OPTIMIZATION AND SIX SIGMA ANALYSIS FOR OCCUPANT SIMULATIONS USING ISIGHT AND MADYMO

*K Vineeth Kumar Reddy, *Nadeem Rizvi, **V Alwan and **Mariayyah Ravishankar

** Mahindra & Mahindra Ltd. ** Dassault Systems India Pvt Ltd.*

Abstract: *Typical passenger vehicles need to pass Crashworthiness, Structural Crash and Occupant Safety regulations before a successful launch in any market of interest. In order to meet the required regulations simulations are performed by changing the respective design parameters manually. After several iterations, optimum configuration would be obtained which is then subjected to six sigma analysis to make the design robust. The manual process of changing the design parameter values so as to come up with an optimum configuration and robust design is time consuming and tedious.*

In this paper an attempt has been made to automate the entire process for Occupant Safety Simulations for Frontal Impact. This was achieved by integrating MADYMO Solver used for Occupant Safety Simulations within Isight framework. Leveraging various design exploration techniques available in Isight such as DOE and approximations, automated studies were performed to achieve the final optimized configuration. Further, six sigma Analysis was performed to achieve robust design solution using the statistical methods on the optimized configuration with the manufacturing tolerances set for design variables.

This integration of MADYMO with Isight has resulted in automating the complete workflow from base design to robust design. This has resulted in significant reduction of computational time needed to achieve the robust design for Occupant Safety Simulations.

1. Introduction

Automobile has become an important means of transportation in the society. Occupant protection is one of the key aspects in designing any automobile. With the development in roads and express ways infrastructure, the fatality rate has also been increasing day by day. Frontal crashes cover over 30% of the total automobile crashes with higher injury and fatality rate.

Avoiding or reducing the injury and death rates is vital in vehicle passive safety performance. Though many crash test facilities are available for final evaluation of a vehicle structural and passive safety performance, the preparatory expenses and the test costs are too expensive. The CAE crash simulations evolved and become popular in this front to reduce and save the cost and in the same time to able interpreting the contribution of different design parameters. The vehicle simulations with passenger dummies can predict the crashworthiness of the structure as well as the occupant injuries. These predictions of occupant injuries with the vehicle in its development stage is advantageous in a way that modifications can be done to reduce the injuries during the crash event in the development phase.

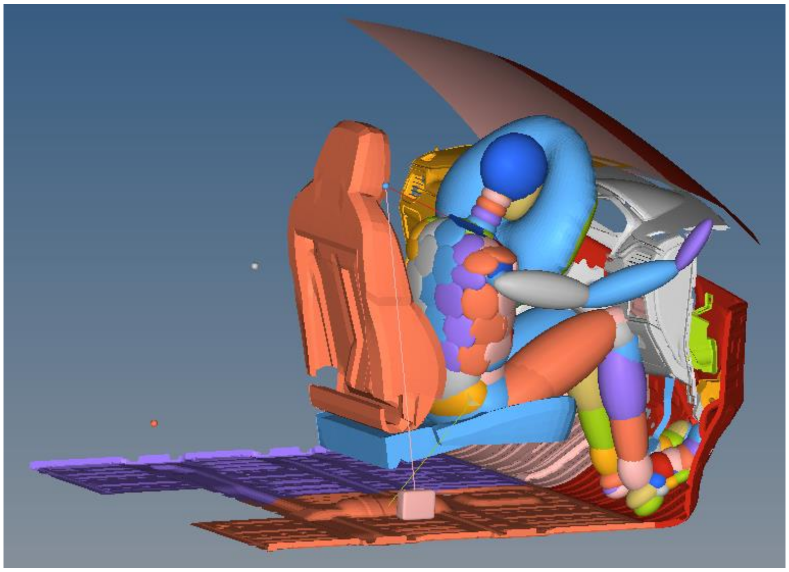

Fig 1.1 Frontal ODB Simulation

To end up with a configuration that meets the required crash and safety regulations is really an uphill task. This requires many simulations to predict the safe vehicle configuration within stipulated time and cost. The regulation limits for Occupant injuries that need to be satisfied for a successful launch of vehicle is shown in table 1.1. Performing simulation iterations by manually changing the parameter values consumes lot of time and effort. Automation of the entire work process here which includes solver – optimizer integration not only helps us in saving time but also provides us several design alternatives. This paper explains one such attempt made to integrate MADYMO, a solver used for crash & occupant safety simulations with Isight, a framework that is used with existing simulation codes to build and execute automated simulation workflows.

