LAWRENCE TECHNOLOGICAL UNIVERSITY

A. Leon Linton Department of Mechanical Engineering

The Prediction and Optimization of Side Door Closing Efforts for Passenger Cars

Presented in partial fulfillment of the requirements for the degree of

Doctor of Engineering in Manufacturing Systems (DEMS)

by

Mukdam Kena

DEMS Committee

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This dissertation has been reviewed and accepted by the examination committee.

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ABSTRACT

The door is the first system to interact with a vehicle's driver. It allows entry into the vehicle; therefore, priority has been given to its performance. The number of studies by automotive door engineers has increased during the past years, while the customer and the market have changed their quality standards.

The door closing effort is a quality issue concerning automobile designers and customers. However, the precise prediction of the door closing energy hasn't been fully developed.

The functions of the automotive door seals are to prevent dust and water from entering the vehicle and to isolate noise. To achieve these design targets, a door seal should have a reaction force higher than a specific criterion, while the effort to close the door requires a minimum reaction force. A door-seal design can be defined as a process of compromise between these two reciprocal design targets.

Automotive weatherstrip seals are used in between the doors and vehicle body along the perimeter of the doors. Door sealing is one of the most important automotive quality issues. The design and manufacturing process are important aspects for functionality and performance of the sealing system. However, door sealing involves many design and manufacturing factors.

In this dissertation, a mathematical model is developed to predict the door closing effort. Response surface methodology enables the development of second order models that accurately describe the responses by conducting Design of Experiment (DOE) for the desirability function with seal gap data from the assembly plant and the Compression Load Deflection (CLD) data.

This approach is applied to create a balanced solution and to find the optimal set of control variables by optimizing the side door closing effort. The variables used are the five different seal segments for the secondary seal and the CLDs for the primary and secondary seal. The goal of this study is to optimize the closing effort by optimizing the seal gap variation for the secondary seal and to optimize the manufacture tolerance for the primary and the secondary seals CLDs; also, identify which seal segment is the main contributor for side door closing effort. These results are particularly helpful in developing and optimizing weather strip designs by computing efforts toward door-seal designs.

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NOMENCLATURE

ABAQUS	A Software Used to Predict the Compression Load and Permanent Deformation of 3D Full Vehicle
ADAMS	Automatic Dynamic Analysis of Mechanical Systems
C.G	Center of Gravity
C_1	Isentropic Constant for Air
CAD	Computer-Aided Design
CAE	Computer Aided Engineer
CAT	Computer-Aided Technique
CLD	Compressed Load Deflection
DIW	Door-In-White
DOE	Design of Experiment
DVA	Design Verification Analysis
EPDM	Ethylene Propylene Diene Monomer
FEA	Finite Element Analysis
HVAC	Heating, Ventilation and Air Conditioning
IQS	Initial Quality Study
L	Door Length
MPP	Most Probable Point
NVH	Noise, Vibration, and Harshness
θ	Door Hinge Angle (Radians)
P	Internal Cabin Pressure (Pascal)

Primary Seal	Seal Mounted to the Door
PRV	Pressure Relief Valve
RSM	Response Surface Methodology
Secondary Seal	Seal Mounted to the AB Flange for the Body Side
V	Total Volume of Control Volume (m^3)
V_{in}	Internal Volume (m^3) of the Cabin, Include the Trunk
VOW	Vehicle on the Wheel
I_D	Mass Moment of Inertia of Door
r_{cm}	Distance from the Center of the Gravity to the Hinge Axis
r_v	Radius to Velocity Gauge
$\dot{\omega}$	Time Derivation of Angular Velocity
A	Air Extractor Area (m^2)
A_1	Constant Exit Area (m^2)
A_2	Area Between the Closing Door and Body
C_m	Mass Center of the Door
h	Distance Between the Upper Hinge and the Lower Hinge
K	Flow Coefficient
T_{hinge}	Torque Around the Hinge
X_u	Upper Hinge Coordinate Point
X_u	Lower Hinge Coordinate Point
ρ_{atm}	Atmospheric Density (kg/m^3)
CDDCE	Customer Desired Door Closing Energy

1. BACKGROUND

1.1 Introduction

The door is the first system to interact with a vehicle's occupant, thus allowing entrance into the vehicle. Therefore, great importance has been given to its performance in all requirements. Automotive door related studies have increased in the past years as the markets have changed their requirements to improve the customer satisfaction.

The minimum door closing speed is an important target in vehicle door design. Engineers need a proper method to evaluate the door closing speed during the design phase.

There are many factors that affect the side door closing efforts as shown in Figure 1. The main factors that have been considered are:

- Cabin pressure or the air compression
- Seal compression
- Hinge axis and friction
- Door latching mechanism and striker (or latch anchor)
- Door Check-Link
- Overslam bumper

The door closing effort is one of the quality issues concerning both automobile designers and customers. It gives a first impression of the quality of the vehicle. If a large effort is needed to close the door, the vehicle is usually perceived as of having poor quality. This is directly linked to a "not pleasing" door closing sound [1]. It is usually necessary to reduce the door closing efforts without sacrificing the weather sealing and the acoustic insulation requirements [2].

A mathematical model will be used to calculate and predict the side door closing efforts. A variety of seal gaps, segment lengths, and weatherstrips CLDs will be used to predict the response functions.

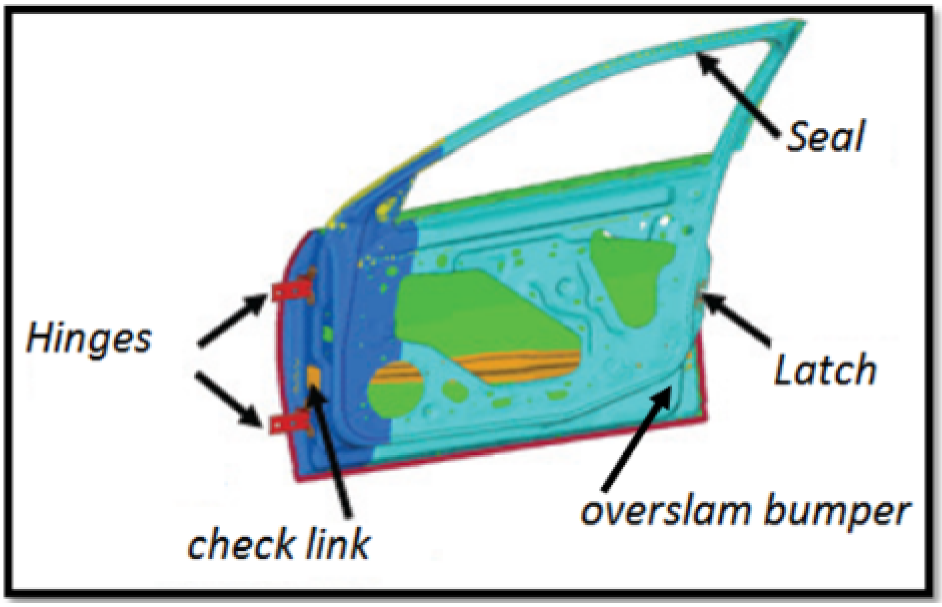


Figure 1. The Vehicle's Side Door Showing the Closing Effort Parameters [3]

The door closing energy mainly consists of five components: the energy losses due to cabin pressure, seal loading, door weight, latch effort, and hinge friction. The first component is caused by the pressure rise in the cabin when the door pushes the air ahead of itself. The seal loading loss is due to the seal compression, and it represents the work to compress the seal. The third loss takes into account the energy contributed by the door weight when the hinge axis is tilted and, therefore, is not vertical [4]. The latching effort and frictional losses at the hinges are also considered. The non-linear interaction of the door gap, seal load, door weight, latch effort, and hinge friction is calculated using an incremental time stepping numerical scheme.

The mathematical model has the potential to provide a rational prediction of closing efforts by assuming that the input data is complete and consistent. The model can be easily used in parametric studies during the design process of a door closure system. The door assembly components are defined as follows: door frame, door inner panel, window system, door mechanism, mirror system, sealing system, hinges, speaker system, power system and power controls as shown in Figure 2 and 3.

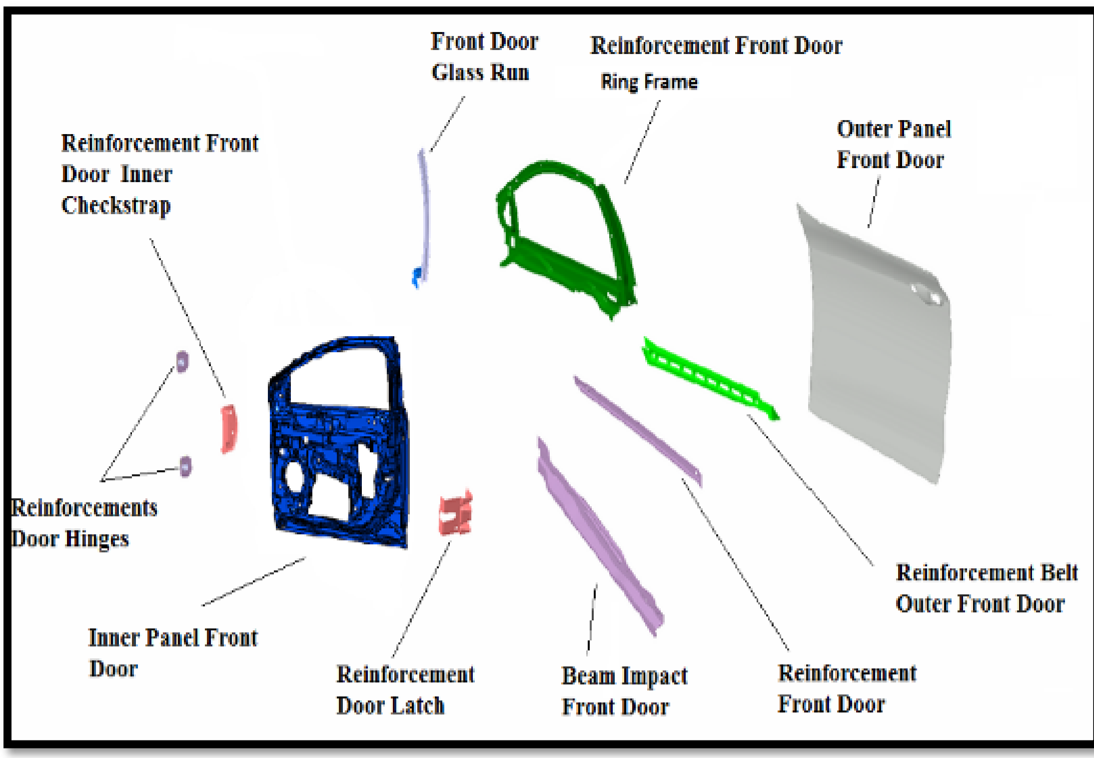


Figure 2. Door Frame Components and Reinforcements [5]

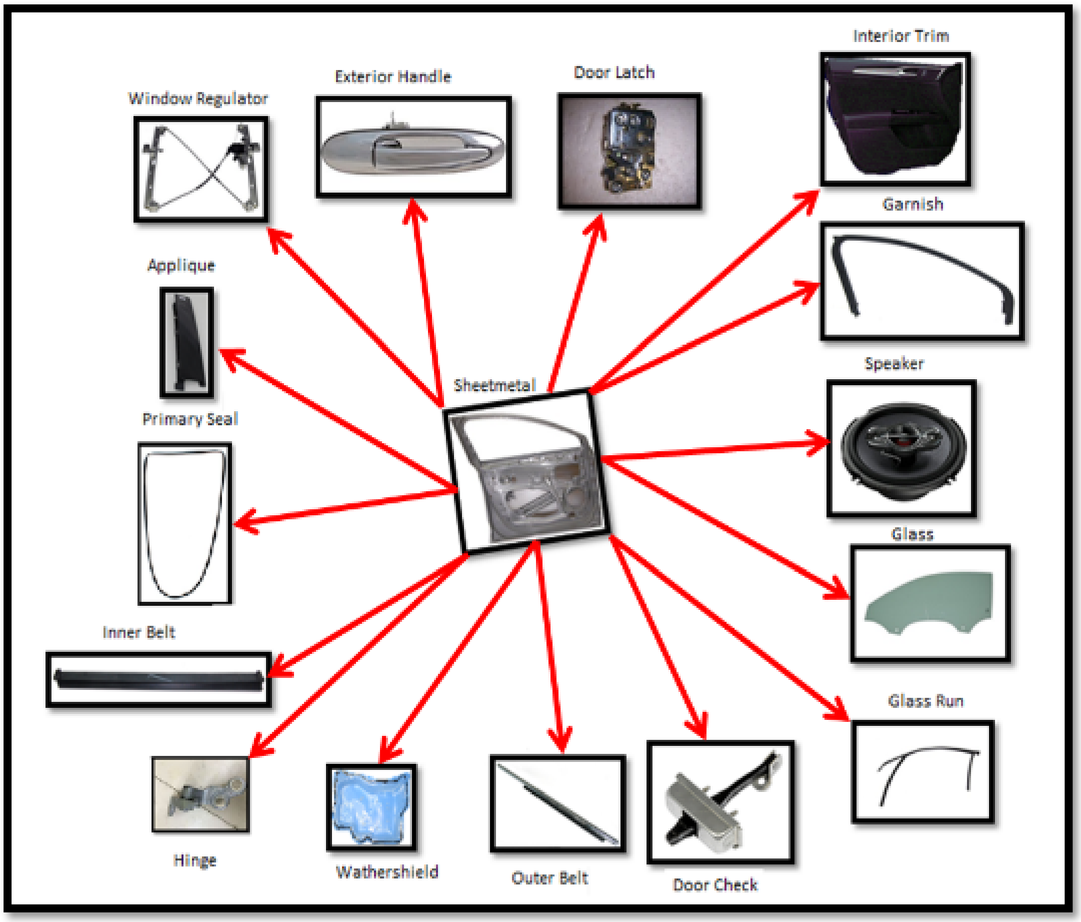


Figure 3. The Main Door Components

1.2 The Main Factors Related to Door-Closing Performance

Geometrical and physical factors of an automotive body must be measured precisely to evaluate the minimum door-closing velocity, which is a criterion of door-closing performance.

1.2.1 Air Compression

The energy loss due to air bind is a substantial contributor to the overall door closing energy. When the air pressure in the inner cabin is greater than the atmospheric pressure, discharged air flows out through cabin pressure relief valve-also called an air extractor and the door opening. However, the airflow path during a door-closing action has been illustrated in Figure 4. The closing door pushes the air ahead of itself and creates a pressure rise in the vehicle called the pressure spike as shown in Figure 5. Air pressure inside vehicle produces a torque on the door, slowing the door velocity. This must be overcome to close and latch the door [6].

The mathematical model will consider the door open detent angle 8° which means 0.25 seconds from the closing time. Because this is the first contact of the door's weatherstrips, the air flow out between the door and the body in Figure 4 is negligible in the mathematical model for this dissertation.

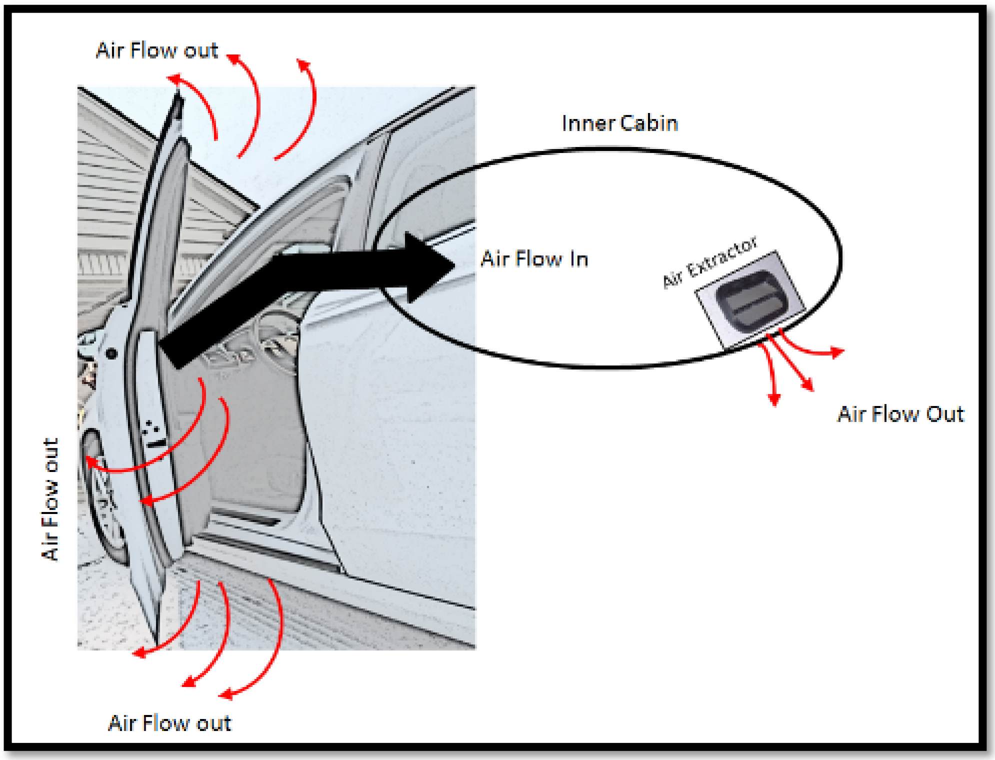


Figure 4. Airflow Path During a Door-Closing Action

The air pressure leaves the cabin with an air path flow through the air extractors as shown in the Figure 4. An air extractor is shown in Figure 6.

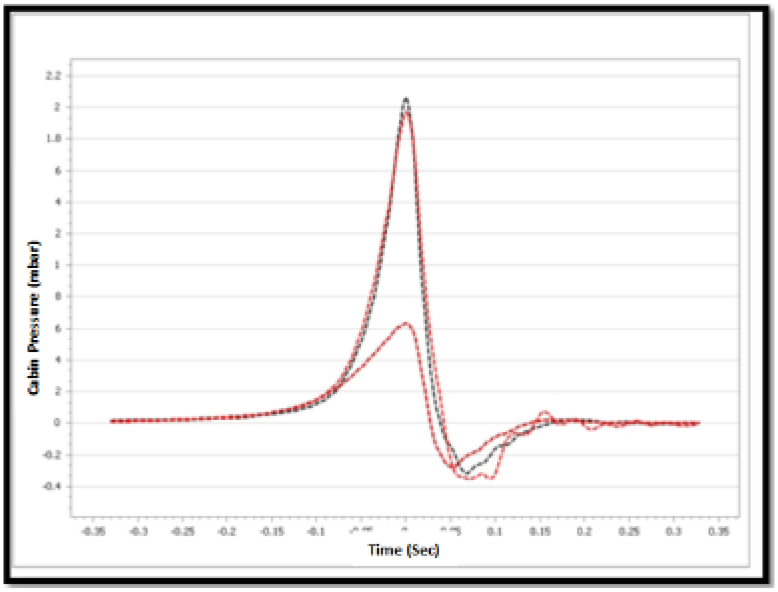


Figure 5. The Air Pressure Spike [7]

Figure 6. The Air Extractor

These air extractors are necessary because vehicle cabins today are practically sealed air tight to prevent exterior noises from entering the passenger cabin and lowering the perceived quality of the vehicle. Since the cabins are sealed, any air source can build up pressure in the vehicle cabin when the windows are closed. This can either be caused by the heating, ventilation and air conditioning (HVAC) system or by the door closure event. Any perceptible increase in cabin pressure also lowers the perceived quality of a vehicle. Thus, the air extractors are installed in the vehicle to relieve the steady state airflow from HVAC or the pressure pulse wave from the door closure event. The air extractors also serve the purpose of allowing airflow so that the HVAC can defrost the windows properly [8].

Usually, the air extractors are located in the rear quarter panel as shown in Figure 7 behind the rear bumper, but sometimes they are located in the back panel for packaging issues. Either way, they need to have a clear airflow from the cabin to the air extractors and minimize the blockage.

Figure 7. The Air Extractor in the Rear Quarter Panel for a Vehicle

1.2.2 Seal Compression

Weather-strip seals are typically extrusion bulbs made of elastomers that are attached to either the car door or the car body in order to seal the vehicle [9].

Door sealing accounts for a substantial portion of the door closing effort [10]. Geometrical and topological parameters of seal cross-section, as well as the appropriate rubber material's property, would result in a desired (CLD) and door- closing performance in the end [11].

Each seal in a sealing system has a different function. The primary seal carries the majority of the burden in preventing the outside elements (wind, water, and noise) from entering the closures compartment. The margin and auxiliary seals act as supporting seals to improve the resistance of the closures panel in preventing the outside elements from entering the compartment [12].

There are typically two configurations of sealing systems. Figure 8 illustrate a level 1 sealing system that consists of one continuous sealing loop on the body. In this system, the primary seal is called the body primary. This style of sealing system is not recommended due to poor attribute performance.

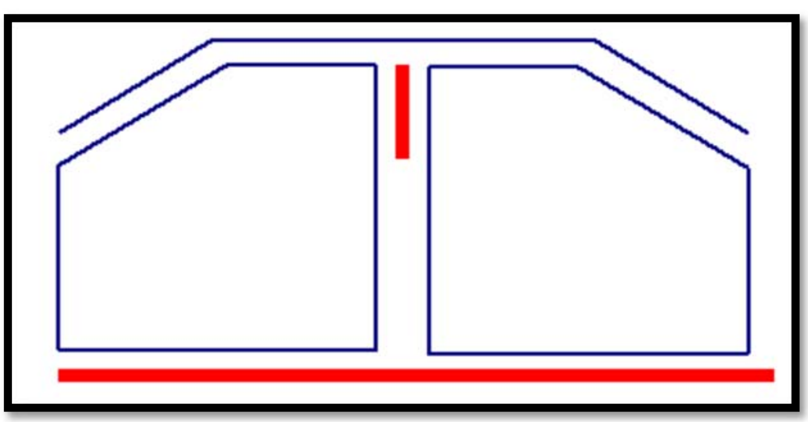


Figure 8. Level 1 Sealing System [13]

A level 2 sealing system is more common for the lower car as shown in Figure 9. This sealing system consists of one continuous sealing loop around the door and another loop around the body.

