Sensitivity analysis of factors influencing the head injury criteria evaluation using computational simulations with a free-motion headform model

SENSITIVITY ANALYSIS OF FACTORS INFLUENCING THE HEAD INJURY CRITERIA EVALUATION USING COMPUTATIONAL SIMULATIONS WITH A FREE-MOTION HEADFORM MODEL

A Thesis by

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The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science, with a major in Mechanical Engineering.

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DEDICATION

To my parents, friends and family

and

To my advisor, Dr. Hamid Lankarani

"Hard work beats talent, when talent doesn't work hard"

-Tim Notke

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First of all, I thank the almighty God for giving me strength and ability to understand, learn and complete this research work.

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ABSTRACT

In aviation and automotive crash scenarios, head injuries are the most severe and fatal type among all the injuries incurred to the occupants. Head injuries typically occur when the head of the occupant comes in to contact with any aircraft cabin interiors, bulkheads, car steering wheel, windshield, etc. The compliance with the Head Injury Criteria (HIC) regulatory requirement is a significant concern for aircraft and automotive industries due to the importance of occupant head injury protection as well as the cost associated with the certification. The objective of this research is to examine various factors that might influence the resulting HIC value in both automotive and aircraft crash scenarios. A Hybrid-III free-motion headform (FMH) model is utilized for this purpose to investigate the variations of the HIC with different combinations of the target conditions (material, thickness, boundary conditions, and friction, etc.), as well as the impact conditions (impact velocity and impact angle). All the computational impact simulations are conducted in the LS-DYNA Finite Element (FE) software. A parametric study is then carried out using the Taguchi methodology and design of experiments (DOE), with combinations of different target and impact conditions. The analysis of variance (ANOVA) approach is utilized to study the relative percentage contribution of these conditions on the resulting HIC evaluation. The sensitivity analysis is carried out to investigate the influence of impact conditions over target conditions, and vice versa. Finally, optimal parameters for the target conditions, for the given impact conditions, are arrived at as a design tool. The significance of various factors among both target and impact conditions are thus identified.

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ABBREVIATIONS

FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
NCAP	New Car Assessment Program
HIC	Head Injury Criteria
MADYMO	Mathematical Dynamic Model
FE	Finite Element
FEM	Finite Element Method
FEA	Finite Element Analysis
CAE	Computer Aided Engineering
DOE	Design of Experiments
ANOVA	Analysis of Variance
WSTC	Wayne State Tolerance Curve
NHTSA	National Highway Traffic Safety Administration

CHAPTER 1

INTRODUCTION

1.1 Background

Head injuries are the most common, fatal and severe type injury incurred to occupants in both automobile and aircraft crash scenarios. Head injuries associated with falls, sports, automotive traffic incidents and aircraft crashes have been identified as one of the important causes of death [1].

There are severe head fatalities recorded in automobile crash scenarios. The most recent statistic from the Center for Diseases Control and Prevention (CDC) states that 1.7 million people sustain a Traumatic Brain Injury (TBI) annually, out of which about 52,000 die [2]. Motor vehicle-accidents have been reported to be the leading cause of TBI with 17% and resulted in the most significant percentage contribution of TBI, with related deaths of total 32%. Figure 1.1 shows the typical cause for the traumatic brain injury [3]. According to NASS data, around 52% injuries casused by the motor vehichle crashes are associated with head injuries, shown in Figure 1.2 [4]. When an automobile crash takes place, the force generated can accelerate the passenger's head forward, leading to an impact with a windshield, side window or on to the front deck. This leads to potential for severe head injuries to car occupants.

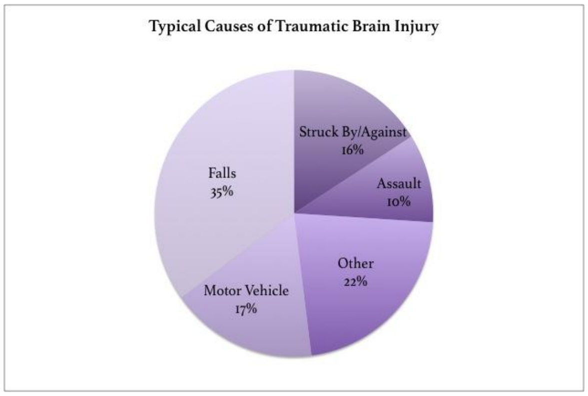


Figure 1.1: Typical Causes of Head Injuries [3]

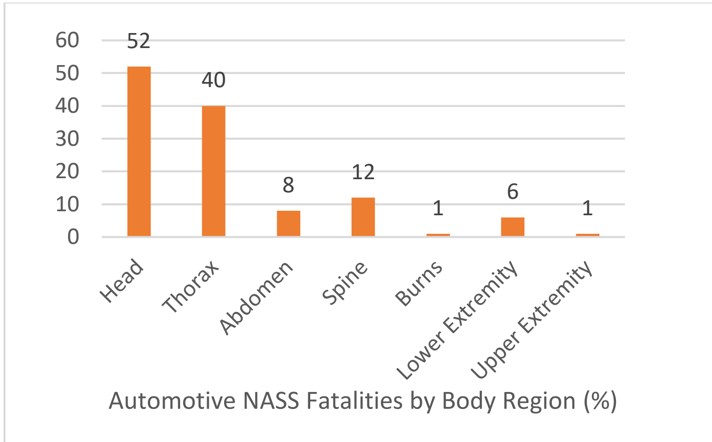


Figure 1.2: Bodily Injuries in Automobile Fatalities [4]

A total of 3448 accidents were reported in US civil and general aviation in 2005, out of which 655 were fatal [5]. In aircraft crashes, most head injuries are caused due to the frontal head impact of the passenger with the bulkhead or to the seat in front. This also leads to fatalities in spine injuries as there is a lot of change in the acceleration involved. A sudden increase in the acceleration during the crash scenarios is the primary reason for head injury occurrences. The increase in the acceleration leads to the head impact. The force generated can accelerate the passenger's head forward, leading to an impact with an obstacle. Head injuries are also caused by obstacles in the "Headpath." Head injuries in the aircraft crash scenarios are generally because of the head impacting on to the following surfaces:

- Bulkhead
- Class Dividers
- Row to Row seats
- Windscreen
- Cabin dividers
- Aircraft Interiors

Figure 1.3 shows typical configurations of the class dividers and aircraft interiors [6].

Figure 1.3: Lateral Class Dividers and Aircraft Interiors [6]

The study carried out on air crash fatalities up until 1988 by the General Aviation Safety Panel (GASP) revealed data which was quantified and divided by the GASP into the various sections of the human body like, head, face/neck, upper extremities, thorax/abdomen, spine, lower extremities and the rest were under "unqualified" [7]. Figure 1.4 shows the GASP data on fatalities in air crashes [7]. The GASP panel identified three criteria namely:

- Head Injury Criteria,
- Lumbar load,
- Upper torso restraint load.

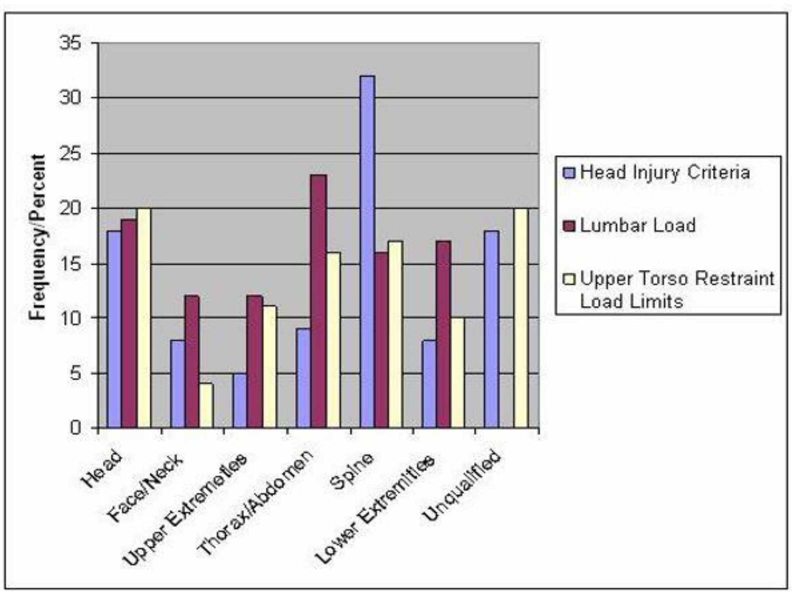


Figure 1.4: GASP Data on Fatalities in Air Crashes [7]

1.2 Head Injury Criteria (HIC)

Regulations in the automobile and aircraft industries have been developed to protect the car/aircraft occupants from serious head injuries for any potential head impact hazard. The Head Injury Criteria (HIC) is used to assess the injury level caused to head in the regulations. The HIC is defined as [8],

$$\text{HIC} = \max \left[(t_2 - t_1)\left\{\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a(t)dt \right\}^{2.5} \right] \tag{1.1}$$

Where,

a(t) = resultant acceleration at the center of gravity of occupant's head in G

t_1 = initial integaration time, in seconds

t_2 = final integration time, in seconds

The maximization is carried out by varying the time interval $(t_2 - t_1)$.

This criterion was improvised by the Federal Motor Vehicle Safety Standard (FMVSS) on testing the Hybrid-III Anthropomorphic Test Device (ATD) [9]. As per aircraft standards, the HIC is measured over a time period when the skull Hybrid-II or FAA-Hybrid-III comes in contact with any part of the structure within the aircraft. The requirements of HIC were accommodated and are included in 14 CFR 23.562 and 14 CFR 25.562 [10].

The tolerance level for HIC should not exceed more than **1000**. The maximum time interval which is considered to give actual HIC values was set to 36 ms (milliseconds). Over the decades, to restrict the use of HIC to hard contact/impacts, the time interval was set to 15 ms (milliseconds) with a threshold limit for HIC reduced to **700**. Head Injury Criteria is quite volatile to many factors. The factors are classified into three categories: Impact conditions, Target conditions and other, etc.

1.3 Aircraft Certification Standards

Federal Aviation Administration (FAA) [11] has implicated a set of rules and regulations. Some of the specific regulations are as follows:

- FAR Part 23 (Pilot and Passenger) – General aviation aircraft
- FAR Part 25 – Transportation aircraft
- FAR Part 27 – Rotorcraft

During "Emergency Landing Dynamic conditions," 16G dynamic seat certification testing procedures are defined. Two testing conditions were proposed: Test-1 and Test-2. The test procedures are carried out for vertical and frontal impacts. In order to evaluate the impact angle and impact velocities, Test -2 dynamic conditions were used in this research.

Test -1 Condition: Figure 1.5 represents the Test -1 condition [11]. This condition is used to assess the response of the occupant for a combined longitudinal and vertical loading environment, and in particular how the occupant is protected in lumbar spine vertical loading.

Test-2 Condition: Figure 1.6 represents the Test-2 condition [11]. This condition is used to evaluate the response the seat, occupant and the restraint system for only longitudinal loading environment. This more severe condition is aimed to assess the structural integrity of the seat as well as the protection of the occupant in the cabin in terms of impact hazards, measured by HIC.

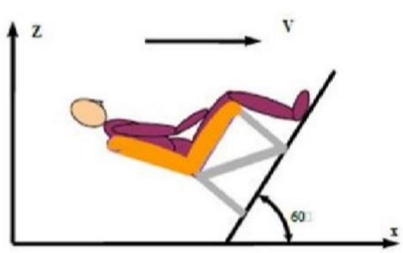


Fig 1.5 FAR Dynamic Test -1 Condition [11]

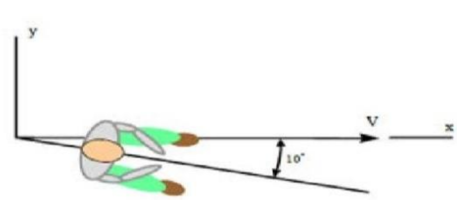


Fig 1.6 FAR Dynamic Test-2 Condition [11]

1.3.1 Federal Aviation Regulation Part 23 and Part 25

Figures 1.7 and 1.8 represent the Part 23 triangular acceleration pulses (pilot and passenger), and Part 25 acceleration pulse for the Test-2 condition [12]. The peak acceleration for Part 23 pilot is 26 G and the peak acceleration for Part 23 passenger is 21 G. Compared to Part 23, the acceleration pulse for the Part 25 passenger is at a lower level. The Part 25 Passenger test pulse is 16G. Table 1.1 illustrates the Federal Aviation Regulation Test conditions 1 and 2 [12].

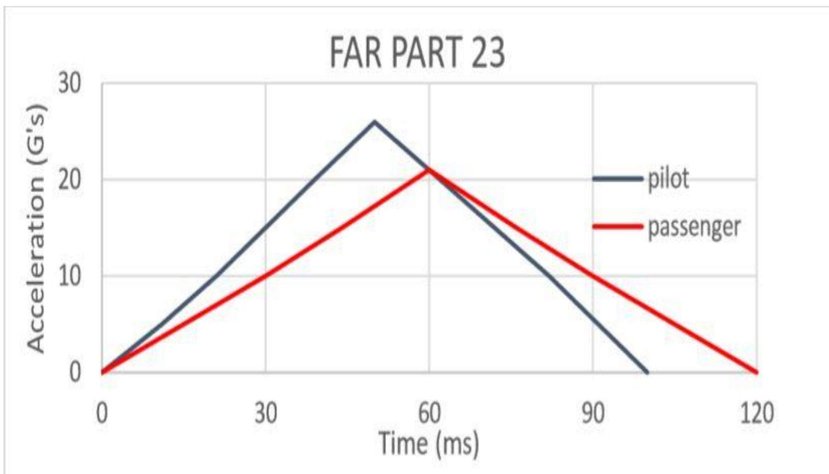


Figure 1.7: Acceleration Pulse in FAR Part 23 Test-2 Condition [12]

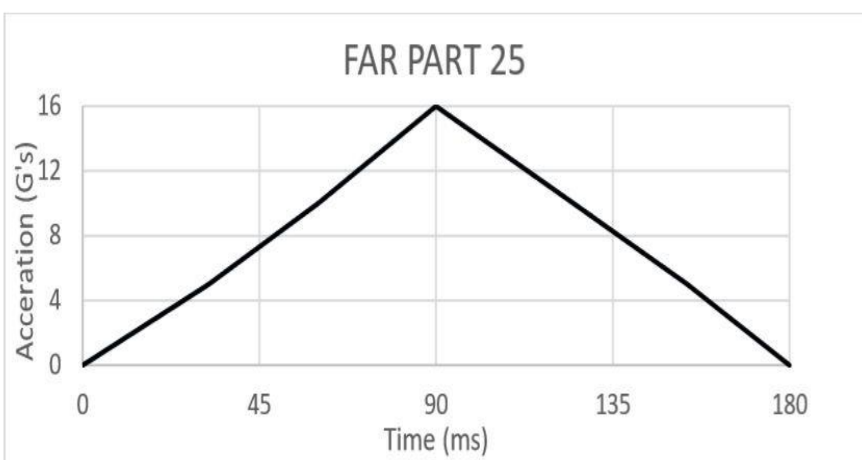


Figure 1.8: Acceleration Pulse in FAR Part 25 Test-2 Condition [12]

TABLE 1.1

FEDERAL AVIATION REGULATIONS TEST CONDITIONS 1 and 2

Test Condition 1	PART 23		PART 25	PART 27
	Pilot	Passenger		
Velocity change (ft/sec)	31	31	35	30
Acceleration Pulse (G's)	19	15	14	30
Rise Time (sec)	0.05	0.06	0.08	0.031
Test Condition 2	PART 23		PART 25	PART 27
	Pilot	Passenger		
Velocity Change (ft/Sec)	42	42	44	42
Acceleration Pulse (G's)	26	21	16	18.4
Rise Time (sec)	0.05	0.06	0.09	0.071

1.4 Automotive NHTSA/FMVSS Regulations

Under the Highway Safety Act of 1970, the U.S. Department of Transportation (DOT) established the National Highway Traffic Safety Administration (NHTSA) [13]. The major goal of NHTSA is to save lives, prevent injuries and to reduce economic costs associated with vehicle crashes. This is achieved by conducting awareness programs by establishing and enforcing safety standards for different types of motor vehicle manufacturers. This helps to conduct effective local highway safety programs. NHTSA also works on constant monitoring and investigating new safety standards which minimize the casualties caused by motor vehicle crashes and implements these new safety standards. This helps the government and local organization to minimize the risk of drunk drivers. Standards are set for promoting the use of child safety seats and seatbelts, establish vehicle anti-theft regulations. There have been many regulatory standards established in the interest of occupant safety. Almost all parts of a car have defined regulations, some of them are [13]:

- FMVSS 201 Occupant Protection in Interior Impact [13]
- FMVSS 202a Head Restraints [13]
- FMVSS 208 Frontal Impact Occupant Protection [13]
- FMVSS 214 Side Impact Occupant Protection [13]
- FMVSS 216 Roof Crush Resistance [13]
- FMVSS 223 Rear Impact Guards [13]
- FMVSS 224 Rear Impact Protection [13]
- FMVSS 301 Fuel System Integrity (Rear impact upgrade in 2005 to 2009) [13]

1.5 Frontal Impact Occupant Protection (FMVSSV 208)

FMVSS 208 is the regulation that is proposed by the National Highway Traffic Safety Administration (NHTSA) [13] to measure occupant protection during a frontal impact. This regulation was proposed to study the front seating passenger injuries. There were some other test conditions proposed by NHTSA to study various frontal crash scenarios. Some of them are:

- Full frontal barrier test
- Oblique frontal fixed barrier test
- Offset frontal barrier test
- Generic sled test
- Moving perpendicular deformable barrier
- Fixed deformable barrier test
- Moving oblique barrier test

The full-frontal rigid barrier impact test is one of the most common impact tests carried out with a rigid barrier being impacted in the perpendicular direction by a sedan class car [13]. In this research, the Toyota Yaris car is used. This test was carried out for 35 mph speed. Figure 1.9 depicts the Full-Frontal Rigid Barrier Test.

Figure 1.9: Full Frontal Rigid Barrier Impact Test [13]

A sudden deceleration is observed when the vehicle hits the rigid barrier. The dummy is placed in the front seat of the car, and from which the dummy injuries are studied.

1.6 Literature Review

Head Injury Criteria (HIC) can be influenced to many factors. Head injuries are caused when the head of the occupant come in contact with any obstacle. The obstacles can be aircraft interiors, bulkheads, cabin dividers, windscreens, dashboards, and steering. Several studies were conducted on head impact protection. These researches were conducted using free motion head forms, full-scale sled tests, and other means. This review highlights development, evaluation and parametric studies of HIC.

In terms of HIC development, Gurdjian, et al. [14] was the pioneer for the concussion work on impact standards. Lisner, et al. [15] proposed the concussion tolerance level. Gurdjian and Lisner, et al. [16] together proposed Wayne State Tolerance Curve [WSTC]. In 1976, National Highway for Traffic and Safety Administration (NHTSA) [17] developed Gadd Severity Index standards. Versace, et al. [8] defined the HIC and incorporated in FMVSS 208. In 1986, NHTSA

[18] revised the HIC to a 36 ms max window. In 1999, NHTSA revised the HIC to a 15 ms max window reducing the HIC limit to 700.

In terms of HIC evaluation, there were many researches conducted. Hutchinson, et al. [19] evaluated the Head Injury Criteria Functional. Lankarani, et al. [20] designed and evaluated HIC for FAR Part 23 / 25 aircraft seat certification. Kleiven, et al. [21] evaluated finite element model validated against experiments on localized brain injuries.

In regarding with the safety measures and occupant protection with respect to interior impacts many studies have been conducted. Williams et al. [22] carried out an analysis of occupant protection in interior impacts with FMVSS 201 regulations, focusing on the design of interior features, such as instrumental panels, and front seat backs. Rychlewski, et al. [23] performed an analysis on interior design alternatives in response to FMVSS 201U – Upper interior head impact protection. In this study, a general discussion on the targeting process was carried out. Deb, et al. [24] carried out an analysis for designing the head impact safety by using a combination of lumped parameter and finite element modeling. Kanigowski et al. [25] performed an analysis on energy absorbing cabinet for aircraft bulkheads.

Many parametric studies have been carried to evaluate HIC. Venkateshappa [26], evaluated HIC and performed parametric analysis on honeycomb core properties by varying the boundary conditions, seat pitch and belt properties. Prabhu [7], evaluated HIC and performed parametric analysis by varying different parameters as seat belt, seat pitch and friction between the body and the seat on to a Ethafoam bulkhead. Gupta [27], performed a parametric study on head impact evaluation in side impact and roll over crash scenarios in automobiles and evaluation of head ejection on both laminated and tempered glass. Chakravarthy [12], performed parametric studied on the Head Injury Criteria evaluation associated with various aircraft and automotive head impact scenarios and developed a response surface curve to show the significance of impact velocity. There are not been studies that have been carried on factorial analysis of the head injury criteria evaluation. In this research, by using the statistical tools and computational methodology, the factorial analysis on the Head Injury Criteria evaluation is carried out.

1.7 Motivation

This research is motivated by the extensive existing research on automobile and aircraft crash scenarios, especially on parameters affecting the head impact responses. This research is aimed at investigating the various factors influencing Head Injury Criteria evaluation. The HIC is quite a volatile quantity, and small changes in one parameter could significantly change the resulting value. A parametric study is thus carried out to develop a database on how various parameters as in Impact conditions and Target conditions are influencing the HIC. A sensitivity analysis is to be carried out in order to observe the relative percentage contribution and dominance of various factors that are instigating the HIC. The methodology and the approach used in this research leads to provide the design parameters for target conditions. The significance of target conditions and impact conditions are known. This study is also aimed at examining the effect of internal combinations of the parameters affecting the HIC evaluation.

