779 |
| 72 | 0 | 0 | 0 | $\alpha$ | 0 | 0 | 0 | 309.8 | 1.245541 | 803.6 | 1.45252 |
| 73 | 0 | 0 | 0 | 0 | $-\alpha$ | 0 | 0 | 435.11 | 1.3193 | 300.572 | 1.23897 |
| 74 | 0 | 0 | 0 | 0 | $\alpha$ | 0 | 0 | 1620.4 | 1.604811 | 1101.3 | 1.52095 |
| 75 | 0 | 0 | 0 | 0 | 0 | $-\alpha$ | 0 | 258.66 | 1.206365 | 245.38 | 1.19492 |
| 76 | 0 | 0 | 0 | 0 | 0 | $\alpha$ | 0 | 343.65 | 1.268058 | 409.67 | 1.30622 |
| 77 | 0 | 0 | 0 | 0 | 0 | 0 | $-\alpha$ | 274.77 | 1.219485 | 1827 | 1.63087 |
| 78 | 0 | 0 | 0 | 0 | 0 | 0 | $\alpha$ | 2612 | 1.708487 | 414.24 | 1.30863 |

* Only the axial values are displayed as the CCF and CCC designs share the similar factorial and centre runs.

CCC offers a higher value of MSE with the difference of 0.0008. From the set of R2 values, the CCF yields a closer curve fit with 81.71%, whereas the CCC design has a 76.48% of fit. The Fisher Statistical Test (F-Test) is used to determine the significance of the models analysed. Both the CCF and CCC designs were significant with F64,35 = 8.1684, p = 3.804x 10-13 for CCF and F64,35 = 5.9472, p = 4.163x10-10 for CCC. It is to be noted here that both the designs are significant and can be ideally used for the optimization procedure as the p-value is $<$ 0.05. The error estimates for The Sum of Squared Residuals (SSR) is a measure of the discrepancy between the data and an estimated model. A small SSR indicates a tight fit of the model to the data. From Table 3 we see that CCC has a smaller value of SSR (2.6826) indicating a better fit of the model to the data. From the ANOVA, it is seen that the CCF design offers a better significance in comaparison to the CCC. Further analysis is made below to compare the designs for the optimization work.

**Table 3:** Results of Analysis of Variance (ANOVA)

| ANOVA | CCF | CCC | |
|---|---|---|---|
| F value | 8.1684 | 5.9472 | Significant |
| P value | 3.804x 10-13 | 4.163x10-10 | $<$ 0.05 |
| Mean Square Error | 0.010 | 0.0129 | |
| R2 | 0.8171 | 0.7648 | |
| Adjusted R2 | 0.7121 | 0.6362 | |
| Error | 0.0064 | 0.0082 | |
| SSR | 2.8659 | 2.6826 | |

## 5.1 Simplified Models

The value of the regression coefficients shows to what extent the control parameters affect the response quantitatively. The coefficients that are less significant are eliminated along with the responses with which they are associated. The stepwise reduction method is used here to simplify the model and enhance its accuracy. The stepwise selection is usually applied in a forward or backward way. The forward selection starts with the inclusion of the most significant candidate covariable in a regression model and the backward selection starts with elimination of the least significant one from a regression model that includes all covariables (a full model). When a stepwise selection is applied, it is commonly agreed upon that the backwards selection is preferred to the forward selection [19]. The stopping rule for inclusion or exclusion applies the standard significance level for testing of hypotheses ($\alpha$ = 0.05). The probablility criterion here is kept at 0.95. The initial mathematical model developed had 36 terms and after using the stepwise reduction method, the final reduced model has

14 terms. It can be seen from Table 4 below that the reduced model offers better accuracy with lower PRESS RMSE values.

### 5.2 Main And Interaction Effects Of Parameters

Table 4 presents the T-value and p-value for the significant parameters in the vehicle profile. The $X_3$, $X_4$ and $X_5$ parameters define the bumper centre height, hood leading edge and hood length respectively. These three parameters contribute mainly to the fall kinematics of the pedestrian. Adjusting either of these parameters incorrectly will contribute to the rise of the HIC values thus reducing the injury mitigation. The CCC design is better able to predict the main and interaction parameters contribution to the sensitivity of the vehicle profile in the optimization. The quadratic parameters have also been significantly highlighted in the CCC design. The CCF design is not able to capture the quadratic interaction well hence proving the nature of the design itself being unable to efficiently estimate quadratic interactions. However, the interaction parameters mostly coincide for both the designs. All the significant parameters captured in the CCC design has p-values of $< 0.05$, well within the confidence limit. The CCF design nevertheless is still able to offer some predictions as to the importance of the parameter interactions but does not give any conclusive findings to the nature of the problem.