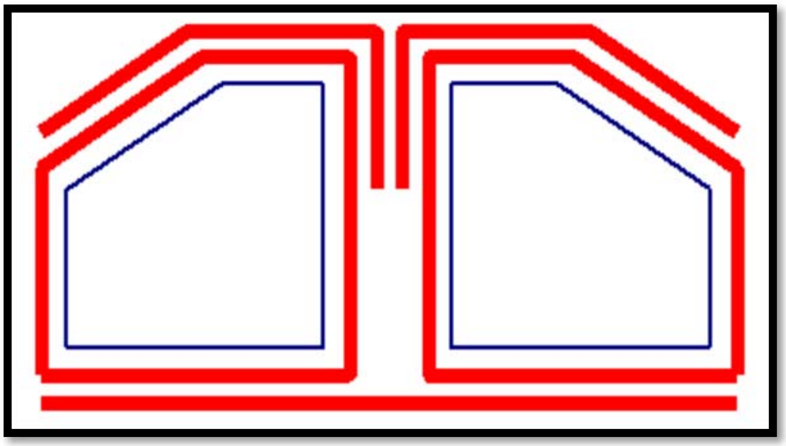


Figure 9. Level 2 Sealing System [14]

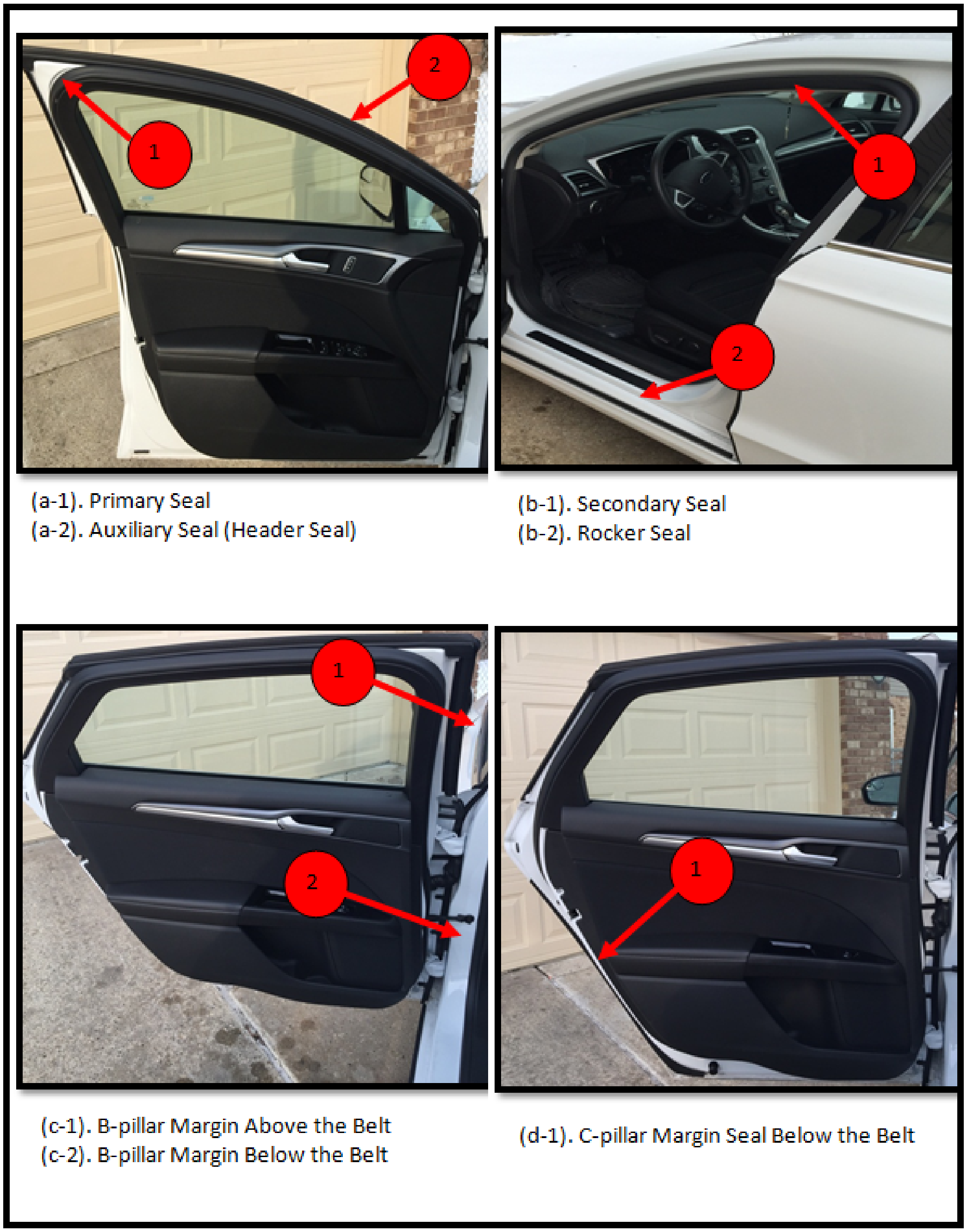
This dissertation will focus on the level 2 sealing system, so the main contributors of the dynamic seals are the primary and the secondary seals.

1.2.2.1 Primary Seal

The first continuous primary barrier against the exterior environment is shown in Figure 10-a-1). The principal functions of the primary seal are to:

- Prevent freezing resistance
- Optimize the path of the water for diverting it away from the vehicle occupants
- Apply the majority of seal load on the door system
- Protect from leakage of wind, water, and dust entry around doors
- Reduce the transmission of noise from outside the vehicle

- Prevent the entry of fumes through the margins and around vehicle closures.



(a-1). Primary Seal
(a-2). Auxiliary Seal (Header Seal)

(b-1). Secondary Seal
(b-2). Rocker Seal

(c-1). B-pillar Margin Above the Belt
(c-2). B-pillar Margin Below the Belt

(d-1). C-pillar Margin Seal Below the Belt

Figure 10. The Compressed Seal

1.2.2.2 Secondary Seal

The secondary seal in level 2 sealing system is installed on the body flange (Figure 10-b-1) to work as a noise reduction barrier. This seal is typically mounted on the body flange, and it is the second continuous bulb seal. The main function of the secondary seal is to prevent wind noise. The other functions for this seal include:

- minimizing the view of exposed paint for the customer when he is inside the vehicle
- covering the AB-flange on the body
- hiding the flange spot welding around the door opening
- providing interfacing to the seal and interior trim components
- aiding minimal door closing efforts
- working as a secondary barrier against outside elements (water, wind, and dust)

1.2.2.3 Rocker Seal

The rocker seal is usually attached to the body rocker (Figure 10-b-2) and sometimes to the door rocker of the lower door to reduce road noise.

The main functions of the rocker seal are follows:

- prevents ice and snow buildup in rocker area
- prevents dust accumulation into vehicle via open door drain holes
- adds additional door rust protection from road salt
- adds NVH (Noise, Vibration, and Harshness), barrier for door drain holes and the open rocker cavity
- minimizes NVH and specifically, low frequency noise from road surface and tires
- allows for a clean rocker by reducing soiling clothing and mud intrusion

1.2.2.4 Auxiliary Seals

The auxiliary seals can be classified as A- Pillar Seal, B-pillar Seal, C-pillar Seal, Margin Seal and the Header Seal (Figure 10- (a-2),(c-1), (c-2) and (d-1)) .

The main functions for the auxiliary seals are:

- to cover the body weld flange
- to work as water management keeping the water away from the body's primary weather-strip
- to close off the A-pillar/roof margin for reducing wind noise [14]

1.2.3 Hinge Axis and Friction

Hinge axis and friction are main factors which directly affect closing efforts. In order to reduce the door closing effort, the door hinge axis is typically tilted towards the inside of the vehicle thus increasing the hinge assist energy to close the door Figure 11.

During door closing, the pair of hinges works to overcome friction against the bushings. Hinges are also responsible for holding door weight while open. Estimating the necessary torque spent on overcoming friction may lead to understanding the energy for the hinges [15]. Hinge axis of the front view has a stronger effect on door closing than one of the side view. The energy to close the door could be minimized and optimized through declining hinge axis, which reduces the effort to swing the side door. Hinge axis is another significant factor that could objectively and subjectively improve the closing velocity of the side door. However, the hinge axis could be declined as much as possible when the slope-way achievement is satisfied. Hinge axis is related to check-link effort, which is illustrated later in section 1.2.5 [16], and door mass energy with center of gravity.

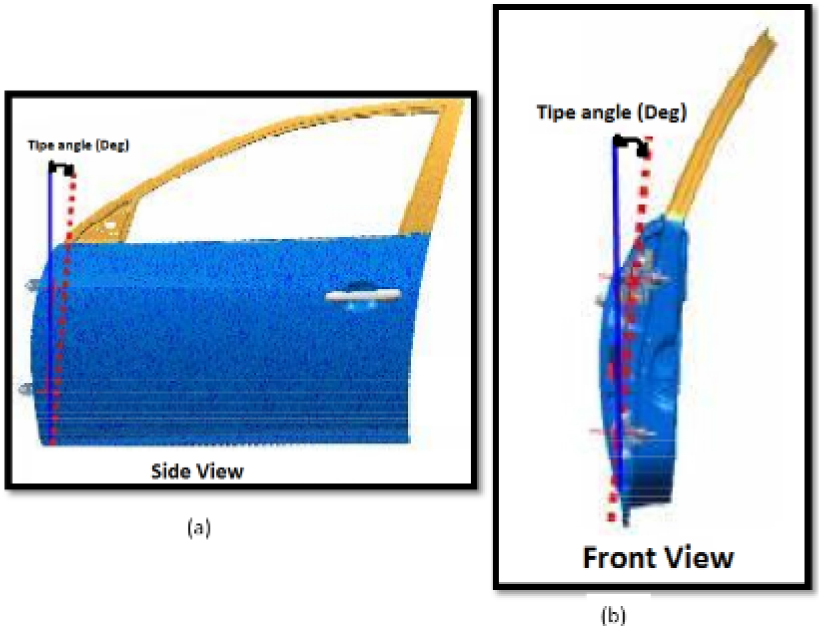


Figure 11-a & b: Hinge Tip Angle Side and Front View [17]

1.2.4 Door Latching Mechanism and Striker

The door of a vehicle is equipped with a latch to lock the door to the body in the closed position. The other main use of the latch is to prevent unauthorized entry to the vehicle [18].

The latch sinks energy which is related to the latch mechanism operation. The latch can be either manually operated or powered by a motor and usually consists of rigid and elastic elements (articulated bars, cams, springs, and levers) and an actuator in the form of a locking lever.

The striker movement that pushes the ratchet inside the latch will be considered in this dissertation. The ratchet is restricted by the pawl and its spring. Because of the surface contact between ratchet and pawl, it is accounted an energy portion related to friction.

The rubber bumper is located at the end of the ratchet route and makes a small interference, so it absorbs an amount of energy then stored in the bumper deflection [19]. The requirements involve a minimum performance in terms of loads both in the primary position (fully latched door) and in the secondary position (partially engaged system).

Latch energy may be expressed as a set of three positions: the primary latching position, the second latching position and the over travel position. A minimum load is required for these three positions.

Since the latching system is exposed to the environment, it must also withstand exposure to water, ice, dust, dirt, and very high and very low temperatures. The latch locks the door by hooking to the striker. The striker is placed on the car's body as shown in Figure 12 and 13. One of the main factors of higher closing effort is misalignment between the latch and the striker. It is important for the latch and the sticker to be in complete alignment. This will result in the best fitting of the door to the body, thus achieving unwanted friction between the components and resulting in minimum closing efforts [14].

Figure 12. The Latch (1) and the Striker (2)

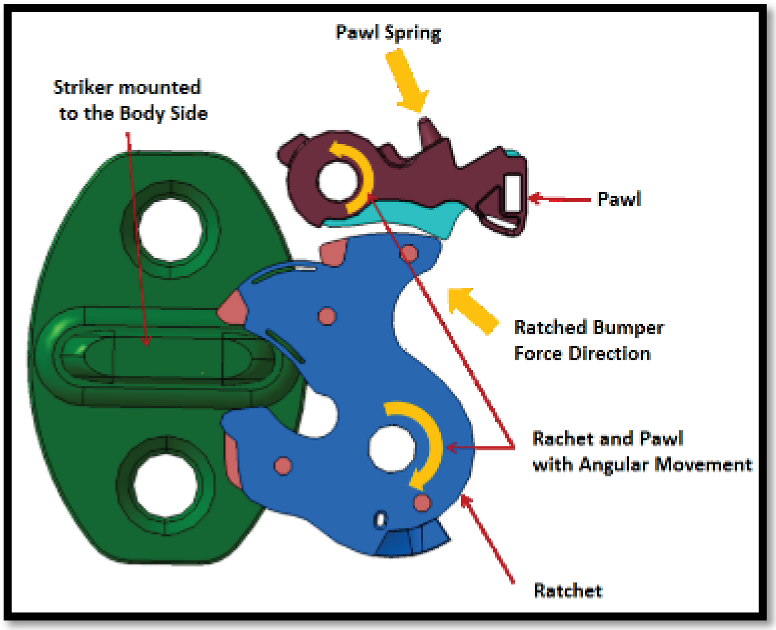


Figure 13. Latch Components [15]

1.2.5 Door Check- Link

Automotive engineers often evaluate the performance of the door closure system design in terms of closing effort by estimating the energy sink in the weatherstrip seals, latch, and the air-bind effect. However, the total closing energy required is just a part of the whole picture. Check design to reduce the door closing effort with taking into account the door opening effort [20].

The hold-open requirements relate to the need for the door to stay open at certain points between the fully closed position and the fully open position. If this requirement is not satisfied, then the door won't swing properly [17].

The design of the check-link affects the function for the check-link. The arm thickness, radius of edge, hardness of rubber (or spring) and the radius of edge are the components, which affect the function of the check link as shown in Figure 14.

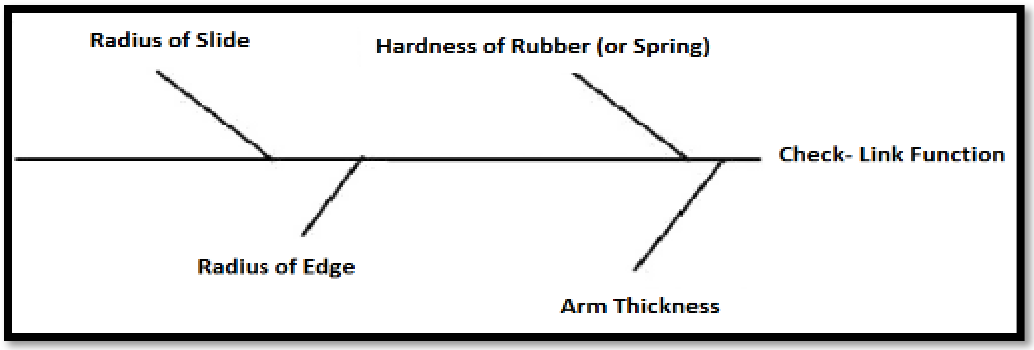


Figure 14. The Ishikawa Diagram for Check-Link Components which are Affecting the Check Function [17]

The check-link maintains peak effort in a very short period in both directions (open/close). The check-link components are shown in Figure 15.

In design, normally the door hinge axis is tilted towards the inside of the vehicle. As a result, the force due to gravity pulls the door towards the vehicle. In addition, if the vehicle is parked on a downward slope, the door may suddenly swing all the way out and not remain in the desired open position. The sudden swinging of the door either in or out is not acceptable by the customer and is considered as a quality issue. The main function of the check-link is to control the motion of the door opening and or closing, thus, offering large resistance to the door swing either opening or closing at certain hold open points. This resistance may be overcome by the operator expending additional effort to have the door out of the hold-open points or the check-points. Figure 16 illustrates the check-link components [21].

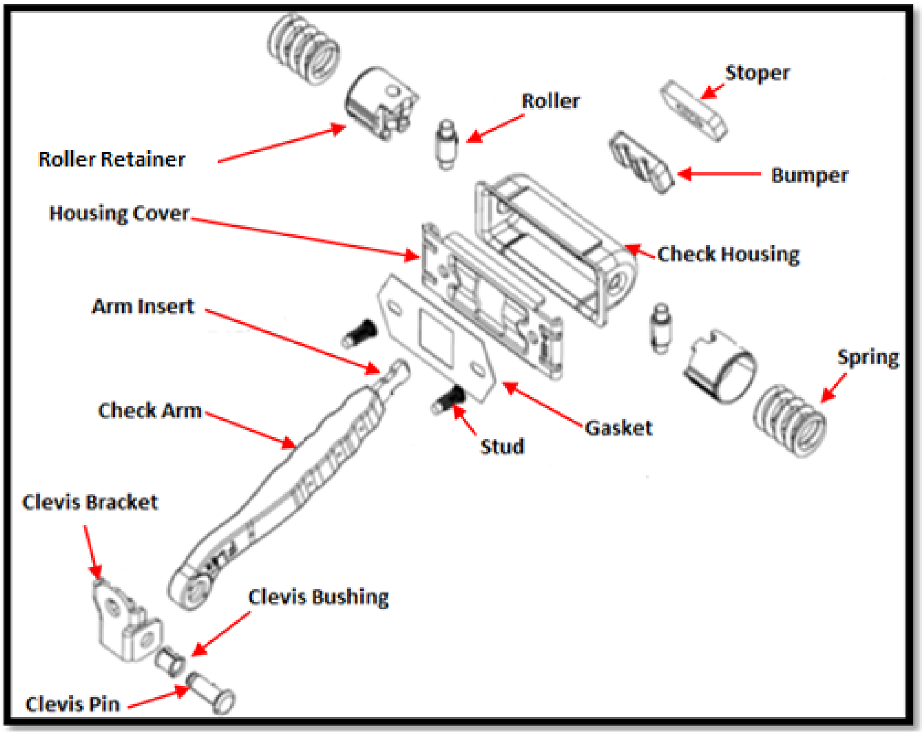


Figure 15. The Check-Link Components [5]

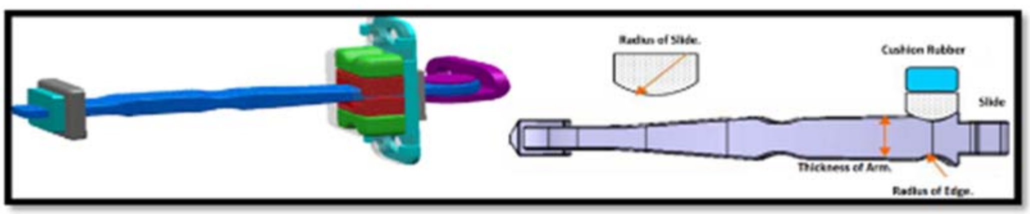


Figure 16. View of the Check-Link [17]

1.2.6 Overslam Bumper

The overslam bumper absorbs some energy from the closing effort and depends on many factors such as the stiffness of the bumper, clearance and the interference to the body side. The overslam bumper, usually at the lower corner on the door, is shown in Figure 17.

Figure 17. The Overslam Bumper

1.3 Research Scope

In addition to the seal gap factors, there are many factors affecting closing effort such as the latch to striker engagement, air compression, hinge tip angle, check link energy, etc. As shown in Figure 18, by studying the seal gap variation and the effect on closing efforts, the closing efforts can be improved.

The scope of this research is to explore the secondary seal gap segments and the compression load deflection (CLD) for the weatherstrips as factors that affect closing efforts. Optimizing the seal gap variation depending on the assembly plan capability vs. what Design Verification Analysis (DVA) or the design criteria assigned definitely improve the side door closing effort. Closing effort is a high priority and a main objective in the automotive development process and throughout the industry. The door closing effort creates an impression in the customer's mind of the engineering and quality of the vehicle.

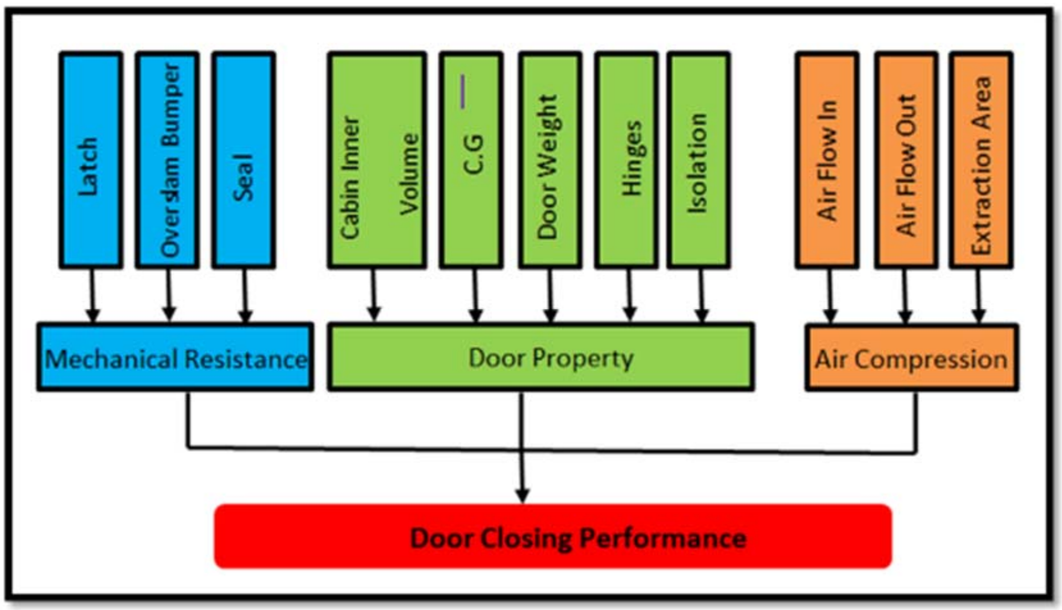


Figure 18. The Factors Related to Door-Closing Performance [22]

1.4 Problem Statement

Door closing effort is a quality issue concern for automobile designers and customers; therefore, it needs to be addressed early in the design phase in order to avoid customer complaints. For this reason, this dissertation will develop a mathematical model to predict the closing effort and to validate the results. A physical test will use factors which are the difference between the Computer Aided Engineer CAE and the physical test for the seal CLD.

One of the main factors that has an effect on the closing effort is the weatherstrip in terms of the CLD and the seal gap. However, designers consider the nominal seal gap and the seal gap variation, thereby, predicting the value by using the DVA study. In many assembly plants, the measured points of the seal gap are different than the designed seal gap value (door inboard or outboard). This effects the side door closing effort and the wind noise. This research will collect the real data from the assembly plant and analyze the effect of the seal gap variation on the side door closing effort. Analysis will be made by using response surface methodology (RSM) to optimize the closing effort and the seal gap variation. RSM is a mathematical and statistical technique used in the development of an adequate functional relationship between a response of interest, y, and a number of associated control variables denoted by $X_1, X_2, \ldots\ldots, X_n$.

To conduct these trials in the mathematical model, it would require a significant amount of time and effort. It would require 2187 experiments. However, with the response surface methodology and the DOE as a Box-Behnken design technique (which are experimental designs for RSM), the number of trials has been reduced to 62, thus, reducing time, effort, cost, and the possibility of errors due to the large number of experiments.

2. LITERATURE SURVEY AND OBJECTIVES

2.1 Literature Search Overview

This chapter is comprised of the four main sections which are focused on factors which have been researched.

Section 2.2 reviews the side door closing effort, the current techniques which are used to study the side door closing effort and the main factors which are used through these studies.

Section 2.3 discusses the weatherstrip and the influence of the seal structure on the door closing force, the nonlinear finite element method used to analyze CLD for the door, finite element method FEM to determine the CLD behavior of a vehicle weatherstrip seal for different hyperelastic models and a comparison with the experimental results obtained using a robotic indenter.

Section 2.4 describes the seal gap and the 3-D analysis to determine the seal deformed shape of the corner and curvature part of the weatherstrip for a closed door. In addition, there is a review of the seal performance factors that are considered in door weatherstrip seal design like the seal CLD response, the deformed shape during compression, the contact pressure distribution and the aspiration pressure.

Section 2.5 summarizes all the literature and identifies factors that are addressed in the mathematical model used to study the side door closing effort.

2.2 Side Door Closing Effort

The side door closing effort has been investigated by the auto industry, and attempts have been made to optimize the closing effort early by prediction in the design phase. In 2003 an efficient method was proposed for the reliability analysis of a vehicle body-door subsystem with respect to the door closing energy. [23] This method combined optimization-based and simulation-based approaches and was particularly applicable for problems with highly non-linear and implicit limit state functions. This approach consisted of two major parts.

In the first part, an optimization-based method was used to search for the most probable point (MPP) on the limit state. This was achieved by using an adaptive response surface constructed through an optimal symmetric Latin hypercube design of experiments.

In the second part, a multi-modal adaptive importance sampling method is proposed using the MPP information from the first part as the starting point. It is demonstrated through numerical examples that the proposed method was superior to existing methods in terms of efficiency and accuracy. This method is illustrated for application to the reliability estimation with respect to the door closing energy problem.

Creating a frame for reliability estimation is established for problems with large numbers of random variables and complicated limit state [23].

Nayak et al. (2003) presented an ADAMS simulation model [24] that included all the different components of the door design Figure 19. The complete opening/closing motion is a result of the effect of the different components of the door closing system which are factors in this equation. Some of these components are the latch, weather seal, energy loss due to air-binding effect, the tip angle of the hinge axis, check-link, etc. The analysis simulates the entire opening/closing motion and the energy/force required during this motion. Analyzing the door opening/closing motion of different vehicles, and connecting this information to customer dissatisfaction (as in JD Power quality survey) enable more accurate quantification of the target performance and will result in greater customer satisfaction. The model is very complicated and needs significant effort to support the input for this tool. It is not optional to add the seal to the system, especially with the new sealing system. In addition, there is not input for more than one seal gap per seal.