CHAPTER 2

OBJECTIVES AND METHODOLOGY

2.1 Objectives

The goal of this research is to investigate the parameters affecting the HIC evaluation**.** To achieve this goal, the following objectives are identified:

- To identify factors that might affect the evaluation of HIC
- To perform a parametric study on how the target conditions and impact conditions vary Head Injury Criteria (HIC)
- To arrive at the range of impact conditions (impact velocity and impact angle) using sled scale tests simulations of automobile and aircraft crash tests using the multibody dynamic software (MADYMO)
- To generate acceleration data utilizing simple bowling ball test simulations and free motion headform (FMH) simulations
- To perform sensitivity analysis with two impact materials being used (hard and soft), with three different impact velocities, impact angles, and boundary conditions with the help of Design of experiments (DOE) and Taguchi methodology
- To obtain the percentage contribution of each factor influencing the variation in HIC, being carried out in two different sets of combinations
- To investigate how the dominance of impact conditions on target conditions vary with respective to HIC and vice-versa
- To arrive at the proper design parameters for the target conditions design setting

2.2 Methodology

The significant portion of this research is carried out using finite element tool LS- Dyna to accomplish the above objectives. Multibody dynamic tools like MADYMO, Msc-ADAMS and statistical methods like DOE, Analysis of Variance (ANOVA) were also used in this research. This research is mainly divided into three parts and is generic for both automobile and aircraft crash scenarios. First is the evaluation of the range for impact conditions by using MADYMO, followed by carrying out a parametric study on the factors influencing HIC with the help of free-motion headform (FMH) simulations and design of experiments (DOE). The third and the final one is to study the relative percentage contribution of factors affecting HIC by using Analysis of Variance (ANOVA). To evaluate the range for the impact conditions, i.e., impact velocity and impact angle, MADYMO occupant models were modeled for both automobile and aircraft crash scenarios. Using the FMVSS 208 regulations, a full frontal impact was carried out in LS-Dyna. The acceleration pulse measured at the driver seat is calculated and imported into the MADYMO model. Similarly, using FAR regulations, the acceleration pulse for both FAR part 23 and FAR part 25 passengers were imported in the MADYMO aircraft occupant model. Using the simulations, the range and the factor levels which are used in further simulations are obtained.

Using the Taguchi methodology and DOE, a parametric study was carried out with a free motion headform model on two different impact materials with three different impact angles, velocities, boundary conditions, and thicknesses. From the data obtained from DOE, Analysis of variance (ANOVA) was carried out and the percentage contribution of the factors affecting HIC and their significance was obtained. The overall methodology is depicted in Figure 2.1.

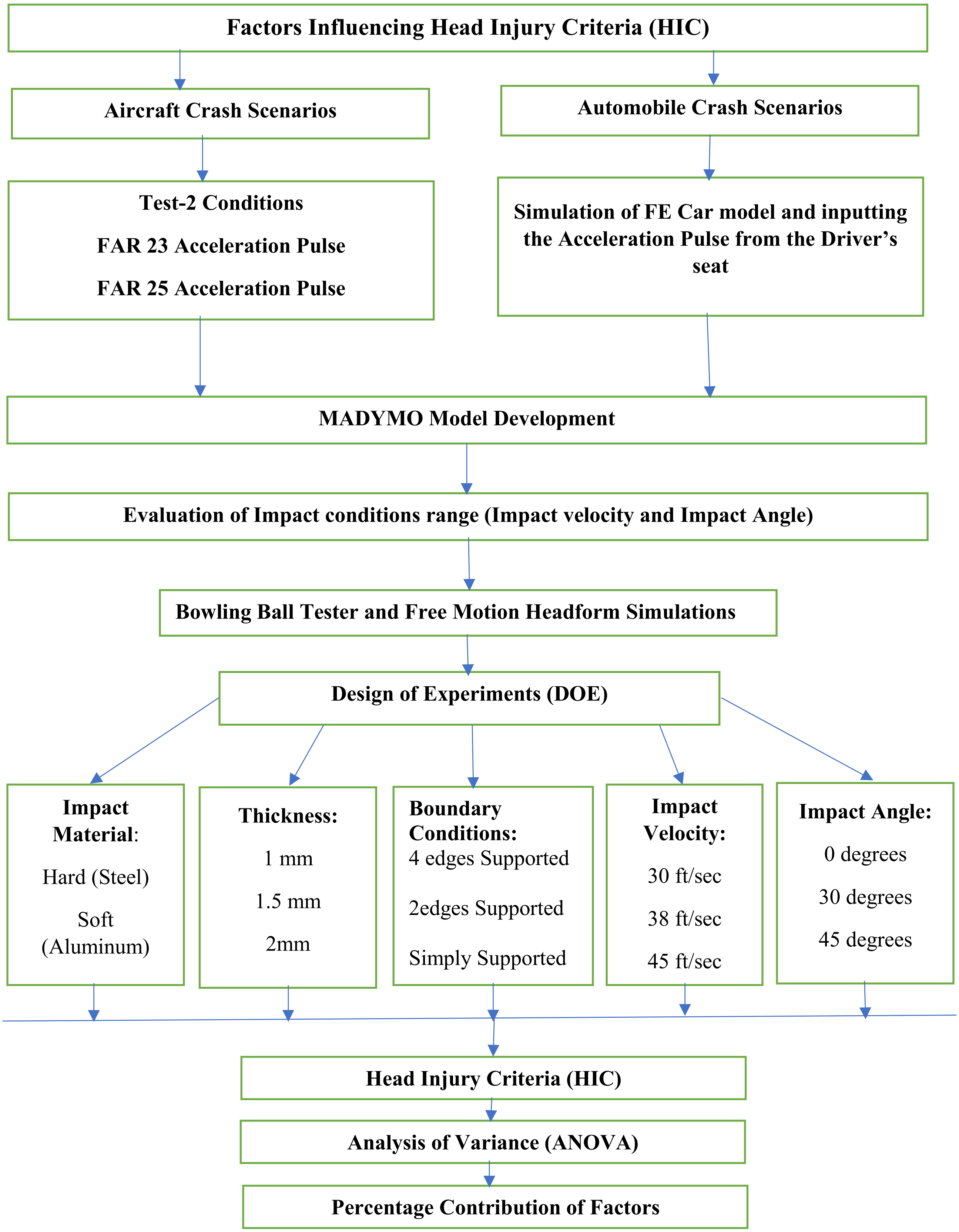


Figure 2.1: Overall Methodology

2.3 Factors Affecting HIC Evaluation

In general, the HIC value can be influenced by many factors such as the condition and severity of the crash event, the occupant protection safety devices, interior car/cabin design and energy-absorption, etc. These factors can be classified to impact conditions, target condition, and other, as described in Figure 2.2.

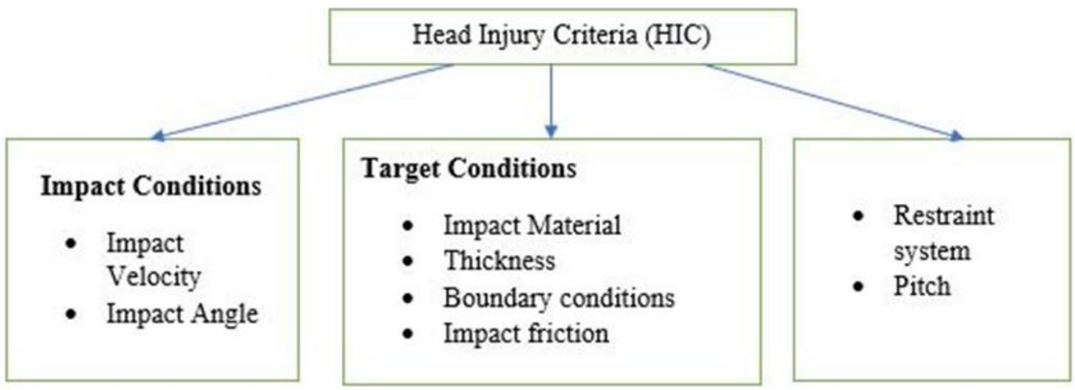


Figure 2.2: Factors Influencing the Head Injury Criteria

The factors that play a critical role in influencing the HIC evalauation can be classified into impact conditions qnd target conditions. These are described next.

Impact Conditions:

- **<u>Impact angle</u>:** The head impact angle is defined as the angle measured at the instant of impact when the normal to the line joining two target points on ATD makes an angle with the horizontal.
- **<u>Impact velocity</u>:** The head velocity is taken at the instant of head impact - the velocity at the starting of the contact time and a step before the contact end are calculated. The head velocity is taken as the average of two velocities.

Target Conditions:

- **Impact material and thickness:** The material stiffness and the type of material used has a significant influence towards the head injuries. The thickness of the material is one of the major contributing factors for fatal injury.
- **Boundary conditions:** The boundary conditions play an essential role in absorbing the impact energy, leading to lesser injuries. There are three different types of boundary conditions considered in this research. They are: four edges supported, two edges supported and simply supported. Depending upon the type of material and application the boundary conditions are varied.
- **Friction:** Friction between the head and the impact material is also one of the factors affecting the HIC. This lead to higher injuries, in terms of ruptures. Friction mostly depends on the type of material. The harder the material is, the higher the friction force would be.

Other Conditions:

- **Seat setback distance:** Seat setback distance or pitch is the distance between the seat reference point to the outer surface of the impact material. The seat reference point is the intersection point between the seat pan and the seat back.
- **Restraint system:** Restrain system is used for occupant protection. There are two types of belts which are used for this research.
    - Nylon belt – 20% elongation
    - Polyester belt- 8% elongation

  Nylon belt is used for automotive crash scenarios whereas polyester is used for aviation purposes. The elongation vs. time curve is adapted to the finite element model of the belt which acts as the respective belt properties.

Figure 2.3 illustrates the impact conditions which influence the HIC evaluation [28]. Velocity,v

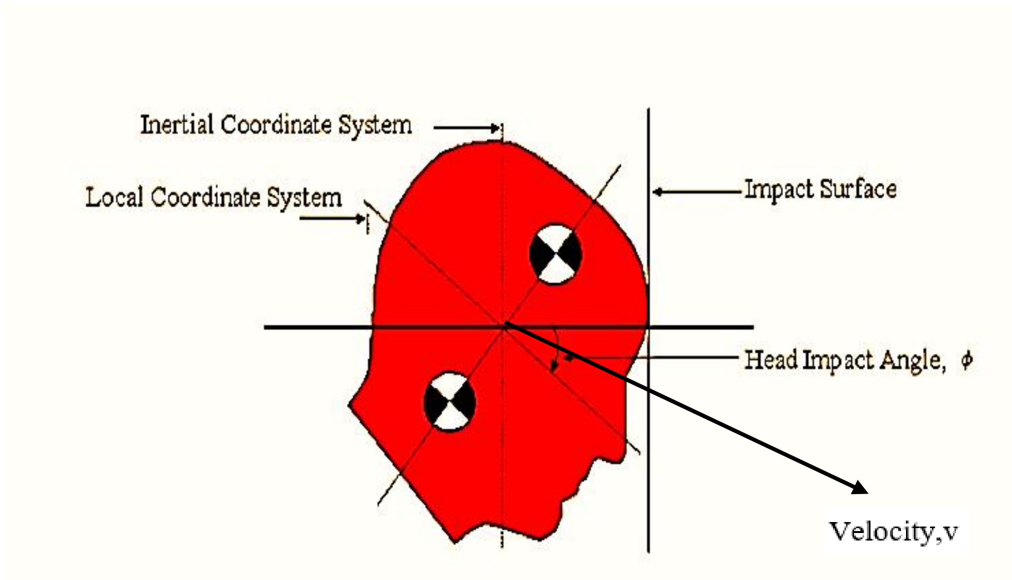


Figure 2.3: Impact Conditions [28]

2.4 Computational Tools

Computational tools are Computer Aided Engineering Tools (CAE). Finite Element Analysis (FEA) and CAE are often used in Engineering. CAE is now a fast-emerging field due to its ease towards in-depth engineering analysis. With proper variables given, the tests/ simulations performed are more like real-world scenarios. Most of the industries rely upon CAE and FEA due to the time factor and cost-effectiveness. In this research following are the computational tools which were used.

1. LS-DYNA
2. MADYMO
3. MSC. ADAMS

2.4.1 LS- DYNA

LS – DYNA software is a product of Livemore Software Technology Corporation (LSTC) [29]. This software can solve the real-world simulations/ processes and is a nonlinear finite element program. This software can be used for the following scenarios such as the investigation of large deformations, structural dynamic problems, and some explicit conditions. Several analysis can be coupled with structural dynamic problems with the aid of LS- DYNA. Some of the analysis which can be carried out are Computational fluid dynamics (CFD), fluid-structure interactions, and thermal analysis, etc. LS- PRE POST tool is used for the pre and post processing of the LS- DYNA models, and several numerical results are obtained. For Automotive crashworthiness and Occupant safety simulations LS-DYNA is extensively used. LS-PRE POST is used in this research to study the free-motion head form interactions, frontal crash scenario of a sedan type car and to observe the post-processing operations as in animation, head accelerations, injury parameters, graphical representation, and other numerical values.

2.4.2 MADYMO

MADYMO is used in this research for the evaluation of range for the impact conditions. MADYMO means MAthematical DYnamic Model [30] which is a computational software used for the analysis of vehicle collisions, the dynamic behavior of physical systems and assessing the injury parameters incurred to the occupants. MADYMO software is a combination of both multi-body dynamic and finite element techniques. MADYMO is a leading software which is used extensively in the automotive, defense and aviation industries. The modeling can be done by finite element methods or by multi-bodies or even both. The safety features as in restraining systems, airbag modeling, etc. can also be studied with the help of MADYMO. Various software such as ABAQUS, LS-DYNA, etc. can be coupled with MADYMO. The MADYMO library is so vast and contains several ranges of dummies, ranging from a pedestrian model to the human model. This helps the user to choose from the variety depending upon an individual's point of research. Apart from the animations, injury parameters such as neck, head, thoracic, femur, etc. and factors like peak acceleration related to ribs, chest, etc. can also be studied.

2.4.3 MSC-ADAMS

MSC. ADAMS [31] is used in this research to carry out the bowling ball tester simulations. ADAMS is the most widely used motion analysis software. It enables the engineers to observe, experiment and study the dynamics of moving parts, force distribution, and contact modeling which eventually improves the performance of the products. ADAMS is a pure multibody dynamic software which incorporates the real physics solving equations for kinematics, statics, quasi-static, and dynamics. Loads and forces incurred due to the motion and other operations can be easily studied in ADAMS.

2.5 Bowling Ball Tester

Bowling ball tester is one of the methods to evaluate the HIC for a head impact on the aircraft interior structures. This procedure was chosen by a technical paper presented by the Federal Aviation Administration Civil Aeromedical Institute (FAA CAMI) [32]. The bowling ball drop test is conducted by impacting the ball on to various padding materials, and the results were compared with the results obtained from the sled tests. This bowling ball tester is used mainly to observe the requirements for the head impact protection for seat installations located aft or cabin interiors.

2.6 Free-Motion Headform Tester (FMH)

A Hybrid-III free-motion headform (FMH) is generally used for the upper interior head impact simulations. These simulations are carried according to FMVSS 201U regulations [9].

FMH is used because of its ease. It can be fired at various targets within the vehicle interiors at an absolute velocity. The general velocity at which the FMH simulations are carried out is at 24Kmph (21.8 ft/sec). The free-motion headform tests are carried out with the help of LSTC's finite element model of FMH. MAT_VISCOELASTIC is used for the headform flesh at initial but was replaced with MAT_ODGEN_RUBBER. The other components were modeled using MAT_RIGID. MAT_NULL is used for the contact layer. The headform was rotated at an angle of 28.5 degrees with the impact surface so that the skull cap comes in contact with the impact surface. An accelerometer is located at the CG of the headform. The node corresponding to the location is represented as NID 1. NID 1 is the node which is used to monitor acceleration date and HIC. Figure 2.4 show the physical dummy head model [33] and Figure 2.5 show the FMH model and Accelerometer [9].

Figure 2.4: Free-Motion Headform Physical Dummy Head [33]

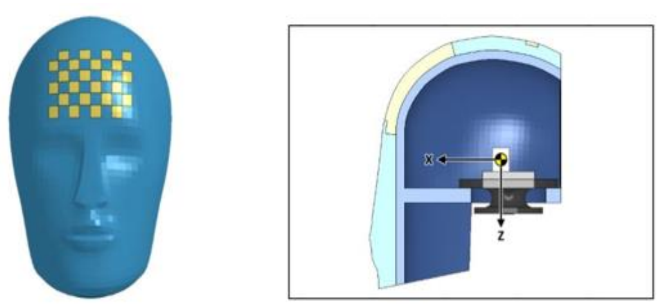


Figure 2.5: Free-Motion Headform (FMH) and Accelerometer [9]

2.7 Taguchi Methodology and Design of Experiments (DOE)

Dr. Genichi Taguchi was the founder and the pioneer of Taguchi methodology which helps to improve engineering productivity [34]. There are some factors termed as noise/variation factors that are to be considered as these play a vital role in predicting the optimal design productivity/ process. Robust design mainly concentrates on improving the design parameters with cost-effectiveness and an increase in quality. The Taguchi methodology can be applied to crashworthiness to analyze the effect of factors influencing injury parameters and to predict the optimal design parameters depending on the type of crash scenario.

Design of Experiments (DOE) or experimental design is a method which determines the relationship between factors affecting a process and the output of that process [34]. To understand the design of experiments, one should know the following factors on which the process is dependent. The following are the factors below:

- *Controllable Input Factors*: These parameters are the one that can be altered.
- *Uncontrollable Input Factors*: These parameters are the ones that cannot be altered.
- *Responses or Outputs*: These are the process outcomes.

The entire layout of the DOE is shown in Figure 2.6 [34].

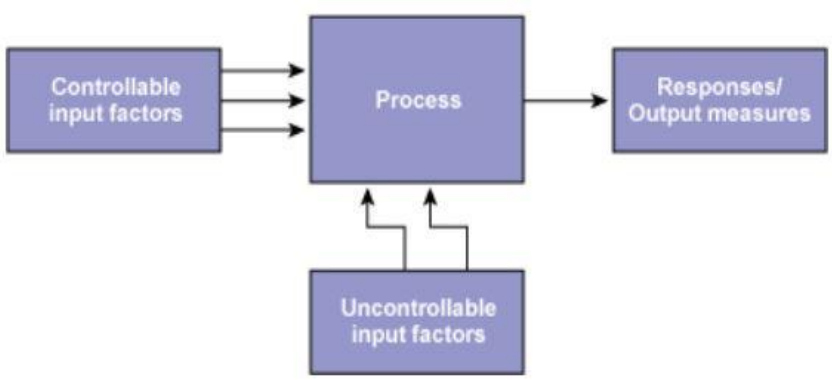


Figure 2.6: Design of Experiments Methodology [34]

As the design of experiments is carried out with more than two variables, the interaction takes place in between them. This is observed to see the influence of two variables on the other. To enhance the process performance by determining the effect of variables on output and leading to obtaining optimum conditions as per design parameters, input parameters and influence of the interaction, DOE is used. There are specific steps involved in the DOE and are as follows:

- Selection of input factors and their levels
- Selection of response variable
- Choosing the type of experimental design
- Carrying out the experiments
- Reviewing the analysis
- Conclusions

The response variable [35] or the output variable should be volatile enough to the variations in the input variables. The output variable is observed throughout the experiments carried out in the range of the input variables. In this research, Head Injury Criteria are considered as the output variable as it is volatile and susceptible to many individual factors. The individual factors within the ranges are taken into consideration, and their interactions between the variables and their influence on Head Injury Criteria are observed in this research.

There are three essential steps which are carried out in the robust design methodology, and they are as follows:

- Planning the experiment
- Carrying out the experiment
- Analyzing and verifying the results

The first step is the critical step, and it involves several other steps and are mentioned below:

- Identifying the primary function of the process
- Identifying its failure modes and noise factors
- Identifying the quality characteristics
- Identifying the control factors and their levels
- Identifying the objective function to be optimized.

The noise and the control factors are two important parameters on the objective function. The signal to noise ratio is used to measure the effect/ quality of the output function. Design parameters can be studied with the help of selection of orthogonal arrays. As we are using the methodology for injury parameters and observe what factors are contributing more towards the head injury, the following S/N ratio is used. The higher the S/N ratio (η) is, the higher is the Head Injury Criteria [35]\

$$\eta = -10 \log \left(\frac{1}{n} \sum \frac{1}{Y_i^2} \right) \quad (2.1)$$

From the S/N values, the optimal conditions in terms with Target conditions are obtained, i.e., the higher S/N values show that the head injury is higher and indicating, that the setting used for that scenario is not optimal or yielding higher head injuries.

Selection of the control factors and their levels/range have much significance on the phenomenon. Browne, et al. [36] stated that by using the Taguchi methodology and its principles, any process can be examined, and information can be obtained on the main factors involved. To study the interactions, an orthogonal array is constructed with the help of some factors involved and their levels. The researchers tabulated 18 orthogonal arrays. An orthogonal array is generally a matric which has rows and columns in it. In an orthogonal array, the number of rows indicates the number of experiments carried out and the number of columns represents the maximum number of factors.

2.8 Analysis of Variance (ANOVA)

Analysis of variance gives a quantitative measure for the relative magnitudes of different factor effects. ANOVA [37] is also used for estimating the error variance for the factor effects and the variation of the prediction error. In this research, the ANOVA is carried out to obtain the relative percentage contribution of the effect of each factor on influencing the variation on the Head Injury Criteria and to observe the sensitivity of the objective function; i.e., HIC.

CHAPTER 3

EVALUATION OF THE RANGE OF IMPACT CONDITIONS

To perform the Design of Experiments (DOE), enough data regarding the control factors and their levels should be collected. Impact conditions also being the control factors, evaluation of their range is much needed. To evaluate the range of impact conditions, MADYMO modeling and simulations are carried out for both aircraft and automotive crash scenarios. The head paths are traced in both the scenarios and the range of impact conditions are obtained.

3.1 Head Paths in Crash Scenarios

In aircraft and automotive crash scenarios, the human body behaves like a multi-body dynamic. The human body experiences high acceleration forces during the crash scenarios. Due to which, various limbs and head acts as open links of the mechanism. Out of all the links of the human body, the most sensitive part is head. Even though if there are any injuries to the limbs, they can be replaced, unlike head. Therefore, the head paths are being traced in both aircraft crash scenarios and automotive so that the information obtained can be used for further research. It also acts as a reference guide for aircraft-cabin interior and automotive interior certification. The setup for full-scale sled tests in both automotive and aircraft scenarios are modeled in MADYMO. A Hybrid-III 50th percentile dummy is used in both the simulations. The bulkhead and steering representation in both aircraft and automotive modeling are removed, as the focus is to get a complete trace of the head paths. The head trace obtained is used to calculate the range of the impact conditions. The peak velocity is being calculated by using special functions in MAD-post, and the impact angle is calculated by plotting the velocities in Z and X directions.

3.2 Aircraft Occupant Seat Restraint System Modeling

The modeling of the aircraft occupant is developed in MADYMO by using planes. The upper seat and the lower seat is designed as a plane with a dimension of 23 inches. The upper seat is inclined at 14 degrees. A two-point seat belt was used with polyester properties (elongation – 8%). Hybrid-III dummy is imported and placed in the right position. The bulkhead is not modeled as the focus is to obtain the head path. The acceleration pulse for Condition-2 FAR Part 23 passenger and FAR Part 25 passenger are given to the seat as a input, and the simulations are carried out. The aircraft occupant seat restraint model is shown in Figure 3.1.