Occupant Injuries – Frontal ODB – AIS – 098/ECE – 094 – 50^{th}% Dummy		
Criterion	**Unit**	**Legal Limit**
Head		
HIC(36)		1000
Head Acceleration, cumulative 3ms	G	80
Neck		
Neck Tension, FZ	N	3300
Neck Shear, FX(+ve)	N	3100
Neck Shear, FX(-ve)	N	3100
Neck bending moment, MY (-ve)	Nm	57
Chest		
Chest Compression (-ve)	mm	50
Viscous Criteria	m/s	1
Femur Force		
Femur Left	N	9070
Femur Right	N	9070
Tibia Index		
Upper Left		1.3
Lower Left		1.3
Upper Right		1.3
Lower Right		1.3
Tibia Compression		
Upper Left	N	8000
Lower Left	N	8000
Upper Right	N	8000
Lower Right	N	8000

Table 1.1 AIS-098/ECE-094 Regulation limits for occupant injuries

2. Objective

The main aim of this paper is to integrate MADYMO with Isight and to find an optimized vehicle configuration which has all the occupant injuries within the frontal ODB regulation limits. This is done by establishing an automated workflow between MADYMO and Isight. The reliability study on the optimized configuration was also explored using the Six Sigma analysis process available within Isight.

3. FE Model

The frontal ODB full vehicle model was built in the LS-DYNA environment and a velocity of 56kmph was applied to the model. The analysis is performed on this model and the final results were obtained. Once the results were obtained the motion is extracted from respective accelerometers data and exported.

Now the Occupant Model was built using the MADYMO tool “XMADGIC”. In this only the components which come in contact with occupant like firewall, Instrument panel, Airbag, Seatbelts, floor, etc., were taken into consideration and modeled. All the components have defined design parameters like vent hole size, time to fire for airbags, load limiter capacity for seatbelts, intrusions for firewall, floorboard, steering column and instrument panel, etc. The motion extracted from the CAE full vehicle crash simulation was applied to this model in terms of displacements and rotations. The 50th % Hybrid III dummy was positioned accordingly and all the contacts between the dummy and the components were defined.

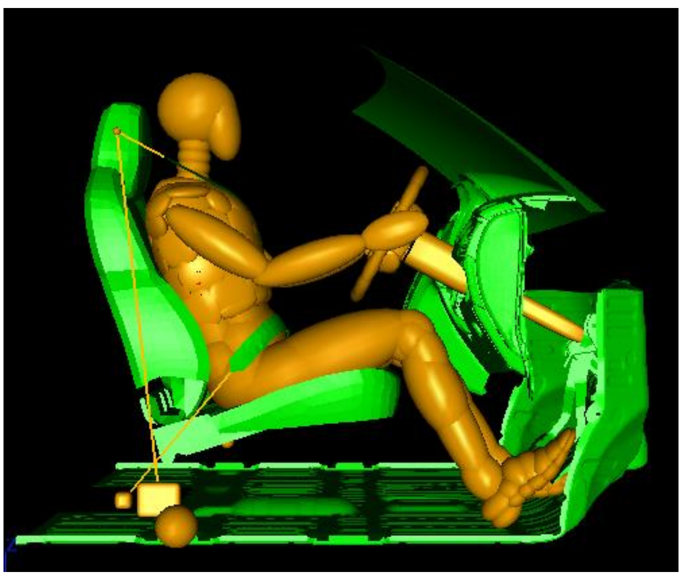

Fig 3.1 MADYMO frontal ODB model for Occupant simulations

Once all the parameters were defined the model is validated and error check was performed. The validated model is now used for initial baseline simulation and is then used for further optimization.