**Table 5:** Parameter Interaction Sensitivity

| | CCF | | CCC | |
|---|---|---|---|---|
| Source | T value | P value | T value | P value |
| $X_3$ | 4.4737 | 3.22E-05 | 4.2179 | 7.29E-05 |
| $X_4$ | 1.7629 | 0.0827 | 2.441 | 0.01743 |
| $X_5$ | 9.1404 | 3.22E-13 | 8.5665 | 3.25E-12 |
| $X_2X_7$ | 2.4539 | 0.0169 | 2.369 | 0.0287 |
| $X_3X_5$ | 4.2889 | 6.18E-05 | 4.1403 | 0.0001 |
| $X_3X_7$ | -4.3001 | 5.93E-05 | -4.1519 | 9.94E-05 |
| $X_4X_5$ | 2.7383 | 8.00E-03 | 2.644 | 0.01031 |
| $X_5X_6$ | 3.6456 | 1.04E-01 | 3.519 | 0.0008 |
| $X_{22}$ | -0.0556 | 0.95579 | 4.5589 | 2.38E-05 |
| $X_{44}$ | -0.72035 | 4.74E-01 | 4.559 | 2.38E-05 |
| $X_{55}$ | 3.2503 | 0.0018 | 3.944 | 0.0002 |
| $X_{66}$ | -0.1761 | 0.8607 | 2.179 | 0.03298 |
| $X_{77}$ | 3.2797 | 0.00016 | 5.1681 | 2.52E-06 |

These parameters affects the kinematics of fall of the pedestrian upon impact and an improper range or value may cause the pedestrian to impact stiff areas on the vehicle causing a rise in the HIC. This is in accordance with previous researches where these parameter have shown to contribute to the HIC [9]. From these results, it can be seen that the CCC design displays a better prediction of the pedestrian crash scenario. It is able to capture the involvement of the parameters more realistically. The figures below show the direct and interaction effects of the various design parameters on the responses.

### 5.3 Predicted Versus Observed HIC

Table 5 below shows us the comparison between the predicted HIC obtained through the MATLAB optimization program and the observed HIC obtained through the numerical simulations (MADYMO) for both the CCF and CCC designs.

**Table 6:** Predicted vs. Observed HIC

| | Head Injury Criteria (HIC) | |
|---|---|---|
| | CCF | CCC |
| Predicted CCD | 45.3419 | 113.6057 |
| Observed (MADYMO) | 233 | 157.29 |
| Practical Error Margin | 187.66 | 43.68 |

The percentage of error for the CCF design is approximately 81% which is large and 28% approximately for the CCC design. Typically, some reasonable amount of error is expected due to the highly non-linear nature of the crash scenario owing to the numerous possibility of the pedestrian post impact fall pattern [5,8]. Thus an allowance is made where a practical error margin of $\pm 100$ HIC is given when judging the acceptability of the response surface models in comparison to the observed values of the HIC [18]. It is vital to note here that a design is deemed suitable when it contributes to a low error between the predicted and the observed values. The MADYMO crash analysis displays the realistic scenario of the pedestrian crash impact and is to be referred to for verification of the statistical design method employed. The findings in this section support fully the CCC design as it offers the best predictions.

## 6 Conclusion

In this study, a statistical optimization method has been used to obtain the optimum design parameters for the vehicle front end geometry, analyzing the differences between the CCC and CCF designs. The conclusion can be sumarized as follows:

– The ANOVA favours the CCF design, however the Sum of Squared Residuals (SSR) value shows that the CCC design offers a better fit of the model to the data. Nevertheless the CCC's ANOVA values are very close to the CCF values and are within the acceptable range. Thus both the designs are deemed significant.
– The CCC design is better able to capture the sensitivity of the parameters as it offers more insight to the aspect of the parameters in the vehicle profile optimization process.