Figure 3.1: Aircraft Occupant Seat Restraint Modeling

3.3. Automotive Occupant Seat Restraint System Modeling

The automotive occupant modeling is also built in MADYMO. The Hybrid-III 50th percentile dummy is used and positioned in the vehicle. As in the aircraft simulations, the steering representation in automotive scenarios is removed as well, to trace the head path. A full-frontal rigid barrier impact collision is performed in LS-Dyna by using an FE model car, and the acceleration pulse is obatined. This pulse is adopted in MADYMO as an input to carry out the multibody dynamic simulation. Unlike the aircraft crash scenarios, a three-point belt with nylon properties with 20% elongation is used in here. Figure 3.2 shows the occupant modeling in an automotive crash scenario.

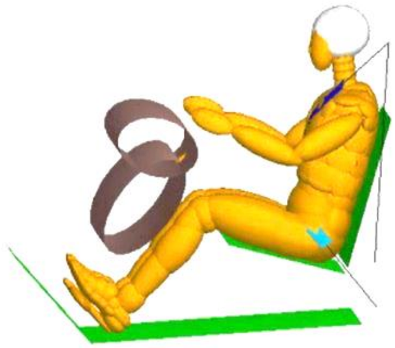
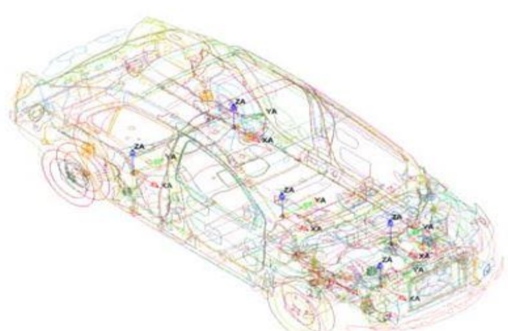


Figure 3.2: Automotive Occupant Seat Restraint Modeling

3.3.1 Frontal Impact of a Vehicle using LS- DYNA

In this research, A full-frontal impact of a typical sedan, 2010 Toyota Yaris FE model is simulated. The National Crash Analysis Center (NCAC) [38] with the help of reverse engineering at The George Washington University (GWU) developed this sedan. This FE model was validated against the National Highway Traffic Safety Administration (NHTSA) [38]. This FE sedan model consists of 917 parts, 1,480, 422 nodes, 1,250,242 shell elements, and four accelerometers [38] as shown in Figure 3.3.



Location	Node ID
Left Seat	319812
Right Seat	319820
Engine Top	319828
Engine Bottom	319836

Figure 3.3: Accelerometer Locations [38]

LS- Dyna and LS-PRE POST are used for the Toyota Yaris rigid barrier frontal impact simulation. The frontal impact test simulation is carried out at 35 mph, which is according to NCAP requirements. The simulation is carried out for 15 milliseconds. Figure 3.4 shows the FE model of the Toyota Yaris setup for frontal impact. Figure 3.5 shows the postprocessing images of the FE car model after the crash.

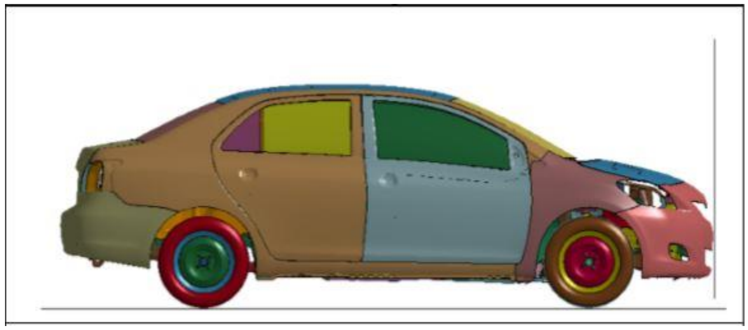


Figure 3.4: Toyota Yaris FE Model Setup [38]

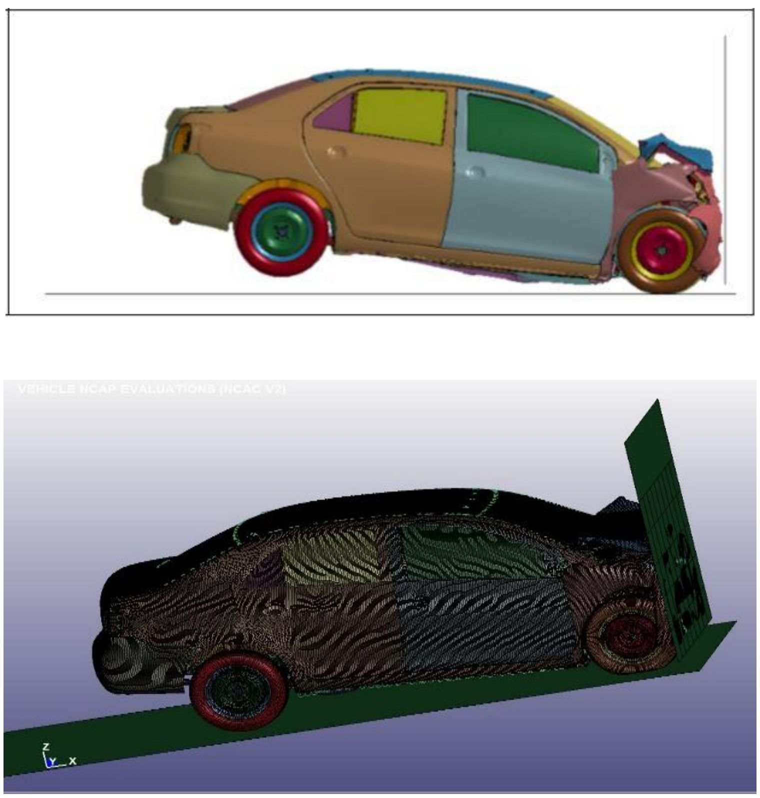


Figure 3.5: Post Process Images of FE Car Model after Crash Simulation

3.3.2 Acceleration Pulse from the Car Driver Seat

MADYMO simulations need an acceleration input to carry out the simulations. A typical FE sedan car simulation is carried out in LS-Dyna. The acceleration pulse is obtained at the driver seat which is imported as an input to the MADYMO program. The acceleration pulse obtained is shown in Figure 3.6.

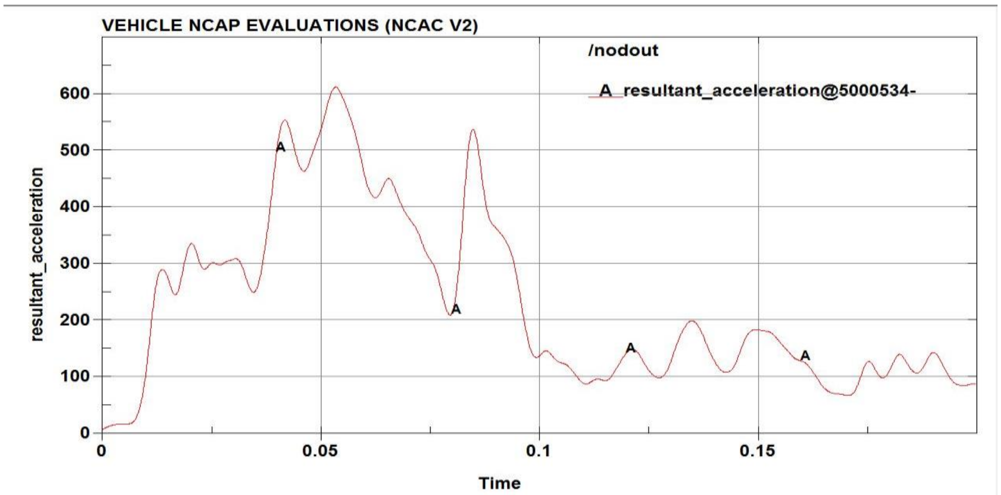


Figure 3.6: Acceleration Pulse at the Driver Seat

3.4 Headpath Simulations for Aircraft Scenarios

The acceleration pulse for both FAR 23 and FAR 25 passenger is taken and given as input to the seats. The MADYMO simulations are then carried out. Figure 3.7 shows the animation sequence of the head movement throughout the path. The MADYMO design is as per the experimental setup of full-scale sled tests. The experiments are carried out with a two-point seat belt with polyester properties given to it. The bulkhead is removed in order to trace the whole head path. The calculations for obtaining the impact angle range and impact velocity are carried out. The displacement of the head in both the Z-direction (vertical) and X-direction (longitudinal) are plotted, which in turn gives the path of the head. Figure 3.8 shows the head trace for FAR Part 23 Passenger and Figure 3.9 shows the head trace for the FAR Part 25 passenger. Sample Velocity vectors at different instances are shown by vectors $v_1, v_{2,}, v_3$, v_N. For the headpath, the initital head position (0,0) is to measure motion with respect to.

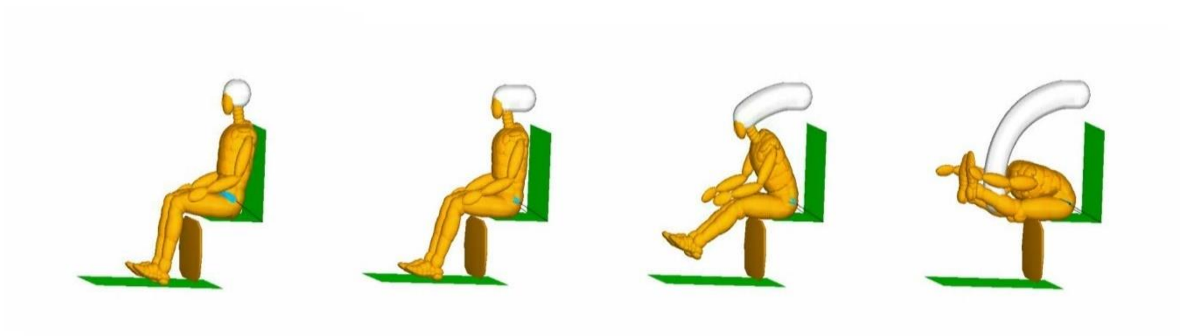


Figure 3.7: Headpath Animation Sequence in Aircraft Scenarios

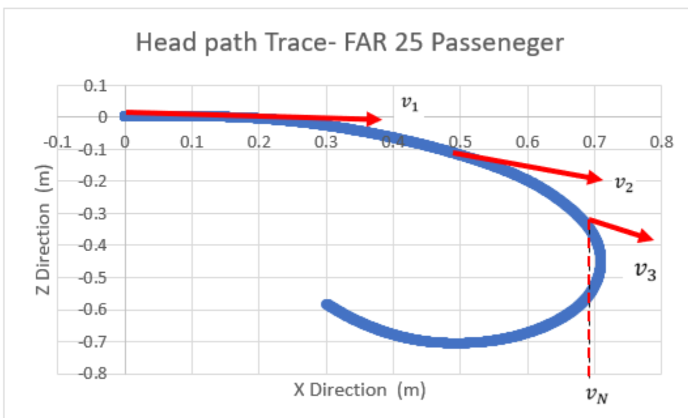


Figure 3.8: Headpath Trace for FAR Part 23 Passenger

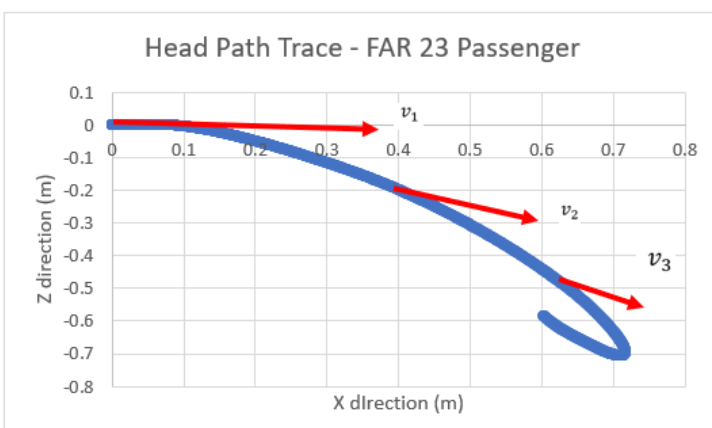


Figure 3.9: Headpath Trace for FAR Part 25 Passenger

3.5 Headpath Simulations for Automobile Scenarios

The acceleration pulse obtained from the frontal crash analysis is used as the input for the automotive MADYMO model and the simulations are carried. The acceleration pulse is imported into MADYMO program. The steering representation is removed to observe the head path trace. As mentioned, a three-point belt is used for the restraint system with nylon properties. Figure 3.10 shows the automotive simulation animation in MADYMO. The impact velocity and impact angles are calculated by using EXCEL. The displacement of the head in both Z-direction (vertical) and X-direction (longitudinal) are plotted in EXCEL graph sheet which in turn gives the path of the head. Figure 3.11 shows the head trace for the automotive crash scenario, with sample velocity vectors $v_1, v_{2,}, v_3$, v_N.

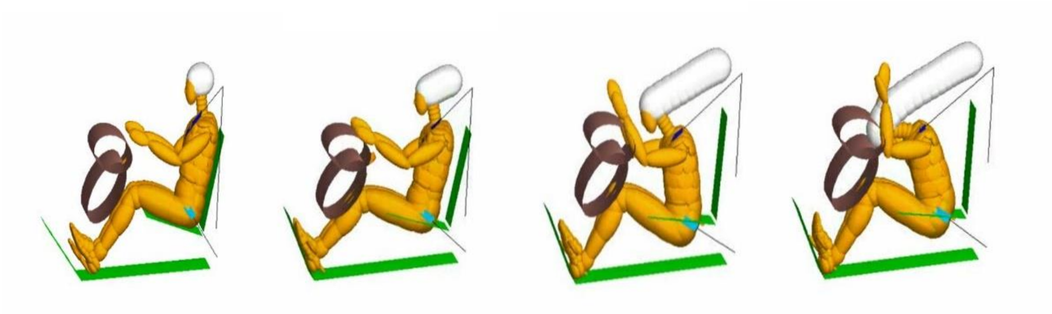


Figure 3.10: Automotive Simulation Animation

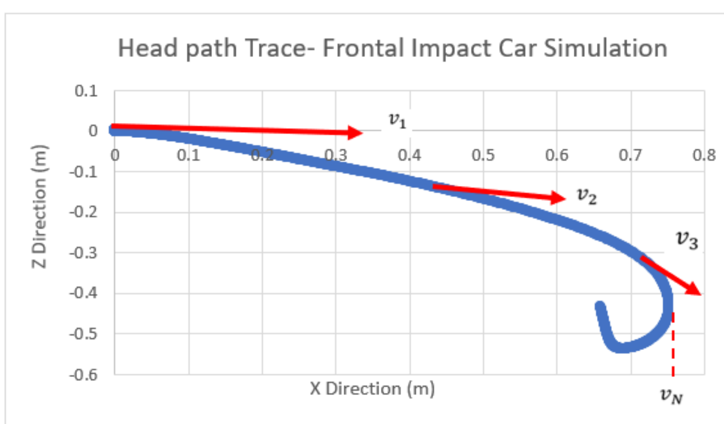


Figure 3.11: Head Trace for an Automotive Crash Scenario

3.6 Impact Angle and Impact Velocity Calculations

To evaluate the range of the impact angle in all the crash scenarios, an obstacle is imagined at each regular interval distance. The head angles are then calculated by plotting the velocities in Z-direction (vertical) Vs. X-direction (longitudinal). The head impact velocity is obtained directly from the MADYMO program where the peak velocity is recorded. The following formula is used for calculation of the impact angles,

$$\theta = Tan^{-1}\,(\frac{V_z}{V_x}) \tag{3.1}$$

3.6.1 Impact Conditions for FAR Part 23 Passenger

The impact conditions for the FAR 23 passenger are obtained after the simulations being run in MADYMO program. The peak velocity obtained for the FAR part 23 passenger is 41.2 ft/sec (13.2 m/s). By using the velocity vectors $v_1, v_{2,}\ and\ v_3$ shown in the headpath trace Figure 3.8, the head impact angles are calculated. It is observed that the range of the head angles are between 0 - 45.3 degree. Note that beyond 45 degrees, the head impact is only glancing and is not severe. Figure 3.12 shows the head impact velocity plot. The impact angles at regular intervals for FAR Part 23 passenger are listed in Table 3.1.

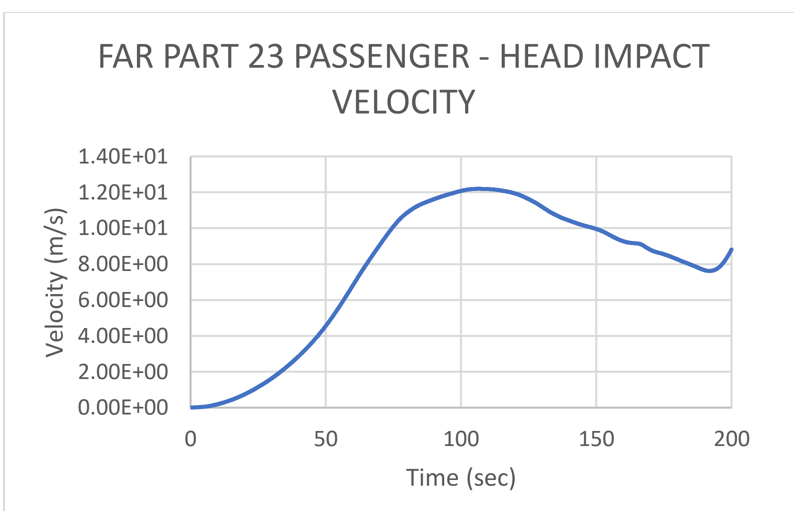


Figure 3.12: Head Impact Velocity for FAR Part 23 Passenger

TABLE 3.1

IMPACT ANGLES FOR FAR PART 23 PASSENGER

Distance from head starting point (m)	Angle (degree)
0.13	0
0.24	0.2
0.35	1.9
0.45	12.6
0.55	30.9
0.71	45.3

3.6.2 Impact Conditions for FAR Part 25 Passenger

The impact conditions for the FAR 23 passenger are obtained after the simulations being run in MADYMO program.The peak velocity obtained for the FAR 25 passenger is 36.68 ft/sec (11.18 m/s). By using the velocity vectors $v_1, v_{2,}\ and\ v_3$ from the Figure 3.9, the head angles are calculated. The impact angle range obtained is in between 0.5 – 43.60 degree. Figure 3.13 shows the head impact velocity plot. The impact angles at regular intervals for FAR Part 25 passenger are shown below in Table 3.2.

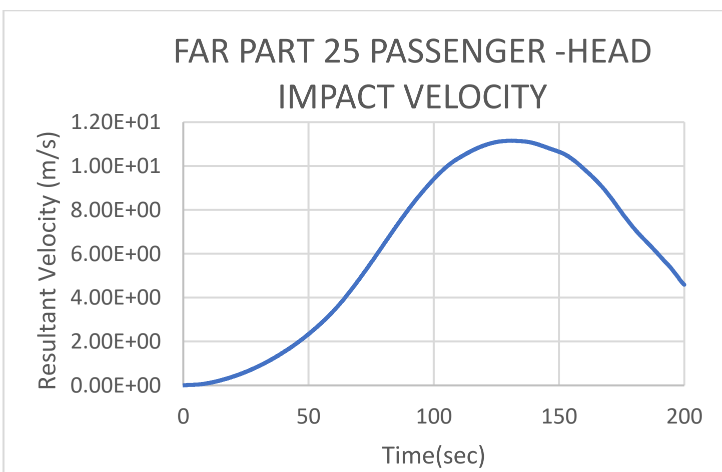


Figure 3.13: Head Impact Velcoity for FAR Part 25 Passenger

TABLE 3.2

IMPACT ANGLES FOR FAR PART 25 PASSENGER

Distance from head starting point (m)	Angle (degree)
0.14	0.5
0.26	8.5
0.40	20.1
0.52	29.8
0.70	43.6

3.6.3 Impact Conditions for Frontal Automobile Crash Scenario

The impact conditions for the full frontal impact of automobiles as per regulations are obtained after the simulation being carried out in MADYMO program. The peak velocity obtained for the driver seat is 30.03 ft/sec (9.15 m/s). By using the velocity vectors $v_1, v_{2,}$ and v_3 from the Figure 3.11, the head angles are calculated. The range obtained is in between 8.53 – 33 degree. Figure 3.14 shows the head impact velocity plot. The impact angles for automobile crash scenarios are shown in Table 3.3.

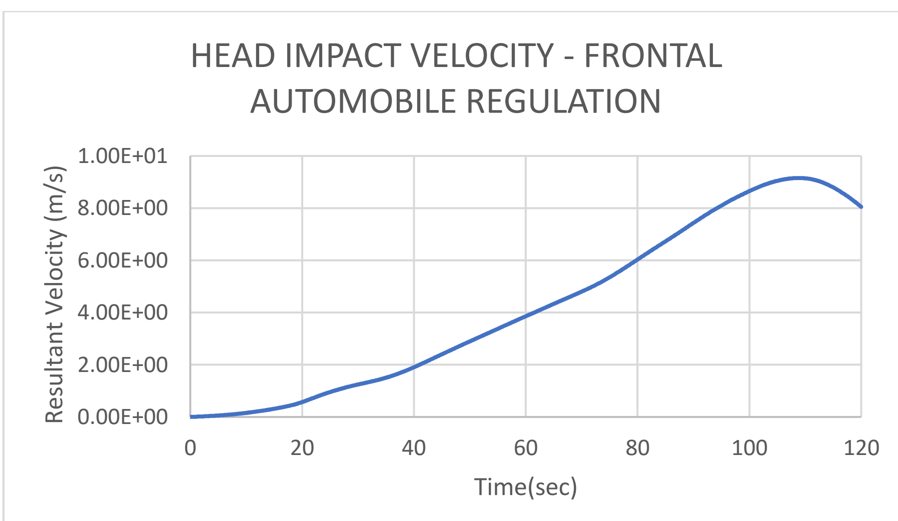


Figure 3.14: Head Impact Velocity for Automobile Scenarios

TABLE 3.3

IMPACT ANGLES FOR FRONTAL AUTOMOBILE CRASH SCENARIO

Distance from head starting point (m)	**Angle (degree)**
0.12	8.5
0.26	14.0
0.39	16.7
0.52	24.8
0.67	30.6
0.74	33.6

3.7 Range of Impact Conditions Selected

The impact conditions for both aircraft and automobile conditions are obtained from the MADYMO simulations. It is observed that the peak impact velocities obtained for both aircraft (FAR Part 23 passenger and FAR Part 25 passenger) and automobile crash are in between the range of 30 ft/sec (9.1 m/s) and 45 ft/sec (13.7 m/s). The impact angles obtained for both aircraft (FAR Part 23 and FAR Part 25) and automobile crash scenario are in between the range of 0 degrees to 45 degrees. As mentioned earlier, to carry out the design of experiments, the input data range needs to be specified and impact conditions being one of the input factors, the range for the impact conditions are classified. The impact conditions range that is considered for further research is tabulated in Table 3.4, which includes the minimal, maximal and intermediate values for both angle and velocity.