4. Integration with the Optimization and Six sigma tool

Once the base line model is built, the solver is integrated with Isight to find out an optimized configuration.

4.1 Optimization Workflow

The objective is to minimize the chest compression injury maintaining all other injuries in limits as constraints. Design variables considered are air bag time to fire, airbag vent hole diameter and firewall intrusions. Optimization process workflow setup between MADYMO and Isight is as shown in the below figure 4.1.

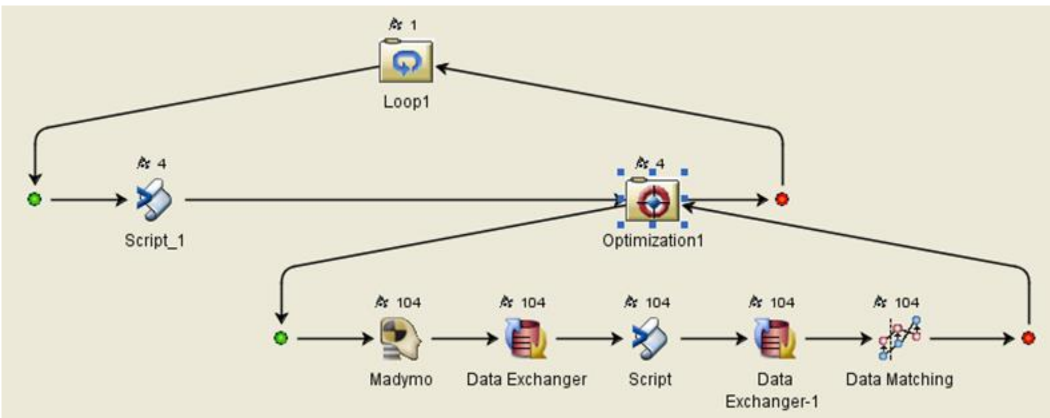

Fig 4.1 Optimization Workflow

The flow is as follows:

1. Under the Optimization flow MADYMO process component was added and the design variables and output responses were selected by reading the xml file.
2. Data exchanger component is added to read and write the data and values from the file. The Data Exchanger is used to prepare input files for external programs and to extract data from program output files.
3. The script component helps in extracting only required response from that output file.
4. Another data exchanger component is added to read the data obtained through script
5. Data exchanger component is used for requesting outputs related to curves as the chest compression injury response is in the form of curve.

6. In the optimization tab the optimization method was selected, design variables selected were assigned with upper and lower boundary values, objective and constraints were defined with their boundaries.

Design Variables	Base value	Lower limit	Upper limit
Accelerator Pedal X intrusions, mm	65	16.25	65
Brake Pedal X intrusions, mm	65	16.25	65
Clutch Pedal X intrusions, mm	65	16.25	65
Airbag Vent hole Dia, mm	20	20	50

Table 4.1 Design variables for Optimization

7. Table 4.2 shows the constraints used for the present optimization.

S. No.	Parameter	Bound Value, <=
1	HIC36 Injury Value	350
2	Left Lower Tibia force, FZ, N	900
3	Right Upper Tibia force, FZ, N	900
4	Right Lower Tibia Index	0.6
5	Left Upper Tibia Index	0.6
6	Right Upper Tibia Index	0.7

Table 4.2 Constraints

8. Table 4.3 shows the objectives

S.No.	Parameter	Objective
1	Chest Compression	Minimize
2	HIC36ms (Head Injury Criteria)	Minimize
3	Thorax Acceleration	Minimize

Table 4.3 Objective

9. The optimization techniques available were of two types exploratory and gradient based techniques. Exploratory techniques though accurate, would consume long run time, where as gradient based techniques were used for a smoother design space. As our design space is non linear, gradient based techniques were ruled out.

10. Hooke jeeves technique was selected for the current study as the design variables were few and it has a capability to search in wider design space. This technique is a combination of exploratory and Gradient based techniques rendering the advantages of both.

11. Once the Optimization is performed the optimized configuration is obtained and is as mentioned in the following tables 4.4 and 4.5.