A dynamic door closing effort simulation tool was developed in 2008. This was necessary for engineers in order to reduce experiment costs during closure development. It is important in the automotive industry to have a good dynamic door-closing effort model. This research demonstrated advanced simulation of door closing effort by redefining the vent hole sizes and the CLD. Achieving a minimum door closing effort level will definitely lead to a costumer's positive feedback on the vehicle quality. Several factors influenced the overall energy required to close the door, Figure 20 (Sandrini et al. 2008) [25].

This model demanded a significant amount of time and experience in order to be programmed. Therefore, conducting the analysis was time consuming, but engineers could rely on it as a very effective cost cutting tool.

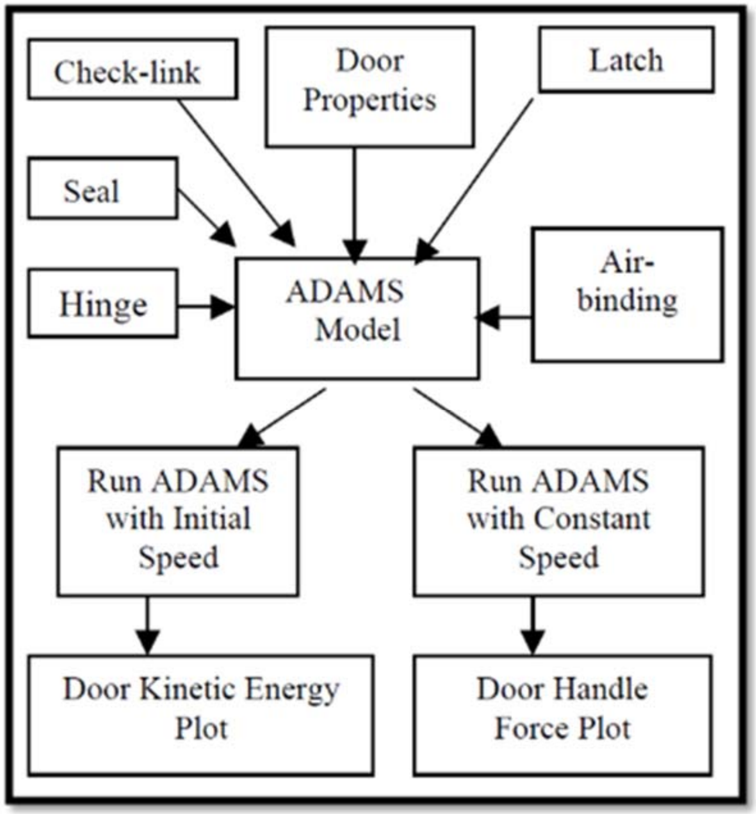


Figure 19. The ADAM Simulation Model for Door Closing/Opening Effort [24]

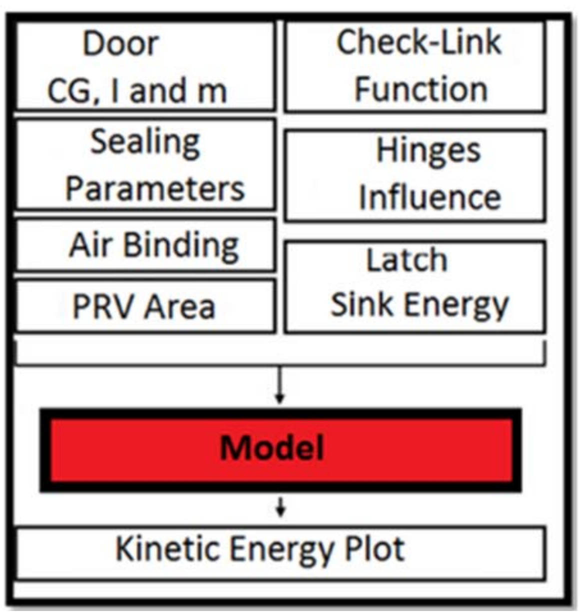


Figure 20. The Model for Door Closing Effort [25]

Li et al. (2009) [26] developed an Excel based mathematical model for predicting the side door closing effort in terms of the required minimum energy or velocity to close the door from a small open position when the check-link ceases to function. A simplified but comprehensive model was developed which included the cabin pressure (air bind), seal compression, door weight, latch effort, and hinge friction effects. The flexibility of the door and car body was ignored. Because the model simplification introduced errors, we will calibrate the flexibility using measured data.

Calibration is necessary because some input parameters are difficult to obtain directly. The option has been provided to calibrate the hinge model, the latch model, the seal compression model, and the air bind model. The door weight effect is geometrically exact and does not need calibration. The capabilities and accuracy of the developed model were demonstrated using the front and rear doors of a production vehicle. Li focused on energy sink by the door component, but it is assumed that the check link does not function.

In 2010, the Excel based software was used with Visual Basic Application programming language to develop mathematical models, which calculated the energy sink of the subsystems. The energy sink of different factors for closing effort of a production vehicle door was measured to verify the accuracy of the calculation software developed.

The tool was an interactive method for the door system. In addition, Excel based software provides the theoretical basis for future door closing energy research, effectively improving the quality and efficiency of vehicle door design.

In response to the deficiencies of current methods, Yunkai et al. (2010),the complicated door closing process into the closing processes of different door closing effort factors which included weatherstrip seal, air binding effect, door weight, hinge, latch and check link. A mathematical model of those factors was established according to their working principles during the door closing process. In this mathematical model, the weatherstrip had one seal gap, and one can not divide it into many segments with different seal gap values [27]. In the same year (Moon et al. 2010) [28] created a design model that calculated the door closing efforts. This compares to the models obtained from the CAE model. The result of Moon's model was a minimum door-closing velocity. This model used the principle of inner pressure increment by airflow during a door-closing action. The designed model showed differences between each part energy components. However, total error for the model is small as shown in Figure 21.

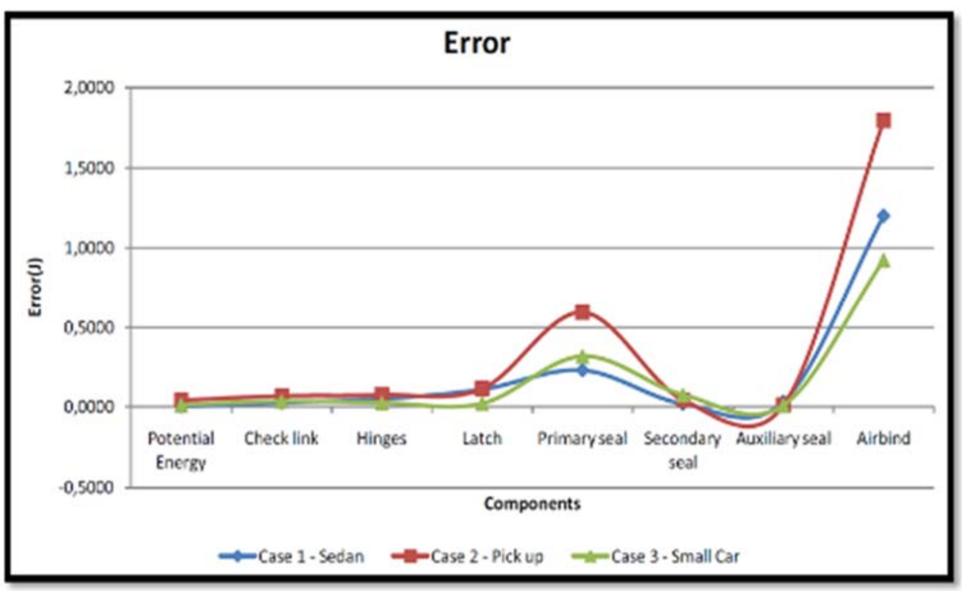


Figure 21. The Error Calculated from CAE and Moon's Models [28]

In all studied cases, the proposed model had the door closing effort values greater than the CAE model values.

Depending on the maximum door closing effort value allowed by each company, the design model used enables simulation of the door closing with many different parts already used until a reasonable door closing effort value is achieved. Some parts such as weatherstrips and seals are basically new for each new vehicle. This is due to the design that may have their CLD limited by the proposed model simulation. The model is able to specify CLD values and simulate with each one of them until it reaches the maximum door closing effort value previously specified. The equation used in this model to calculate the side door closing effort is shown in equation (1).

$$E_{closing} + E_{air} + E_{seals} + E_{latch} + E_{door\ check} + E_{potential} + E_{hinges} = 0 \ldots \ldots . \ldots . (1)$$

The designed model is considered an exceptional tool in the study of the door closing effort estimate during vehicle concept phases. Then the system integration engineer has more time to change the door assembly construction to release all necessary data for the tooling development . The model (Fernando et al. 2010) [28]reduced costs and development time. The maximum CLD value was calculated based on the maximum allowed door closing effort through the exploration of material used on the weatherstrips and seals. The model was compared to the CAE and showed minimum error. When it was compared with physical tests, it had more error [29]. Door-seal resistance was evaluated numerically by integrating the reaction force for a two-dimensional cross-section of a single seal component along seal installation points located on the outer surface of the door and body [11].

Thorough door-closing analysis was required for seal reaction force because it is an essential factor in door closing velocity. To minimize the difference between the results from analysis and experiments, a seal assembling analysis was introduced. Both analyses used only an explicit code because an implicit code had a lower convergence ratio.

To predict the minimum door-closing velocity, the calculated seal reaction force and air properties in Table 1 were used [5].

Table 1. Input Data for the Study of Minimum Door-Closing Velocity [5]

Variable	Unit	Value
Opening angle	Degree	9
Initial velocity	mm/s	10
Final velocity	mm/s	5
Velocity increment	mm/s	2000
Total step	Step	3000
Time increment	S	0.0001
Initial air-bag temperature	Kelvin	Atmospheric
Initial air-bag pressure	MPa	Atmospheric
Maximum reaction force	kgf	25.7
Reaction force of latch	kgf	5

Door-closing velocity involves a number of factors including the door seal, and to date, has only been evaluated using experimental methods. Moon et al. (2010) developed a numerical process to predict minimum door-closing velocity from both a real vehicle's geometrical / physical data and virtual reaction force versus closing time [22]. The reason for that was because experimental methods make it difficult to determine the main factors in door-closing effort. However, the experimental methods are particularly helpful to develop optimum seal design.

In addition, computational efforts toward door-seal design have only focused on drawings and structural analysis. Jei A. (2011) [17] developed a simulation method to improve the IQS (Initial Quality Study) by reducing the closing velocity (Figure 22). It used a CAE method for analyzing the influencing factor of the minimum door closing velocity because engineers need a proper method to evaluate the door closing speed during the design phase. In performing the subjective evaluation, higher numbers mean better feelings (like easiness, comfort, etc.) to users. It is a useful measuring metric for representing quality level; therefore the IQS score could become the standard for evaluating a door's difficulty of opening and closing. The objectives of Jei A. (2011) [17] were to:

- Develop a correlation between subjective evaluations, some test results and IQS score (hard to open/close).
- Reduce closing velocity to improve IQS score (hard to open/close).

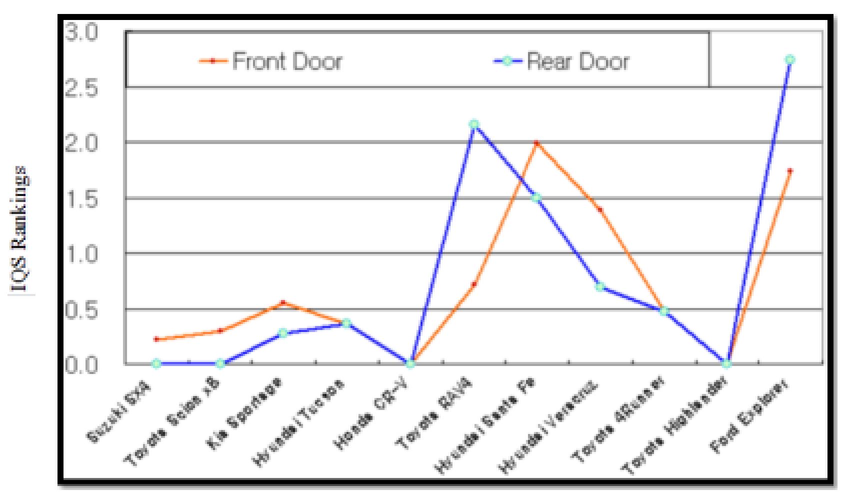


Figure 22. The 2008 IQS for Front & Rear Door [17]

Jei A. (2011) [17] focused on the check link energy more than the other factors in the analysis of the opening/closing efforts. It used the door closing velocity as an indicator for side door closing efforts. The weatherstrip has been simplified to a discrete model with several spring elements. In addition, the minimum closing speed is presented by using the energy equation which needs one iteration only [30]. This method has a high efficiency level and can be used effectively to evaluate the door closing speed during the design phase in the automotive industry.

The calculation of the Seal Energy (E_{Seal}) did not consider the effect of the air flow in the seal. The compression of the weatherstrip pushed out the air through the hole in the seal. The process could increase the stiffness of the seal, so that the energy absorbed by the seal would be more than what was assumed. The energy absorbed by the seal could be corrected by considering the fluid-structure interaction, which deserves additional effort.

Hartley C. [31], in 2011, investigated the application of the finite element for predicting the small-strain dynamic response superimposed onto a large static deformation of a viscoelastic component. The finite element approach was applied to simulate the dynamic stiffness and damp loss factor of a closed-cell Ethylene Propylene Diene Monomer (EPDM) sponge foam rubber automotive weatherstrip component which has a complex cross-sectional geometry. Finite element analysis and correlation of a simple extension specimen were first developed and followed by the analysis and correlation of a weatherstrip component. The large static deformation, dynamic stiffness, and damping loss factor as a function of frequency, preload, and strain amplitude were evaluated and compared to experimental test results.

It was observed that the response of the EPDM sponge foam material was sensitive to excitation frequency, large-strain preload and vibration amplitude [31]. The results indicated that in order to achieve good correlation between simulation and experiment for a component with a complex cross-section and loading condition, it was critical to capture the actual cross-sectional geometry and contact friction. Although an actual weatherstrip component may not exist during early vehicle development, simulating the design intent geometry with a known material type can help significantly reduce the level of uncertainty in the closure resonance prediction.

A better assumption has been developed for the dynamic rate properties to use in the vehicle-level analysis instead of simply applying general "rule of thumb". Future work could involve using an iterative approach to optimize the simple extension simulated results to better match the experimental results by parameterizing the material model input variables. The optimized material model could then be applied to the weatherstrip component to potentially improve correlation of the dynamic stiffness and damping loss factor prediction [31].

Mozzone [5] compared the door closing performance of an aluminum door with a steel door of a C segment vehicle. Two methods were used: the physical testing of the doors in the body shop with the EZ Slam technology and the simulation of the closing event with an existing closing effort predictive model.

In Jing [26] particular focus was given to the contribution of the check system to the closing effort and how its final profile affected the closing event of the door. The methodology applied was particularly useful as it allowed quantification of the closing performance of the doors. This demonstrated the energy and closing speed values to perform an immediate comparison between the contributions to the door closing effort. The automotive industry spends efforts to reduce the door closing effort or try to achieve the self close doors to meet the customer expectations [32].

2.3 The Weatherstrip

The weatherstrip is one of the main factors affecting side door closing efforts. Each seal in a sealing system has a different function. Seals need to design to favorable for wind noise, water leakage, door closing effort, and it does not cause squeak and rattle as well [33]. In 2002 LS-DYNA was used to simulate the door seals system. LS-DYNA explicit code was used as the solver for the door sealing system analysis by choosing proper element type, material model, and contact algorithm. This method endeavored to capture the door closing dynamic effect and seal nonlinear material nature [34]

The main structural component, the rubber seal, was modeled and simulated. Different types of elements, material models and contact algorithms from LS-DyNA element, material and contact libraries were tried and compared [34]. Consequently, the best modeling and simulation link and simulation technology were developed for door sealing system analysis. The analysis results were compared with some available test data, and good correlations were obtained. The analysis also evaluated the influence of manufacturing deviations. With the results obtained from this analysis, the relationship between the major parameters could be established and used as a tool to derive a better sealing system designed at an early stage. This analysis method could also be used to evaluate the influence of certain types of process errors. The newly developed method illustrated the great potential of comprehensive studies of door sealing systems. The analysis results provided some major parameters, such as seal deformation, contact pressure and energy transformation which would influence the functionality and performance of the door sealing system [34].

In the same year, Zhao et al. [35], developed a test set for obtaining compression deformation of the door weatherstrip by using the stereovision theory. Precision instruments of optical grating and force sensor were also integrated in this set. Force-displacement response characteristics of compression at varied speeds could be controlled. This research provided solid foundations as well as optimization design of the automotive weatherstrip.

Zou et al. [3] presented an efficient method for the reliability analysis of systems with nonlinear limit states.

While in 2004, the influence of the seal structure on door closing force was evaluated. A nonlinear finite element method was introduced to analyze CLD for a door for SANTANA (car made by Shanghai Volkswagen Co. Ltd). The calculated results showed that the compression loads of the door seal were larger than the standard value of Shanghai Volkswagen Co. Ltd and the seal structure needed to be optimized. The computed results were proven by experiment [36].

The method of Zou et al. [3] consisted of two major parts. In the first part, an optimization-based method was used to search for the Most Probable Point MPP on the limit state. In the second part, as the starting point, a multi-modal adaptive Importance Sampling Method was proposed using the MPP information from the first part. This method was applied to the reliability estimation of a vehicle body-door subsystem with respect to one of the important quality issues such as the door closing effort. A generalized framework for reliability estimation was also proposed for problems with large numbers of random variables and complicated limit states.

The main efficiency of Zou's method is demonstrated with a numerical example of a highly nonlinear limit state problem, as well as an automotive door closing effort application.

In 2004, the structure-borne vibration transmission of a car door weather seal was analyzed. A simplified two-dimensional set-up was used to describe a car door weather seal [37].

In the same year, an analytical method was developed to calculate the over bend needed in the door design to counteract the nonlinear seal forces acting on the door header. This method allowed the original equipment manufacturer to achieve the design above belt line in terms of flushness to the header area. The design synthesis process used to meet the overbends design criteria. The analytical methodology was demonstrated, and improved product quality and reduced door fit warranty, Baskar et al. [38]. Baskar's research combined two analytical models of the weatherstrip and the DIW to forecast the design over bend necessary to achieve good fit and finish. These models are:

- Seal compression-load deflection models for each angle of attachment of the weatherstrip to the door.
- A nonlinear FEA model of the trimmed Door-In-White (DIW).

The two-dimensional setup using a nonlinear finite element model was developed to investigate the role of the seal pre-stress on the door dynamic response. The seal influence on the door dynamic response was divided into three main contributions: a damping, a resonant and a stiffness contribution. The results were used to extract an equivalent linearized seal model in the form of a mass spring-dashpot system, which included a full-vehicle linear NVH model. Superimposing dynamic analyses on non-linear analyses is generally time consuming. This research focused on the seal stiffness contribution which was modeled only by an equivalent spring [37].

All these studies used an FEM to determine the CLD behavior of a vehicle weatherstrip seal for different hyperelastic models and the model predictions were compared with the experimental results obtained using a robotic indenter [39]. However, modeling the weatherstrip seal using the hyperelastic and viscoelastic models, was not practical when the whole vehicle dynamics were investigated. The detailed modeling of the seal increased the computational cost significantly [40].

The results of the numerical computations were compared with the experimental modal analysis results in order to determine the best value of the spring coefficient for the seal. This approach was verified by comparing the results of the experiments with forward FEM solutions for different loading rates. This experimentally verified FEM displaying hyperelastic and viscoelastic behavior of the seal can be used to investigate the door closing effects. Boundary conditions altered both the natural frequency and the mode shape of the door.

2.4 Seal Gap

The seal gap has a major effect on the seal's closing effort contribution. Therefore, the automotive industry spends considerable effort to determine the best seal section as well as to predict the seal gap variation by the DVA studies. In 1997, a nonlinear finite element analysis was developed to analyze a seal cross section and compression load deflection's (CLD) behavior. In addition, a contact pressure distribution was analyzed as well as aspiration due to a pressure differential across the seal [29]

Automotive door system weatherstrip seals play a major role in determining door closing effort, isolating the passenger compartment from water and reducing the wind noise inside the vehicle. The seal CLD response, the deformed shape during compression, the contact pressure distribution and the aspiration pressure difference are all important seal performance factors that are considered in door weatherstrip seal design. The analyses described and the associated design evaluations can be performed before any prototype hardware is developed if sufficient geometry and material property information are available [29]. The automotive industry uses the dimensional management process to optimum design to achieve the function and appearance desired for door system [41].

After many years, a model was built in order to analyze positioning errors of the assembly fixture of car SANTANA 2000, a 3D CAD. Six typical deviation models were defined on the basis of six points positioning principle for the fixture. The assembly gap distribution between door and side frame was analyzed, and the influence of different deviation patterns on the assembly gap and the effect of assembly gaps on door closing force were evaluated. The results indicated that positioning errors of the door assembly fixture were the most important factors to affect the door closing force [42].

Park [43] introduced a new test method to predict the compression load and permanent deformation of 3D full vehicle by using ABAQUS. Uniaxial tension and creep tests were conducted to obtain the material data. The lab test for the permanent deformation was accelerated at high temperatures during a shorter time of 300 hours.

The test method can provide an accurate prediction under the different loading conditions and section shapes as shown in Figure 23. This method will also save time and cost.

3D analysis can illustrate the deformed shape of the corner and curved part of the weatherstrip of a closed door. The predicted result (compression set) demonstrated good agreement with the measured results.

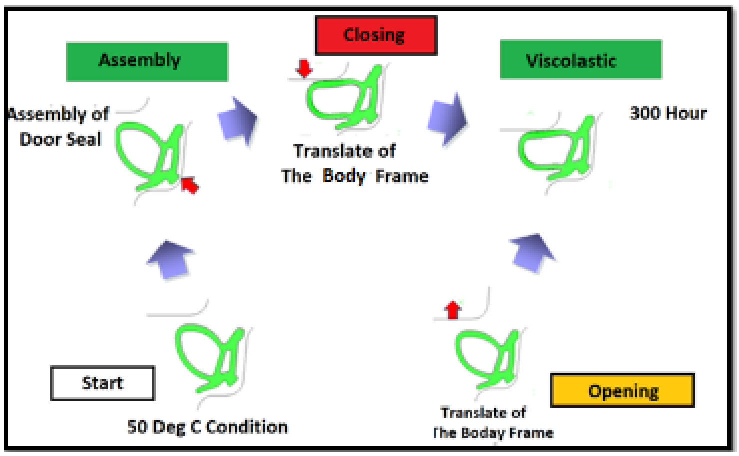


Figure 23. The Process of Permanent Deformation Analysis [43]

2.5 Literature Summary

A door closing effort tool is necessary for engineers in order to reduce experiment costs during closure development in the design phase. The door closing effort depends on many factors which are classified as first factors sink energy (such as air compression, seal compression, hinge friction, door latching mechanism, and striker). The second factors which are affecting on closing effort and it given support energy to the system (like door mass and the center of gravity, hinge tip angle, door check-link, and the customer effort to close the door). The main goal of the research was to reduce closing efforts by predicting the closing effort early in the design phase. This tool would allow the system integration engineer to predict the door closing effort. In addition to all of these factors, there is the door adjusting was require during the assembly process.

Most of the related research in the literature used a mathematical model, ADAM or CAE simulation. This was used to predict the closing efforts, focusing on simplifying the tool by calculating just the sink energy or by adopting just the main factors in the side door closing efforts equation.

The weatherstrip plays a role in closing efforts either by the shape design, material thickness, and material type or by optimizing the seal gap variation.

This dissertation will investigate the seal gap segments for the secondary seal and the CLD for the weatherstrip as factors for the closing efforts by using a mathematical model.

2.6 Research Objectives

The door closing effort is a quality issue of concern to automobile designers and customers [44]. This applied research will determine the factors that play a significant role in door closing efforts. The weatherstrips that absorb energy will be studied, and the secondary seal gap segments will be reviewed with the CLDs. Design of experiments (DOE) will be used to plan, design, conduct, and analyze the experiment to effectively draw objective conclusions. A mathematical model will be developed to predict the side door closing efforts at a variety of seal gaps segment lengths and weatherstrip CLDs. This will predict the response functions. The objectives are shown in Figure 24.