TABLE 3.4: IMPACT CONDITIONS RANGE

Impact Angle (degree)	**Impact velocity (m/s)**
0	9.1
30	11.4
45	13.7

CHAPTER 4
HEAD IMPACT SIMULATIONS WITH BOWLING BALL TESTER AND FREE MOTION HEAD FORM TESTER

4.1 Bowling Ball Tester

There are several tests which were developed by the Federal Aviation Administration (FAA) [32] to test the head injury potentials. The tests are as follows:

- Bowling Ball Tester
- Free motion headform tester
- MGA Head/Neck impactor
- Pendulum Rig tester

In this research, a comparison between the bowling ball tester and the free-motion head form is carried. The bowling ball tester is carried out in multibody dynamics software MSC -ADAMS and the free-motion headform tester is carried in finite element software LS- Dyna.

Bowling ball tester is one of the methods to evaluate the HIC for a head impact on the aircraft interior structures. This procedure was chosen by a technical paper presented by the Federal Aviation Administration Civil Aeromedical Institute (FAA CAMI). The bowling ball drop test is conducted by impacting the ball on to various padding materials, and the results were compared with the results obtained from the sled tests. This bowling ball tester is used mainly to observe the requirements for the head impact protection for seat installations located aft or cabin interiors. The experimental set up used for the bowling ball tester is shown in Figure 4.1 [32]. The bowling ball used for the test and its specifications are shown in Figure 4.2 [32].

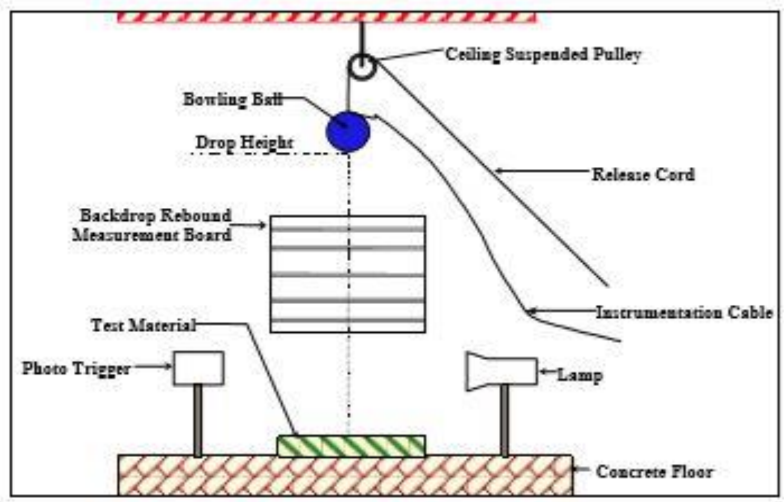


Figure 4.1: Experimental Setup for Bowling Ball Tester [32]

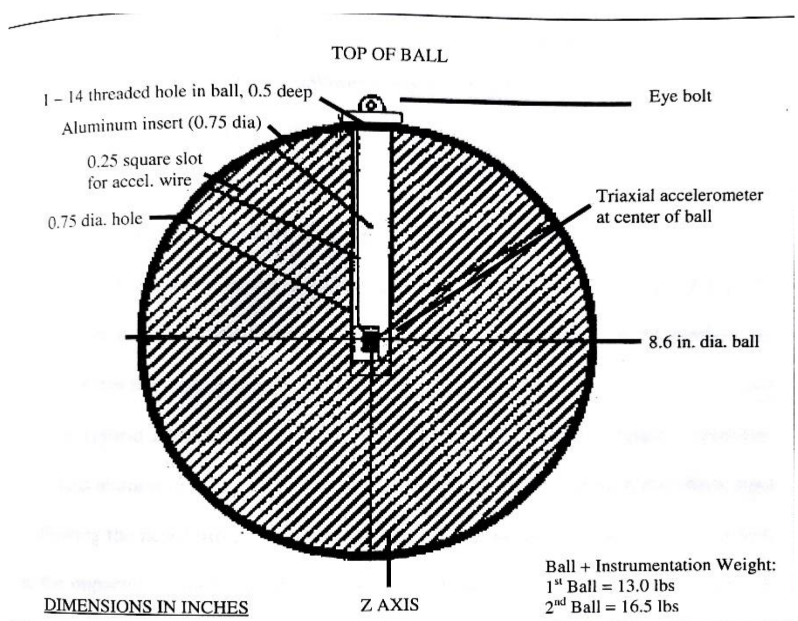


Figure 4.2: Instrumental Bowling Ball [32]

The ball is raised to the desired height through a pulley as shown in the experimental setup and dropped off freely on to the test material. An infrared photosensor is used in the path of the falling ball which generates the electrical signal to trigger the data acquisition system before the impact. By using high-speed video data collected, the rebound kinetic energy and the height is calculated.

By using the same dimensions, the experimental set up for the bowling ball tester on to the bulkhead is developed in ADAMS -View. The experimental setup for the bowling ball tester in MSC. ADAMS - View is shown in Figure 4.3. The main drawback in using MSC.ADAMS view version is that the deflection of the bodies cannot be observed. ADAMS-flex version is the software in which the multibody dynamic deflection can be observed. To avoid the complexities and to carry out the validations between the free-motion headform tester and the bowling ball tester, MSC. ADAMS- view version is used. The testing conditions used in both the software are similar.

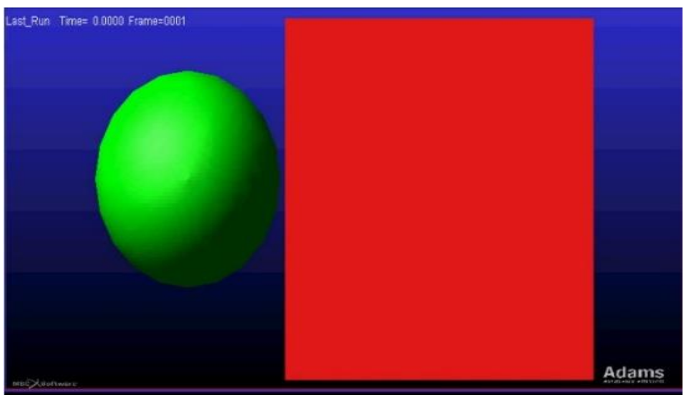


Figure 4.3: Experimental Setup for the Bowling Ball Tester

The bowling ball specifications are defined in the MSC. ADAMS are mentioned below:

- Mass of the ball = 4.5 kg
- Inertia = 0.404 kg.m^2
- Radius = 0.15 m

As shown in Figure 4.3, a contact force should be defined for the impact to take place between the ball and the bulkhead. A fixed joint is assigned to the bulkhead and two types of materials properties, i.e., hard (Steel) and soft (Aluminum) are assigned to it. The contact stiffness between the bulkhead and the Steel ball is calculated by using the following [39],

$$K = \frac{4}{3\pi(h_i+h_j)} \left(\frac{R_i R_j}{R_i+R_j}\right) \quad (4.1)$$

Where *K* is the contact stiffness, R_i and R_j are the radii of the bodies. This formula is applicable when two bodies are spherical. When the impacting surface is flat, such as bulkheads or other automobile interiors the following is used instead [39],

$$K = \frac{4\sqrt{R_H}}{3\pi(h_H+h_S)} \quad (4.2)$$

where *S* represents the impact surface, *H* denotes the head, R_H denotes the radius of the head, and h_H and h_S are the material constants. The material constants are calculated as [39]:

$$h_H = \frac{1-v_H^2}{\pi E_H} \qquad h_S = \frac{1-v_S^2}{\pi E_S} \quad (4.3)$$

where v the Poisson's ratio, and E is the young's modulus of the impacting bodies.

A variation of Hertzian contact model with dissipative damping is used to model the contact force variation [39]

$$f = K\,\delta^n + \mu\,\delta^n \dot{\delta} \quad (4.4)$$

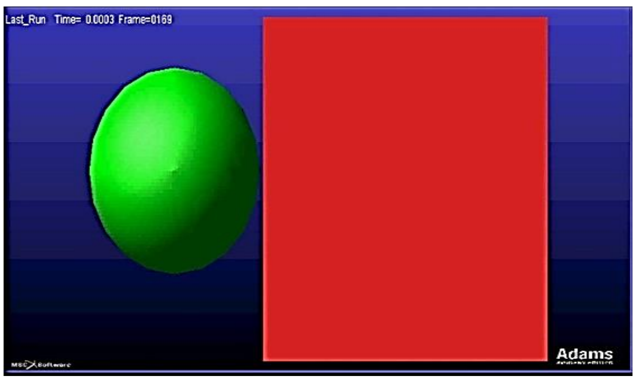
Other than contact stiffness, there are three other parameters: force exponent, damping and penetration depth which are also defined to assign the contact force. The contact stiffness is thus calculated for Steel and Aluminum are tabulated in Table 4.1.

TABLE 4.1

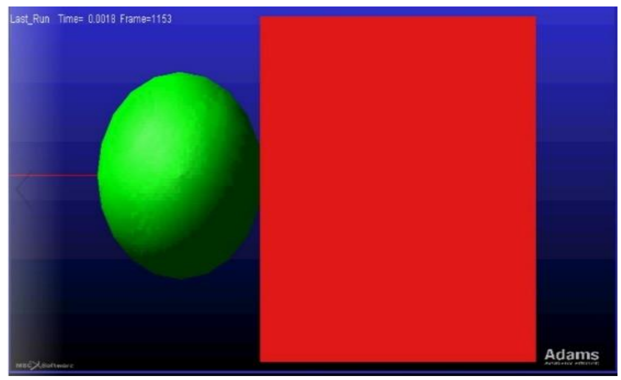
INPUT VARIABLES FOR THE CONTACT DEFINITION

Material	**Stiffness- *K*** $(N/m)^{2.5}$	**Force Exponent** $(n)^{2.5}$	**Damping** (N.s/$m^{3.5}$) (μ)	**Penetration Depth (m)** (δ)
Steel	5.79 E+10	2.5	1000	1.0E-04
Aluminum	3.07 E +10	2.5	1000	1.0E-04

The simulations for the bowling ball tester is carried in ADAMS- View with all the data inputted. The simulations are carried out with three sets of impact velocities (ranging 15ft/sec, 30ft/sec and 45ft/sec.) and impact angles ranging (0, 30, and 45 degree). Figure 4.4 shows the sequence of the simulation motion of the bowling ball impacting on to the bulkhead. As bulkhead being rigid, there is no local deformation observed. The rebound of the ball is observed, and the peak acceleration at the center of the ball is calculated in G.



t = 0 secs



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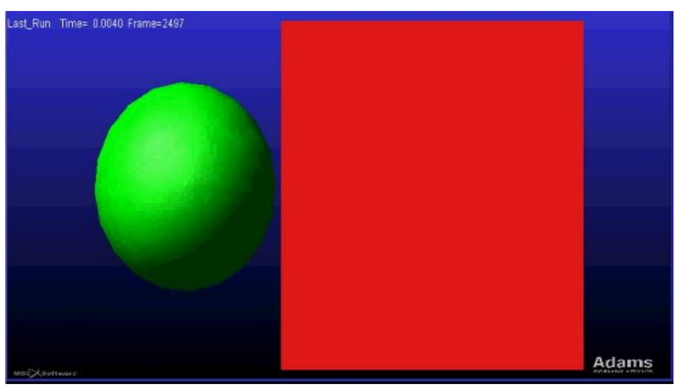


t=0.004 secs

Figure 4.4: Bowling Ball Impact Simulation

The contact force plays a key role in the impact response. As the material is rigid, the thickness of the material does not have much effect because of its constrained degree of freedom.

4.2 Free-Motion Headform Tester

The free-motion headform impact tester was designed for the simulation of head impacts on the automotive interiors and bulkheads. The main purpose of the free-motion head form tester is to act as a supplement for full-scale sled test impacts on to rigid surfaces. As discussed earlier, a Hybrid-III headform was developed and is used to assess the impact behavior of an occupant in a vehicle collision. The free-motion head form weighs 4.58 kg which is near to the value of the bowling ball weight. The test conditions used for the bowling ball tester are being used in the free motion headform test as well. As the FMH tests are being simulated in LS- DYNA. It is an FE software, and the contact forces are calculated by default. Figure 4.5 shows the free-motion headform impact on rigid bulkhead simulations.

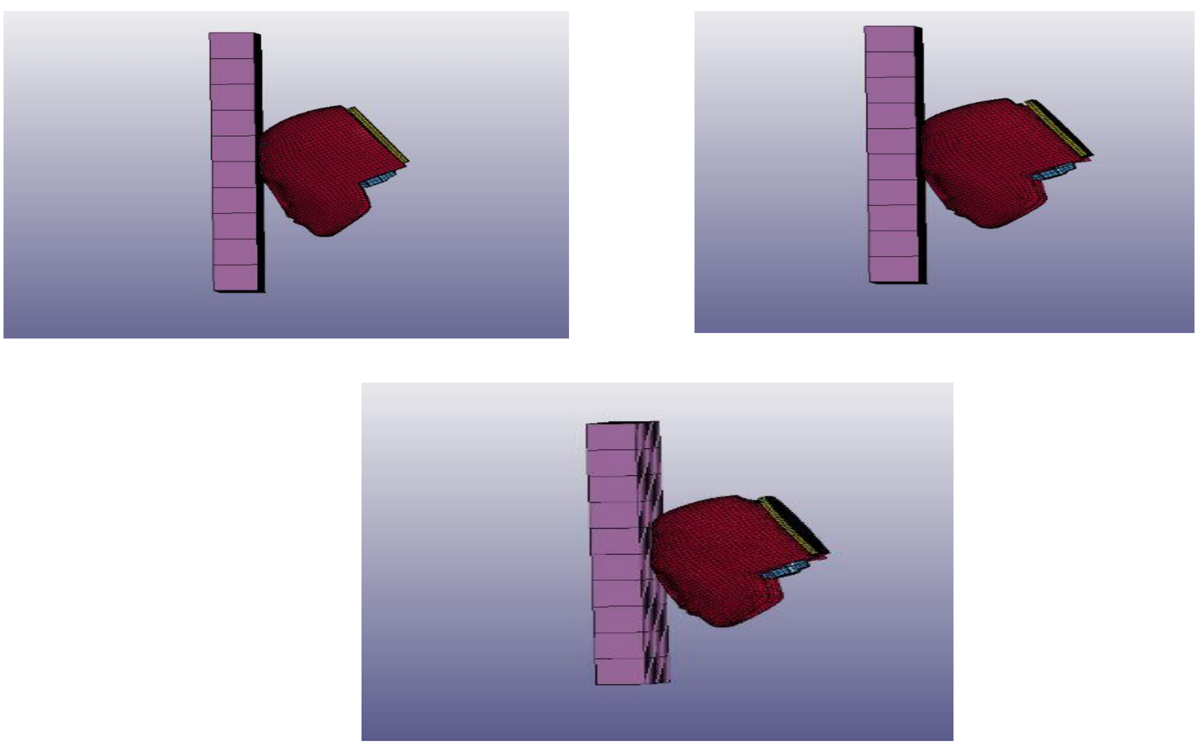


Figure 4.5: Free Motion Headfrom Impact on a Rigid Surface

The bulkhead is modeled with solid elements with dimensions being 500mmx500mmx50mm, with degrees of freedom constrained in all the directions. When the impact took place, there is a deformation and a rebound in the free-motion headform. The resultant acceleration values are calculated which are obtained directly from the LS-Dyna.

4.3 Evaluation and Comparison of Bowling Ball Tester and Free-Motion Headform Tester

The two tests are performed in two different software which deals with multibody dynamics and finite element modeling. The resultant acceleration values were measured for both the bowling ball tester and free-motion headform tester. The tests were carried out with three different sets of impact conditions i.e., impact velocity ranging from 4.5 m/s (15 ft/sec) – 13.7 m/s (45 ft/sec) and impact angles ranging from 0 degree – 45 degrees and two different sets of impact material i.e., Steel (hard) and Aluminum (soft). The whole sets of data for both the tests are tabulated in the below tables. Tables 4.2 and 4.3 show the resultant acceleration results for the bowling ball tester with impact materials being Steel and Aluminum respectively.

TABLE 4.2

BOWLING BALL TESTER IMPACT DATA ON STEEL BULKHEAD

Angle (Degree)	**Velocity 4.5 m/s (15 ft/sec)**	**Velocity 9.1 m/s (30 ft/sec)**	**Velocity 13.7 m/s (45 ft/sec)**
	Acceleration (G)	***Acceleration (G)***	***Acceleration (G)***
0	834	2,359	4,308
30	668	1,900	3,477
45	492	1,403	2,572

TABLE 4.3

BOWLING BALL TESTER IMPACT DATA ON ALUMINUM BULKHEAD

Angle (Degree)	**Velocity 4.5 m/s (15 ft/sec)**	**Velocity 9.1 m/s (30 ft/sec)**	**Velocity 13.7 m/s (45 ft/sec)**
	Acceleration (G)	***Acceleration (G)***	***Acceleration (G)***
0	669	1,911	3,507
30	535	1,536	2,826
45	392	1,131	2,085

Tables 4.4 and 4.5 show the resultant accelerations for free-motion headform tester with impact material being Steel (hard) and Aluminum (soft) respectively. The impact material is modeled rigid; i.e., constrained in all the directions. The tests were carried out with three different sets of impact conditions as conducted for bowling ball tester.

TABLE 4.4

FREE-MOTION HEADFORM TESTER IMPACTS DATA ON RIGID STEEL BULKHEAD

Angle (Degree)	**Velocity 4.5 m/s (15 ft/sec)**	**Velocity 9.1 m/s (30 ft/sec)**	**Velocity 13.7 m/s (45 ft/sec)**
	Acceleration (G)	***Acceleration (G)***	***Acceleration (G)***
0	589	2,079	4,093
30	434	1,545	3,210
45	307	1,103	2,350

TABLE 4.5

FREE-MOTION HEADFORM TESTER IMPACTS DATA ON A RIGID ALUMINUM BULKHEAD

Angle (Degree)	**Velocity 4.5 m/s (15 ft/sec)**	**Velocity 9.1 m/s (30 ft/sec)**	**Velocity 13.7 m/s (45 ft/sec)**
	Acceleration (G)	***Acceleration (G)***	***Acceleration (G)***
0	483	1,706	3,235
30	379	1,350	2,620
45	275	969	2,026

In this research, an attempt has been made to compare the test results obtained between two different tests, performed in two different software whose primary purpose is to evaluate the head injuries. These tests are generic to the occupant collisions in both aircraft and automobile. The graphs are plotted for the results obtained from the simulations. Figures 4.6 and 4.7 represent the plots of bowling ball tester simulation and free-motion headform simulations of Steel and Aluminum respectively. The blue line indicates the acceleration data of the bowling ball tester simulations obtained when Steel/Aluminum ball being impacted on to rigid bulkhead. As mentioned, these tests were performed in multibody dynamic software MSC. ADAMS-View version. The simulations are carried out at three different velocities and three different angles. The red line indicates the acceleration data of the free-motion headform tester simulations where head being impacted on Steel and Aluminum rigid bulkheads. The simulations are carried out in finite element (FE) software. The simulations are carried out at three different velocities and three different angles.

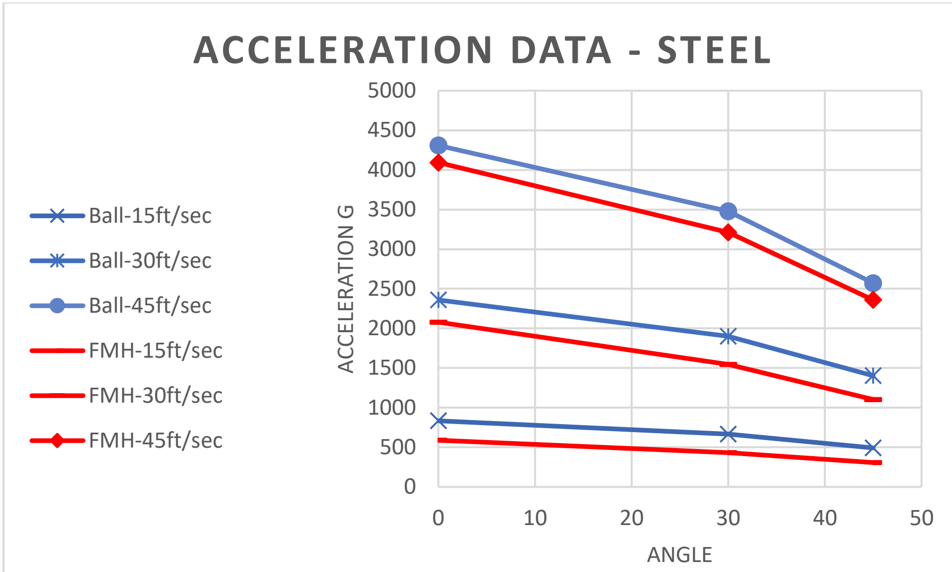


Figure 4.6: Acceleration Data on Steel Bulkhead

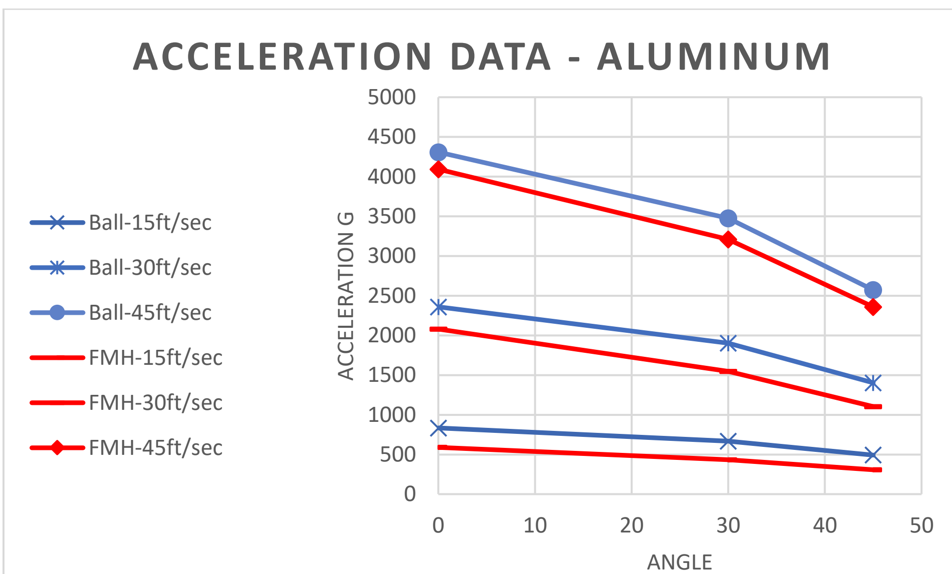


Figure 4.7: Acceleration Data on Aluminum Bulkhead

The bowling ball tester is modeled in ADAMS – view and the free-motion headform tester is modeled in LS-Dyna with bulkheads being rigid. From the results obtained and from the simulations, the following are observed:

- Modeling a contact force in a multi-body dynamic, the contact force calculations and other factors such as damping, force exponent and penetration depth have a very prominent role in determining the contact force. This contact force provides the spring back effect due to which the rebounding of the object takes place. The variables used in this research are tested and can be used in the future researches if the impact material used are Steel and Aluminum.
- There is no local deformation observed at the impact location in ADAMS simulations, as the multibody models are rigid and there is no energy absorption taking place.
- As the impact velocity increases, the resultant acceleration value increases. As the impact angle increases, there is a decrease in the resultant acceleration.
- As the velocity increases, it is observed that the acceleration values obtained in both the tests are very near. The comparison difference obtained is 5% between the two tests.