Congifuration	**Accelerator pedal Intrusions, mm**	**Brake pedal Intrusions, mm**	**Clutch pedal Intrusions, mm**	**Vent hole Size, mm**
Base	65	65	65	20
Optimized	56.25	16.25	16.25	50

Table 4.4 Design Variables of Base and Optimized Configurations

Objectives	**Base Configuration Results**	**Optimized Configuration Results**
HIC36	278.0	212.9
Thorax Acceleration, m/s^2	301.9	287.8
Chest Compression, mm	31.0	26.2

Table 4.5 Comparison of Base and Optimized results of the objectives

4.2 Six Sigma Analysis workflow

Six Sigma Analysis was performed to check the reliability of the model allowing the manufacturing tolerances on the design variables. As the six sigma analysis requires many number of runs to be performed it is a computationally expensive and time consuming process to proceed with the solver. Therefore, a DOE was performed for the set of given discrete variables and approximation model was developed which generates a response surface. This response surface was further used for six sigma analysis. Below flow diagram Fig 4.2 shows the six sigma analysis flow.

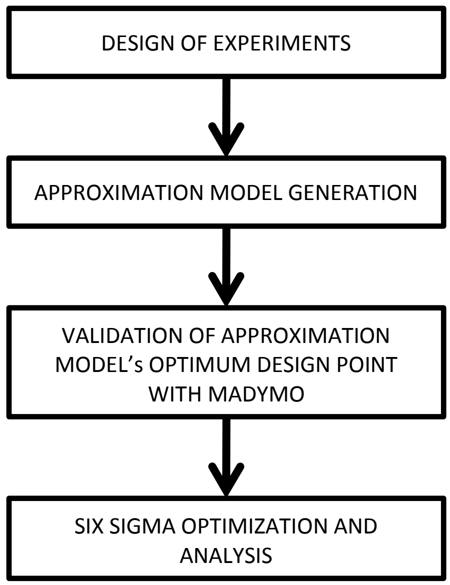

Fig 4.2 Six Sigma Analysis Workflow

4.2.1 Design of Experiments (DOE)

The design variables used for DOE in this study were all discrete and were mentioned in the below table 4.6.

Design Variable	Base Value	Lower Bound	Upper Bound
Pedal Intrusions, mm	65	16.25	65
Driver Airbag TTF, ms	20	20	50
Load Limiter Capacity, Nm	51	51	76
Vent Hole size, mm	20	20	50

Table 4.6 Design Variables for DOE

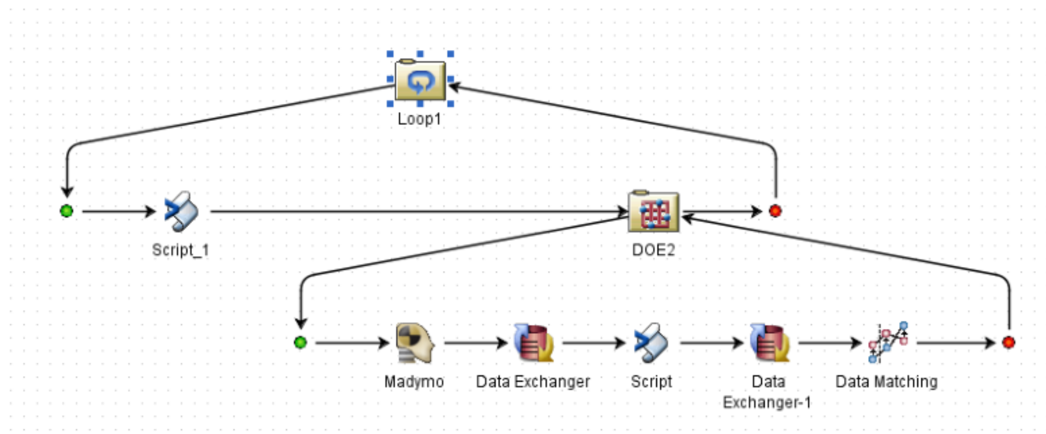

Fig 4.3 DOE Workflow

In the similar way as we defined the design variables and responses in optimization, all the process and application components were added and all parameters were defined in DOE. As all the design variables were discrete DOE was performed using full factorial algorithm.