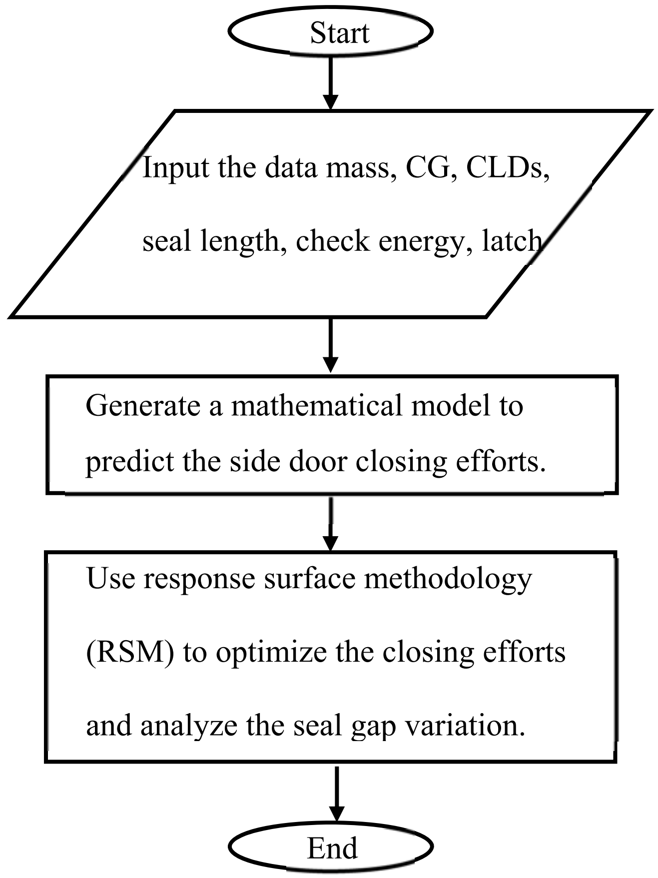


Figure 24. Dissertation Objectives

3. RESEARCH APPROACH AND EXPERIMENTATION

Automotive door weatherstrips are intended to prevent dust and water inflow from outside as well as to isolate noise. The effort necessary to close the door requires a minimum closing force.

A door-seal design can be defined as a process of compromise between two reciprocal design targets. Seals are one of the main variables affecting the side door closing efforts. In most instances, the automotive industry suggests that seal resistance comprise approximately 35-50% of the energy to close the front door. The primary seal (seal mounted to the door) and the secondary seal (seal mounted to the body) contribute 19 % and 9%, respectively, of the energy necessary to close the door. However, the designer must take into consideration the nominal seal gap. In the assembly plant, different seal gap values (such as the door inboard or outboard) affect the side door closing effort and the NVH [45].

This research will use the analytical method and the computer evaluation for side door closing efforts. The study will be accomplished by dividing the secondary seal into segments with certain lengths and using the weatherstrip CLD as factors. The design of experiment (DOE) technique and the Response Surface Methodology (RSM) have been used to optimize the closing effort and the seal gap variation. These results will be particularly helpful for optimizing of the weatherstrips design. This research will help to predict the seal gap per segment needed to produce a minimum side door closing effort.

The high numbers of factors to be studied will result in a very large experiment. However, based on experience, this exhaustive list may be pared down to its essentials, realizing that the response of the dependent variable is non-linear. Therefore, the factors that appear in the experiment should suffice at three levels (maximum, minimum and nominal). The objective should be to reduce the number of factors to focus on controlling those variables with appropriate specifications. Although factors may be quantitative or qualitative in nature, this research will overwhelmingly focus on specific factors that are quantitative with levels assumed to be fixed or controlled. Screening experiments is an effective methodology to determine the critical factors with a minimal number of experimental runs and without committing to a larger amount of resources.

In addition to the experimental setup for measuring side door closing effort, a theoretical model will be used to predict the relative importance of the seal CLD segment efficiency performance. Based on experience, seal gap is one of the major elements that significantly influences the closing effort levels. Therefore, due to the door setting process and door adjustability process, one can define the seal gap segments which have the most significant effect on the closing efforts. Table 2 shows the factors which affect the closing effort.

To merge the theoretical outputs into the experimental model, the underlying implicit assumption is that the factors which have used in the experimental model for this research are the main factors for the side closing effort.

Table 2. Factors which affect side door closing effort

The main Factors effect on DCE	Main contributor for each factor
Seal CLD	Primary seal Secondary seal Margin seal above belt Margin seal below belt Rocker seal Glass run lips
Door Latch	Door latch force
Hinge	Hinge friction Hinge tip angle
Cabin Pressure	VOW target Air extractors
Door and Body Setting	Seal gap Latch to striker alignment
Check Energy	Door check energy

3.1 Theoretical Analysis

When designing a new subsystem for a new vehicle the platform, technical requirements, performance targets and cost implications drive the decision process towards which concept to be adopted. If this platform planned for worldwide introduction, local requirements, and capabilities have to be put into the business equation [46].

The automotive industry has methods and models for designing a vehicle door system to address the issues of the first build prototype. This is done by selecting a door design and then generating a set of system data properties (door structure, panels, mating surfaces, vehicle attributes, and seals). The door system is then subjected to redetermined conditions and compared to the design criteria as shown in Figure 25 & 26. If performance does not meet criteria, the system is modified, and model generation is repeated until performance meets criteria.

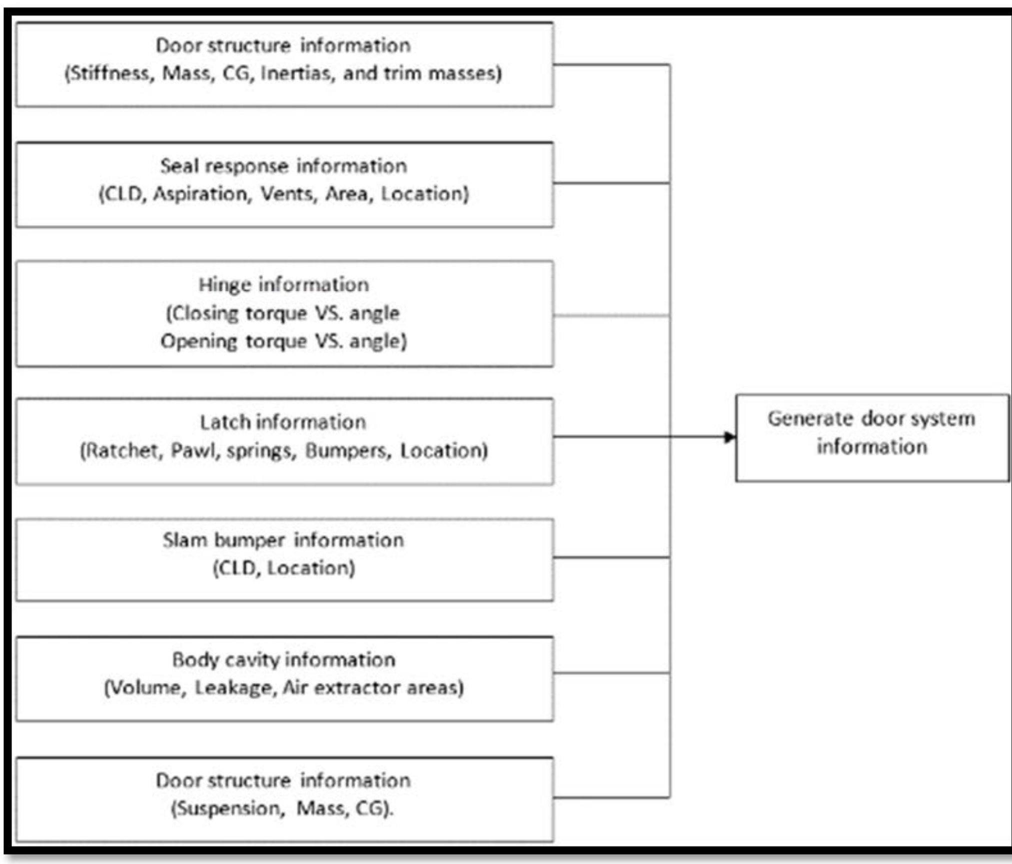


Figure 25. The Algorithm for the Door System Design Criteria [47]

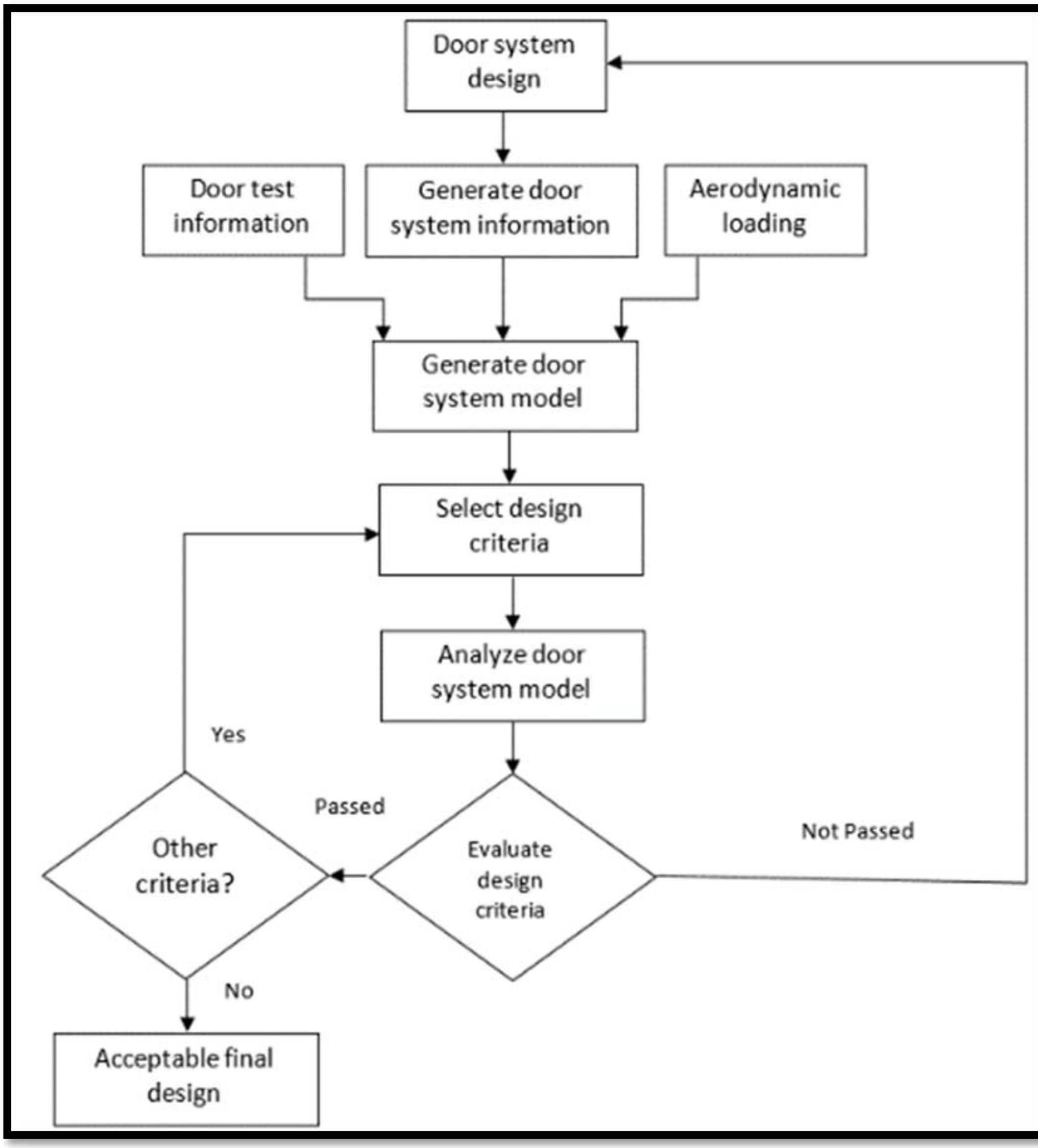


Figure 26. Continuation of the Algorithm for the Door System Design Criteria [47]

3.2 Door Closing Efforts Test Tear Down

In order to better understand the door closing effort contribution analysis, one must know what each component will contribute. This dissertation will focus on weatherstrip regarding seal gap and the CLDs. As shown in Figure 27, the primary and the secondary seal are the main contributors to the closing effort after the air pressure. Therefore, controlling the variation of the seal gap and adjusting the CLD will most likely minimize the closing efforts.

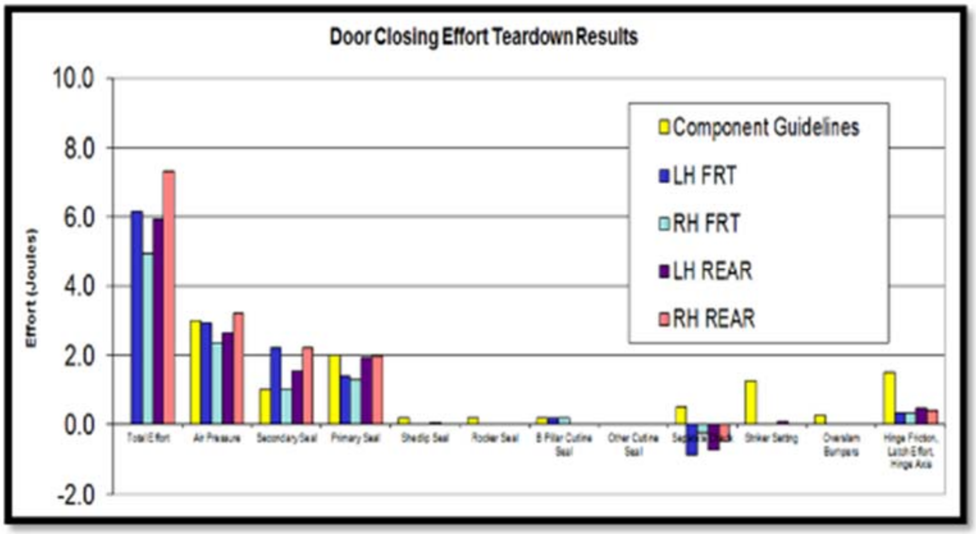


Figure 27. The Chart for a Vehicle Showing the Door Closing Effort Teardown Results

3.3 Seal Gap for the Secondary Seal

The secondary seal is the seal that is mount to the body side. In section 1.2.2.2, the functions of this seal were summarized. To measure the seal gap on the vehicle, an LMI device (Linear Measurement Instruments device) is needed, Figure 28. The LMI device measures the seal gap at 12 points on the AB flange, Figure 29. The data needed for this research will be collected by using the LMI device. Operator adjust the doors to meet the desired look for the vehicle (margin/ flushness), so the seal gap must likely absorb any adjustment [48].

When the door closed, seals around the door perimeters are undergoing a gradual compression process. The seal first contacts its mating surface in a line fashion. Then the contacting area becomes bigger and bigger as the seals are compressed [49].

Figure 28. The LMI Device to Measure the Seal Gap for the Secondary Seal

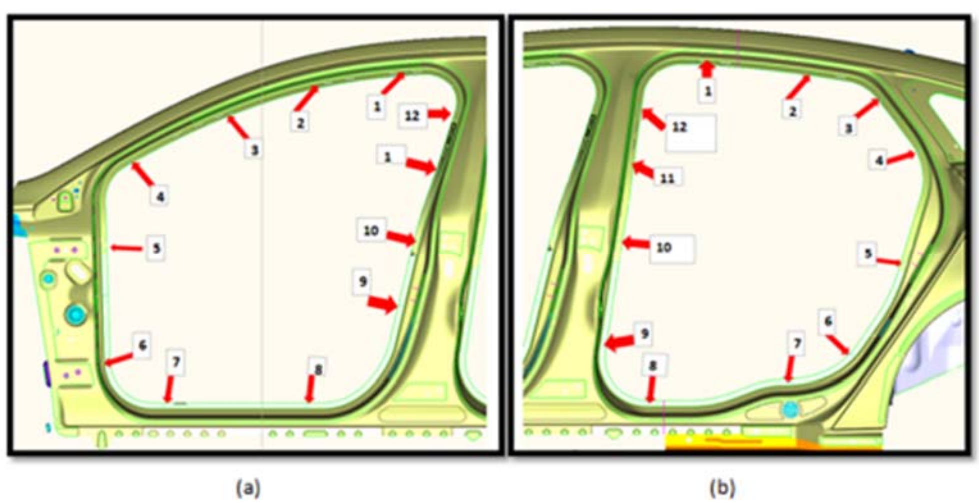


Figure 29. The Seal Gap Measurement Points, (a) is the Front Door and (b) is the Rear Door

The effect of the seal gap on the closing efforts, illustrated in Figure 30, shows the range on the seal gap variation. When the door is inboard, it increases the closing efforts, and when the door is in the outboard position, it reduces the closing efforts.

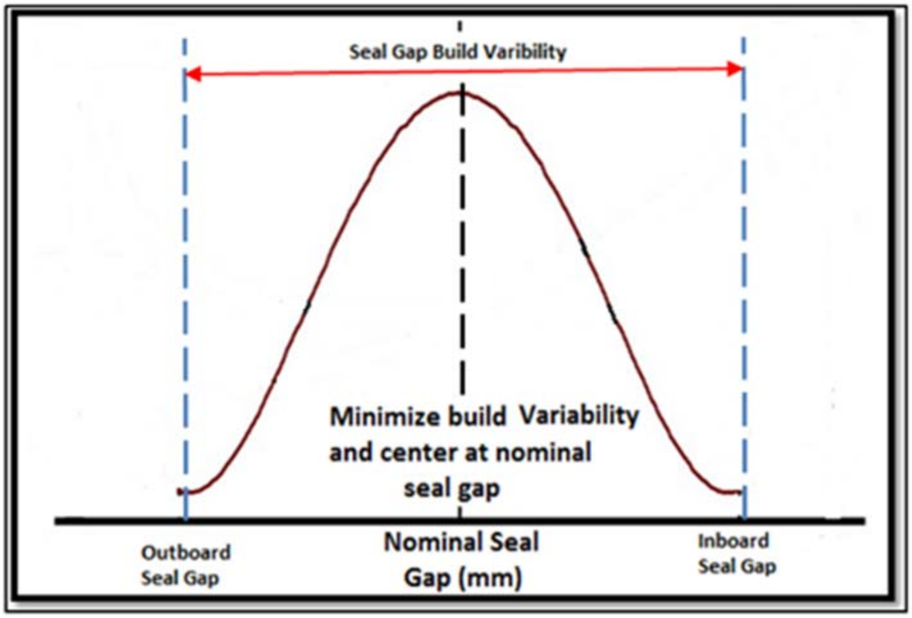


Figure 30. Side Door Dynamic Sealing System Optimization

3.4 The Door Sealing System and the CLD Curve

Sealing impacts many attributes that affect both internal and external customer satisfaction. The internal is the wind noise air leakage, and the external is the side door closing effort. The sealing system for the vehicle that is illustrated in the mathematical model in this dissertation is shown in Figure 31, which is a level 2 sealing system. The compression set is measured by two metrics, residual seal load F (which was measured by Newtons) and the compression set (height loss) in Figure 32. To validate the results, a constant factor will be used as the difference between the CAE and the experiment test to the seal.

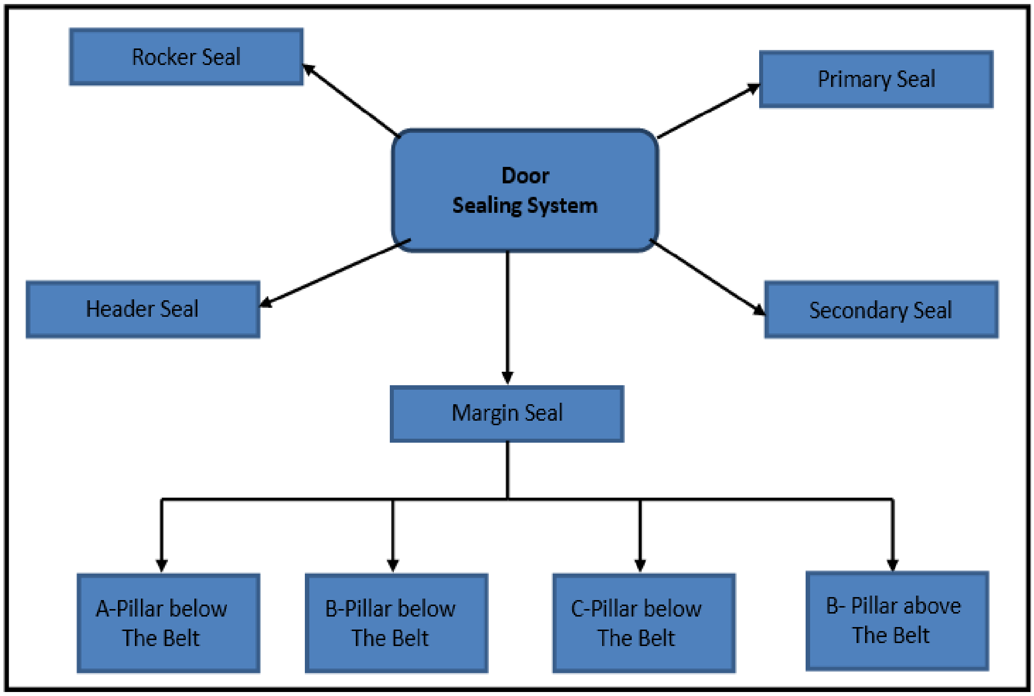


Figure 31. The Level 2 Sealing System Which is used in the Mathematical Model

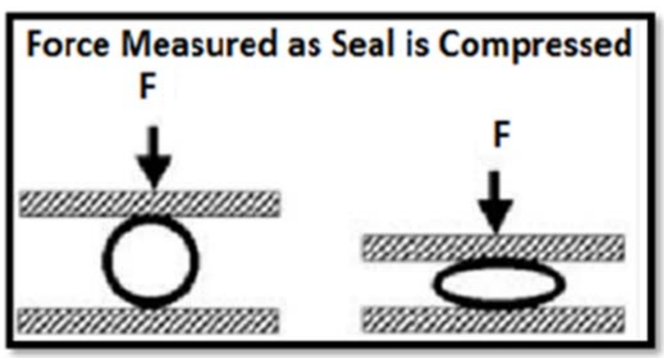


Figure 32. The Measured Force Set for the Seal [14]

To have a better understanding of the CLD curve, one needs to take a look at the ideal CLD curve and how the seal gap affects seal behavior such as the compression in Figure 33. Typically, the CLD curve for the seals was generated at the beginning of the design phase by the CAE analysis. When the vehicle moves forward in the process design, all the seals are tested to obtain an accurate CLD curve. The manufacturing and assembly variation are a noise problem even if the variation in seal gap is biased towards the high side and falls in the designed range [50]

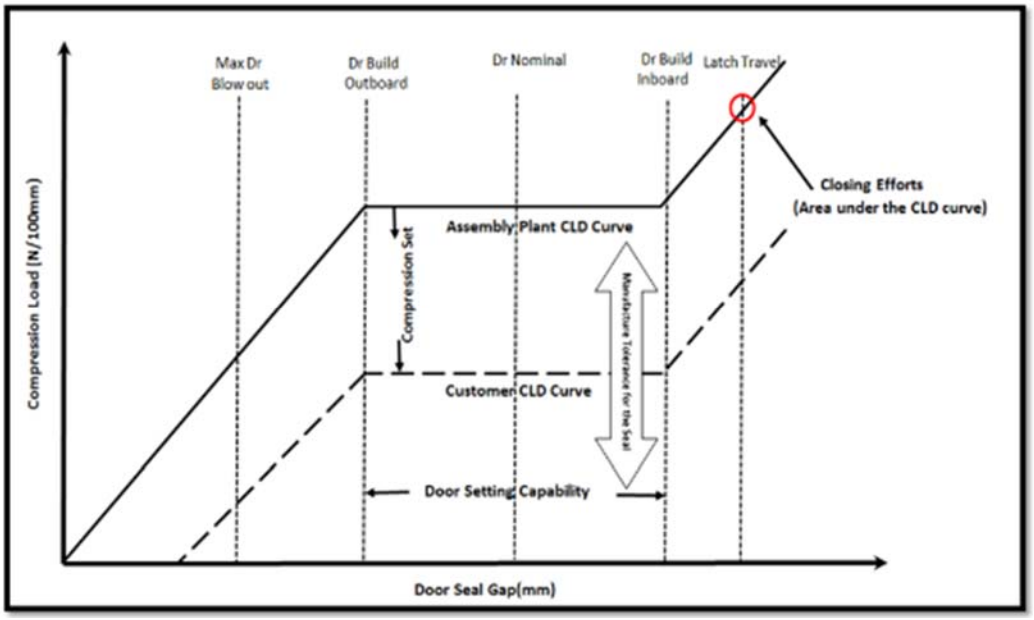


Figure 33. Ideal CLD Curve vs. Assembly Plant CLD Curve

3.5 The Door Closing Effort (DCE) Mathematical Model

The DCE model calculates the static status of the door when the door is open with detent angle 8° and time 0.25 seconds. However, this model is built to generate the DOE iteration to optimize the seal gap variation in order to reduce the closing effort.