4.4 Additional Target Models

From the results, it is observed that the thickness and constrainment of degrees of freedom contribute a vital percentage towards the head injuries. Therefore, energy absorbing panels (different boundary conditions) are used to carry out as target models for further research are shown in Figures 4.8 (four edges supported), 4.9 (simply supported) and 4.10 (two edges supported on right and left sides). The modeling of these panels is carried in LS-Dyna by using MAT24_Linear piecewise plasticity properties.

The bowling ball tester could not represent the structural deformation of the target models. Therefore, free-motion headform model is used for the remaining research. There is also ease in using the free-motion headform which can be impacted on to different materials at different levels of impact angles and impact velocities.

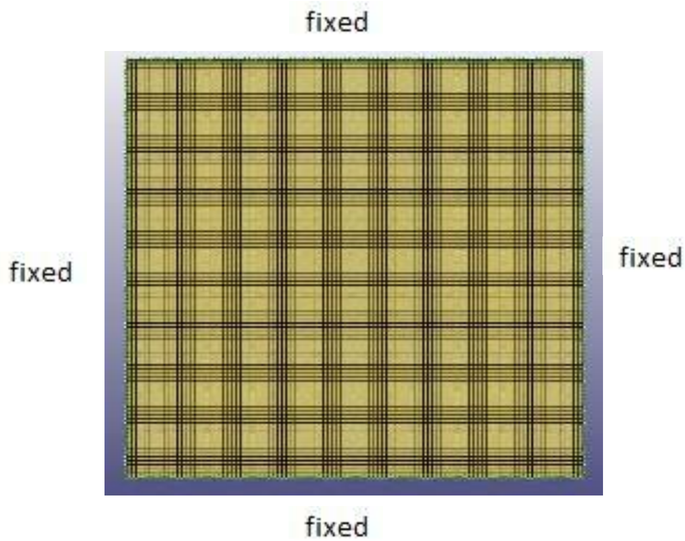


Fig 4.8: Four Edges Supported

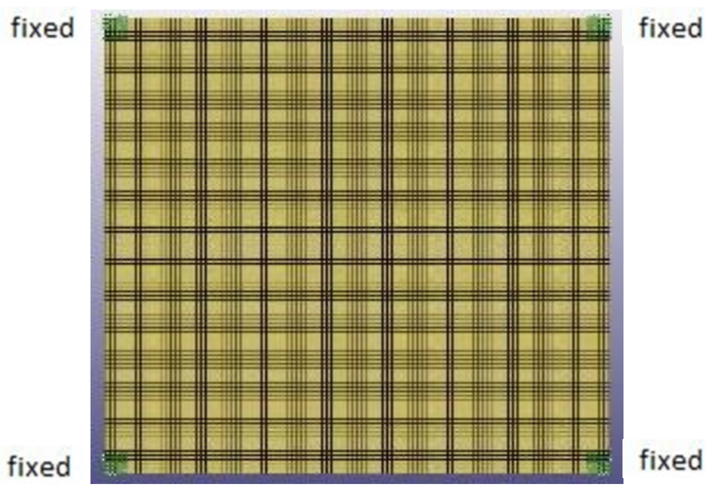


Fig 4.9: Simply Supported

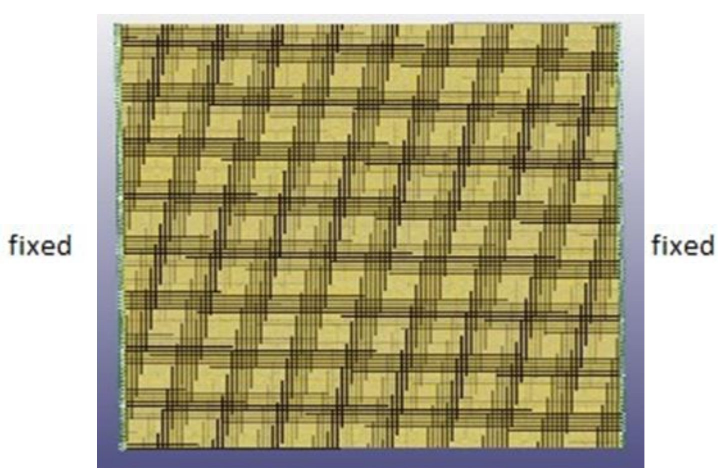


Fig 4.10: Two Edges Supported

CHAPTER 5

DESIGN OF EXPERIMENTS

Design of experiments is an experimental method which determines the relationship between factors affecting the process and the output of the process. Taguchi methodology is used to increase productivity and also to know the correct setting for the design parameters. In this research, there are five factors considered for both automotive and aircraft crash scenarios which influence the head injury criteria. They are:

- Impact conditions
    - Impact velocity
    - Impact angle
- Target conditions
    - Impact Material
    - Boundary conditions
    - Thickness

The control factors and their levels play a crucial role in conducting the design of experiments. The control levels for the above factors are obtained from the previous study and experiments are carried out. From chapter 3, the impact conditions control levels are obtained and are tabulated in Table 5.1.

TABLE 5.1

IMPACT CONDITIONS AND THEIR LEVELS

Impact Angle (degree)	Impact velocity (m/s)
0	9.1
30	11.4
45	13.7

Two materials namely Steel and Aluminum are considered as the impact materials. From chapter 4, it is observed that there is a considerable contribution by the boundary conditions and thickness towards the Head Injury Criteria. Therefore, there is a need for the energy absorbing panels. To evaluate the percentage contribution and to obtain optimal design parameters, three different types of energy absorbing panels and three different thicknesses are considered into this study. The control levels for these parameters are tabulated in Table 5.2.

TABLE 5.2

CONTROL LEVELS FOR BOUNDARY CONDITIONS AND THICKNESS

Boundary Conditions	**Thickness (mm)**
Four edges supported	1.0
Simply supported	1.5
Two edges supported	2.0

The energy absorbing panels with four edges supported, simply supported and two edges supported respectively are shown in the Chapter 4 (Figures 4.8, 4.9 & 4.10 respectively) . These energy panels are designed in LS-Dyna with shell elements. The degrees of freedom in x, y, z directions are constrained along the four edges in a four-edge supported panel. The degrees of freedom in x, y, z directions are constrained at the four ends in a simply-supported panel. The degrees of freedom in x, y, z directions are constrained along the two edges in a two-edge supported panel. These panels are constructed in three different thicknesses, with three different boundary conditions. The material properties of Steel and Aluminum are assigned to them, and free-motion headform impacts are carried out. MAT24_Linear piecewise plasticity is used for modeling the impact surfaces. These impact surfaces are meshed finely and consists of 10000 solid elements.

5.1 Steps in Taguchi Methodology

The Taguchi methodology is applied to crashworthiness to analyze the effect of the factors that are influencing the Head Injury Criteria [40]. Taguchi methodology is also used to predict the optimal conditions for the factors used. There are several steps in this methodology and are listed below:

1. Identify the main Function, side effects, and failure Mode
2. Identify the noise Factors, testing conditions, and quality characteristics
3. Identify the objective function to be optimized
4. Identify the control factors and their levels
5. Select the orthogonal array matrix experiment
6. Conduct the matrix experiment
7. Analyze the data, predict the optimum levels and performance
8. Perform the verification experiment and plan future action.

As discussed earlier, there are two categories of conditions which are affecting the head injury criteria. In order to observe their sensitivity and to observe their influence on head injuries, two different combinations of noise factors and control factors are considered. To achieve the objective of this research, the following are steps that are considered [40]:

Main Function: Investigate the parameters affecting the HIC evaluation

Side Effects: Since the Free-Motion Head Form is used for the testing conditions, no other Injury parameters are considered.

Failure Mode: Control Factor Levels are selected so that there will not be any failure.

Noise Factors:

- **Combination-1**

  1. Variation in Stiffness of Material
  2. Variation in the boundary conditions

- **Combination-2**

  1. Variation in Stiffness of Material
  2. Variation in the impact velocity

Testing Conditions: Keep the Simulation Run Time Constant, i.e., 15 ms

Noise Capturing Test Conditions: For each experiment, two experiments are carried under the described noise conditions

The next step is identifying the control factors and their levels. As there are two sets of different noise conditions, the control factors and their levels differ for each set. The noise conditions, control factors, and their levels are described below for each combination.

5.1.1 Noise Factors, Control Factors and their Levels for Combination-1

In Combination-1, the impact conditions (i.e., impact velocity and impact angle) and material thickness are considered as the control factors. Impact material and boundary conditions are considered as the noise factors in this combination, to observe the dominance of the impact conditions over the target conditions effecting the variation in HIC.

TABLE 5.3 NOISE FACTORS: COMBINATION-1

Experiment No.	Material	Boundary Conditions
1	Steel	4 Edges Supported
2	Steel	Simply Supported
3	Aluminum	4 Edges Supported
4	Aluminum	Simply Supported

TABLE 5.4

CONTROL FACTORS AND THEIR LEVELS: COMBINATION-1

Factor	Level -1	Level-2	Level-3
Thickness (mm)	1	1.5	2
Impact Velocity (m/s)	9.1	11.4	13.7
Impact Angle (degree)	0	30	45
Misc.	E	E	E

5.1.2 Noise Factors, Control Factors and their Levels for Combination-2

In Combination-2, material thickness, boundary conditions and impact angle are considered as the control factors. Impact material and impact velocity are considered as the noise factors in this combination. Varying the levels of the control factors, the head injury criteria is observed. Table 5.5 shows the noise factors considered, and Table 5.6 shows the control factors and their levels for the Combination-2. This latter combination is used to investigate how target conditions as in boundary conditions and thickness are dominating the resulting HIC. Impact velocity is taken as noise condition especially because velocity is a vector quantity, and the effect of it seems to have much impact on the injury criteria.

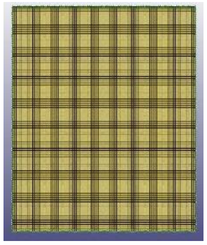
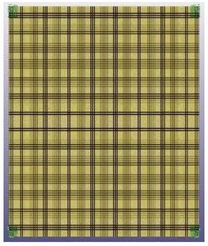
TABLE 5.5

NOISE FACTORS: COMBINATION-2

Experiment No.	Material	Velocity (m/s)
1	Steel	13.7
2	Steel	9.1
3	Aluminum	13.7
4	Aluminum	9.1

TABLE 5.6

CONTROL FACTORS AND THEIR LEVELS: COMBINATION-2

Factor	Level -1	Level-2	Level-3
Thickness (mm)	1	1.5	2
Boundary Conditions	4-edges supported 	Simply supported 	2-edges supported 
Impact Angle (deg)	0	30	45
Misc.	E	E	E

5.1.3 Selection of Orthogonal Array

The selection of orthogonal array depends on the number of factors considered. Table 5.7 shows the orthogonal array type to be selected depending on the number of factors.

TABLE 5.7

SELECTION OF ORTHOGONAL ARRAY

No. of Factors	2-4	5-7	8-13
Orthogonal Array	L9	L18	L27

The orthogonal array matrix gives the effect of interactions between the control factors and their levels. In this research, three control factors are used for both combinations. Therefore, from Table 5.7 L-9 orthogonal array is chosen. Nine experiments are conducted with different combinations of control factors and their levels. The Head Injury Criteria is measured as the output, and the further calculations are conducted. The orthogonal array and its interactions for both the combinations are mentioned in Table 5.8.

TABLE 5.8

L9 ORTHOGONAL ARRAY

EXPERIMENT NO.	A	B	C	D
1	A1	B1	C1	-
2	A1	B2	C2	-
3	A1	B3	C3	-
4	A2	B1	C2	-
5	A2	B2	C3	-
6	A2	B3	C1	-
7	A3	B1	C3	-
8	A3	B2	C1	-
9	A3	B3	C2	-

A, B, C - Control Factors

1,2,3 - Levels of the Control Factors

Table 5.8 data is used for both the combinations and the free-motion head impact are carried out with the different interactions of the control factors.

5.1.4 Calculations for S/N Ratio

After the Head Injury Criteria is obtained for all the interactions, the signal to noise ratio is calculated. This signal to noise ratio helps in determining the fatal conditions and optimal design parameters for the impact material. The equation used for the signal to noise ratio (η) measured in Db, for both the combinations is listed next.

The higher the S/N ratio (η) is, higher is the Head Injury Criteria [40]:

$$\eta = -10 \log(\frac{1}{n}\sum \frac{1}{Y_i^2}) \text{ dB} \tag{5.1}$$

There are some calculation steps that need to be followed to find the signal to noise ratio [40]. The steps are listed next.

Calculation-1:

- Find the sum of squares (SSQ) of all measured values, i.e., HIC values
- SSQ = $\frac{1}{Y_1^2} + \frac{1}{Y_2^2} + \frac{1}{Y_3^2} + \frac{1}{Y_4^2} + \cdots + \frac{1}{Y_n^2}$ (5.2)
- where Y value is the obtained HIC value for a particular combination

Calculation-2:

- Find the mean sum of squares of reciprocals (MSSQ)
- MSSQ = $\frac{(SSQ)}{(number\ of\ measurements}$
- SSQ is obtained from the Calculation-1
- Number of measurements = 9

Calculation-3:

- Calculate the signal to noise (S/N) ratio
- The S/N ratios are denoted by η
- Where $\eta = -10 log_{10} of\ (MSSQ)$ (5.3)
- $\eta = -10 log_{10}(\frac{1}{n}\Sigma(\frac{1}{Y_1^2} + \frac{1}{Y_2^2} + \frac{1}{Y_3^2} + \frac{1}{Y_4^2} + \cdots + \frac{1}{Y_n^2}))$ (5.4)

5.2 Design of Experiments with Combination-1

The design of experiments with Combination-1 is carried out in this chapter. As discussed earlier, the L9 orthogonal array is built, and the free-motion head impacts are carried as per the interactions. The calculations are carried out then after to obtain the S/N ratio. The L-9 orthogonal array for Combination-1 is shown in Table 5.9.

TABLE 5.9

ORTHOGONAL ARRAY FOR COMBINATION-1

Experiment No.	Thickness	Impact Velocity	Impact Angle	Miscellaneous
1	1	9.1	0	-
2	1	11.4	30	-
3	1	13.7	45	-
4	1.5	9.1	30	-
5	1.5	11.4	45	-
6	1.5	13.7	0	-
7	2	9.1	45	-
8	2	11.4	0	-
9	2	13.7	30	-

Noise Conditions:

- Variation in impact material
- Variation in boundary conditions

The free-motion head impacts are carried out as per the interactions mentioned in Table 5.9. The Impact surfaces are designed with two different materials, i.e., Steel and Aluminum, and with two different boundary conditions; i.e., four edges supported and simply supported. Therefore, four sets of experiments are conducted with 9 experiments in each set; i.e.,

a) Steel impact surface with four edges supported

b) Steel impact surface with simply supported

c) Aluminum impact surface with four edges supported

d) Aluminum impact surface with simply supported

A Total of 36 free-motion headform impact simulation test have been conducted in Combination-1. A sample animation sequence for the free-motion headform tests with the Combination-1 specification are shown in Figure 5.1.

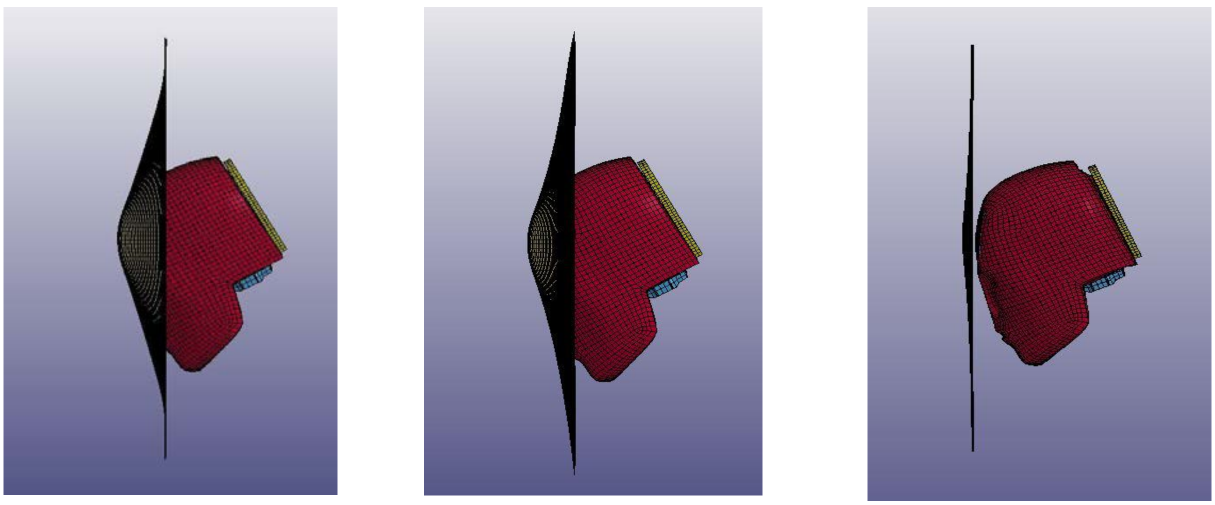


Figure 5.1: Animation Sequence for Free-Motion Head Impacts: Combination-1

All the 36 impacts are conducted on Steel and Aluminum impact surfaces. The deformation and the animation sequence are almost similar for all the experiments. The head injury criteria for all the experiments are obtained directly.

5.2.1 HIC Data for Combination-1

The simulations are carried out for all the 4 sets and the Head Injury Criteria is obtained. All four sets are mentioned in Table 5.10. The HIC responses for the 36 experiments are tabulated in the below tables. Tables 5.11 and 5.12 are the tabulated HIC responses for Steel being the bulkhead / impact material and Tables 5.13 and 5.14 are the tabulate HIC responses for Aluminum being the bulkhead/impact material.

TABLE 5.10

SET OF FOUR EXPERIMENTS – COMBINATION 1

Experiment No.	Material	Boundary Conditions
1	Steel	4 Edges Supported
2	Steel	Simply Supported
3	Aluminum	4 Edges Supported
4	Aluminum	Simply Supported

TABLE 5.11

HIC DATA FOR STEEL BULKHEAD WITH FOUR EDGES SUPPORTED

S. No	Thickness (mm)	Impact Velocity (m/s)	Impact Angle (degree)	Resultant Acceleration (G)	HIC_{15}	Δt (ms)
1	1	9.1	0	392	676	3.7
2	1	11.4	30	203	1,026	4.0
3	1	13.7	45	175	1,204	2.8
4	1.5	9.1	30	323	781	3.8
5	1.5	11.4	45	232	1,042	2.7
6	1.5	13.7	0	276	5,787	2.6
7	2	9.1	45	275	667	3.7
8	2	11.4	0	348	4,165	4.4
9	2	13.7	30	298	4,288	2.4

TABLE 5.12

HIC DATA FOR STEEL IMPACT SURFACE WITH SIMPLY SUPPORTED

S. No	Thickness (mm)	Impact Velocity (m/s)	Impact Angle (degree)	Resultant Acceleration (G)	HIC_{15}	Δt (ms)
1	1	9.1	0	120	279.3	3.3
2	1	11.4	30	179	494.8	3.8
3	1	13.7	45	310	615.7	3.8
4	1.5	9.1	30	277	511.3	2.8
5	1.5	11.4	45	452	748.2	2.9
6	1.5	13.7	0	187	1783	2.6
7	2	9.1	45	257	539.3	3.7
8	2	11.4	0	290	1815	4.6
9	2	13.7	30	301	2097	2.8

TABLE 5.13

HIC DATA FOR ALUMINUM IMPACT SURFACE WITH FOUR EDGES SUPPORTED

S. No	Thickness (mm)	Impact Velocity (m/s)	Impact Angle (degree)	Resultant Acceleration (G)	HIC_{15}	Δt (ms)
1	1	9.1	0	90	78	2.7
2	1	11.4	30	153	183	2.9
3	1	13.7	45	175	193	3.1
4	1.5	9.1	30	108	155	3.1
5	1.5	11.4	45	134	180	3.0
6	1.5	13.7	0	276	1,130	2.8
7	2	9.1	45	93	108	3.7
8	2	11.4	0	189	848	2.6
9	2	13.7	30	298	1,252	2.4

TABLE 5.14

HIC DATA FOR ALUMINUM IMPACT SURFACE WITH SIMPLY SUPPORTED

S. No	Thickness (mm)	Impact Velocity (m/s)	Impact Angle (degree)	Resultant Acceleration (G)	HIC_{15}	Δt (ms)
1	1	9.1	0	65	35	2.1
2	1	11.4	30	78	86	2.8
3	1	13.7	45	79	81	2.7
4	1.5	9.1	30	85	101	3.2
5	1.5	11.4	45	93	110	2.3
6	1.5	13.7	0	107	284	2.2
7	2	9.1	45	75	78	2.9
8	2	11.4	0	100	300	3.0
9	2	13.7	30	145	517	2.2

The Head Injury Criteria for all the 36 experiments are thus shown in the tables. The S/N ratios for the Combination-1 are then carried out.