4.2.2 Approximation Model

The Approximation component was used to generate a mathematical model of our data, which is further used for quick and efficient design studies. There are four techniques available namely

- RBF Model
- Response Surface Model
- Kriging Model
- Orthogonal Polynomial Model

For each technique the goodness of the fit was measured by performing error check analysis and the method with least error percentage was considered for further study. The approximation model development flow is as shown in the below figure 4.5

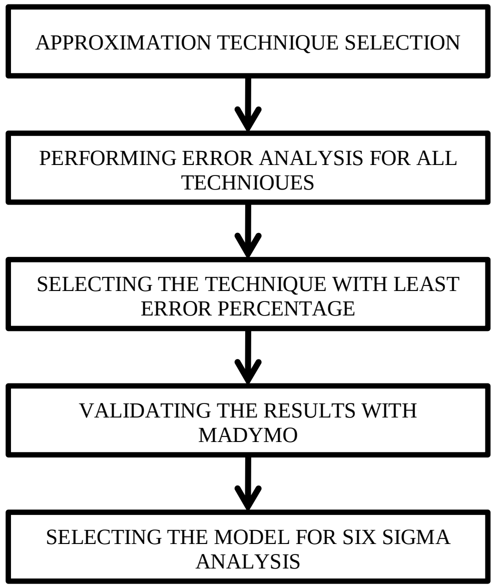

Fig 4.4 Approximation Workflow

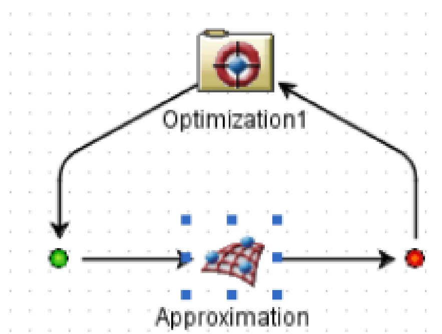

Fig 4.5 Approximation Workflow in Isight

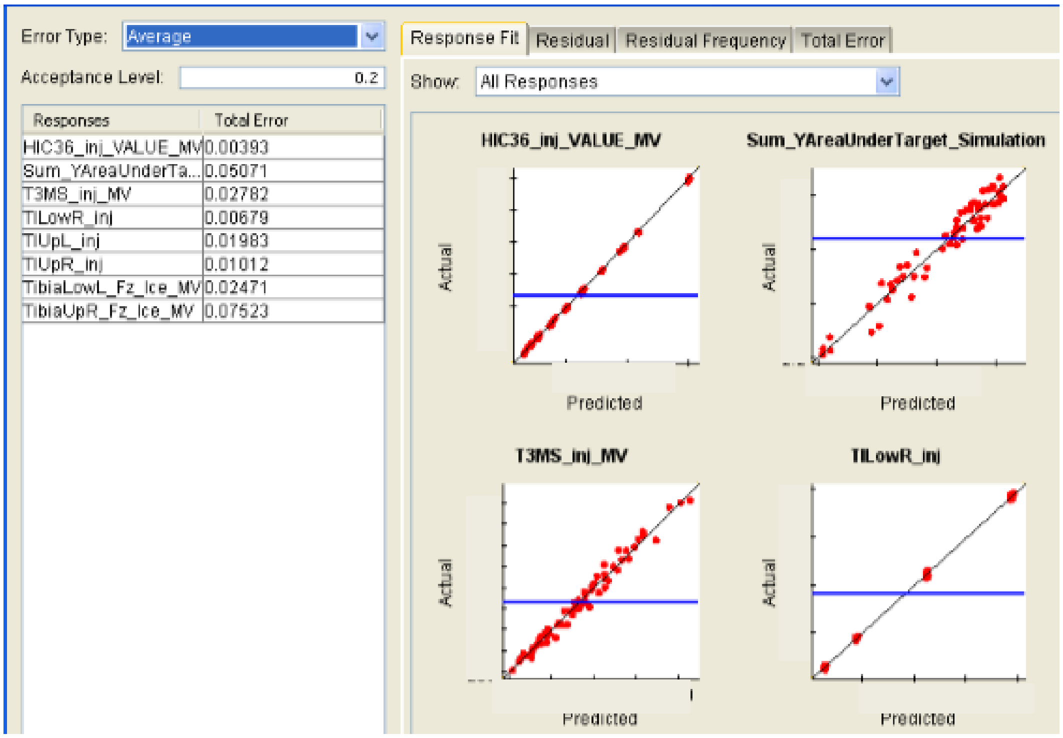

Fig 4.6 Error Analysis window

It was observed that Radial basis function technique has provided the better results with least error percentage when both the solver and approximation results were compared.

4.2.3 Comparison of the Approximation results with that of Numerical solver Results

The technique with least error percentage was selected and the respective approximation model is used for further analysis. Optimization was performed with the approximation model and the optimized design point thus obtained is further validated with the solver and the comparison of the results were as mentioned in the table 4.7.

Optimized point on Optimization of Approximation Model	