3.5.1 Air Compression or the Air Bind

Figure 34 illustrates an analytical model for the closing efforts which were created based on the control model for the air bind.

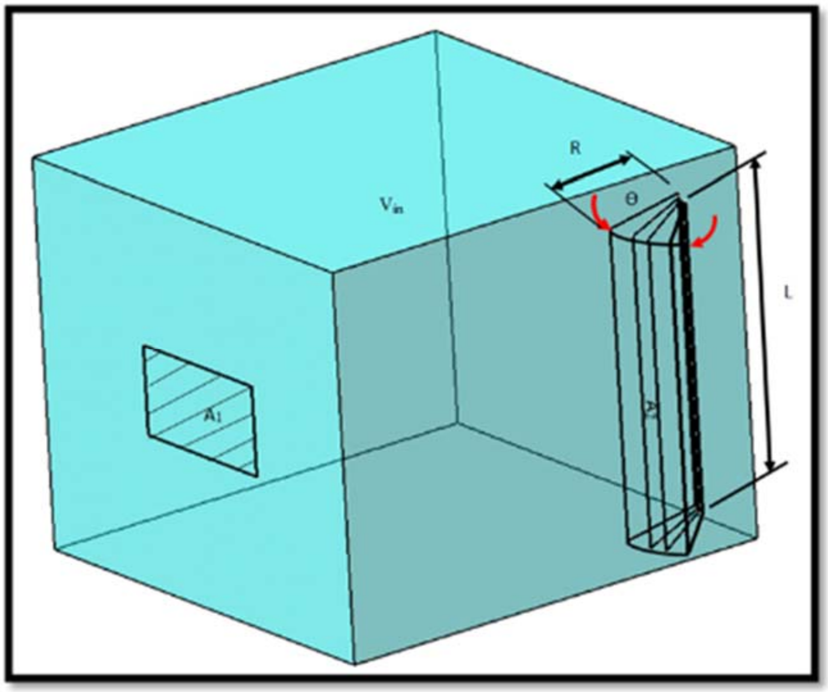


Figure 34. The Control Model for Pressure Calculation [51]

A_1 is the total area of the design air extractors and the body leakage. The volume (V_{in}) is the total cabin volume. A_2 is the area that the door closing parameter makes with the body side. The distance R and L are the door radius and the height, respectively. The angle θ is the door hinge open angle.

The simple equation for this model was shown in Equation (2).

$$\frac{d(\rho V)}{dt} = -\sum \rho v_e A_e \qquad \text{……………………………….(2)}$$

Where ρ is the air density, V is the air volume and v_e is the exit velocity of the air and A_e is the exit area. From the experimental result V_e can be calculated in Equation (3)

$$V_e = K_e\sqrt{\Delta p} \qquad \text{……………………………..…(3)}$$

Where Δp is gauge pressure inside the vehicle and K_e is the slope from plot of the volumetric flow rate versus $\sqrt{\Delta p}$. By substituting Equation (3) in Equation (2) and after reconstructing, it simplifies the expression in Equation (4)

$$V\frac{d\rho}{dt}+\rho\frac{dV}{dt}=-\rho(K_1\sqrt{\Delta p}\;\;A_1+K_2\sqrt{\Delta p}\,A_2) \quad \ldots\ldots(4)$$

K_1 and K_2 are the flow coefficients with the two exit area, $A_1$and A_2

Assume both exit areas exhaust to standard atmosphere conditions.

$$K_1=K_2=\sqrt{2/\rho_{atm}} \quad \ldots\ldots(5)$$

The change in density with time during door closing is then,

$$\frac{d\rho}{dt}=\frac{1}{v}[-\rho_2(A_1K_1+A_2K_2)\sqrt{p-p_2}-\rho\frac{dV}{dt}] \quad \ldots\ldots(6)$$

ρ_2 is the atmosphere density and $p_2$is the atmosphere pressure.

v is the velocity of the air at the air extractors

By using the isentropic relation for pressure and density as shown in Equation (7)

$$\frac{p}{\rho^{\gamma}}=constant. \quad \ldots\ldots(7)$$

$$\therefore \rho=\frac{p^{\frac{1}{1.4}}}{C_1^{\frac{1}{1.4}}} \quad \ldots\ldots(8)$$

$$so\ \frac{dp}{dt}=\frac{1}{C_1^{\frac{1}{1.4}}}(\frac{1}{1.4}p^{-\frac{2}{7}}\frac{dp}{dt}) \quad \ldots\ldots(9)$$

By combining Equations (8) and (9) into Equation (6) and after rearranging, the equation to express the time deviation of pressure with air pressure deviation, area yield and volume is shown in Equation (10).

$$\frac{dp}{dt}=-1.4\frac{C_1^{\frac{1}{1.4}}}{V}\left[\rho_{atm}\,(A_1+A_2)Kp^{\frac{2}{7}}\sqrt{p-p_{atm}}\right]-(1.4.\frac{p}{V}\frac{dV}{dt}) \quad \ldots\ldots(10)$$

Where,

t = time (sec).

P = internal cabin pressure (Pa).

C_1 = isentropic constant for air.

L = Door Length (m).

R = Door radius (m).

V = total volume of control volume (m^3) from Figure 34.

$$V = V_{in} + LR^2\frac{\theta}{2} \quad \text{.....................................(11)}$$

Θ = door hinge angle (rad).

V_{in} = Internal volume (m^3) of the cabin, including the trunk.

ρ_{atm} = atmospheric density (Kg/m^3).

A_1 = constant exit area (m^2).

$$A_1 = A_{leakage} + A_{air\ extractors} \quad \text{.....................................(12)}$$

$A_{air\ extractor}$ = air extractor area (m^2).

A_2 = Area between the closing door and body.

$$A_2 = R\,(L+R)\,\Theta. \quad \text{.....................................(13)}$$

K = flow coefficient.

$$K = \sqrt{2/\rho_{atm}} \quad \text{.....................................(14)}$$

Therefore, equation (10) is used in the mathematical model to predict the compression pressure with the changing time and hinge angle [13]. For the analytic modeling of the cabin pressure, the door angle $\theta(t)$ is required as a function of time. However, the steps to achieve that are the following:

One can take the overslam distance from experimental data and build the mathematical equation for the overslam relative to the door speed as shown in Equation (15) and Figure 35.

$$y = -2.01831 + 0.0027507x \quad \text{.....................................(15)}$$

Where,

y: Overslam (mm)

x: The door velocity (mm/sec)

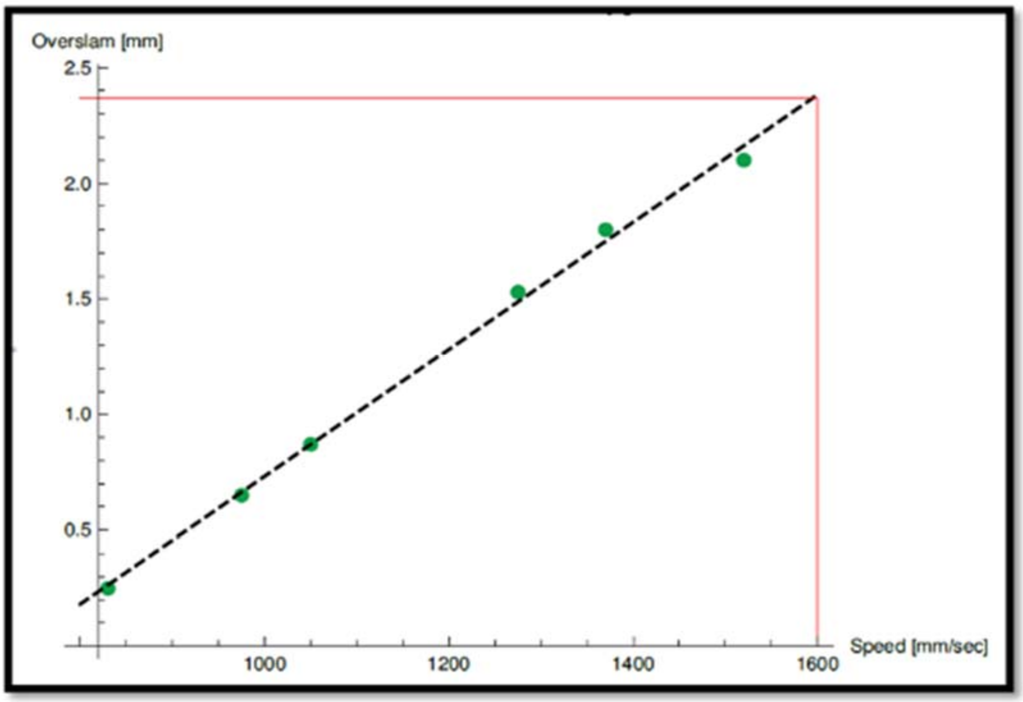


Figure 35. The Relation between the Door Overslam to the Door Speed

Obtain the overslam angle in [rad] by taking the Arctan(y) as shown in Figure 36.

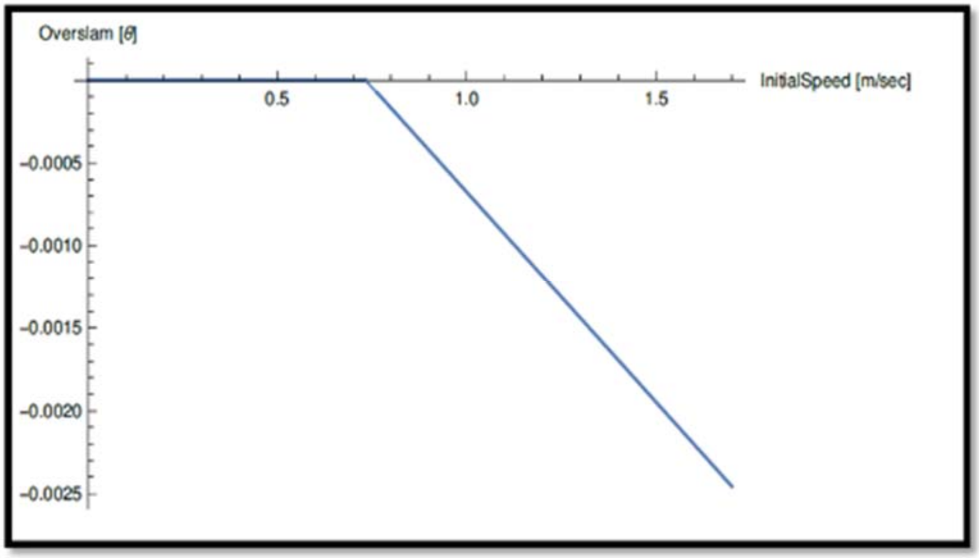


Figure 36. The Relation between the Door Speed and the Overslam [θ] rad

We assume the opening angle of the door is a quadratic polynomial in time t as shown in Equation (16).

$\theta(t) = at^2 + bt + c$ ……………………………..…(16)

At time 0, the opening angle given as θ_0

$\theta(0) = c = \theta_0$ …………………………..…....(17)

At time 0, the derivative of the opening angle given as V_0

$\theta'[0] = b = -V_0/(R\cos[\theta_0])$ …………………………….....(18)

The minimum of the function evaluates to the overslam angle

$\theta\left[-\frac{b}{2a}\right] = -\frac{b^2}{4a} + C = Overslam\ [V_0]$ ……………..………..….(19)

The quadric polynomial curve plotted in Figure 37 represents the relationship between the door open angle $\theta[t]$ and the time to close the door, from Equation (18) one can calculate V_0 and plot it as shown in Figure 38.

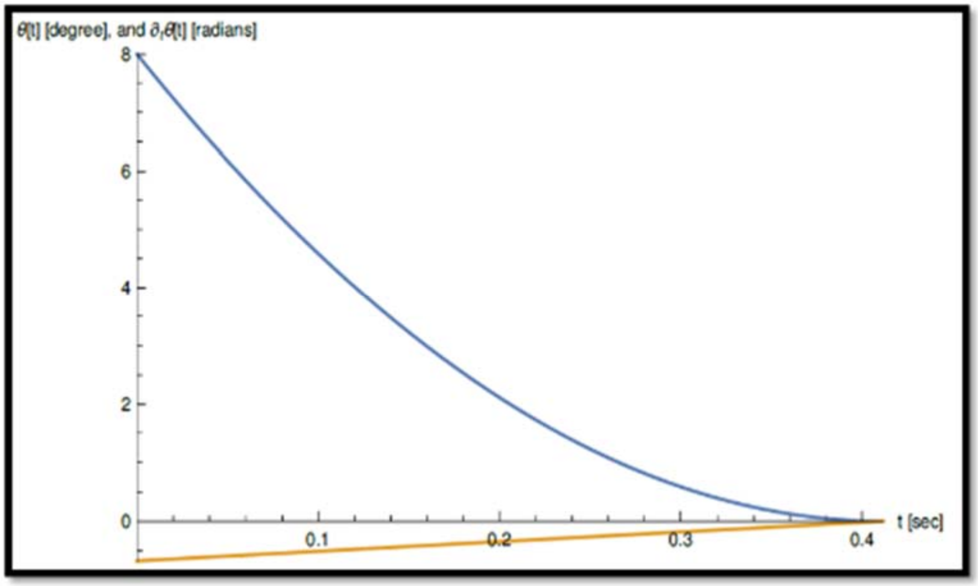


Figure 37. The Relation between the θ[t] in Degree and the Time in Second

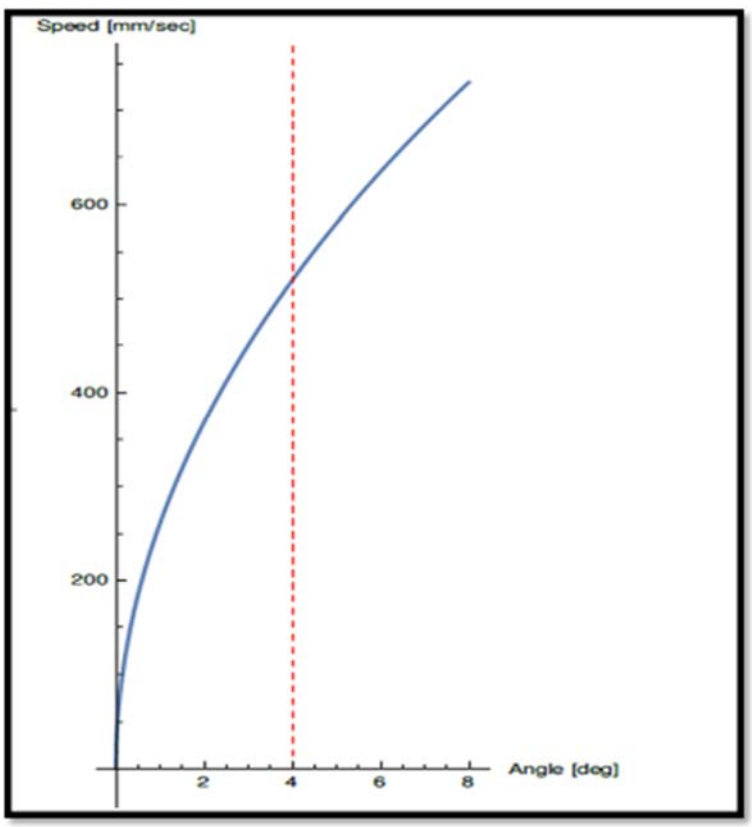


Figure 38. Illustrate the relation between Door Closing Speed to the Door Open Angle

The Equation (8) can expressed by dp as follows in Equation (20)

$$dp = \frac{7p^{\frac{2}{7}}(-dTLp^{\frac{5}{7}}R^2 - 327.411\sqrt{-101300 + p}\,(0.0630782 + ef + 35.9712Max[0, R\,(L + R)T]))}{10(3.0016 + 0.5\,L\,R^2\,T)} \quad ..(20)$$

However, the air leakage constant A_1 has a significant influence on the resulting pressure curve as shown in Figure 39. We assume the efficiency for the airflow through the air extractor was 85%.

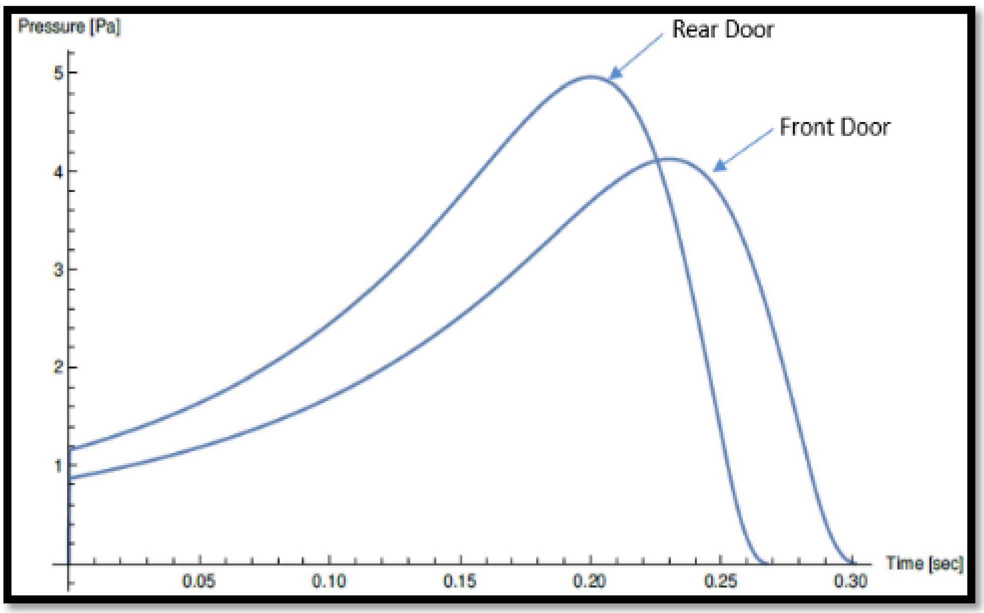


Figure 39. The Relation between Door Closing Velocity with the Door Open Angle

This model assumes the steady state airflow, the air is incompressible, and the results were within 80% of the experimental results. Consequently, the curves in Figure 39 multiply the result by the correction factor 1.2 to calibrate the results and is shown in Figure 39 which represents the pressure spike with time for front and rear door. Pressure spike increased with respect to the door closing velocity as shown in Figure 40 for the front door and Figure 41 for the rear door.

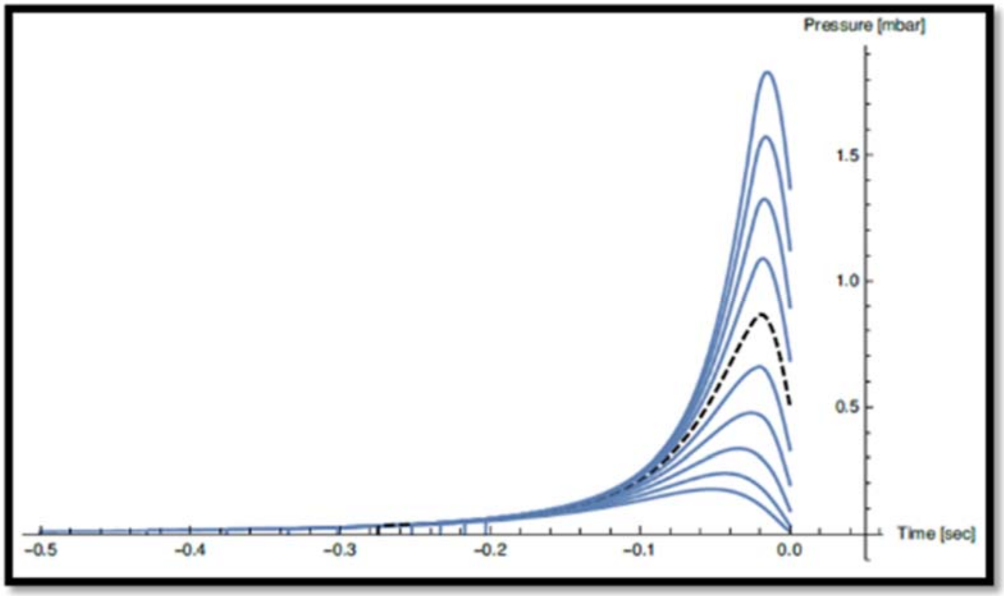


Figure 40. Front Door Pressure Spike with Time. The Multi-Curves Showing the Multi-Door Closing Velocities and the Black Dash Line is The Pressure Spike with The Minimum Closing Effort

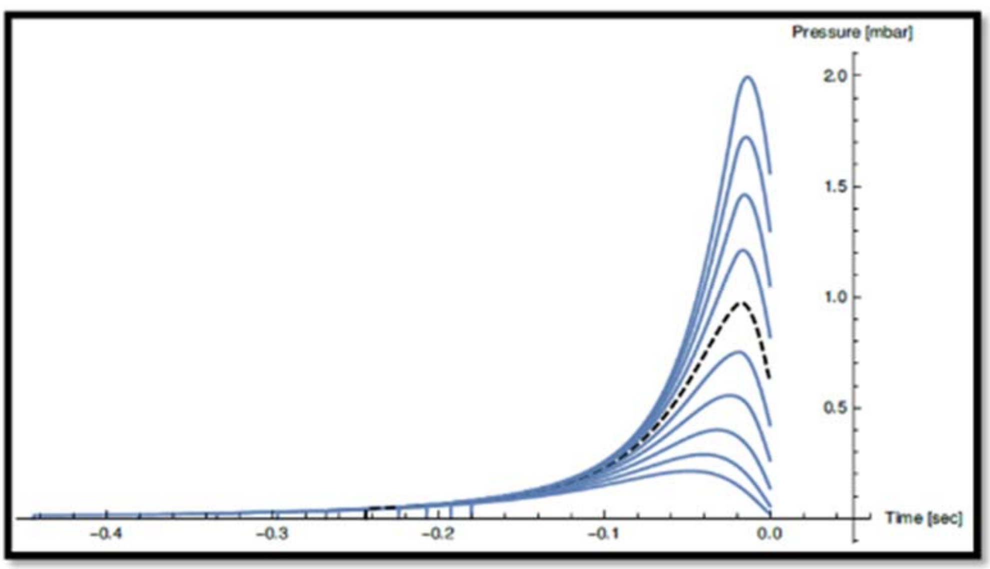


Figure 41. Rear Door Pressure Spike with Time. The Multi-Curves Showing the Multi-Door Closing Velocities and the Black Dash Line is The Pressure Spike with the Minimum Closing Effort

Figure 42 and 43 shown the door closing velocity that caused by the pressure spike, not the total door closing velocity for front and rear door respectively. Also, in Figure 42 and 43 the dashed line is a linear approximation of the green data points.