5.2.2 S/N Calculations for Combination-1

The HIC for all the experiments are obtained. The S/N calculations are carried out for the Combination-1. Steel and Aluminum calculations are calculated separately. Two sets of each are tabulated, and the calculations are carried out as per the steps mentioned in section 5.1.4.The steps are mentioned below:

- Calculating SSQ, where Y terms are Head Injury Criteria
- Calculating MSSQ
- Calculating S/N

As per the above steps, the calculations are proceeded and tabulated in the Tables 5.15 and 5.16. The HIC-1 and HIC-2 in tables are the HIC values based on Combination-1 and Combination-2.

TABLE 5.15

S/N CALCULATIONS FOR STEEL IMPACT SURFACE: COMBINATION-1

Expt. No	HIC-1	HIC-2	Sum of Squares of Reciprocals (SSQ)	Means of Sum of Squares of Reciprocals (MSSQ)	S/N Ratio (The larger, the more injurious)
1	676.7	279.3	1.50E-05	7.50E-06	51.24
2	1026	494.8	5.03E-06	2.51E-06	55.99
3	1204	615.7	3.32E-06	1.66E-06	57.78
4	781.6	511.3	5.46E-06	2.73E-06	55.63
5	1042	748.2	2.70E-06	1.35E-06	58.68
6	5787	1783	3.44E-07	1.72E-07	67.63
7	667.7	539.3	5.68E-06	2.84E-06	55.46
8	4165	1815	3.61E-07	1.80E-07	67.43
9	4288	2097	2.81E-07	1.40E-07	68.51

TABLE 5.16

S/N CALCULATIONS FOR ALUMINUM IMPACT SURFACE: COMBINATION-1

Expt. No	HIC-1	HIC-2	Sum of Squares of Reciprocals (SSQ)	Means of Sum of Squares of Reciprocals (MSSQ)	S/N Ratio (The larger, the more injurious)
1	78.2	35.6	9.52E-04	4.76E-04	33.22
2	183.2	86.22	1.64E-04	8.21E-05	40.85
3	193.4	81.1	1.78E-04	8.93E-05	40.48
4	155.9	101.2	1.38E-04	6.93E-05	41.58
5	180	110.7	1.12E-04	5.62E-05	42.50
6	1130	284	1.31E-05	6.59E-06	51.81
7	108.7	78.46	2.47E-04	1.23E-04	39.08
8	848.9	300.8	1.24E-05	6.21E-06	52.06
9	1252	517.4	4.37E-06	2.18E-06	56.60

The S/N ratio; i.e., signal to noise ratio, is a frequency which shows the disturbances caused due to the effect of the input factors. As it is a frequency, the units are specified in decibels (dB). The S/N ratios are calculated. The highest values are marked in red, and the ones with smaller values are marked in green. The graphs for the S/N ratio versus control factor levels for both Steel and Aluminum with the Combination-1 are shown in Figures 5.2 and 5.3 respectively.

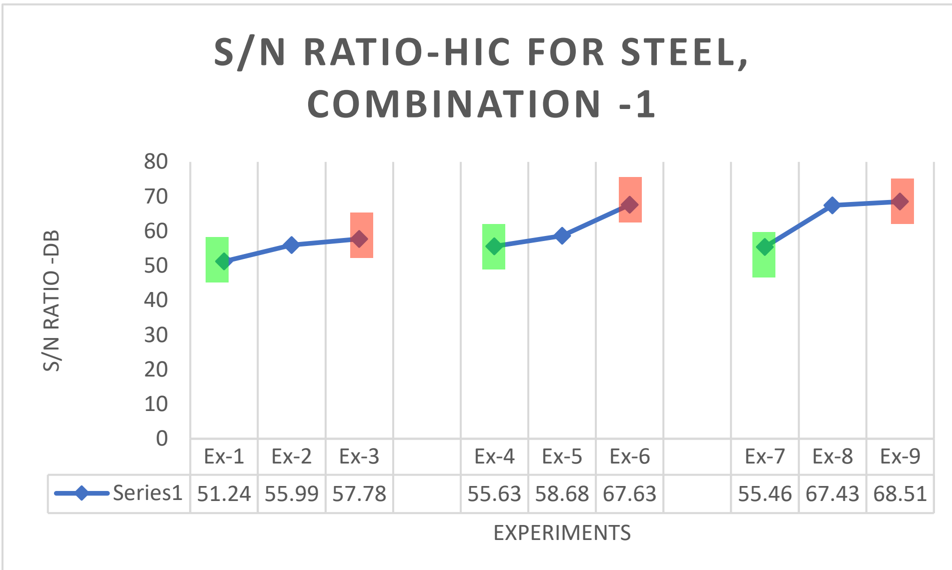


Figure 5.2: S/N Analysis for Steel: Combination-1

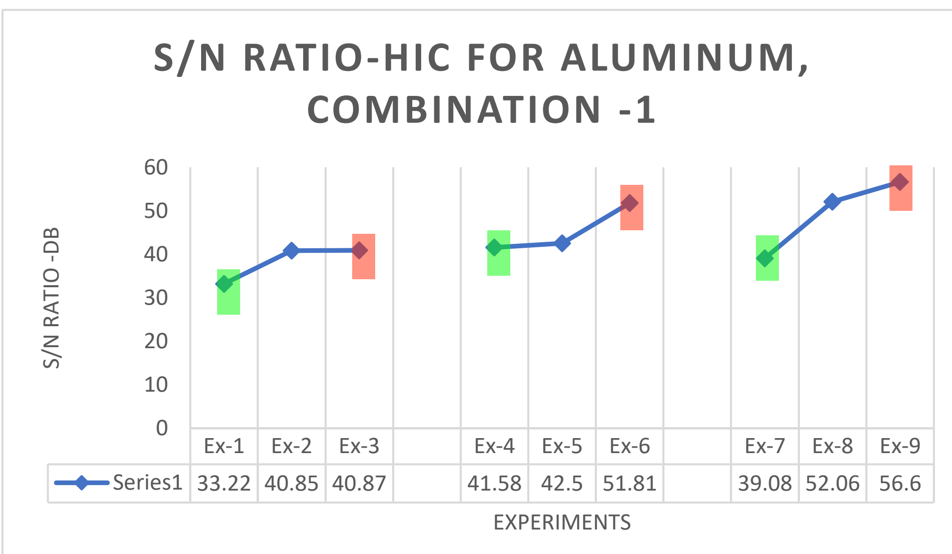


Figure 5.3: S/N analysis for Aluminum: Combination-1

5.3 Design of Experiments with Combination-2

The design of experiments with the Combination-2 is carried out in this chapter. As discussed earlier, the L9 orthogonal array is built, and the free-motion head impacts are carried as per the interactions. The calculations are carried out to obtain the S/N ratio. The L-9 orthogonal array for Combination-2 is shown in Table 5.17.

TABLE 5.17

ORTHOGONAL ARRAY FOR COMBINATION-2

Experiment No.	**Thickness (mm)**	**Boundary Conditions**	**Impact Angle (degree)**	**Miscellaneous**
1	1	4 Edges	0	-
2	1	2 Edges	30	-
3	1	Simply Supported	45	-
4	1.5	4 Edges	30	-
5	1.5	2 Edges	45	-
6	1.5	Simply Supported	0	-
7	2	4 Edges	45	-
8	2	2 Edges	0	-
9	2	Simply Supported	30	-

Noise Conditions:

- Variation in Impact Material
- Variation in Impact Velocity

The free-motion head impacts are carried out as per the interactions mentioned in Table 5.17. The impact surfaces are designed with two different materials, i.e., Steel and Aluminum, the head is impacted on to the impact surfaces at two different impact velocities; i.e., at 9.1 m/s and 13.7 m/s. Therefore, four sets of experiments are conducted with nine experiments in each set, i.e.,

1. Steel impact surface impacted at 13.7 m/s

2. Steel impact surface impacted at 9.1 m/s
3. Aluminum impact surface impacted at 13.7 m/s
4. Aluminum impact surface impacted at 9.1 m/s

A total of 36 free-motion headform impact test simulations have been conducted in Combination-2. A sample animation sequence for the free-motion headform tests with the Combination-2 specifications are shown in Figure 5.4.

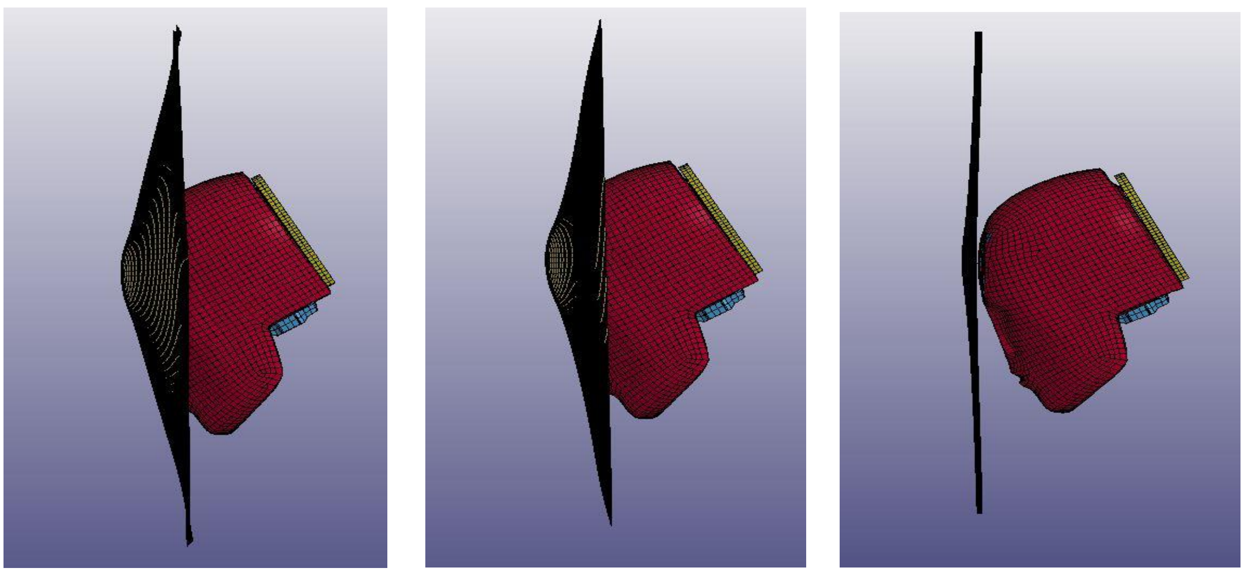


Figure 5.4: Animation Sequence for Free Motion Head Impacts: Combination-2

All the 36 impacts are conducted on Steel and Aluminum impact surfaces. The deformation and the animation sequence are almost similar for all the experiments. The Head Injury Criteria for all the experiments are obtained directly from the LS-Dyna software.

5.3.1 HIC Data for Combination-2

The simulations are carried out of all the four sets and the Head Injury Criteria is obtained. All four sets are mentioned in Table 5.18. The HIC responses for the 36 experiments are tabulated in the below tables. Tables 5.19 and 5.20 list the HIC responses for Steel being the bulkhead / impact material. Tables 5.21 and 5.22 list the HIC responses for Aluminum being the bulkhead/impact material.

TABLE 5.18

SET OF EXPERIMENTS – COMBINATION 2

Experiment No.	Material	Impact Velocity (m/s)
1	Steel	13.7
2	Steel	9.1
3	Aluminum	13.7
4	Aluminum	9.1

TABLE 5.19

HIC DATA FOR STEEL IMPACT SURFACE IMPACTING AT 13.7 m/s

S. No	Thickness (mm)	Boundary Conditions	Impact Angle (degree)	Resultant Acceleration G	HIC_{15}	Δt (ms)
1	1	4 edges	0	392	3,403	3.7
2	1	2 edges	30	203	1,083	4.1
3	1	simply	45	175	597	2.6
4	1.5	4 edges	30	323	3,422	3.7
5	1.5	2 edges	45	232	1,289	2.5
6	1.5	simply	0	276	1,715	2.4
7	2	4 edges	45	275	2,499	3.1
8	2	2 edges	0	348	4,032	4.1
9	2	simply	30	298	2,129	2.2

TABLE 5.20

HIC DATA FOR STEEL IMPACT SURFACE IMPACTING AT 9.1 m/s

S. No	Thickness (mm)	Boundary Conditions	Impact Angle (degree)	Resultant Acceleration G	HIC_{15}	Δt (ms)
1	1	4 edges	0	254	676	3.7
2	1	2 edges	30	201	496	4.1
3	1	simply	45	172	196	2.9
4	1.5	4 edges	30	200	781	3.1
5	1.5	2 edges	45	211	407	2.1
6	1.5	simply	0	173	653	2.4
7	2	4 edges	45	208	682	2.9
8	2	2 edges	0	289	1114	3.5
9	2	simply	30	291	1184	2.3

TABLE 5.21

HIC DATA FOR ALUMINUM IMPACT SURFACE IMPACTING AT 13.7 m/s

S. No	Thickness (mm)	Boundary Conditions	Impact Angle (degree)	Resultant Acceleration G	HIC_{15}	Δt (ms)
1	1	4 edges	0	208	504	3.4
2	1	2 edges	30	122	236	3.7
3	1	simply	45	68	80	3.7
4	1.5	4 edges	30	190	795	3.6
5	1.5	2 edges	45	116	233	3.5
6	1.5	simply	0	133	279	3.2
7	2	4 edges	45	169	688	3.2
8	2	2 edges	0	205	874	4.1
9	2	simply	30	150	510	3.3

TABLE 5.22

HIC DATA FOR ALUMINUM IMPACT SURFACE IMPACTING AT 9.1 m/s

S. No	Thickness (mm)	Boundary Conditions	Impact Angle (degree)	Resultant Acceleration G	HIC_{15}	Δt (ms)
1	1	4 edges	0	80	78	2.9
2	1	2 edges	30	79	46	3.1
3	1	simply	45	40	27	2.6
4	1.5	4 edges	30	99	155	2.9
5	1.5	2 edges	45	62	46	2.5
6	1.5	simply	0	77	95	3.3
7	2	4 edges	45	98	113	2.5
8	2	2 edges	0	95	181	3.4
9	2	simply	30	99	160	3.2

The HIC for all the 36 experiments are shown in the tables. The S/N ratios for the Combination-2 are then carried out.

5.3.2 S/N Calculations for Combination-2

The Head Injury Criteria for all the experiments are obtained. The S/N calculations are carried out for the Combination-2. Steel and Aluminum calculations are calculated separately. Two sets of each are tabulated, and the calculations are carried out as per the steps mentioned in chapter 5.1.4. The steps are mentioned below:

- Calculating SSQ, where Y terms are Head Injury Criteria
- Calculating MSSQ
- Calculating S/N

As per the above steps, the calculations are proceeded and tabulated in the below Tables 5.23 and 5.24.

TABLE 5.23

S/N CALCULATIONS FOR STEEL IMPACT SURFACE: COMBINATION-2

Expt. No	HIC-1	HIC-2	Sum of Squares of Reciprocals (SSQ)	Means of Sum of Squares of Reciprocals (MSSQ)	S/N Ratio (The larger, the more injurious)
1	3403	676.7	2.27E-06	1.13E-06	59.44
2	1083	496.4	4.91E-06	2.45E-06	56.09
3	597.4	196.5	2.87E-05	1.43E-05	48.43
4	3422	781.6	1.72E-06	8.61E-07	60.64
5	1289	407.9	6.61E-06	3.30E-06	54.80
6	1715	653.5	2.68E-06	1.34E-06	58.72
7	2499	682	2.31E-06	1.155E-06	59.37
8	4032	1114	8.67E-07	4.33E-07	63.62
9	2129	1184	9.33E-07	4.66E-07	63.30

TABLE 5.24

S/N CALCULATIONS FOR ALUMINUM IMPACT SURFACE: COMBINATION-2

Expt. No	HIC-1	HIC-2	Sum of Squares of Reciprocals (SSQ)	Means of Sum of Squares of Reciprocals (MSSQ)	S/N Ratio (The larger, the more injurious)
1	498	78.2	1.68E-04	8.37E-05	40.76
2	236.3	46.52	4.80E-04	2.40E-04	36.19
3	80.9	17.2	3.53E-03	1.76E-03	27.52
4	795.2	155.59	4.29E-05	2.14E-05	46.68
5	233	46.62	4.79E-04	2.39E-04	36.21
6	279	95.54	1.22E-04	6.12E-05	42.13
7	688	113	8.04E-05	4.02E-05	43.95
8	874	181.2	3.18E-05	1.58E-05	47.99
9	510	160.1	4.29E-05	2.14E-05	46.68

The S/N ratio; i.e., signal to noise ratio is a frequency which shows the disturbances caused due to the effect of the input factors. As it is a frequency, the units are specified in decibels (dB). The S/N ratios are calculated. The highest values are marked in red, and the ones with smaller values are marked in green. The graphs for the S/N ratio versus Control factor levels for both Steel and Aluminum with the Combination-2 are shown in the Figures 5.5 and 5.6 respectively.

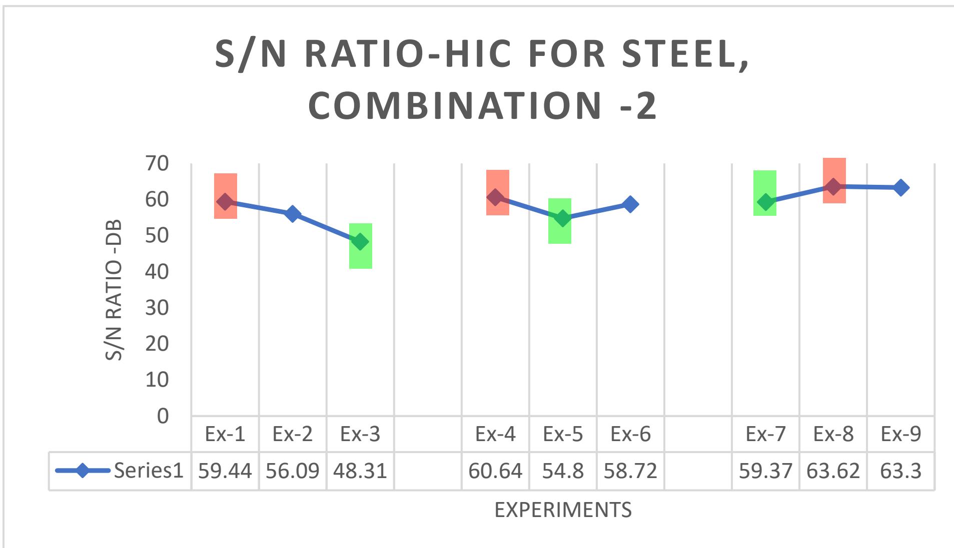


Figure 5.5: S/N Ratio of HIC for Steel with Combination-2

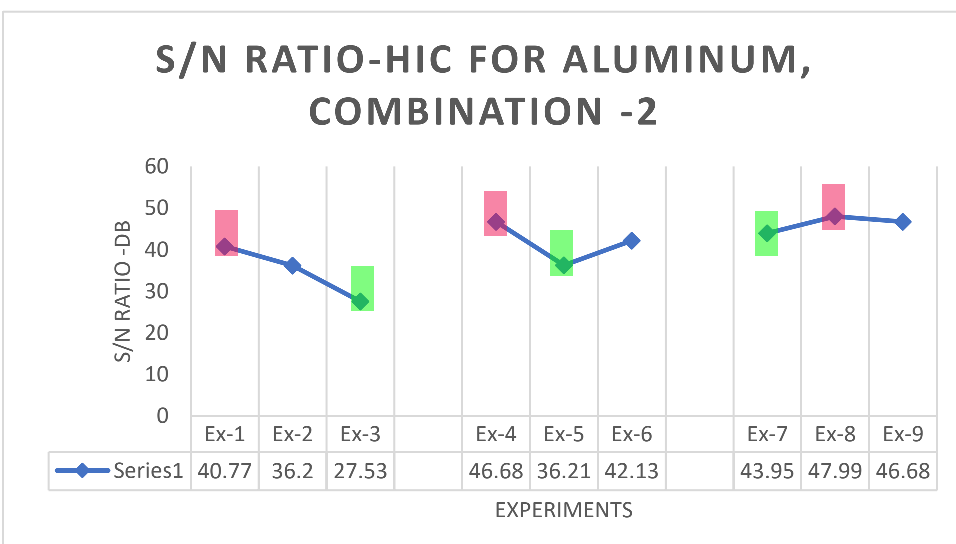


Figure 5.6: S/N Ratio of HIC for Aluminum with Combination-2

5.4 Observations

The design of experiments is conducted as per the Combination-1 (Variation in material and boundary conditions being the noise conditions) and Combination-2 (Variation in material and impact velocity are the noise conditions). The S/N analysis is carried out as well, and the following observations are made.

- The Combination-1 shows the effect of the impact conditions; i.e., impact velocity and impact angle on to the Head Injury Criteria.
- It is observed that the higher the impact angles, the lower the head injury.
- From the tabulated results from section 5.2.1, it is observed that the impact velocity and impact angle dominates the thickness.
- From the S/N calculations of the Combination-1 the following are observed:
    - Variation in the impact material and the boundary conditions as the noise factors, experiment 9 has the highest value of S/N ratio, and experiment 1 has the lowest S/N ratio (for both Steel and Aluminum).
    - The higher the S/N ratio, the higher the fatality rate.
    - Therefore, the factor level setting with the thickness being 2mm, impact velocity being 13.7 m/s, and impact angle being 0 degrees yields the highest injury rate for both Steel and Aluminum impact surfaces.
    - The setting with the thickness being 1mm, impact velocity being 9.1 m/s and impact angle being 0 degrees yields the lowest fatality.
- The Combination-2 shows the effect of target conditions; i.e., boundary conditions and thickness on to the Head Injury Criteria.

- It is observed that the thickness and boundary conditions play a very vital role in the Head Injury Criteria from the tables tabulated in section 5.3.1.
- From the S/N calculations of the Combination-2, the following are observed
    - Variation in the impact material and the impact velocity as the noise factors, experiment 8 has the highest value of S/N ratio, and Experiment 2 has the lowest S/N ratio.
    - The higher the S/N ratio, the higher the head injury criteria.
    - Therefore, the factor levels setting with the thickness being 2mm, with boundary conditions being two edges supported, with impact angle being 0 degrees yields the highest injury rate for both Steel and Aluminum.
    - The setting with thickness 1mm, with simply supported boundary conditions and impact angle being 45 degrees yields the lowest fatality.
- It is observed that in the Combination-2, the thickness and impact angle domination is higher than the other conditions. This statement is based on the experiment -8. Though the boundary condition is being two edges supported which should yield minor head injury compared to the other boundary conditions, due to the thickness being 2mm and impact angle being 0 degrees the HIC value is higher in that group.