Pedal Intrusions, mm	16.25
Airbag Time to Fire, ms	30
Airbag Vent Hole Size, mm	50

Table 4.7a Optimized point

RADIAL BASIS FUNCTION			
VARIABLES	**APPROXIMATION**	**MADYMO**	**%ERROR**
HIC 36	247.84	251.23	1.34
CHEST ACCELERATION	304.75	302.60	0.71
TIBIA FORCE LOWER LEFT	731.65	746.31	1.96
TIBIA FORCE UPPER RIGHT	666.27	668.74	0.36
TIBIA INDEX LOWER RIGHT	0.409	0.407	0.34
TIBIA INDEX UPPER LEFT	0.361	0.362	0.05
TIBIA INDEX UPPER RIGHT	0.378	0.380	0.57

Table 4.7b Comparison of Solver and Optimization Tool Results

Once all the techniques were validated in Madymo with their optimum design points the technique with least error percentage (Radial Basis Function) is selected for the Six Sigma optimization analysis.

4.2.4 Six sigma optimization

Six sigma analysis was performed using the six sigma optimization method which implements a probabilistic analysis process used to measure the quality of a design given uncertainty or randomness of a product or process. The optimized design point obtained from approximation method which has least error percentage was worked out for six sigma analysis. The work flow setup for six sigma optimization is as shown in the Fig 4.7.

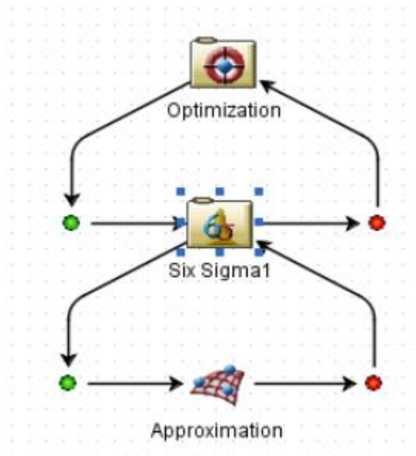

Fig 4.7 Six Sigma Optimization Workflow

The design variables were defined with the boundary values using normal distribution and are solved using the developed approximation model.