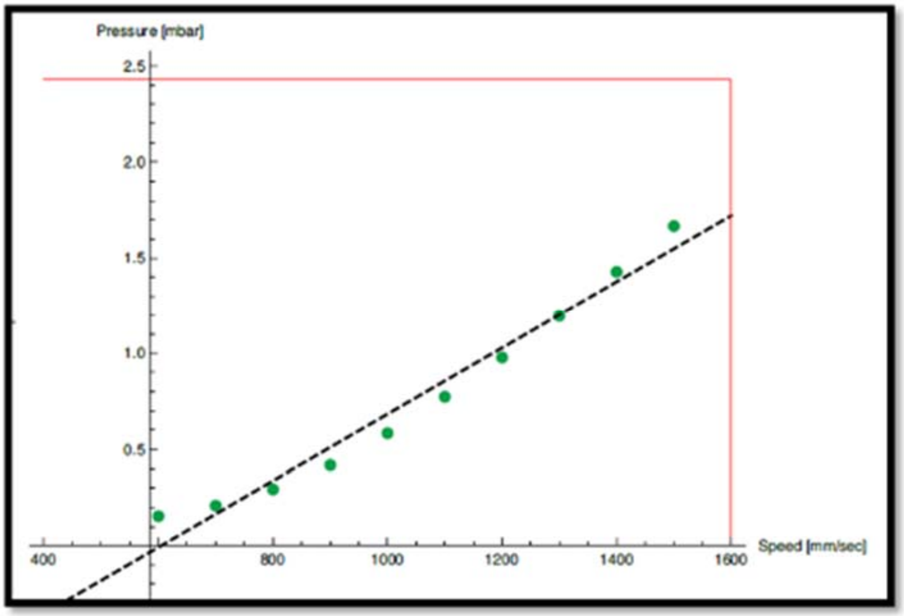


Figure 42. Front Door Pressure Spike with the Door Closing Velocity

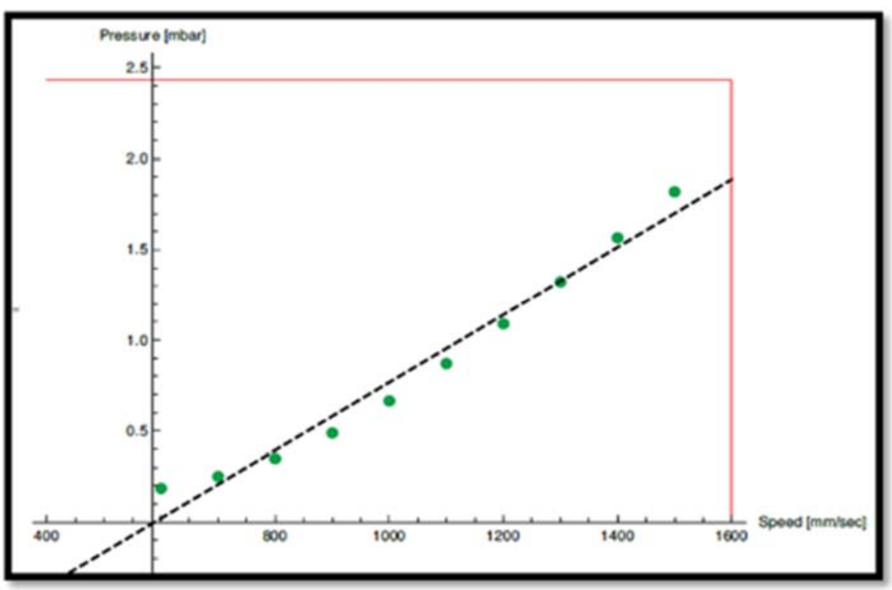


Figure 43. Rear Door Pressure Spike with the Door Closing Velocity

To calculate the energy that is absorbed by the air bind, One needs to calculate $E_{air\ bind}$ as illustrated in equation 21 and Figure 44.

$$E_{air\ bind} = \int_{s}^{0} p(s)A\,ds = \int_{\theta_0}^{0} (\theta)A\,d\theta = \int_{t_0}^{t_1} p\big(\theta(t)\big)|\theta'(t)|\,A\,dt \qquad \text{.................(21)}$$

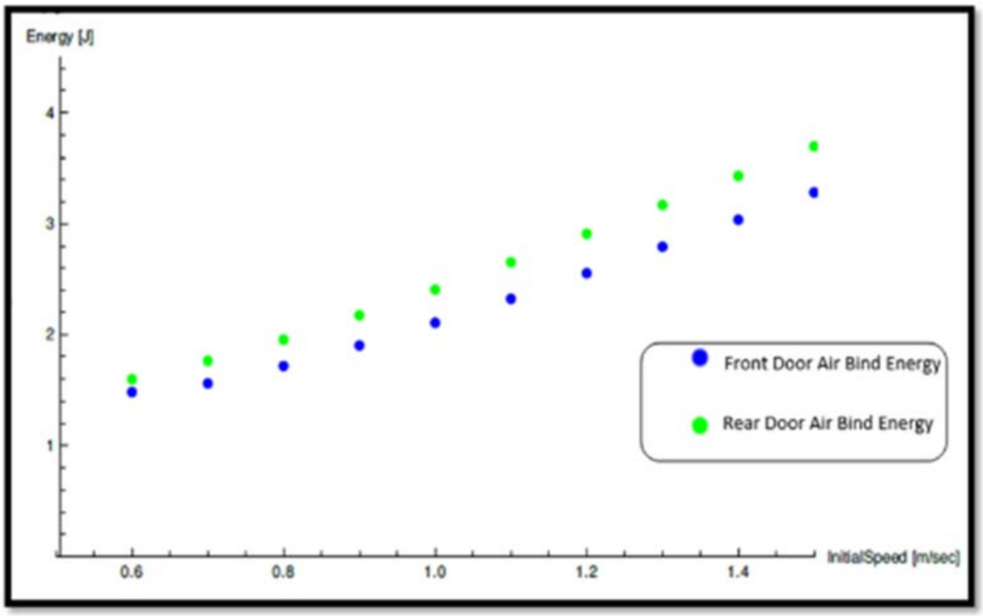


Figure 44. Air Bind Energy with Door Closing Speed for the Front and Rear Door

3.5.2 Seal Compression

The seal compression sink energy shown in Figure 45 should be the same for the following seals: primary, secondary, header, margin, and the rocker seal. Locations of the seals are shown in Figure 46. Lowering the seal CLD improve door closing effort but it effect door closing sound quality [52].

Compression load deflection (CLD) behavior of a highly non-linear type of joint, automotive weatherstrip seal made of Ethylene Propylene Diene Monomer (EPDM) sponge rubber is examined using finite element modeling technique [53].

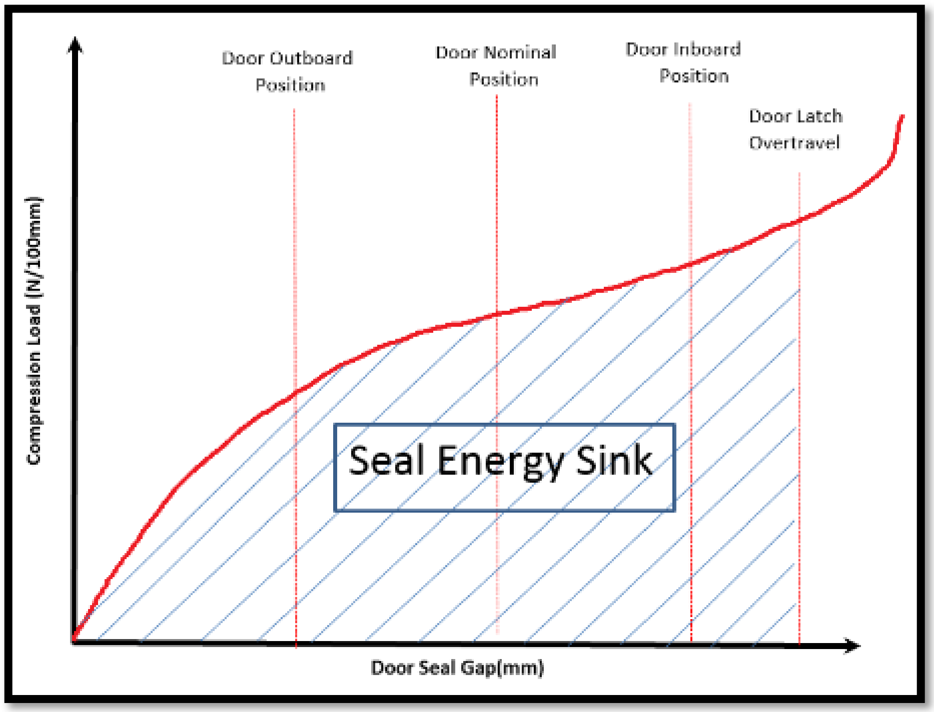


Figure 45. Showing the Sink Seal Energy [54]

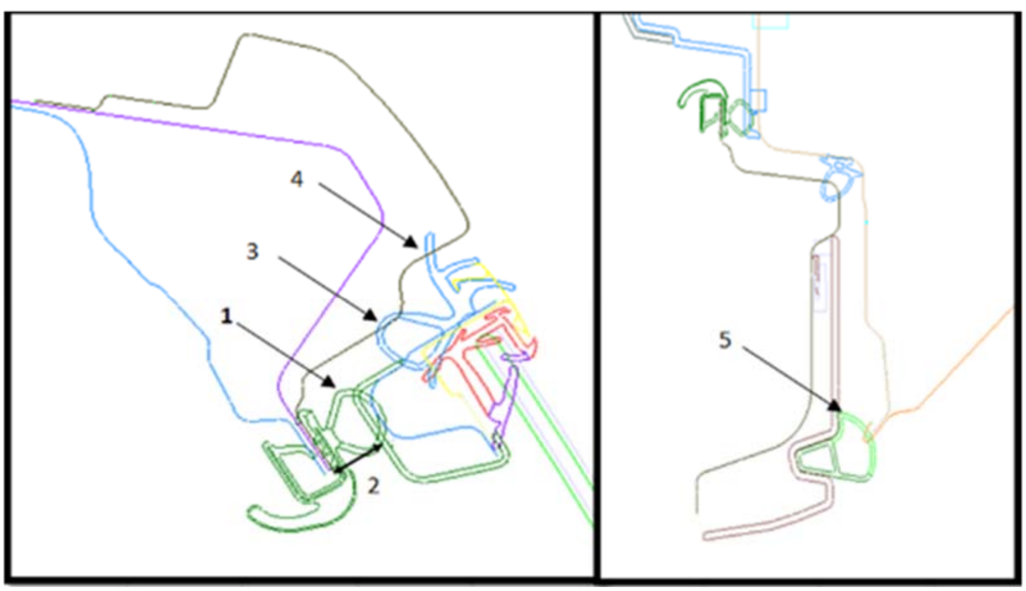


Figure 46. Cross Section for the Seal. (1) Secondary Seal, (2) Secondary Seal Gap, (3) Primary Seal, (4) Header Seal and (5) Rocker Seal [55]

3.5.3 Hinge Axis and Friction

The energy sink due to hinge friction is predicted by a simple quasi-static torque model [26], with a vertical hinge axis, as shown in Figure 47. Hinge friction caused by the frictional resistance between hinge leaf and hinge pin [56].

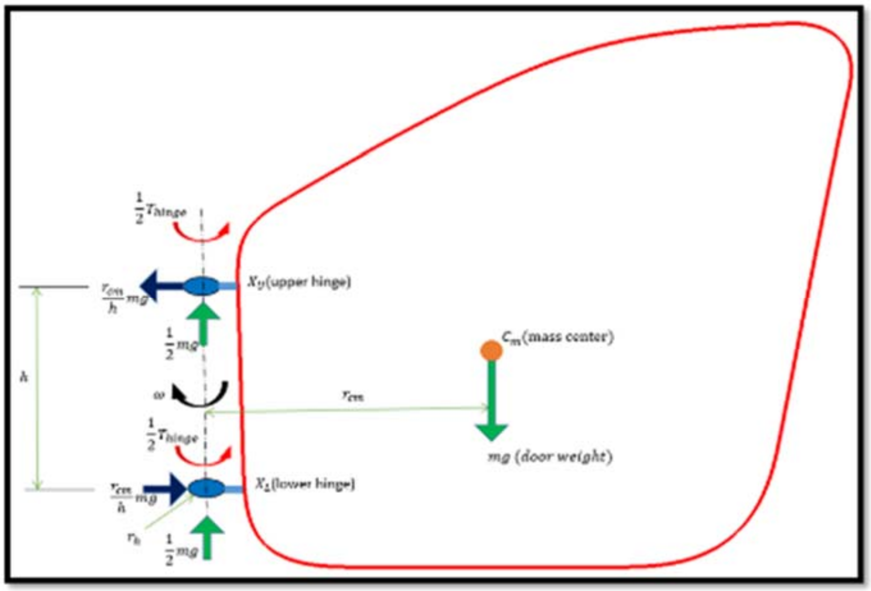


Figure 47. Schematic of Hinge Friction Model [26]

The door weight is assumed to be carried equally by the upper and lower hinges with each hinge carrying half of the door weight. Because the door mass center is at a distance r_{cm} from the hinge axis, there is a moment due to reactions r_{cm}/h mg at the two hinge pins which balance the door momentmgr_{cm}. If the hinge pin has a radius r_h , and the hinge friction coefficient is μ_h, the torque from the two hinge pin sides is [26].

$$T_{hinge} = 2\left(\frac{r_{cm}}{h} + 1\right)\mu_h mgr_h. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (22)$$

$$\Delta E_{hinge} = T_{hinge}\Delta\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (23)$$

$$E_{hinge} = E_{hinge} + \Delta E_{hinge} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (24)$$

$\Delta\theta$: where $\theta = 0\ to\ \theta =$ minimum door open angle with minimum closing effort

3.5.4 Door Latching Mechanism and Striker

Automotive side door latches are considered safety critical systems due to federal regulations [57].

The energy absorbed by the latch affects the side door closing effort [58]. The data for testing the latch on the fixture provides the curve shown in Figure 48. The curve is used to calculate the energy sink from the latch.

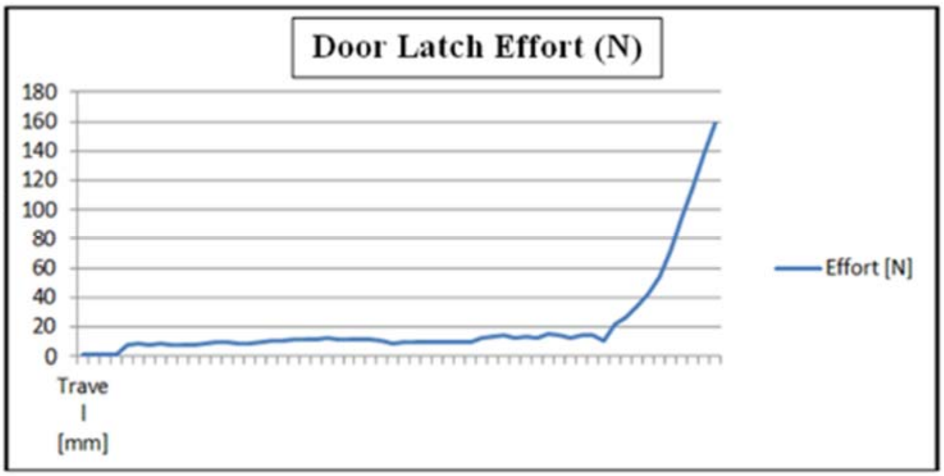


Figure 48. The Latch Sink Effort [59]

3.5.5 Door Check-Link

The check link provides energy to close the door during the closing process. It has been calculated by CAE, which was illustrated in section 1.2.5, then embedded in the mathematical model for the side door closing efforts Figure 49.

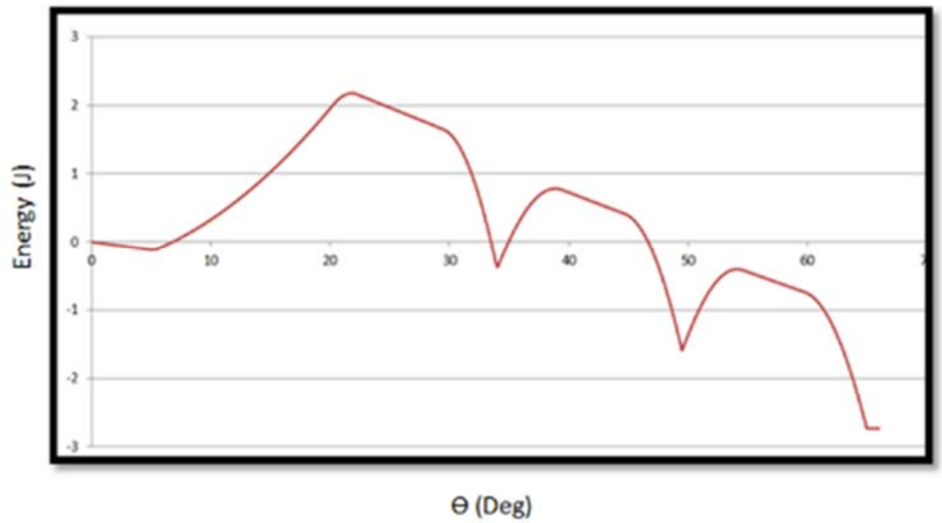


Figure 49. Door Check Energy [60]

3.5.6 Door Weight

When the door hinge axis is not vertical, the door weight, -m.g.k, will generate a torque, $T_{weight} = T_{weight}(\theta)$ around the hinge axis, which may help to close the door where T_{weight} is a function of θ

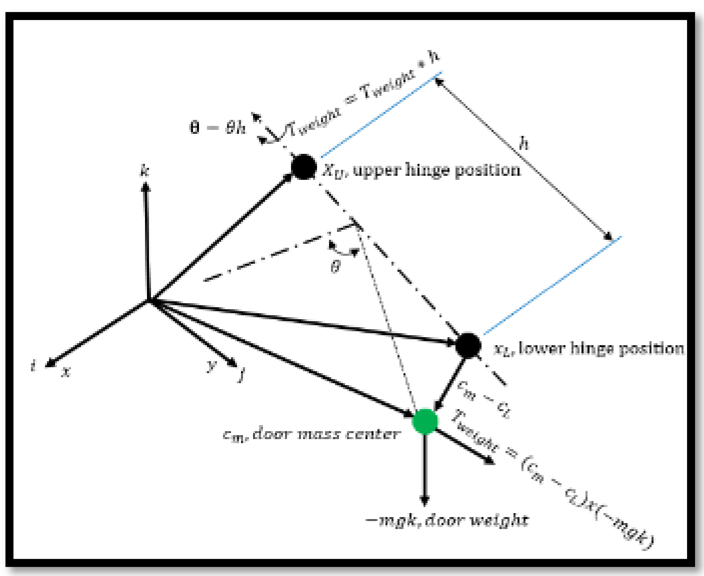


Figure 50. Schematic of Door Weight Effort Model [26]

Figure 50 illustrates the upper hinge location, X_U, and the lower hinge location, X_L. The door mass center $C_m = C_m(\theta)$ is located approximately at the geometric center of the door plane. If k is the unit basis vector in the z-axis, and h is the unit vector of the door hinge directed from X_L to X_U, (Li 2009)

$$T_{weight} = [(C_m - X_L) \times (-mgk)].h \qquad \text{.. (25)}$$

The mass center can expressed as

$$C_m = C_m(\theta) = X_L \Lambda(\theta)[C_m(0) - X_L] \qquad \text{.. (26)}$$

Where the rotation matrix $\Lambda(\theta)$ is calculated using the following Rodrigues formula

$$\Lambda(\theta) = \mathbf{I} + \frac{\sin\theta}{\theta}\,\theta^{\wedge} + \frac{1-\cos\theta}{\theta^2}\,\theta^{\wedge 2} \qquad \text{.. (27)}$$

$$= \mathbf{I} + \sin\theta h^{\wedge} + (1-\cos\theta)h^{\wedge 2}$$

Where the "hat" over a vector $V = V_x\mathbf{i} + V_y\mathbf{j} + V_z\boldsymbol{k}$ for example, represents the skew matrix

$$[\mathbf{V}^{\wedge}] = \begin{bmatrix} 0 & -v_z & v_y \\ v_z & 0 & -v_x \\ -v_y & v_x & 0 \end{bmatrix} \qquad \text{.. (28)}$$

The energy due to door weight is

$$E_{weight} = mg[C_m - C_m(0)].K\,, \qquad \text{.. (29)}$$

E_{weight} is a geometrically exact expression for the weight energy.

However, the analytical model to calculate the side door closing effort depends on the principle Energy in = Energy out. .... (30)

Energy in = Potential+ Kinetic+ Check Energy .... (31)

Potential = drop upon closing. .... (32)

Kinetic = customer supplied energy .... (33)

Energy out = Energy Sink = Air compression, seals, latch, hinges, friction and door deflection.

This model build depends on the physical test for the force gauge, Figure 51, which is showing the spring on the right side and the force gauge on the left side. Figure 52 illustrates the door open with θ detent angle.