By comparing the Combination-1 and Combination-2, it is observed that the impact velocity and material thickness in the Combination-1 has much impact on the variation in Head Injury Criteria. Whereas, in the second combination it is observed that the material thickness and impact angle have much impact on the Head Injury Criteria.

To obtain the correct setting of design parameters for the impact material (bulkhead) and to know which factor have higher dominance on to the variation in Head Injury Criteria, the

Analysis of Variance (ANOVA) is used. It is also used to obtain the percentage contribution of each factor towards head injury. The Analysis of Variance (ANOVA) is discussed in the next chapter.

CHAPTER 6

FACTORIAL EFFECTS FOR HEAD INJURY CRITERIA

The control factors and their levels have a significant impact on the Head Injury Criteria. In this chapter, the individual factor effects are studied. The effect of factor levels is used to observe the deviation it caused from the overall mean (μ).

6.1 Steps in Factorial Effects

To obtain the factor effects, the orthogonal array matrix is to be studied as shown in Table 6.1, and the steps mentioned are followed

TABLE 6.1

ORTHOGONAL ARRAY MATRIX WITH FACTORS LEVELS

EXPERIMENT NO.	A	B	C	D	S/N
1	A1	B1	C1	-	η_1
2	A1	B2	C2	-	η_2
3	A1	B3	C3	-	η_3
4	A2	B1	C2	-	η_4
5	A2	B2	C3	-	η_5
6	A2	B3	C1	-	η_6
7	A3	B1	C3	-	η_7
8	A3	B2	C1	-	η_8
9	A3	B3	C2	-	η_9

The Steps followed [40]:

- Factor effect of A with level 1, 2, 3:

- A1 occurs in experiments 1,2,3, A2 occurs in 4,5,6 and A3 in 7,8,9
- $mA1=1/3(\eta_1+\eta_2+\eta_3)$ (6.1)
- $mA2=1/3(\eta_4+\eta_5+\eta_6)$
- $mA3=1/3(\eta_7+\eta_8+\eta_9)$

➢ Factor effect of B with level 1,2,3:

- B1 occurs in experiments 1,4,7, B2 occurs in 2,5,8 and B3 occurs in 3,6,9
- $mB1=1/3(\eta_1+\eta_4+\eta_7)$ (6.2)
- $mB2=1/3(\eta_2+\eta_5+\eta_8)$
- $mB3=1/3(\eta_3+\eta_6+\eta_9)$

➢ Factor effect of C with level 1,2,3:

- C1 occurs in experiments 1,6,8, C2 occurs in 2,4,9 and C3 in 3,5,7
- $mC1=1/3(\eta_1+\eta_6+\eta_8)$ (6.3)
- $mC2=1/3(\eta_2+\eta_4+\eta_9)$
- $mC3=1/3(\eta_3+\eta_5+\eta_7)$

➢ Overall mean (μ) = $1/9*(\eta_1+\eta_2+\eta_3+\eta_4+\eta_5+\eta_6+\eta_7+\eta_8+\eta_9)$ (6.4)

The above steps are followed for both combinations, and the factor effects are calculated. The calculated values are tabulated in Tables 6.2 through 6.5.

TABLE 6.2

FACTOR EFFECTS FOR STEEL IMPACT SURFACE: COMBINATION-1

Thickness (mA_n)	**Impact Velocity (mB_n)**	**Impact Angle (mC_n)**
55.00	54.11	62.10
60.65	60.70	60.04
63.80	64.64	57.31

TABLE 6.3

FACTOR EFFECTS FOR ALUMINUM IMPACT SURFACE: COMBINATION-1

Thickness (mA_n)	Impact Velocity (mB_n)	Impact Angle (mC_n)
33.22	41.58	39.08
40.85	42.50	52.06
40.48	51.81	56.60

TABLE 6.4

FACTOR EFFECTS FOR STEEL IMPACT SURFACE: COMBINATION-2

Thickness (mA_n)	Boundary conditions (mB_n)	Impact Angle (mC_n)
54.65	59.82	60.60
58.06	58.17	60.01
62.10	56.82	54.20

TABLE 6.5

FACTOR EFFECTS FOR ALUMINUM IMPACT SURFACE: COMBINATION-2

Thickness (mA_n)	Boundary conditions (mB_n)	Impact Angle (mC_n)
34.83	43.80	43.63
41.67	40.13	43.19
46.21	38.78	35.89

- Overall mean for Steel impact surface: Combination-1 (μ) = 59.8
- Overall mean for Aluminum impact surface: Combination-1 (μ) = 43.9
- Overall mean for Steel impact surface: Combination-2 (μ) = 58.2
- Overall mean for Aluminum impact surface: Combination-2 (μ) = 40.9

6.2 Observations

The calculations for each individual control factors and their levels are calculated. These values are represented graphically. The graphical representations are convenient for drawing qualitative inferences, observing the factor levels which cause more fatality and help in choosing the optimum levels of factors. The observations and conclusions are discussed under each graphical plot for both Steel and Aluminum materials.

6.2.1 Steel as Impact Material

The results from Table 6.2 are graphically represented in Figure 6.1.

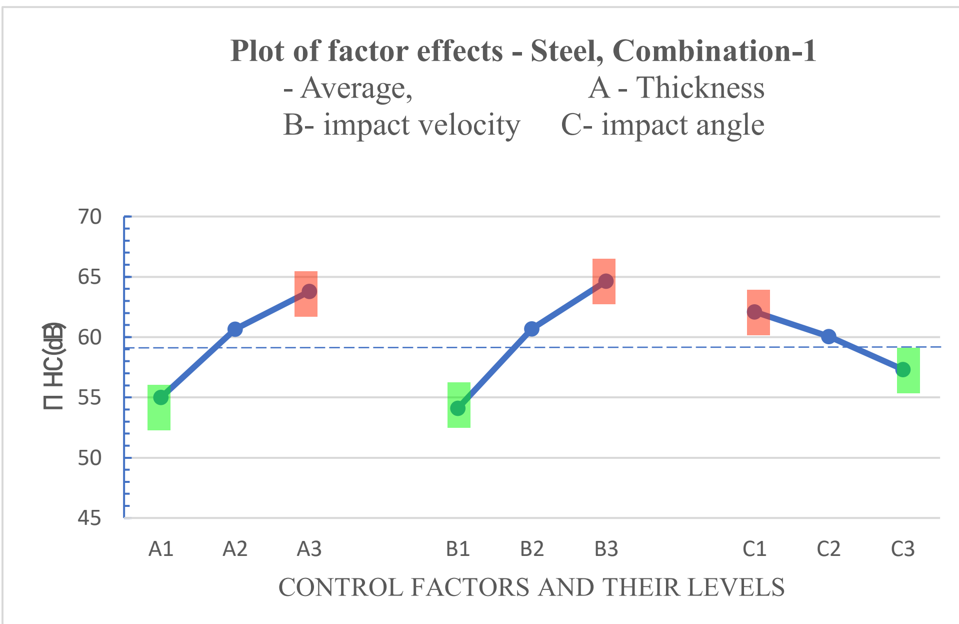


Figure 6.1: Plot of Factor Effects with Steel Impact Surface: Combination-1

The red values indicate the control factor levels which contribute towards higher Head Injury Criteria and the green color indicates the control factor level which contribute less Head Injury criteria. In other terms these are the factors which are the reason for the maximum and minimal variation in Head injury Criteria evaluation.

The results from Table 6.3 are graphically represented in Figure 6.2.

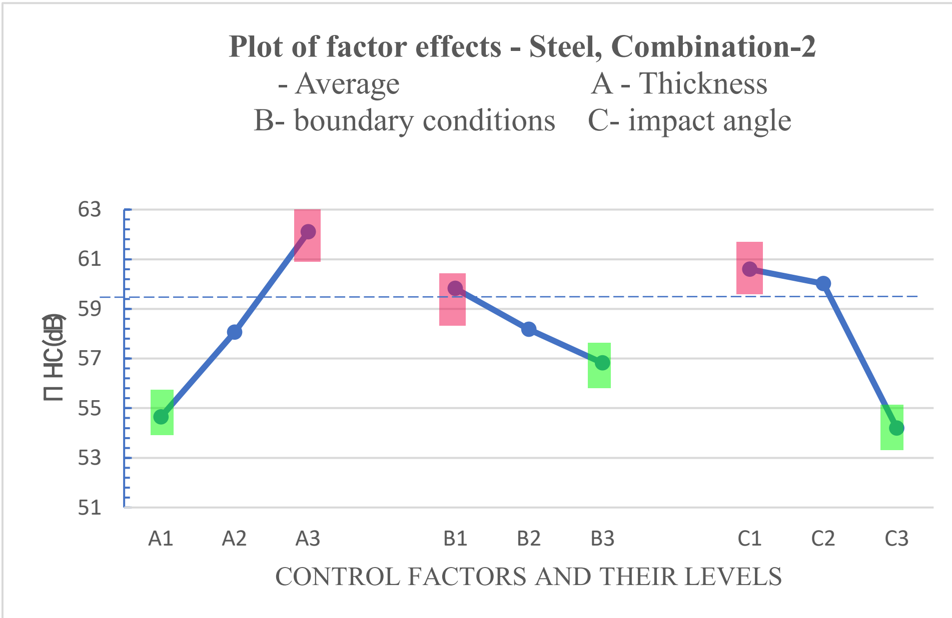


Figure 6.2: Plot of Factors Effects with Steel Impact Surface: Combination-2

From both the plots, the optimal conditions for all the parameters yielding lower HIC values are as follows:

- Impact velocity = 9.1 m/s
- Impact angle = 45 degrees
- thickness = 1mm
- boundary conditions = simply supported

From the previous chapter, even with the optimal thickness settings, the HIC values obtained are higher. This scenario can be observed with the combinations of higher impact velocities and lower impact angles. Therefore, Steel being the impact material, the optimal thickness should be constrained to less than 0.75mm. From the above observations, the below setting is found to be optimal and will be yielding lesser head injury values (within the permissible range), irrespective the impact conditions. They are:

Optimal thickness: 0.1mm – 0.75mm and Optimal boundary conditions: simply supported

6.2.2 Aluminum as Impact Material

The results from Table 6.4 are graphically represented in Figure 6.3.

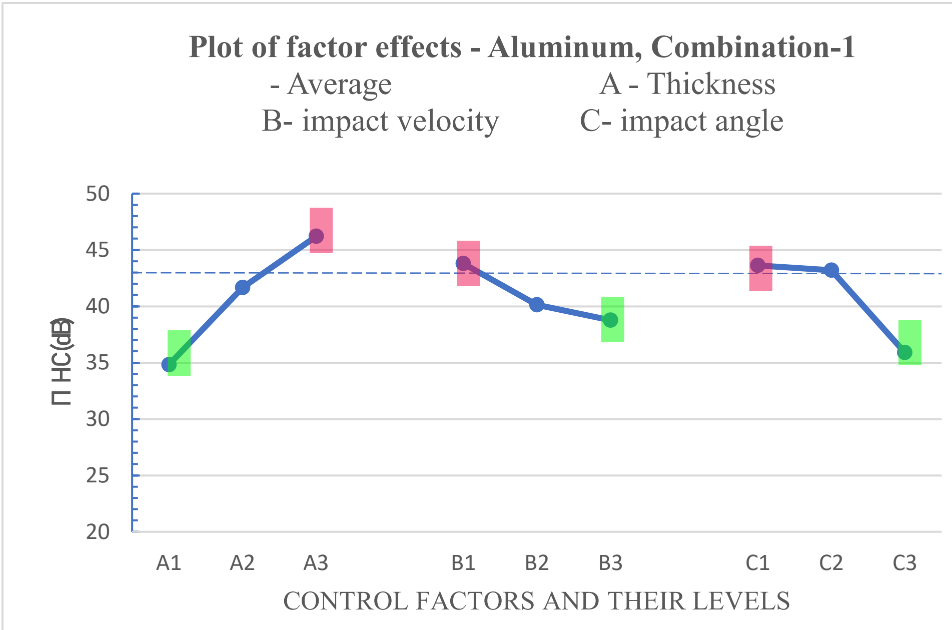


Figure 6.3: Plot of Factor Effects with Aluminum Impact Surface: Combination-1

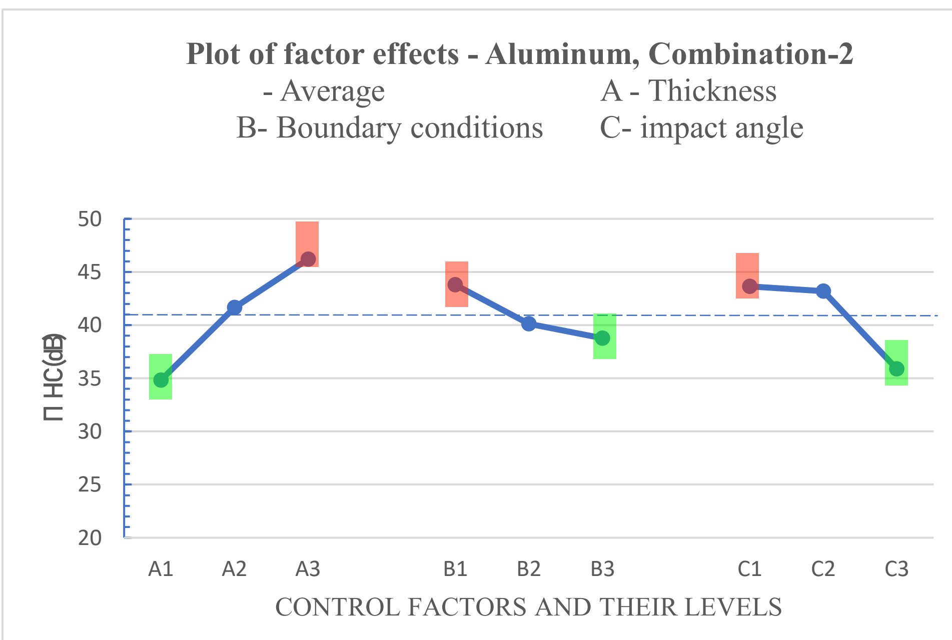


Figure 6.4: Plot of Factor Effects with Aluminum Impact Surface: Combination-2

From both the plots, the optimal conditions for all the parameters yielding lower HIC values are as follows:

- Impact velocity = 9.1 m/s
- Impact angle = 45 degrees
- thickness = 1mm
- boundary conditions = simply supported

From chapter 5, it can be observed that the HIC values are lower (within the permissible range) for the following control factor levels:

- Thickness: 1mm and 1.5mm
- Boundary conditions: two edges supported and simply supported

Even with the thickness being 2mm and in combination with some impact conditions, the head injury values obtained are below the permissible values. However, for higher velocities, which are more than 13.7 m/s, the thickness with 2mm is not optimal.

Therefore, Aluminum being the impact material:

- The optimal thickness range can be from 1mm-1.5mm, depending upon the application.
- Depending on the type of application, both simply supported, and two-edges supported boundary conditions can be used.

CHAPTER 7

ANALYSIS OF VARIANCE (ANOVA)

Analysis of variance (ANOVA) gives a "Quantitative" measure for the relative magnitudes of different factor effects. The relative magnitude is generally derived from the graphs. ANOVA is conducted in this research to obtain the percentage contribution of each factor affecting the head injury criteria (HIC). The percentage contribution leads to the most significant factor affecting the head injury criteria. In this research, ANOVA is needed for estimating the following:

- Error Variance for the factor effects
- Percentage contribution of the factors
- The variance of each factor

7.1 ANOVA Calculations

ANOVA is conducted for both combinations. The S/N values obtained from the chapter DOE, and the factor effects calculations are used in this chapter. These values are used to carry out the calculations for ANOVA [40]. The steps that are followed in ANOVA are described next.

Calculation-1:

- Finding the ANOVA-factor effects
- The ANOVA factor effects are denoted by a_n, b_n, c_n
- a_n= mA_n-μ (7.1)
- b_n= mB_n-μ
- c_n= mC_n-μ

Where mA_n, mB_n, mC_n are the factor effects from DOE and the overall mean (μ) are already calculated in the Chapter 6.

Calculation-2:

- Finding Grand Total Sum of Squares (G_T)
- $G_T = \sum_{i=1}^{9} \eta_i^2$ (7.2)

Calculation-3:

- Find the Sum of Squares due to mean (S_M)
- $S_M = 9 * \mu^2$ (7.3)

Calculation-4:

- Total sum of squares (TSSQ) = G_T - S_M (7.4)

Calculation-5:

- Calculating the sum of squares due to factors (7.5)
- SSQ_A = $3(a_1^2 + a_2^2 + a_3^2)$
- SSQ_B = $3(b_1^2 + b_2^2 + b_3^2)$
- SSQ_C = $3(c_1^2 + c_2^2 + c_3^2)$
- SSQ_D = $3(d_1^2 + d_2^2 + d_3^2)$
- Sum of squares due to all factors (SSQF)= SSQ_A+SSQ_B+SSQ_C+SSQ_D (7.6)

Calculation-6:

- Calculating Degrees of freedom (DF)
- Degrees of freedom are the number of independent parameters or levels associated with a matrix experiment, factor or sum of squares
- DF (matrix experiment) = 9
- DF (overall mean) = 1
- DF (factors) = (3 levels -1) *3 factors =6
- DF (error)= 9-1-6= 2

The above is the calculation for the degree of freedom, and this calculated value is used in further calculation related to ANOVA.

Calculation-7:

- Calculate the Sum of squares due to factors per DF (7.7)
- Sum of Squares due to factor A per DF = SSQ_A/ DF [40]
- Sum of Squares due to factor B per DF = SSQ_B/ DF [40]
- Sum of Squares due to factor C per DF = SSQ_C/ DF [40]
- Sum of Squares due to factor D per DF = SSQ_D / DF [40]

Calculation-8:

- Calculating Percentage contributions of factor effects (7.8)
- %contribution = $\frac{Sum\ of\ squares\ due\ to\ a\ factor}{Total\ sum\ of\ sqaures}$
- %contribution of factor A = $\frac{SSQ\_A}{TSSQ}$
- %contribution of factor B = $\frac{SSQ\_B}{TSSQ}$
- %contribution of factor C = $\frac{SSQ\_C}{TSSQ}$

Calculation-9:

- Calculating the sum of squares due to error
- SSQ_err = TSSQ – SSQF (7.9)
- Calculating the sum of squares due to error / DF = SSQ_err/DF

Calculation-10:

- The variance of the effect of each control factor level (7.10)

  = (Error Variance)/ (repeat no. for CF)

Calculation-11:

- Calculate confidence intervals
- For a 95% confidence interval
  - Choose two standard deviations for error as the confidence interval
  - Confidence interval

= $\pm$2 [SQRT (error variance for each level)] dB (7.11)

7.2 ANOVA DATA

The proceeding calculations are performed stepwise for both combinations. The ANOVA Factor effects for the combinations are tabulated next.

TABLE 7.1

ANOVA FACTOR EFFECTS FOR STEEL WITH COMBINATION-1

Thickness (a_n)	Impact Velocity (b_n)	Impact Angle (c_n)	Misc. (d_n)
-4.81	-5.70	2.28	-0.34
0.83	0.88	0.22	-0.12
3.98	4.82	-2.50	0.46

TABLE 7.2

ANOVA FACTOR EFFECTS FOR STEEL WITH COMBINATION-2

Thickness (a_n)	Boundary Conditions (b_n)	Impact Angle (c_n)	Misc. (d_n)
-3.61	1.54	2.32	0.91
-0.21	-0.09	1.74	-0.20
3.82	-1.45	-4.07	-0.70

TABLE 7.3

ANOVA FACTOR EFFECTS FOR ALUMINUM WITH COMBINATION-1

Thickness (a_n)	**Impact velocity** (b_n)	**Impact Angle** (c_n)	**Misc.** (d_n)
-6.05	-6.28	1.45	-0.13
1.05	0.89	2.10	-0.32
5.00	5.38	-3.55	0.46

TABLE 7.4

ANOVA FACTOR EFFECTS FOR ALUMINUM WITH COMBINATION-2

Thickness (a_n)	**Boundary Conditions** (b_n)	**Impact Angle** (c_n)	**Misc.** (d_n)
-6.07	2.89	2.72	0.31
0.76	-0.77	2.28	-0.14
5.30	-2.12	-5.00	-0.17

The rest calculations are carried out as per the equations mentioned, and the results are tabulated as per the combinations.

7.3 Percentage Contribution for Steel: Combination-1

As per the steps, the calculations are carried out. The previous chapter results were also used for some of the equations, and the following values are obtained:

- Mean = 59.82
- Gt = 32532.76
- Sm = 32208.13

The relative percentage contributions are as follows:

- Thickness (A) - 36.6%
- Impact Velocity (B) - 52.0%
- Impact Angle (C) -10.6%
- Misc. E (D) - 0.8%

The total sum of the percentage contributions is 100%. In this combination, the impact velocity has a higher percentage contribution towards the variation in HIC, the thickness being the second highest contributing factor. The percentage contribution of the factors affecting the variation in the HIC evaluation for Steel: Combination-1 are shown in Figure 7.1.