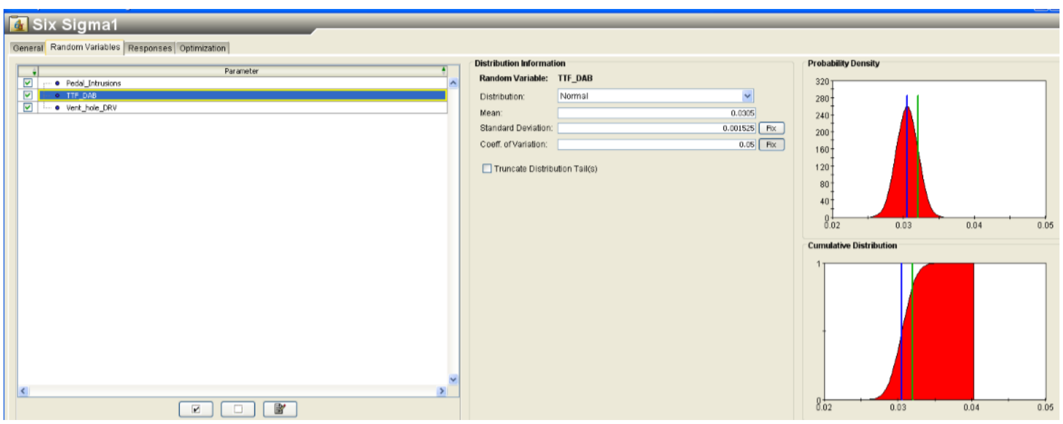

Fig 4.8 Distribution of design variables

Once the design variables were defined the six sigma optimization was performed.

SIX SIGMA OPTIMIZATION	
Analysis Type	Reliability technique
Technique	Mean value method
Number of runs	100000

Table 4.8 Specifications for Six Sigma Optimization

Design variables considered for the six sigma analysis with boundary values were as mentioned in the table 4.9

Design variables	**Lower bound**	**Upper bound**
Driver airbag Time to fire (ms)	30	40
Vent hole diameter, (mm)	20	50
Pedal intrusions, (mm)	10	65

Table 4.9 Design Variables for Six Sigma optimization

The Constraints and Objectives for the six sigma analysis were as mentioned in the following table 4.10 and 4.11.

S. No.	Parameter	Bound Value, <=
1	HIC36 Injury Value	350
2	Left Lower Tibia force, FZ, N	900
3	Right Upper Tibia force, FZ, N	900
4	Right Lower Tibia Index	0.6
5	Left Upper Tibia Index	0.6
6	Right Upper Tibia Index	0.7

Table 4.10 Constraints defined for Six Sigma Optimization

S.No.	Parameter	Objective
1	HIC36 injury	Minimize
2	Chest Compression	Minimize
3	Thorax Acceleration	Minimize

Table 4.11 Objectives

After the six sigma optimization was performed the optimized configuration was obtained and this configuration was further validated with MADYMO and the results were compared as shown in table 4.12.

Six Sigma Optimized point	
Pedal Intrusions, mm	15
Airbag Time to fire, ms	30
Vent hole size, mm	50

Table 4.12 Six Sigma Optimized Design Point

The optimized design point obtained through six sigma optimization was applied to the MADYMO model and the results were compared as tabulated in the following table.

Injuries	Six sigma optimization results	MADYMO results	% Variation
Chest acceleration, m/s^2	314.51	311.67	0.91
HIC36	263.08	261.26	1.29
Tibia index upper right	0.449	0.441	1.76
Tibia index upper left	0.359	0.360	0.21
Tibia index lower right	0.431	0.429	0.56
Tibia force lower left, N	542.17	581.41	6.74
Tibia force upper right, N	606.76	616.58	1.59

Table 4.13 Comparison of Solver and Sis Sigma Optimized point Results

It could be observed that the results were well correlated when compared as shown in the table 4.13

4.2.5 Six sigma Analysis on the six sigma optimized point :

The following table 4.14 shows the design variables used for six sigma Analysis performed on six sigma optimized point.

Design Variables	Six Sigma Optimized Value	Tolerance
Pedal Intrusions, mm	15	+/- 5
Airbag Time to Fire, ms	30	+/- 4
Airbag Vent hole size, mm	50	+/- 5

Table 4.14 Design Variables with tolerances for Six Sigma Analysis

S. No.	Parameter	Bound Value, <=
1	HIC36 Injury Value	350
2	Chest Acceleration, m/s^2	350
3	Chest Compression, mm	30
4	Left Lower Tibia force, FZ, N	900
5	Right Upper Tibia force, FZ, N	900
6	Right Lower Tibia Index	0.6
7	Left Upper Tibia Index	0.6
8	Right Upper Tibia Index	0.7

Table 4.15 Constraints with Boundary Values for Six Sigma Analysis

Once the six sigma analysis was performed results were analysed for the sigma level which shows the probability of success for objectives.