**Table 4:** Adjusted $R^2$ and PRESS RMSE Values for Full and Reduced Models

| Response | Adjusted $R^2$ | | | | PRESS RMSE | | | |
|---|---|---|---|---|---|---|---|---|
| | Full Model | | Reduced Model | | Full Model | | Reduced Model | |
| | CCF | CCC | CCF | CCC | CCF | CCC | CCF | CCC |
| HIC | 0.712 | 0.636 | 0.72 | 0.648 | 0.145 | 0.152 | 0.1071 | 0.1079 |

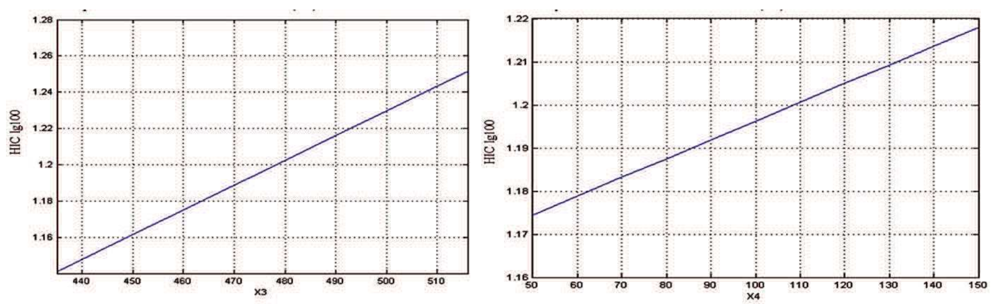


**Fig. 5:** a) Response for Main Effect of BCH ($X_3$) on HIC. b) Response for Main Effect of HLE ($X_4$) on HIC

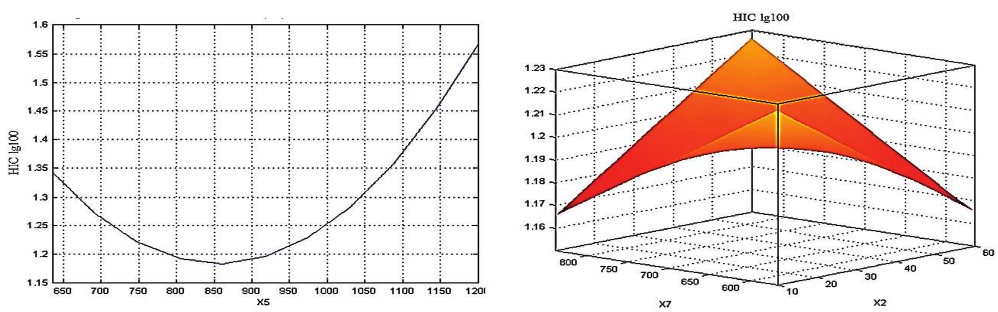


**Fig. 6:** a) Response for Main Effect of HL ($X_5$) on HIC. b) Response Surface for Interactive Effect of BL ($X_2$) and HEH ($X_7$) on HIC

– The CCC design is also able to predict the HIC values closer to the numerical values obtained through the crash simulations in MADYMO. This is of great significance as the design employed should be able to predict closely to the real values.

Therefore it is concluded that the CCC design offers a better prediction for the optimum values in comparison to the CCF design in the vehicle front end profile optimization study. It can be seen from the ANOVA that the CCC though seemingly less significant still offers very close values to that of the CCF designs and is very much within the acceptable range, thus affirming the conclusion made.

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## References

[1] Department of Transportation (US), National Highway Traffic Safety Administration (NHTSA). Traffic Safety Facts 2010: Pedestrians. Washington (DC): NHTSA; 2012 [cited 2013 April 11]. Available from URL: http://wwwnrd.nhtsa.dot.gov/Pubs/811625.

[2] L.F. Beck , A.M. Dellinger, M.E. O'Neil, Motor vehicle crash injury rates by mode of travel, United States: Using exposure-based methods to quantify differences, American Journal of Epidemiology **166**, 212-218 (2007)

[3] Critical Factor Associated with Pedestrian Casualties in Motor Vehicle Crashes, Vehicle Safety Biomechanics, Malaysian Institute of Road Safety Research, MIROS Report 2011