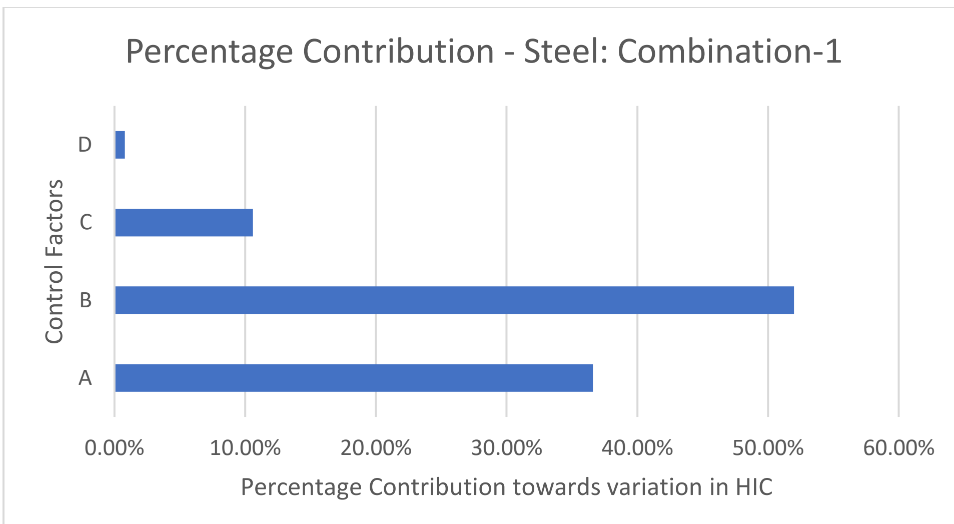


Figure 7.1: Percentage Contribution of Factors - Steel, Combination-1

7.4 Percentage Contribution for Steel: Combination-2

As per the steps, the calculations are carried out. The previous chapter results were also used for some of the equations, and the following values are obtained:

- Mean = 58.27
- Gt = 30739.49
- Sm = 30563.42
- The Percentage Contributions are as Follows for Steel impact surface:

– Thickness (A) - 47.1%

– Boundary Conditions (B) - 7.6%

– Impact Angle (C) - 42.5%

– Misc. E (D) - 2.8%

The total sum of the percentage contribution is 100%. In this combination, thickness has a higher percentage contribution towards the variation in HIC followed by, impact angle. Miscellaneous factors like the friction between the head and the impact material contribute around 2.8%. As the simulations are carried out by free-motion head form, there are no other factors other than friction coming into the play. Therefore, it is concluded that friction is also one of the factors contributing towards the head injury. The percentage contribution of the factors affecting the variation in the HIC evaluation for Steel: Combination-2 are shown in Figure 7.2

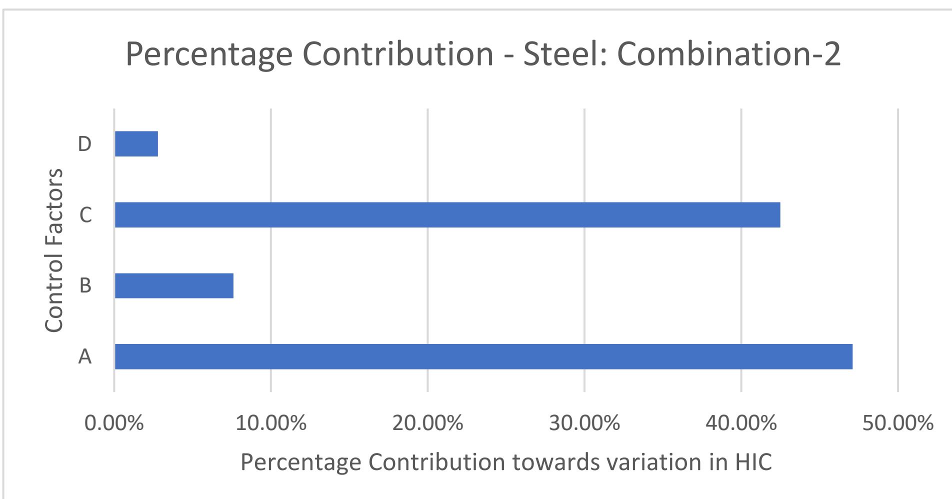


Figure 7.2: Percentage Contribution of Factors - Steel, Combination-2

7.5 Percentage Contribution for Aluminum: Combination-1

As per the steps, the calculations are carried out. The previous chapter results were also used for some of the equations, and the following values are obtained:

- Mean = 44.24

- Gt =18073.61
- Sm =17618.66

The Percentage contributions for Aluminum impact surface:

- Thickness - 41.3%
- Impact Velocity - 45.6%
- Impact Angle - 12.6%
- Misc. E (D) - 0.5%

The total sum of the percentage contributions is 100%. In this combination, the impact velocity has a higher percentage contribution towards the variation in the HIC, the thickness being the second highest contributing factor. The percentage contribution of the factors affecting the variation in the HIC evaluation for Aluminum: Combination-1 are shown in Figure 7.3.

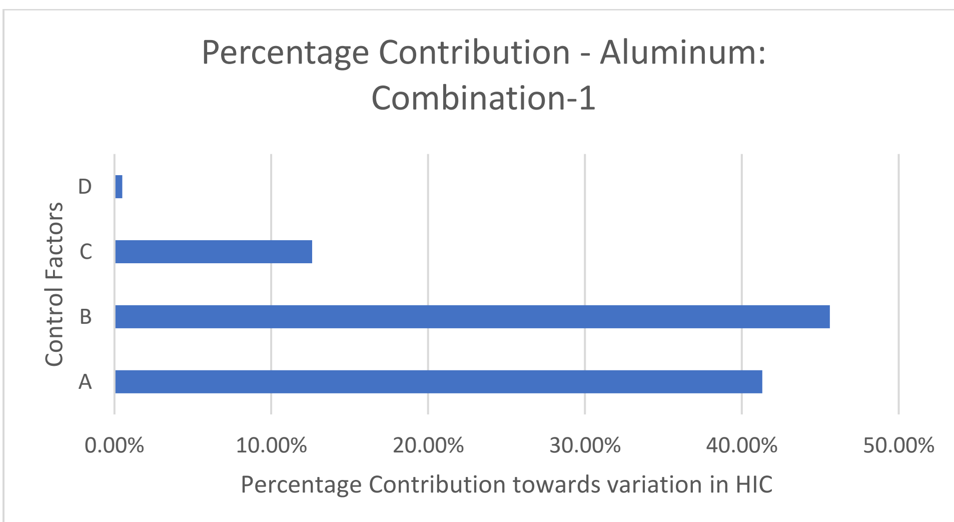


Figure 7.3: Percentage Contribution of Factors - Aluminum, Combination-1

7.6 Percentage Contribution for Aluminum: Combination-2

As per the steps, the calculations are carried out. The previous chapter results were also used for some of the equations, and the following values are obtained:

- Mean = 40.90

- Gt= 15411.48
- Sm= 15060.43
- After Performing the DOE Calculations, The Percentage Contributions are as Follows for Steel impact surface:
  - Thickness (A) - 56.0%
  - Boundary Conditions (B) - 11.0%
  - Impact Angle (C) - 32.0 %
  - Misc. E (D) - 1.0%

The total sum of the percentage contribution is 100%. In this combination, thickness has a higher percentage contribution towards the variation in HIC followed by, impact angle. Miscellaneous factors like the friction between the head and the impact material contribute around 1.0%. As the simulations are carried out by free-motion head form, there are no other factors other than friction coming into the play. Therefore, it is concluded that friction is also one of the factors contributing towards the head injury. The percentage contribution of the factors affecting the variation in the HIC evaluation for Aluminum: Combination-2 are shown in Figure 7.4.

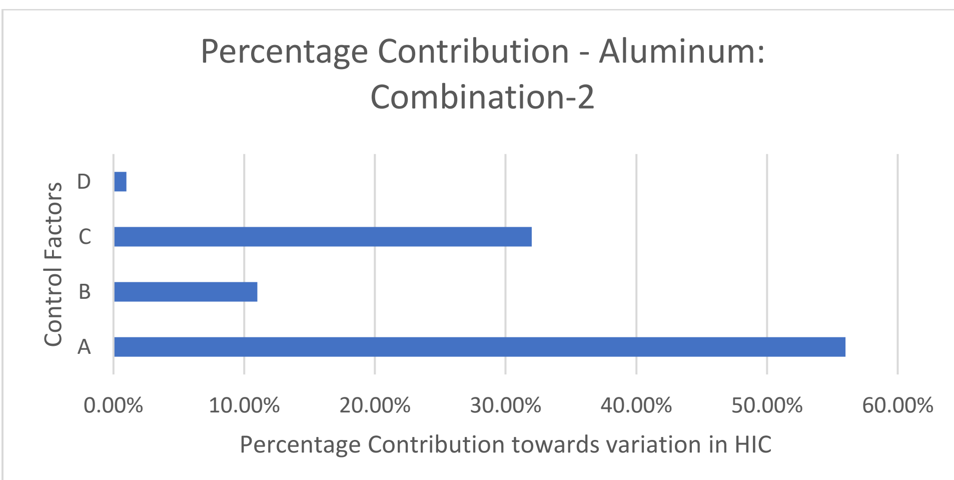


Figure 7.4: Percentage Contribution of Factors - Aluminum, Combination-2

7.7 Variance of Different Control Factors

By using the equations shown in calculations 10 and 11(Equations (7.10) and (7.11)), the variance of each control factor levels are calculated, and the following results are obtained:

- The variance for the factors affecting Steel as impact material with Combination-1 setting is $\pm$ 0.228 dB
- The variance for the factors affecting steel as impact material with Combination-2 settings is $\pm$ 0.226 dB
- The variance for the factors affecting Aluminum as impact material with Combination-1 setting is $\pm$ 0.438 dB
- The variance for the factors affecting Aluminum as impact material with Combination-2 setting is $\pm$ 0.228 dB

The variance levels for steel and Aluminum with both the combination settings are plotted. These plots are depicted in the Figures (7.5) through (7.8).

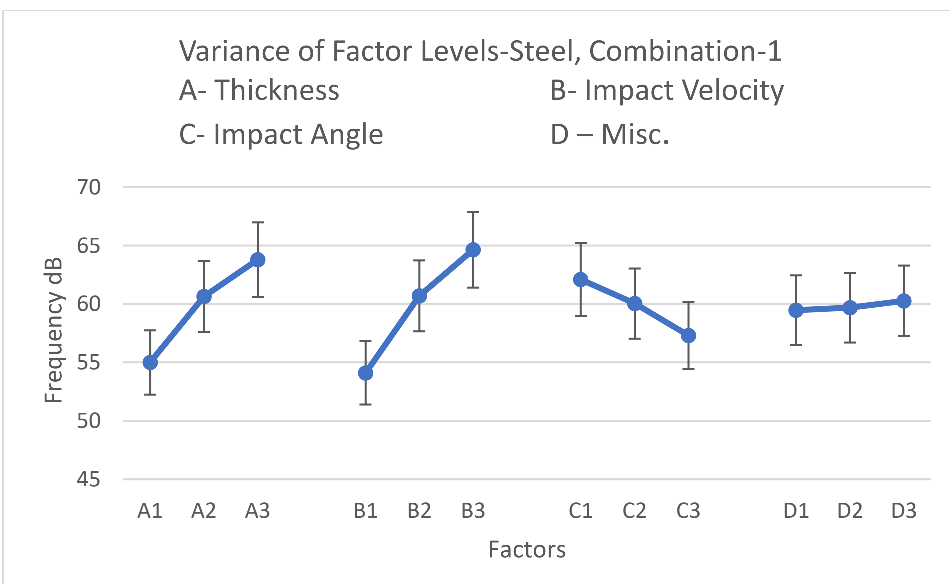


Figure 7.5: Variance of Factor Levels-Steel, Combination-1

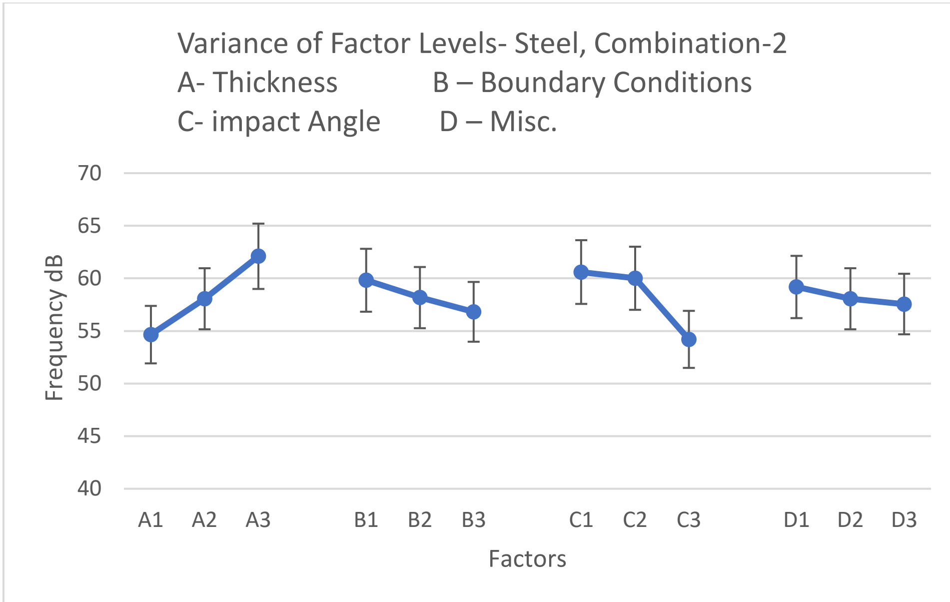


Figure 7.6: Variance of Factor Levels-Steel, Combination-2

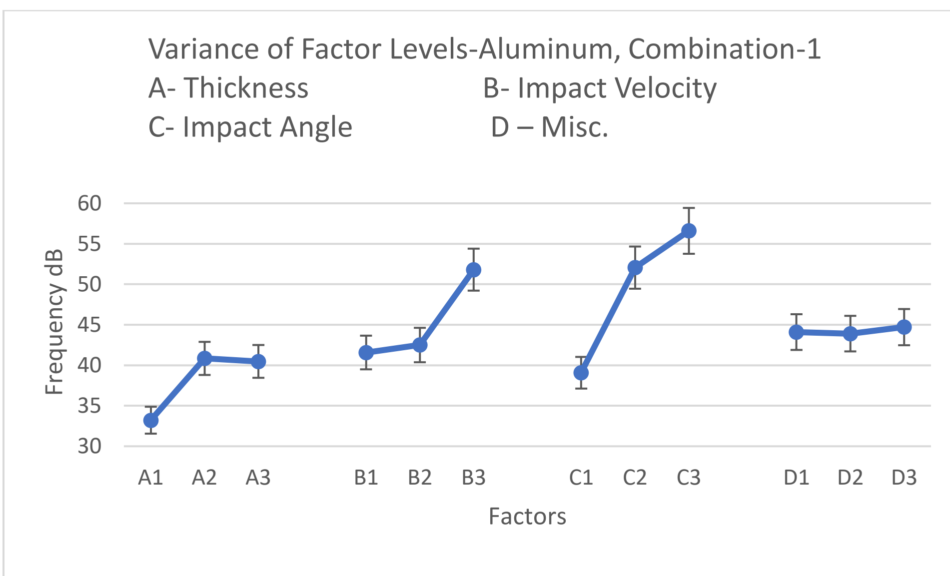


Figure 7.7: Variance of Factor Levels-Aluminum, Combination-1

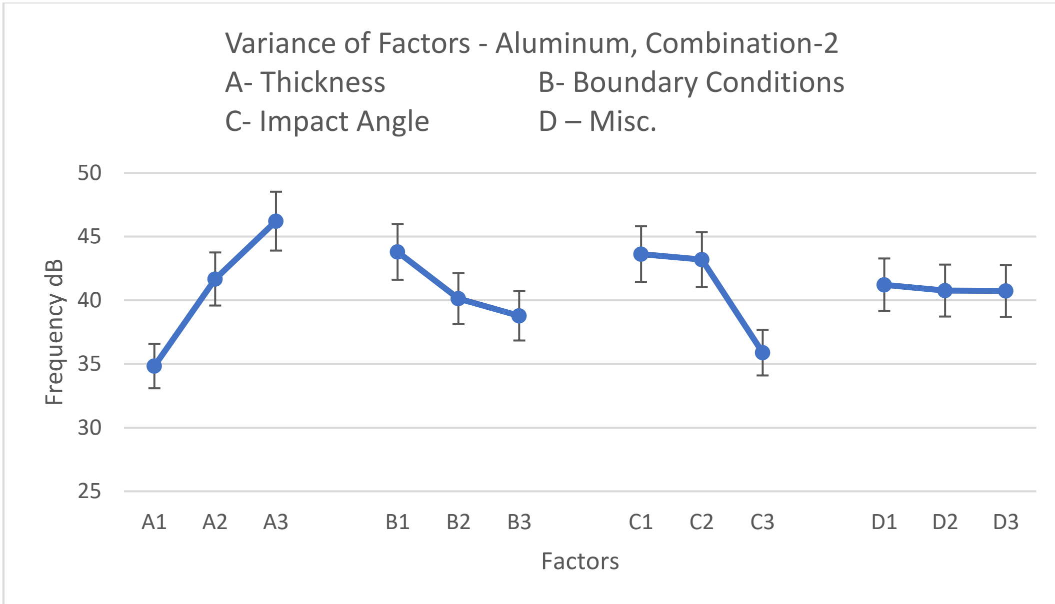


Figure 7.8: Variance of Factor Levels-Aluminum, Combination-2

7.8 Observations

For the Steel and Aluminum being the impact material with Combination-1 and Combination-2 settings, the following are observed.

- In impact condition, impact velocity has more influence compared to the impact angle.
- In target conditions, the thickness is the most influential factor leading to higher injuries.
- Overall, impact velocity is the highest contributing factor towards higher head injuries, followed by material thickness.
- The boundary conditions have a practical impact in absorbing the impact energy, leading to minor contribution towards higher values of head injuries.
- The boundary conditions in Steel have a lesser impact compared to Aluminum.
- As Aluminum is a softer material, the impact energy absorption is much higher than Steel.
- From sections 7.3 through 7.6, it is observed that friction also contributes towards the head injuries. The higher the friction is, the higher is the HIC.

- The friction/ misc. factor contribution in Aluminum is lesser, nearly half the value of Steel. This is due to the stiffness variation in between the materials.
- It is observed that for Combination-1 setting, the variance confidence interval levels for Aluminum are nearly two times to that of the Steel confidence intervals. This represents the softness properties of both the materials.

Overall, it is observed that the impact conditions are more influential and dominant then target conditions. It is also observed that, altering the target conditions to their optimal levels can tame the impact conditions, which would lead to higher head impact safety.

CHAPTER 8

CONCLUSIONS AND RECOMENDATIONS

8.1 Conclusions

The objective of this study was to investigate the most influential parameters affecting the Head Injury Criteria. The effect of material properties, thickness, boundary conditions, impact-velocity and impact angles on the head injury were studied. The design of experiments is conducted in order to observe the effects of different combinations of impact and target conditions on to the Head Injury Criteria. The Taguchi methodology was utilized for analyzing the factor effects. This was also used for optimizing the material parameters. The ANOVA approach was used to study the relative contribution of both target conditions and impact conditions. A sensitivity analysis was carried out to investigate the influence and domination of factor effects on to the head injury and, internal interactions between the factors as well. Finally, the optimized design conditions for both Steel and Aluminum were predicted.

The evaluation of the impact condition range was carried. This evaluation was carried out by using multibody dynamic software, and the range for the impact conditions was obtained. The obtained impact conditions range were generic; i.e., applicable for both automobile and aircraft scenarios. It was observed that the peak impact velocities obtained for both aircraft (FAR Part 23 passenger and FAR Part 25 passenger) and automobile frontal crash were in between the range of 30 ft/sec (9.1 m/s) and 45 ft/sec (13.7 m/s). The impact angles obtained for both aircraft (FAR Part 23 and FAR Part 25) and automobile frontal crash scenario were in between the range of 0 degree to 45 degrees. The obtained results were used as the control factor levels in DOE. HIC component testers were compared in this research. This was achieved by comparing the data from the bowling ball tester with a free-motion headform tester simulation. The bowling ball tester was modeled in

MSC. ADAMS – View and the free-motion headform tester was modeled in LS-Dyna with bulkheads being rigid. A comparison difference of 5% was obtained when both the tester simulation results were compared. From the results, it was observed that the thickness and constrainment of degrees of freedom contributes a vital percentage towards the head injuries. Therefore, energy absorbing panels were used. The values obtained in LS-Dyna were much precise. It was also observed that the bowling ball tester had a limitation in representing the deformation of the target models. Therefore, the remaining research was conducted by using the free-motion headform model. There was an ease in using the free-motion headform model, which were impacted on different materials at different levels of impact angles and impact velocities.

The DOE was carried out by using the impact conditions range and with different boundary conditions. As the analysis was conducted on both impact conditions and target conditions, two combinations of different factors were used. This helped in studying the effects of interaction between the factors. The Combination-1 (impact material and boundary conditions as noise factors) showed the effect of the impact conditions. While the Combination-2 (impact material and impact velocity as noise factors) showed the effects of target conditions. The S/N analysis was carried out as per the steps, and the following was observed:

- In Combination-1, the factor levels setting with the thickness being 2mm, impact velocity was 13.7 m/s and impact angle being 0 degree, yielded the highest injury rate for both Steel and Aluminum impact surfaces.
- In Combination-2, the factor levels setting with the thickness being 2mm, with boundary conditions being two edges supported with impact angle being 0 degree, yielded the highest injury rate for both Steel and Aluminum.

- By comparing the Combination-1 and Combination-2, it was observed that the impact velocity and material thickness in the Combination-1 had much impact on the head injury criteria. Whereas, in the second combination it was observed that the material thickness and impact angle had much impact on to the Head Injury Criteria.

The factor effects calculations were carried out to obtain the optimal design thickness and boundary conditions for both Steel and Aluminum. From the results, the following was observed and concluded:

- Steel being used as any of the interior components/ target components in both automobile and aircraft, the thickness should be constrained within the range of 0.1mm- 0.75mm with boundary conditions as simply supported.
- Aluminum being used as any of the interior components/target components in both automobile and aircraft, the optimal thickness to be used should be no more than 1.5mm with boundary conditions as simply supported and two-edges supported.
- Depending on the interior component design and application of the component, the thickness and the boundary conditions can be varied.

Finally, the Analysis of Variance was conducted to obtain the percentage contribution of each factor. From the results, the following were observed:

- Impact velocity is the highest contributing factor towards higher head injuries, followed by material thickness.
- It was observed that the impact conditions are more influential and dominant then target conditions. It was also observed that, altering the target conditions to their optimal levels can tame the impact conditions leading to higher head impact safety.

The benefit of factorial analysis was demonstrated in this research to find the relative percentage contributions of different factors affecting the variation in the HIC evaluation.

8.2 Recommendations

The following recommendations are provided in extending the current research.

- For the impact surface, a softer material which has lower stiffness can be considered, and corresponding optimal parameters can be obtained.
- More control factor levels can be used for ANOVA to examine the interaction effects on to variation in the HIC evaluation.
- For automotive conditions, a similar testing procedure can be used on different interior components. This way, the optimal parameters for different components can be obtained, and there will be an increase in the head safety.
- Different dummy head forms can be used ranging from female to child, and the responses can be a guideline for further research.
- Different impact conditions can be tested at different target points out through the impactor.
- This study is restricted to front-row passengers. Therefore a "row- to -row" analysis can be carried in the case of aircraft and a rear passenger analysis in automotive.
- This study can be carried out in MSCADAMS-Flex version and can be compared.
- This analysis can be carried out on different materials such as glass, wood, etc., and the optimal parameters for them can be obtained.
- As the impact velocity and impact angle are related with distance, if the seat setback distance from the bulkhead and steering are set to an optimal distance (>35 feet for aircraft and >18 feet for the automobile), there would be lesser injuries.

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