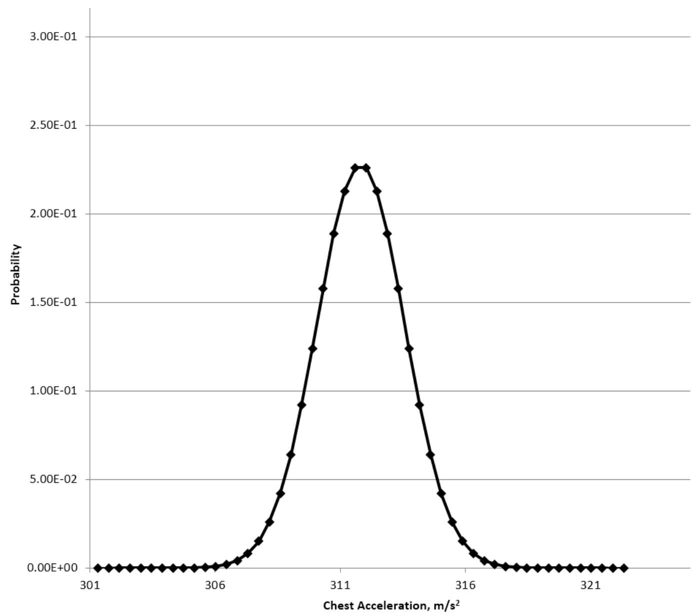

Fig 4.9 Curve showing the probability of Occurance of Chest Acceleration injury value

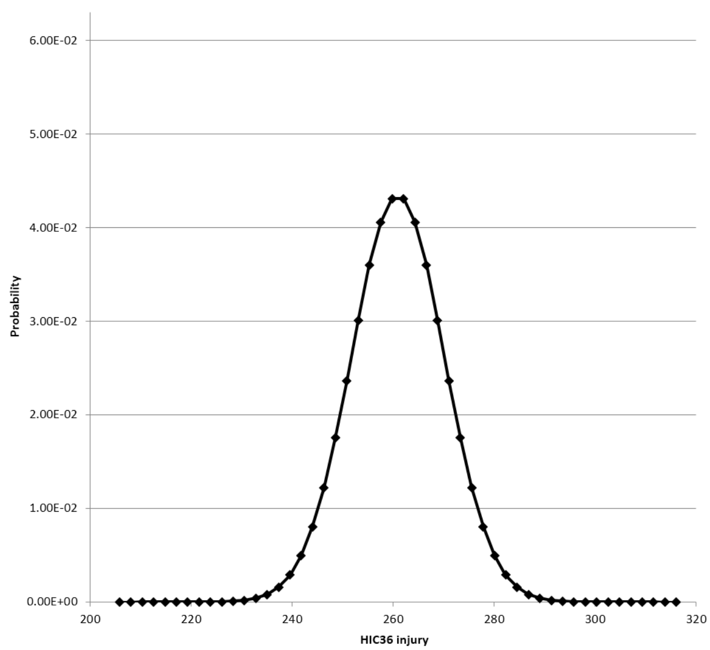

Fig 4.10 Curve showing the probability of Occurance of HIC 36 injury value

With the given bound values the six sigma analysis results were obtained and the six sigma level for the outputs are as mentioned in the below table 4.16.

Parameter	Sigma level	Mean value	Probability of success	Defects per Million
HIC36 Injury	6.0	260.9	1.0	0
Chest compression	6.0	28mm	1.0	0
Chest Acceleration	6.0	311.8m/s^2	1.0	0

Table 4.16 Six Sigma Analysis Results

5. Conclusion

MADYMO solver was successfully integrated with the optimization and six sigma tool, Isight. An automated workflow process has been developed which helps in exploring design spaces otherwise couldn’t have been thought off. Optimization and Six sigma capabilities of Isight are well explored. The results obtained with solver and mathematical methods were compared and seem to have an excellent agreement. It could be inferred that the integration of MADYMO with Isight proved beneficial to find an optimum configuration and robust design. The integration also has helped in making the entire process automated saving a lot of manual effort and time.

6. References

- AIS – 098/ECE R 94 regulation for the protection of occupants during the frontal crash.
- Madymo reference manual and theory manual
- Isight Theory manual