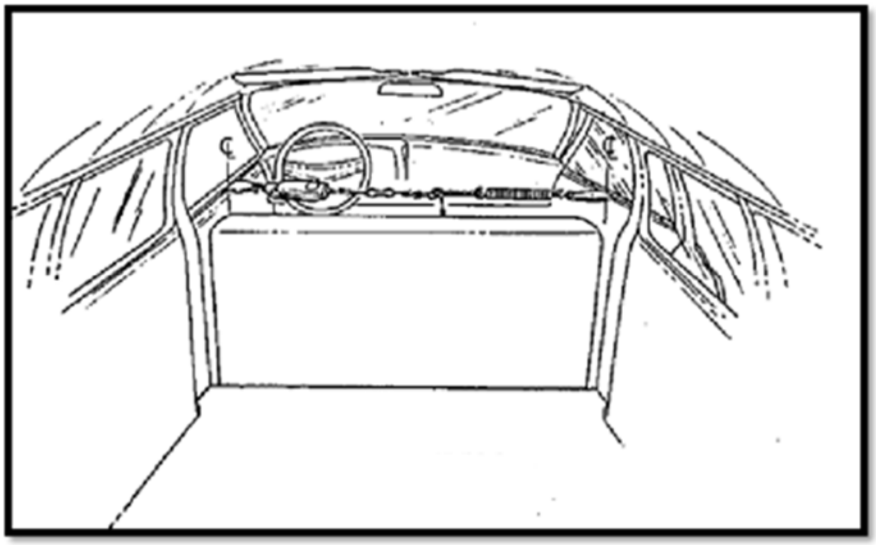


Figure 51. Force Gauge to Measure the Closing Force [14]

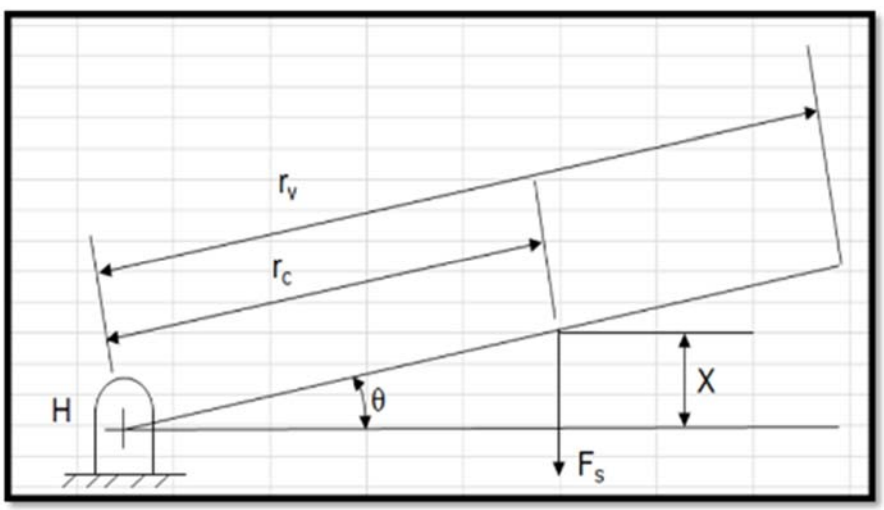


Figure 52. Schematic for the Force Gauge to Measure the Closing Force

Assuming planar motion

k = Spring constant

A = Pre-Stretch in spring 22N

$x = r_c \sin\theta$

$F_s = kx + ka$

r_v = radius to velocity gauge

r_c = radius to customer

I_D = mass moment of inertia of door

$\dot{\omega}$ = Time derivation of angular velocity

The summation of the moment around point H of all the forces acting on the door is equal to the time rate of change of the angular momentum of the door about H point.

$$+\sum M_M = I_D\dot{\omega} \quad \text{.....................................(34)}$$

$$-(kr_c \sin\theta + ka)r_c \cos\theta = I_D\dot{\omega} \quad \text{.....................................(33)}$$

$$kr_c^2 \sin\theta + kar_c \cos\theta = -I_D\dot{\omega} \quad \text{.....................................(35)}$$

$$\text{where } \dot{\omega} = \frac{d\omega}{dt} \quad \text{.....................................(36)}$$

multiply by $\frac{d\theta}{d\theta}$

$$kr_c^2 \sin\theta\cos\theta + kar_c \cos\theta = -I_D\frac{d\omega}{dt}.\frac{d\theta}{d\theta} = -I_D\omega\frac{d\omega}{d\theta} \quad \text{..........................(37)}$$

Integrate from $\theta_\circ$ to 0 and 0 to ω_f

$$kr_c^2 \int_{\theta_\circ}^{0} \sin\theta\cos\theta\, d\theta + kar_c \int_{\theta_\circ}^{0} \cos\theta d\theta = -I_D \int_0^{\omega_f} \omega\, d\omega \quad \text{..........................(38)}$$

$$\frac{kr_c^2}{2}[\sin^2\theta]_{\theta_\circ}^{0} + kar_c \sin\theta]_{\theta_\circ}^{0} = -I_D\frac{\omega^2}{2} \quad \text{..........................(39)}$$

$$K.E. = 1xER2\omega^2 I_D = \text{Kinetic Energy} \quad \text{..........................(40)}$$

$$\frac{kr_c^2}{2}(\sin^2 0 - \sin^2\theta_\circ) + kar_c(\sin 0 - \sin\theta) = -K.E \quad \text{..........................(41)}$$

$$-\frac{kr_c^2\sin^2\theta}{2} - kar_c\sin\theta = -K.E. \quad ....(42)$$

While $x = r_c\sin\theta_\circ$ ....(43)

so $x^2 = (r_c\sin\theta_\circ)^2 = r_c^2\sin^2\theta_\circ$ ....(44)

$$\frac{k}{2}x^2 + kax = K.E. \quad ....(45)$$

$$x^2 + 2ax - 2\frac{K.E}{K} = 0 \quad ....(46)$$

$$x = \frac{-2a \pm \sqrt{(2a)^2 - 4(-2\frac{K.E}{K})}}{2} \quad ....(47)$$

x can′t be negative

$$\therefore x = -a + \sqrt{a^2 + 2\frac{K.E}{K}} \quad ....(48)$$

$$\theta = (180/\pi * ASIN(x/(r_c/1000))$$

$$v_{C.G} = [\frac{2KE}{m}]^{1/2}$$

$$\omega = v_{C.G}/r_c$$

$$v = \omega \ r_v$$

Where x represents the spring displacement in (mm)

$v_{C.G}$ = Velocity of the door at the C.G (m/s)

ω = Angular velocity of the door (rad/sec)

$v = door\ closing\ velocity$ (m/s) $at\ the\ edge\ of\ the\ door.$

With a couple of iterations, one can find the minimum θ that can be used with minimum closing effort. Depending on the mathematical model, which includes all the factors contribute to the closing effort. The seal gap trial and the CLDs will be used with the

DOE technique to analyze the effect of these factors on the closing effort and the optimization of the seal gap variation.

3.6 Experimental Approach

Response Surface Methodology (RSM) includes the application of regression analysis and a powerful set of optimization techniques. RSM is used to design a set of experiments that will result in reliable predictions of the response function allowing the development of a mathematical model by performing tests of the hypothesis. After that, the optimal settings of the influencing factors or input variables may be determined to achieve the desired optimized dependent variable [61].

Box-Behnken designs are experimental designs for RSM to achieve the following goals:

- The design must be sufficient to fit a second order polynomial.
- The ratio of the number of experimental points to the number of coefficients in the quadratic model should be reasonable, which means more than one as value.
- The predicted variance should depend only on the distance from the center of the design and should not vary significantly inside the smallest hypercube containing the experimental points.

Each design may be considered as a combination of a 2k factorial design with an incomplete block design. In each block, a certain number of factors are put through all combinations of the factorial design, while the other factors remain at the central values. The resulting design is either rotatable or nearly rotatable and is typically very efficient concerning the number of runs. In such a design, the contours associated with the variance of the estimation values are concentric circles, and its primary advantage is avoiding treatment combinations that are extreme (corner points).

A 3-level, 7-factor factorial design requires 2187 runs, whereas a Box-Behnken design requires 62 runs. This Box-Behnken design for seven factors and three levels includes two blocks contains each block 31 experiments. It is necessary to include center points where all factors are at their central values. Therefore, Box-Behnken designs are considered economic and useful, especially when significant expenses are required to conduct the needed experimental runs. An additional benefit of the Box- Behnken design is the redundancy factor defined as R=N/L

Where N is the number of runs and L is the number of constants, L can be estimated as (k + d)! / k! d! Where k is the number of quantitative experimental variables and d is the degree of the polynomial; therefore, L = (7 + 2)! / 7! 2! = 36 resulting in a redundancy factor of R = 62 / 36 = 1.72, a measure of the number of experimental runs required to determine each coefficient of the second degree polynomial. In comparison, the 3-level, 7-factor factorial design would have a redundancy factor of 2187/62 = 35.3.

3.6.1 Model Postulation

Upon identifying the significant factors using screening factorial experiments, a functional relationship between side door closing efforts and the selected independent variables can be represented by Equation (49).

$$E = CX_1^k X_2^m X_3^n X_4^p X_5^q X_6^r X_7^t \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (49)$$

Where: E is a velocity of the rear edge of the door measured by m/sec and

X_1: First secondary seal segment at the B-Pillar above the belt

X_2: Second secondary seal segment at the header

X_3: Third secondary seal segment at the rocker

X_4: Fourth secondary seal segment at the B-Pillar below the belt

X_5: Fifth secondary seal segment at the A-pillar for the front door and at the C pillar for the rear door

X_6: Secondary seal CLD

X_7: Primary seal CLD as shown in Figure 53.

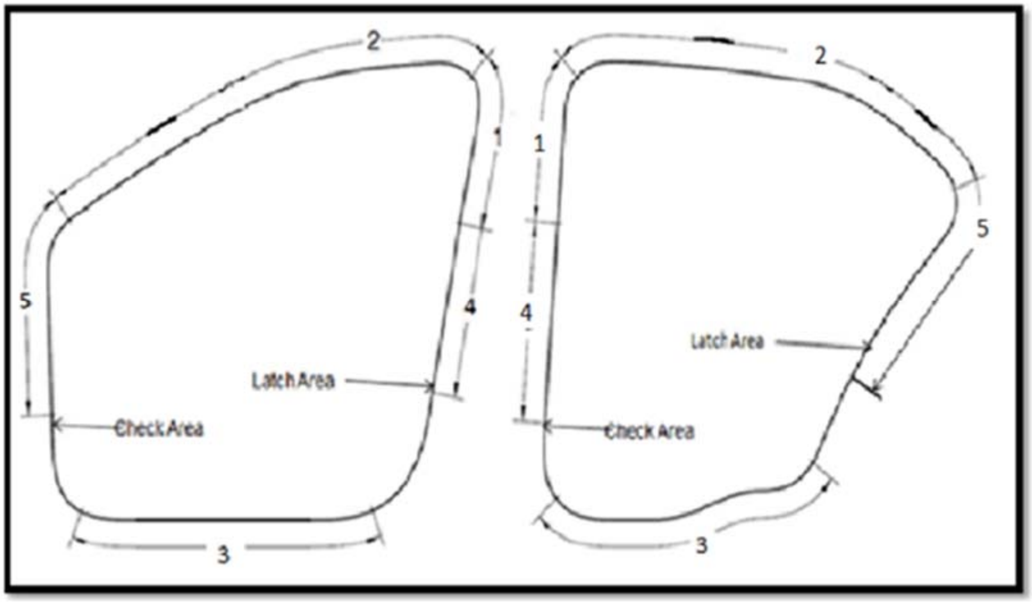


Figure 53. Numbers 1 to 5 Represent the Secondary Seal Segments X_1 to X_5

Equation (49) can be written as:

$$\eta = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \varepsilon \quad \text{...........(50)}$$

The above equation represents a logarithmic scale. The parameters β_1, β_2, …,β_7 are called regression coefficients or parameters and X_1, X_2, …, X_7 are logarithmic transformations of the input variables in the regression function. The experimental error is denoted as ε and may be defined as a combination of the random measurement error caused by sources such as test equipment and operators, as well as nonrandom errors caused by excluding factors from the designed experiment. Every experiment includes some degree of error that effect the value of the response corresponding to a specific combination of factor levels.

If the unknown parameters $\beta_o, \beta_1, \beta_2, \ldots, \beta_7$ are replaced by estimates $b_0, b_1, \ldots, b_7$, the first-order prediction equation becomes:

$$\hat{y} = b_\circ + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_6X_6 + b_7X_7 \quad \ldots\ldots\ldots\ldots\ldots(51)$$

The above "$\hat{y}$" is the estimated response on a logarithmic scale.

The second order model can be represented by

$$\begin{aligned}\hat{y} = {} & b_\circ + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_6X_6 + b_7X_7 + \\ & b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{44}X_4^2 + b_{55}X_5^2 + b_{66}X_6^2 + b_{77}X_7^2 + \\ & b_{12}X_1X_2 + b_{13}X_1X_3 + b_{14}X_1X_4 + b_{15}X_1X_5 + b_{16}X_1X_6 + b_{17}X_1X_7 + \\ & b_{23}X_2X_3 + b_{24}X_2X_4 + b_{25}X_2X_5 + b_{26}X_2X_6 + b_{27}X_2X_7 + \\ & b_{34}X_3X_4 + b_{35}X_3X_5 + b_{36}X_3X_6 + b_{37}X_3X_7 + \\ & b_{45}X_4X_5 + b_{46}X_4X_6 + b_{36}X_4X_7 + \\ & b_{56}X_5X_6 + b_{66}X_5X_7 + \\ & b_{67}X_6X_7 \text{ [62]} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(52)\end{aligned}$$

If this polynomial exactly represents the response function ŷ, then b0 is the response at $X_1 = X_2 = X_3 = X_4 = \cdots = X_7 = 0$. The coefficients $b_1, b_2, b_3, \ldots.b7$ are the values of the 1st order partial derivatives $\frac{\partial\hat{y}}{\partial X_1}, \frac{\partial\hat{y}}{\partial X_2}, \frac{\partial\hat{y}}{\partial X_3}, \frac{\partial\hat{y}}{\partial X_4}, \frac{\partial\hat{y}}{\partial X_5}, \frac{\partial\hat{y}}{\partial X_6}, \frac{\partial\hat{y}}{\partial X_7}$, of $\hat{y}$ with respect to $X_1, X_2, X_3, X_4, \ldots X_7$ evaluated at $X_1 = X_2 = X_3 = X_4 = \cdots = X_7 = 0$ and are referred to as 1st order effects. The remaining coefficients $b_{11}, b_{22}, b_{33}, b_{44} \ldots b_{67}$ are defined as the values of the 2nd order partial derivatives, $\frac{\frac{1}{2}\partial^2\hat{y}}{\partial x_1^2}, \frac{\frac{1}{2}\partial^2\hat{y}}{\partial x_2^2}, \frac{\frac{1}{2}\partial^2\hat{y}}{\partial x_3^2}, \frac{\frac{1}{2}\partial^2\hat{y}}{\partial x_4^2}, \ldots. \frac{\frac{1}{2}\partial^2\hat{y}}{\partial x_7^2}$ respectively, at $X_1 = X_2 = X_3 = X_4 = \cdots = X_7 = 0$, and are called the 2nd order effects.

3.6.2 Coding of Variables

The range of settings for these quantitative factors (which were explained in section 3.6.1) will be determined. While experimenting, their measurement and control techniques must be defined.

The secondary seal gap segments, which are defined by $X_1$to X_5,were measured by the LMI device for several vehicle platforms. The factors are designed with the same seal gap variation and have the same sealing system. Therefore, the zero will define the nominal seal gap, and the other factors will define the nominal seal CLD. (-1) will define the minimum seal gap (maximum door going inboard). The CLD factor will define the minimum CLD for the seals. (+1) represents the maximum seal gap (maximum seal going outboard in the plan) and the CLD factor will define the maximum seal CLD value. Table 3 and 4 will illustrate the levels and the coding of the independent variables for front and rear doors.

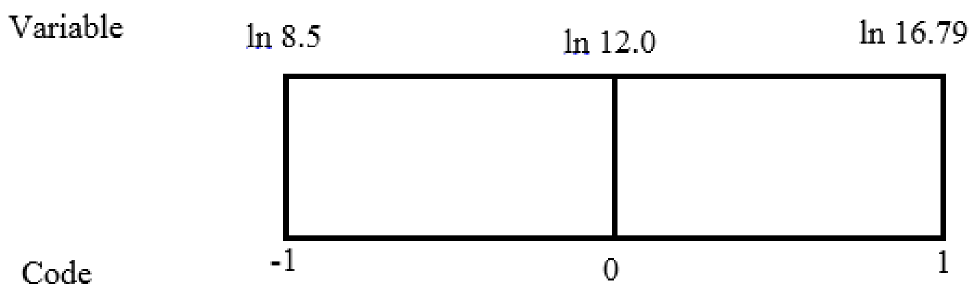
Table 3. Levels and Coding of the Independent Variables for Front Doors

Independent Variable	1st B- pillar Segment above the Belt (mm)	2nd Header Segment (mm)	3rd Rocker Segment (mm)	4th B-Pillar Segment below the belt (mm)	5th A-Pillar & C Pillar Segment for the FR & RR DR Perspectival (mm)	6th Secondary Seal CLD (N/100mm)	7th Primary Seal CLD (N/100mm)
Code	X_1	X_2	X_3	X_4	X_5	X_6	X_7
-1	8.5	8.5	10.79	9.17	9.49	1.59	1.99
0	12.0	12.03	13.8	12.8	13	2.59	3.99
+1	16.79	17.82	18.33	16.08	18.5	4.59	5.99

Table 4. Levels and Coding of the Independent Variables for Rear Doors

Independent Variable	1st B- pillar Segment above the Belt (mm)	2nd Header Segment (mm)	3rd Rocker Segment (mm)	4th B-Pillar Segment below the belt (mm)	5th A-Pillar & C Pillar Segment for the FR & RR DR Perspectival (mm)	6th Secondary Seal CLD (N/100mm)	7th Primary Seal CLD (N/100mm)
Code	X_1	X_2	X_3	X_4	X_5	X_6	X_7
-1	8.68	8.5	10.57	9.85	10.23	1.59	1.99
0	12.1	12.00	13.8	12.65	12.93	2.59	3.99
+1	16.4	17.5	18.5	18.5	17.27	4.59	5.99

The coding of the surface roughness is illustrated as follows:



The variables $X_1, X_2, X_3, X_4, \dots X_7$ are coded variables defined as

$$X_1 = \frac{\ln(\text{B} - \text{ pillar segement above the belt}) - \ln 12.0}{\ln 16.79 - \ln 8.5} \qquad \text{……………..………(53)}$$

$$X_2 = \frac{\ln(\text{Header Segment}) - \ln 12.03}{\ln 17.82 - \ln 8.5} \qquad \text{………………………(54)}$$

$$X_3 = \frac{\ln(\text{Rocker Segement}) - \ln 13.80}{\ln 18.5 - \ln 10.57} \qquad \text{………………………..(55)}$$

$$X_4 = \frac{\ln(\text{B} - \text{ pillar segement below the belt}) - \ln 12.65}{\ln 18.5 - \ln 9.85} \qquad \text{………………………(56)}$$

$$X_5 = \frac{ln(A - Pillar\ \&\ C - \ Pillar\ Segment\ for\ the\ FR\ DR\ ) - ln\ 12.93}{ln\ 17.27 - ln\ 10.23} \quad (57)$$

$$X_6 = \frac{\ln(\text{Secondary Seal CLD }) - \ln 2.59}{\ln 4.59 - \ln 1.59} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(58)$$

$$X_7 = \frac{\ln(\text{Primary Seal CLD }) - \ln 3.99}{\ln 5.99 - \ln 1.99} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(59)$$

The use of these coded variables facilitates performing the calculations to obtain the parameter estimates, and applies to both linear and second-order models [63].

3.6.3 Design of Experiments

A Box-Behnken design was aimed at estimating the maximum number of main effects in an unbiased (orthogonal) fashion by performing a minimum number of experimental runs. This research uses the Box-Behnken technique to reduce the number of experiments which are used with the mathematical model to calculate the side door closing effort. The data matrix represented in Table 3 required for studying seven factors in 62 trials. The plus signs indicate the high levels of the independent variables, while the minus signs represent the low levels, and the central levels are represented by zeroes as coded in Table 3 and 4. The 36 coefficients for the second order model shown in Equation (40). One can determine the variables by conducting and analyzing the 62 runs outlined in Table 4. Full factorial design requires 152 runs compared to a Box-Behnken design, which consists of two blocks, each block including 31 trials, ending up with 62 experiments as shown in Table 5.

3.7 Experimentation

A mathematical model will be used to predict the side door closing effort with seven factors and three variables. This experimentation will consist of 62 runs [62] as shown in Table 5 and 7. This Box-Behnken design for 7 factors involves 7 blocks, wherein each block contain 3 factors and it can vary through the 8 possible combinations of high and low. It is necessary to include center points where all factors are at their central values. The result will be analyzed in Chapter 4. The fundamental design matrix is written in the form as shown below:

$$\text{DCE}=\begin{bmatrix} 0 & 0 & 0 & \pm1 & \pm1 & \pm1 & 0 \\ \pm1 & 0 & 0 & 0 & 0 & \pm1 & \pm1 \\ 0 & \pm1 & 0 & 0 & \pm1 & 0 & \pm1 \\ \pm1 & \pm1 & 0 & \pm1 & 0 & 0 & 0 \\ 0 & 0 & \pm1 & \pm1 & 0 & 0 & \pm1 \\ \pm1 & 0 & \pm1 & 0 & \pm1 & 0 & 0 \\ 0 & \pm1 & \pm1 & 0 & 0 & \pm1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(60)$$

Table 5. Design Matrix for Front and Rear Door

Run	X_1	X_2	X_3	X_4	X_5	X_6	X_7
1	0	0	0	-	-	-	0
2	0	0	0	+	-	-	0
3	0	0	0	-	+	-	0
4	0	0	0	+	+	-	0
5	0	0	0	-	-	+	0
6	0	0	0	+	-	+	0
7	0	0	0	-	+	+	0
8	0	0	0	+	+	+	0
9	-	0	0	0	0	-	-
10	+	0	0	0	0	-	-
11	-	0	0	0	0	+	-
12	+	0	0	0	0	+	-
13	-	0	0	0	0	-	+
14	+	0	0	0	0	-	+
15	-	0	0	0	0	+	+
16	+	0	0	0	0	+	+
17	0	-	0	0	-	0	-
18	0	+	0	0	-	0	-
19	0	-	0	0	+	0	-
20	0	+	0	0	+	0	-
21	0	-	0	0	-	0	+
22	0	+	0	0	-	0	+
23	0	-	0	0	+	0	+
24	0	+	0	0	+	0	+
25	-	-	0	-	0	0	0
26	+	-	0	-	0	0	0
27	-	+	0	-	0	0	0
28	+	+	0	-	0	0	0
29	-	-	0	+	0	0	0
30	+	-	0	+	0	0	0
31	-	+	0	+	0	0	0
32	+	+	0	+	0	0	0
33	0	0	-	-	0	0	-
34	0	0	+	-	0	0	-
35	0	0	-	+	0	0	-
36	0	0	+	+	0	0	-
37	0	0	-	-	0	0	+
38	0	0	+	-	0	0	+
39	0	0	-	+	0	0	+
40	0	0	+	+	0	0	+
41	-	0	-	0	-	0	0
42	+	0	-	0	-	0	0
43	-	0	+	0	-	0	0
44	+	0	+	0	-	0	0
45	-	0	-	0	+	0	0
46	+	0	-	0	+	0	0
47	-	0	+	0	+	0	0
48	+	0	+	0	+	0	0
49	0	-	-	0	0	-	0
50	0	+	-	0	0	-	0
51	0	-	+	0	0	-	0
52	0	+	+	0	0	-	0
53	0	-	-	0	0	+	0
54	0	+	-	0	0	+	0
55	0	-	+	0	0	+	0
56	0	+	+	0	0	+	0
57	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0
59	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0
61	0	0	0	0	0	0	0
62	0	0	0	0	0	0	0