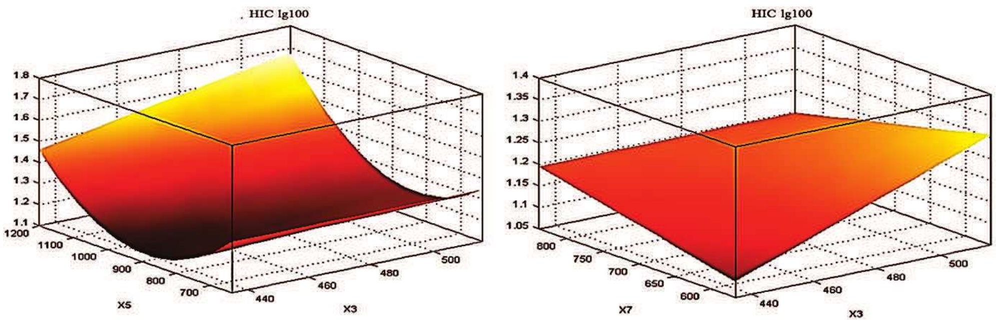


**Fig. 7:** Response Surface for Interactive Effect of: a) BCH ($X_3$) and HL ($X_5$) on HIC. b) BCH ($X_3$) and HEH ($X_7$) on HIC

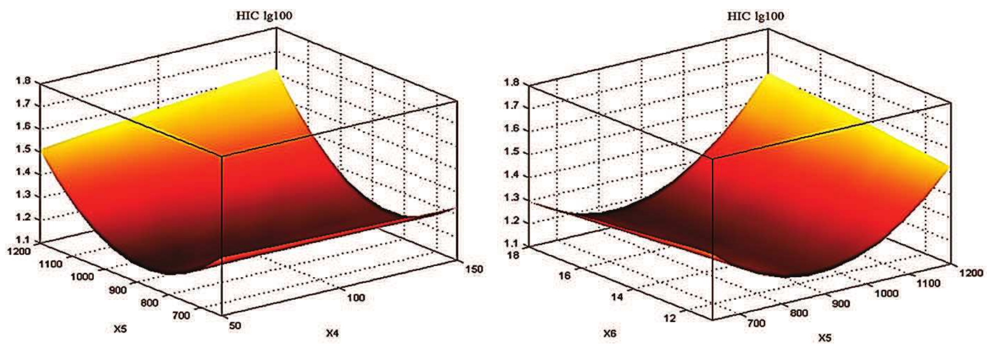


**Fig. 8:** Response Surface for Interactive Effect of: a) HLE ($X_4$) and HL ($X_5$) on HIC. b) HL ($X_5$) and H$\alpha$ ($X_6$) on HIC

[4] J.R. Crandall, K.S. Bhalla, N.J. Madeley, Designing Road vehicles for pedestrian protection, British Medical Journal **324**, 1145-1148 (2002)

[5] E. Carter, N.S. Clive, E. Steve, Optimization of Passenger Car Design for the mitigation of pedestrian head injury Using a Genetic algorithm, 5th European MADYMO Users Meeting 100-110 (2005)

[6] M.R. Niederer, P.F. Schlumpf, Influence of Vehicle Front geometry on Impacted pedestian kinematics, Stapp Car Crash Conference (1984)

[7] V. Kausalyah, S. Shasthri, A.A. Kassim, M.I. Moumen, H.S. Qasim, S.V. Wong, Validation Of Pedestrian Head Form and LegForm Impact Testing Upon Hybrid Vehicle Front End Profile, 2nd International Conference on Mechanical, Automotive and Aerospace Engineering (ICMAAE'13) (2013)

[8] Y. Zhao, G.F. Rosala, I.F. Campean, A.J. Day, A Response surface approach to front car optimization for minimizing pedestrian head injury levels, International Journal of Crashworthiness **15**, 143-150 (2010)

[9] X.J. Liu, J. Yang, Effects of Vehicle Impact Velocity and Front End Structure on Dynamic Responses of Child Pedestrians, Traffic Injury Prevention **4**, 337-344 (2003)

[10] TNO, MADYMO Human Models Manual, in Madymo TNO Automotive: The Netherlands (2006)

[11] EuroNCAP, Pedestrian Testing Protocol, Version 4.3, Available at http://www.euroncap.com/files/ (2009)

[12] European Enhanced Vehicle Safety Committee, Improved Test methods to Evaluate Pedestrian Protection Afforded by Passenger Cars, EEVC Working Group 17 Report (1998)

[13] D.C. Montgomery, Design and Analysis of Experiments, 3rd Edition (1991)

[14] J.H. Hong, M.S. Mun, S.H. Song, An Optimum Design Methodology Development Using A Statistical Technique For Vehicle Occupant Safety, Proceedings of IMechE, Part D:Journal of Automobile Engineering (2001)

[15] J.N. Sahu, J. Acharya,B.C. Meikap, Response Surface Modeling and Optimization of Chromium(VI) Removal from Aques Solution Using Tamarind Wood Activated Carbon in Batch Process, Journal of Hazard Materials 818-825 (2009)

[16] J. Sobieszczanski-Sobieski, S. Kodiyalam, R. Yang, Optimization of car body under constraints of noise, vibration, and harshness (NVH), and crash. Structural and Multidisciplinary Optimization **22**, 295-306 (2001)

[17] R.J. Yang, L. Gu, C.H. Tho, J. Sobieszczanski-Sobieski, Multidisciplinary design optimization of a full vehicle with high performance computing, AIAA-2001-1273. Proceedings of the 42nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit (2001)

[18] V. Kausalyah, S. Shasthri, K.A. Abdullah, M.M. Idres, Q.H. Shah, S.V. Wong , Optimisation of vehicle front-end geometry for adult and pediatric pedestrian protection, International Journal of Crashworthiness (2014)

[19] F.E. Harrell, K.L. Lee, D.B. Mark, Multivariable prognostic models: issues in developing models, evaluating assumptions and adequacy, and measuring and reducing errors, Stat Med **15**, 361-87 (1996)

**Kausalyah Venkatason** is a PhD student at the Department of Mechanical Engineering, International Islamic University Malaysia (IIUM). She completed her B Eng from the Department of CAD/CAM Engineering, University Malaya, Malaysia in 2000. She obtained her MSc in Engineering from University Malaya, Department of Mechanical Engineering in 2002. She is currently a scholar of the Ministry of Higher Education of Malaysia and is also a Senior Lecturer at the Faculty of Mechanical Engineering of the University Technology of MARA.

**Shasthri Sivaguru** is a PhD student at the Department of Mechanical Engineering, International Islamic University Malaysia (IIUM). He is attached to the University Selangor as Senior Lecturer in the Department of Mechanical Engineering. He completed his Bachelor of Engineering from University Malaya, Malaysia in 2000 and went on to pursue his MSc in Mechanical Engineering from University Malaya and completed it in 2002. His research interests are in the field of finite element methods, structural dynamics, vehicle crashworthiness, modelling and simulation.

**Kassim A Abdullah** is an Assistant Professor at the Department of Mechanical Engineering, International Islamic University Malaysia (IIUM). He completed his B.S. Eng in Mechanical Engineering from the Faculty of Engineering, University of Dar Es Salaam, Tanzania in 1987. He obtained his M.Sc Eng in Mechanical Engineering from the Faculty of Engineering, Queen?s University, Canada in 1993 and his Doctorate in Engineering from Queen?s University, Canada in 1998. His research interests are light weight structures for aerospace and automotive applications, structural mechanics, finite element methods, strength and fracture of engineering solids, clean car technologies and human biomechanics.

**Moumen M Idres** is an Assistant Professor at the Department of Mechanical Engineering, International Islamic University Malaysia (IIUM) since 2008. He completed his B.S in Aerospace Engineering from the Faculty of Engineering, Cairo University, Egypt in 1992. He obtained his M.S in Aerospace Engineering from the Faculty of Engineering, Cairo University, Egypt in 1995 and his Doctorate in Engineering Mechanics from Old Dominion University, USA in 1999. His specializations are in the field of aerospace engineering and mechanical controls.

**Qasim H Shah** is an Associate Professor at the Department of Mechanical Engineering, International Islamic University Malaysia (IIUM) since 2007, where he has been working since 2000. He completed his BSc in Mechanical Engineering from North West Frontier Province University of Engineering and Technology at Peshawar Pakistan in 1981. He completed his MSc in Mechanical Engineering from Nagoya Institute of Technology Japan in 1987 and his Doctorate of Engineering from Toyohashi University of Technology Japan in 1994. He possesses working experience in Japanese, Pakistani and Malaysian universities and industries.

**Wong Shaw Voon** is currently the Director General of the Malaysian Institute of Road Safety Research (MIROS) and also a Professor at the Department of Mechanical Engineering, University Putra Malaysia. He was conferred Bachelor of Engineering in Mechanical and System Engineering by University Putra Malaysia in 1997. He completed his research work within two years and secured his degree within 32 months. He is registered as a Chartered Engineer in the Engineering Council, United Kingdom, and is a Corporate Member of the Institute of Mechanical Engineers, United Kingdom, as well as the American Society of Mechanical Engineers and Society of Automotive Engineers, USA.