Table 6. Coding and Actual Levels for the Front Doors

Run	X1	X2	X3	X4	X5	X6	X7	1st B- pillar Segment above the Belt (mm)	2nd Header Segment (mm)	3rd Rocker Segment (mm)	4th B-Pillar Segment below the belt (mm)	5th A-Pillar & C Pillar Segment for the FR & RR DR Perspectival (mm)	6th Secondary Seal CLD (N/100mm)	7th Primary Seal CLD (N/100mm)
1	0	0	0	-	-	-	0	12	12.03	13.8	9.3	9.5	1.59	3.99
2	0	0	0	+	-	-	0	12	12.03	13.8	16.08	9.5	1.59	3.99
3	0	0	0	-	+	-	0	12	12.03	13.8	9.3	18.5	1.59	3.99
4	0	0	0	+	+	-	0	12	12.03	13.8	16.08	18.5	1.59	3.99
5	0	0	0	-	-	+	0	12	12.03	13.8	10.0	9.5	4.59	3.99
6	0	0	0	+	-	+	0	12	12.03	13.8	16.08	9.5	4.59	3.99
7	0	0	0	-	+	+	0	12	12.03	13.8	9.3	18.5	4.59	3.99
8	0	0	0	+	+	+	0	12	12.03	13.8	16.08	18.5	4.59	3.99
9	-	0	0	0	0	-	-	8.5	12.03	13.8	12.8	13.0	1.59	1.99
10	+	0	0	0	0	-	-	16.79	12.03	13.8	12.8	13.0	1.59	1.99
11	-	0	0	0	0	+	-	8.5	12.03	13.8	12.8	13.0	4.59	1.99
12	+	0	0	0	0	+	-	16.79	12.03	13.8	12.8	13.0	4.59	1.99
13	-	0	0	0	0	-	+	8.5	12.03	13.8	12.8	13.0	1.59	5.99
14	+	0	0	0	0	-	+	16.79	12.03	13.8	12.8	13.0	1.59	5.99
15	-	0	0	0	0	+	+	8.5	12.03	13.8	12.8	13.0	4.59	5.99
16	+	0	0	0	0	+	+	16.79	12.03	13.8	12.8	13.0	4.59	5.99
17	0	-	0	0	-	0	-	12	8.53	13.8	12.8	9.5	2.59	1.99
18	0	+	0	0	-	0	-	12	17.82	13.8	12.8	9.5	2.59	1.99
19	0	-	0	0	+	0	-	12	8.53	13.8	12.8	18.5	2.59	1.99
20	0	+	0	0	+	0	-	12	17.82	13.8	12.8	18.5	2.59	1.99
21	0	-	0	0	-	0	+	12	8.53	13.8	12.8	9.5	2.59	5.99
22	0	+	0	0	-	0	+	12	17.82	13.8	12.8	9.5	2.59	5.99
23	0	-	0	0	+	0	+	12	8.53	13.8	12.8	18.5	2.59	5.99
24	0	+	0	0	+	0	+	12	17.82	13.8	12.8	18.5	2.59	5.99
25	-	-	0	-	0	0	0	8.5	8.53	13.8	9.3	13.0	2.59	3.99
26	+	-	0	-	0	0	0	16.79	8.53	13.8	9.3	13.0	2.59	3.99
27	-	+	0	-	0	0	0	8.5	17.82	13.8	9.3	13.0	2.59	3.99
28	+	+	0	-	0	0	0	16.79	17.82	13.8	9.3	13.0	2.59	3.99
29	-	-	0	+	0	0	0	8.5	8.53	13.8	16.08	13.0	2.59	3.99
30	+	-	0	+	0	0	0	16.79	8.53	13.8	16.08	13.0	2.59	3.99
31	-	+	0	+	0	0	0	8.5	17.82	13.8	16.08	13.0	2.59	3.99
32	+	+	0	+	0	0	0	16.79	17.82	13.8	16.08	13.0	2.59	3.99
33	0	0	-	-	0	0	-	12	12.03	10.79	9.3	13.0	2.59	1.99
34	0	0	+	-	0	0	-	12	12.03	18.33	9.3	13.0	2.59	1.99
35	0	0	-	+	0	0	-	12	12.03	10.79	16.08	13.0	2.59	1.99
36	0	0	+	+	0	0	-	12	12.03	18.33	16.08	13.0	2.59	1.99
37	0	0	-	-	0	0	+	12	12.03	10.79	9.3	13.0	2.59	5.99
38	0	0	+	-	0	0	+	12	12.03	18.33	9.3	13.0	2.59	5.99
39	0	0	-	+	0	0	+	12	12.03	10.79	16.08	13.0	2.59	5.99
40	0	0	+	+	0	0	+	12	12.03	18.33	16.08	13.0	2.59	5.99
41	-	0	-	0	-	0	0	8.5	12.03	10.79	12.8	9.5	2.59	3.99
42	+	0	-	0	-	0	0	16.79	12.03	10.79	12.8	9.5	2.59	3.99
43	-	0	+	0	-	0	0	8.5	12.03	18.33	12.8	9.5	2.59	3.99
44	+	0	+	0	-	0	0	16.79	12.03	18.33	12.8	9.5	2.59	3.99
45	-	0	-	0	+	0	0	8.5	12.03	10.79	12.8	18.5	2.59	3.99
46	+	0	-	0	+	0	0	16.79	12.03	10.79	12.8	18.5	2.59	3.99
47	-	0	+	0	+	0	0	8.5	12.03	18.33	12.8	18.5	2.59	3.99
48	+	0	+	0	+	0	0	16.79	12.03	18.33	12.8	18.5	2.59	3.99
49	0	-	-	0	0	-	0	12	8.53	10.79	12.8	13.0	1.59	3.99
50	0	+	-	0	0	-	0	12	17.82	10.79	12.8	13.0	1.59	3.99
51	0	-	+	0	0	-	0	12	8.53	18.33	12.8	13.0	1.59	3.99
52	0	+	+	0	0	-	0	12	17.82	18.33	12.8	13.0	1.59	3.99
53	0	-	-	0	0	+	0	12	8.53	10.79	12.8	13.0	4.59	3.99
54	0	+	-	0	0	+	0	12	17.82	10.79	12.8	13.0	4.59	3.99
55	0	-	+	0	0	+	0	12	8.53	18.33	12.8	13.0	4.59	3.99
56	0	+	+	0	0	+	0	12	17.82	18.33	12.8	13.0	4.59	3.99
57	0	0	0	0	0	0	0	12	12.03	13.8	12.8	13.0	2.59	3.99
58	0	0	0	0	0	0	0	12	12.03	13.8	12.8	13.0	2.59	3.99
59	0	0	0	0	0	0	0	12	12.03	13.8	12.8	13.0	2.59	3.99
60	0	0	0	0	0	0	0	12	12.03	13.8	12.8	13.0	2.59	3.99
61	0	0	0	0	0	0	0	12	12.03	13.8	12.8	13.0	2.59	3.99
62	0	0	0	0	0	0	0	12	12.03	13.8	12.8	13.0	2.59	3.99

Table 7. Coding and Actual Levels for the Rear Doors

Run	X1	X2	X3	X4	X5	X6	X7	1st B- pillar Segment above the Belt (mm)	2nd Header Segment (mm)	3rd Rocker Segment (mm)	4th B-Pillar Segment below the belt (mm)	5th A-Pillar & C Pillar Segment for the FR & RR DR Perspectival (mm)	6th Secondary Seal CLD (N/100mm)	7th Primary Seal CLD (N/100mm)
1	0	0	0	-	-	-	0	12.1	12.0	13.8	9.85	10.23	1.59	3.99
2	0	0	0	+	-	-	0	12.1	12.0	13.8	18.5	10.23	1.59	3.99
3	0	0	0	-	+	-	0	12.1	12.0	13.8	9.85	17.27	1.59	3.99
4	0	0	0	+	+	-	0	12.1	12.0	13.8	18.5	17.27	1.59	3.99
5	0	0	0	-	-	+	0	12.1	12.0	13.8	9.85	10.23	4.59	3.99
6	0	0	0	+	-	+	0	12.1	12.0	13.8	18.5	10.23	4.59	3.99
7	0	0	0	-	+	+	0	12.1	12.0	13.8	9.85	17.27	4.59	3.99
8	0	0	0	+	+	+	0	12.1	12.0	13.8	18.5	17.27	4.59	3.99
9	-	0	0	0	0	-	-	8.68	12.0	13.8	12.65	12.93	1.59	1.99
10	+	0	0	0	0	-	-	16.4	12.0	13.8	12.65	12.93	1.59	1.99
11	-	0	0	0	0	+	-	8.68	12.0	13.8	12.65	12.93	4.59	1.99
12	+	0	0	0	0	+	-	16.4	12.0	13.8	12.65	12.93	4.59	1.99
13	-	0	0	0	0	-	+	8.68	12.0	13.8	12.65	12.93	1.59	5.99
14	+	0	0	0	0	-	+	16.4	12.0	13.8	12.65	12.93	1.59	5.99
15	-	0	0	0	0	+	+	8.68	12.0	13.8	12.65	12.93	4.59	5.99
16	+	0	0	0	0	+	+	16.4	12.0	13.8	12.65	12.93	4.59	5.99
17	0	-	0	0	-	0	-	12.1	8.5	13.8	12.65	10.23	2.59	1.99
18	0	+	0	0	-	0	-	12.1	17.5	13.8	12.65	10.23	2.59	1.99
19	0	-	0	0	+	0	-	12.1	8.5	13.8	12.65	17.27	2.59	1.99
20	0	+	0	0	+	0	-	12.1	17.5	13.8	12.65	17.27	2.59	1.99
21	0	-	0	0	-	0	+	12.1	8.5	13.8	12.65	10.23	2.59	5.99
22	0	+	0	0	-	0	+	12.1	17.5	13.8	12.65	10.23	2.59	5.99
23	0	-	0	0	+	0	+	12.1	8.475	13.8	12.65	17.27	2.59	5.99
24	0	+	0	0	+	0	+	12.1	17.5	13.8	12.65	17.27	2.59	5.99
25	-	-	0	-	0	0	0	8.68	8.5	13.8	9.85	12.93	2.59	3.99
26	+	-	0	-	0	0	0	16.4	8.5	13.8	9.85	12.93	2.59	3.99
27	-	+	0	-	0	0	0	8.68	17.5	13.8	9.85	12.93	2.59	3.99
28	+	+	0	-	0	0	0	16.4	17.5	13.8	9.85	12.93	2.59	3.99
29	-	-	0	+	0	0	0	8.68	8.5	13.8	18.5	12.93	2.59	3.99
30	+	-	0	+	0	0	0	16.4	8.5	13.8	18.5	12.93	2.59	3.99
31	-	+	0	+	0	0	0	8.68	17.5	13.8	18.5	12.93	2.59	3.99
32	+	+	0	+	0	0	0	16.4	17.5	13.8	18.5	12.93	2.59	3.99
33	0	0	-	-	0	0	-	12.1	12.0	10.57	9.85	12.93	2.59	1.99
34	0	0	+	-	0	0	-	12.1	12.0	18.5	9.85	12.93	2.59	1.99
35	0	0	-	+	0	0	-	12.1	12.0	10.57	18.5	12.93	2.59	1.99
36	0	0	+	+	0	0	-	12.1	12.0	18.5	18.5	12.93	2.59	1.99
37	0	0	-	-	0	0	+	12.1	12.0	10.57	9.85	12.93	2.59	5.99
38	0	0	+	-	0	0	+	12.1	12.0	18.5	9.85	12.93	2.59	5.99
39	0	0	-	+	0	0	+	12.1	12.0	10.57	18.5	12.93	2.59	5.99
40	0	0	+	+	0	0	+	12.1	12.0	18.5	18.5	12.93	2.59	5.99
41	-	0	-	0	-	0	0	8.68	12.0	10.57	12.65	10.23	2.59	3.99
42	+	0	-	0	-	0	0	16.4	12.0	10.57	12.65	10.23	2.59	3.99
43	-	0	+	0	-	0	0	8.68	12.0	18.5	12.65	10.23	2.59	3.99
44	+	0	+	0	-	0	0	16.4	12.0	18.5	12.65	10.23	2.59	3.99
45	-	0	-	0	+	0	0	8.68	12.0	10.57	12.65	17.34	2.59	3.99
46	+	0	-	0	+	0	0	16.4	12.0	10.57	12.65	17.27	2.59	3.99
47	-	0	+	0	+	0	0	8.68	12.0	18.5	12.65	17.27	2.59	3.99
48	+	0	+	0	+	0	0	16.4	12.0	18.5	12.65	17.27	2.59	3.99
49	0	-	-	0	0	-	0	12.1	8.5	10.57	12.65	12.93	1.59	3.99
50	0	+	-	0	0	-	0	12.1	17.5	10.57	12.65	12.93	1.59	3.99
51	0	-	+	0	0	-	0	12.1	8.5	18.5	12.65	12.93	1.59	3.99
52	0	+	+	0	0	-	0	12.1	17.5	18.5	12.65	12.93	1.59	3.99
53	0	-	-	0	0	+	0	12.1	8.5	10.57	12.65	12.93	4.59	3.99
54	0	+	-	0	0	+	0	12.1	17.5	10.57	12.65	12.93	4.59	3.99
55	0	-	+	0	0	+	0	12.1	8.5	18.5	12.65	12.93	4.59	3.99
56	0	+	+	0	0	+	0	12.1	17.5	18.5	12.65	12.93	4.59	3.99
57	0	0	0	0	0	0	0	12.1	12.0	13.8	12.65	12.93	2.59	3.99
58	0	0	0	0	0	0	0	12.1	12.0	13.8	12.65	12.93	2.59	3.99
59	0	0	0	0	0	0	0	12.1	12.0	13.8	12.65	12.93	2.59	3.99
60	0	0	0	0	0	0	0	12.1	12.0	13.8	12.65	12.93	2.59	3.99
61	0	0	0	0	0	0	0	12.1	12.0	13.8	12.65	12.93	2.59	3.99
62	0	0	0	0	0	0	0	12.1	12.0	13.8	12.65	12.93	2.59	3.99

3.8 Experimental Setup

An experimental test was conducted on a sedan vehicle which correlated the air bind to the mathematical model. The seal gap variation was collected for multi vehicles with a sample size of thirty. The seal gap variation was added to the nominal seal gap of the sedan vehicle and was compared to the experimental test as shown in Figure 54. For the front door, the predicated model showed 13.1% door closing effort less than the experimental test. For the rear door, the predicted model shown 3.8% door closing effort higher than the physical test. However, the efficiency of the predicted model was within the range 96.2% - 86.9% from the physical test.

Figure 54. Experimental test for the secondary seal gap

4. RESEARCH RESULTS AND ANALYSIS

4.1 Data Analysis

The T statistic describes how the mean of a sample with a certain number of observations is expected to behave. In this section, one will look for the regression coefficient, which is the coefficient divided by its corresponding standard error. The standard error is an estimate of the standard deviation of the coefficient. This may explain a measure of the precision with which the regression coefficient is measured.

The p-value for each term tests the null hypothesis that the coefficient is equal to zero (no effect). A low p-value (< 0.05) indicates strong evidence that the null hypothesis should be rejected. It is important to note that the size of the p-value for a coefficient does not translate into the size of the effect that the variable is having on the dependent variable. The T-value measures the size of the difference relative to the variation in your sample data. T is simply the calculated difference represented in units of standard error. The greater the magnitude of T (it can be either positive or negative), the greater evidence against the null hypothesis that there is no significant difference. The closer T is to zero, the more likely there isn't a significant difference. In Table 8, the terms that are significant in the front door closing effort model are $X_1, X_{2,}X_3, X_4, X_6, X_7, X_4X_4$, X_6X_6 *and* X_4X_6. The coefficient of determination R-Squared R^2 for the regression predict model at 80.71% is adequate for fitting door closing effort. The adjusted R^2 value attempts to provide a more honest value to estimate $R^2$and an adjusted R^2 of 93.64% suggests the second order model is very adequate to represent the variability of the door closing effort as a function of all the noted factors. The linear and exponential model has been trials but it wasn't shows better predicted value compare to the quadratic model. Since there are many variables in Table 8 and in the regression Equation 61 which has a P value more than 0.05. A P value is an indicator the variable is negligible [64]. Therefore, one can apply all the effective variables are shown in Table 9 and in Equation 62.

Table 8. Estimated Regression Coefficients for Side Door Closing Effort for Front Door

Term	Coef	SE Coef	T	P
Constant	2.2580	0.0679	33.25	0.0000
X_1	-0.1157	0.0340	-3.410	0.0020
X_2	-0.1468	0.0340	-4.320	0.0000
X_3	-0.1026	0.0340	-3.020	0.0060
X_4	-0.2005	0.0340	-5.910	0.0000
X_5	-0.0515	0.0340	-1.520	0.1420
X_6	0.6892	0.0340	20.300	0.0000
X_7	0.6159	0.0340	18.140	0.0000
X_1X_1	0.0225	0.0453	0.500	0.6240
X_2X_2	-0.0211	0.0453	-0.470	0.6450
X_3X_3	-0.0007	0.0453	-0.020	0.9870
X_4X_4	0.1078	0.0453	2.380	0.0250
X_5X_5	0.0655	0.0453	1.450	0.1600
X_6X_6	0.3722	0.0453	8.220	0.0000
X_7X_7	-0.0188	0.0453	-0.420	0.6820

Term	Coef	SE Coef	T	P
X_1X_2	0.0001	0.0588	0.000	0.9980
X_1X_3	0.0000	0.0588	0.000	1.0000
X_1X_4	-0.0001	0.0588	0.000	0.9980
X_1X_5	0.0003	0.0588	0.000	0.9970
X_1X_6	-0.0251	0.0588	-0.430	0.6730
X_1X_7	0.0001	0.0588	0.000	0.9980
X_2X_3	-0.0001	0.0588	0.000	0.9980
X_2X_4	-0.0001	0.0588	0.000	0.9980
X_2X_5	-0.0001	0.0588	0.000	0.9980
X_2X_6	-0.0951	0.0588	-1.620	0.1180
X_2X_7	0.0001	0.0588	0.000	0.9980
X_3X_4	0.0000	0.0588	0.000	1.0000
X_3X_5	0.0000	0.0588	0.000	1.0000
X_3X_6	-0.0766	0.0588	-1.300	0.2040
X_3X_7	0.0000	0.0588	0.000	1.0000
X_4X_5	-0.0005	0.0588	-0.010	0.9930
X_4X_6	-0.3372	0.0588	-5.730	0.0000
X_4X_7	0.0062	0.0588	0.110	0.9160
X_5X_6	-0.0458	0.0588	-0.780	0.4440
X_5X_7	-0.0001	0.0588	0.000	0.9980
X_6X_7	0.0001	0.0588	0.000	0.9980

S=0.166349; R-sq=97.29%; R-Sq (Pred) =80.71%; R-Sq(adj)=93.64%

The regression equation or resulting model for front door closing effort is shown below in Equation 61.

$$
\begin{aligned}
&\mathit{Front\ Door\ Closing\ Effort}\ (J) \\
&= 2.258 - 0.1157X_1 - 0.1468X_2 - 0.1026X_3 - 0.2005X_4 - 0.0515X_5 \\
&+ 0.6892X_6 + 0.6159X_7 + 0.0225X_1X_1 - 0.0211X_2X_2 - 0.0007X_3X_3 \\
&+ 0.1078X_4X_4 + 0.0655X_5X_5 + 0.3722X_6X_6 - 0.0188X_{67}X_7 \\
&+ 0.0001X_1X_2 - 0.0000X_1X_3 - 0.0001X_1X_4 + 0.0003X_1X_5 \\
&- 0.0251X_1X_6 + 0.0001X_1X_7 - 0.0001X_2X_3 - 0.0001X_2X_4 \\
&- 0.0001X_2X_5 - 0.0951X_2X_6 + 0.0001X_2X_7 + 0.0000X_3X_4 \\
&- 0.0000X_3X_5 - 0.0766X_3X_6 + 0.0000X_3X_7 - 0.0005X_4X_5 \\
&- 0.3372X_4X_6 + 0.0062X_4X_7 - 0.0458X_5X_6 - 0.0001X_5X_7 \\
&+ 0.0001X_6X_7 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (61)
\end{aligned}
$$

A Meta Model or surrogate model for front door closing effort is a model of a model. It eliminates all the factors with P value more than 0.05 as shown in Table 9.

S=0.139407; R-sq=96.19%; R-sq (adj)=95.53%; R-sq(Pred)=93.52%

The second iteration gives an improvement for the R-sq prediction from 80.71% to 93.52% and is excellent for fitting the door closing effort. The R-sq adjust from 93.64% to 95.53% and the Meta Model equation for the front door closing effort defined in the Equation 62.

Table 9. Estimated Meta Model Coefficients for the Side Door Closing Effort for Front Door

Term	Coef	SE Coef	T	P
Constant	0.0273	83.39	0.000	0.000
X_1	-0.1157	0.0285	-4.070	0.000
X_2	-0.1468	0.0285	-5.160	0.000
X_3	-0.1026	0.0285	-3.610	0.001
X_4	-0.2005	0.0285	-7.050	0.000
X_6	0.6892	0.0285	24.220	0.000
X_7	0.6159	0.0285	21.640	0.000
X_4X_4	0.1032	0.0365	2.830	0.007
X_6X_6	0.3677	0.0365	10.080	0.000
X_4X_6	-0.3372	0.0493	-6.840	0.000

$$Front\ Door\ Closing\ Effort\ (J) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(62)$$

$$= 2.2799 - 0.1157X_1 - 0.1468X_2 - 0.1026X_3 - 0.2005X_4 + 0.6892X_6 + 0.6159X_7 + 0.1032X_4X_4 + 0.3722X_6X_6 - 0.3372X_4X_6$$

In Table 10, the terms that are significant in the rear door closing effort model are $X_{2,}X_3, X_5, X_6, X_7, X_6X_6, X_2X_6$ *and* X_3X_6 . The coefficient of determination R-Squared R^2 for the regression predict model at 84.58% is adequate for fitting the door closing effort. The adjusted R^2 value attempts to provide a more honest value to estimate R^2 and an adjusted R^2 of 94.91% suggests the second order model is very adequate to represent the variability of the door closing efforts as a function of all the noted factors. Since there are many variables in Table 10 and in the regression Equation 63. It will have P value of more than 0.05 which is an indicator that this variable is negligible. Therefore, one can apply the Meta Model with all the effective variables in Table 11 as shown in Equation 64.

Table 10. Estimated Regression Coefficients for Side Door Closing Effort for Rear Door

Term	Coef	SE Coef	T-Value	P-Value
Constant	2.854	0.042	67.700	0.000
X_1	-0.022	0.021	-1.030	0.313
X_2	-0.195	0.021	-9.270	0.000
X_3	-0.103	0.021	-4.890	0.000
X_4	-0.037	0.021	-1.760	0.091
X_5	-0.140	0.021	-6.620	0.000
X_6	0.484	0.021	22.970	0.000
X_7	0.381	0.021	18.050	0.000
X_1X_1	-0.024	0.028	-0.840	0.406
X_2X_2	0.057	0.028	2.020	0.054
X_3X_3	0.030	0.028	1.070	0.294
X_4X_4	0.026	0.028	0.920	0.368
X_5X_5	0.045	0.028	1.600	0.122
X_6X_6	0.327	0.028	11.650	0.000
X_7X_7	0.050	0.028	1.780	0.086
X_1X_2	0.000	0.037	0.000	0.997

Term	Coef	SE Coef	T-Value	P-Value
X_1X_3	0.000	0.037	0.010	0.995
X_1X_4	0.000	0.037	0.000	0.997
X_1X_5	0.000	0.037	0.000	1.000
X_1X_6	-0.020	0.037	-0.540	0.593
X_1X_7	0.000	0.037	0.000	1.000
X_2X_3	0.000	0.037	0.000	1.000
X_2X_4	0.000	0.037	0.000	0.997
X_2X_5	0.000	0.037	0.000	0.997
X_2X_6	-0.077	0.037	-2.110	0.045
X_2X_7	0.000	0.037	0.000	0.997
X_3X_4	0.000	0.037	0.000	1.000
X_3X_5	0.000	0.037	0.000	1.000
X_3X_6	-0.080	0.037	-2.180	0.038
X_3X_7	0.000	0.037	0.000	1.000
X_4X_5	0.000	0.037	0.000	1.000
X_4X_6	-0.035	0.037	-0.940	0.353
X_4X_7	0.000	0.037	0.000	1.000
X_5X_6	-0.100	0.037	-2.740	0.011
X_5X_7	0.000	0.037	0.000	0.997
X_6X_7	0.000	0.037	0.000	1.000

S=0.103265

R-sq=97.83%

R-sq (adj)=94.91%

R-sq(Pred)=84.58%

The regression equation or resulting model for rear door can show below in Equation 63

$$
\begin{aligned}
&Rear\ Door\ Closing\ Efforts\ (J) \\
&= 2.854 - 0.0217X_1 - 0.1954X_2 - 0.1030X_3 - 0.0370X_4 - 0.1396X_5 \\
&+ 0.4841X_6 + 0.3805X_7 - 0.02375X_1X_1 + 0.0568X_2X_2 + 0.0301X_3X_3 \\
&+ 0.0258X_4X_4 + 0.0449X_5X_5 + 0.3273X_6X_6 - 0.0501X_7X_7 \\
&+ 0.0001X_1X_2 + 0.0003X_1X_3 - 0.0001X_1X_4 + 0.0000X_1X_5 \\
&- 0.0198X_1X_6 + 0.0000X_1X_7 - 0.0000X_2X_3 - 0.0001X_2X_4 \\
&- 0.0001X_2X_5 - 0.0770X_2X_6 + 0.0001X_2X_7 + 0.0000X_3X_4 \\
&+ 0.0000X_3X_5 - 0.0798X_3X_6 + 0.0000X_3X_7 + 0.0000X_4X_5 \\
&- 0.0345X_4X_6 + 0.0000X_4X_7 - 0.1000X_5X_6 - 0.0001X_5X_7 \\
&- 0.0000X_6X_7 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (63)
\end{aligned}
$$

A Meta Model or surrogate model for rear door closing effort is a model of a model. It eliminates all factors with P value more than 0.05 as shown in Table 11.

S= 0.0924978; R-sq= 96.52%; R-sq (adj) = 95.92%; R-sq(Pred)= 94.54%

The second iteration improves the R-sq prediction from 80.71% to 94.54% and is excellent for fitting the door closing effort. The R-sq adjust from 94.91%% to 95.92% and the Meta Model equation for the rear door closing effort is defined in Equation 64

Table 11. Estimated Meta Model Coefficients for the Side Door Closing Effort for Rear Door

Term	Coef	SE Coef	T	P
Constant	0.0161	181.5800	0.0000	
X_2	-0.1954	0.0203	-9.6200	0.0000
X_3	-0.1030	0.0203	-5.0700	0.0000
X_5	-0.1396	0.0203	-6.8700	0.0000
X_6	0.4841	0.0203	23.8300	0.0000
X_7	0.3805	0.0203	18.7300	0.0000
$X_6 X_6$	0.3112	0.0259	11.9900	0.0000
X_2X_6	-0.0770	0.0352	-2.1900	0.0330
X_3X_6	-0.0797	0.0352	-2.2700	0.0280
X_5X_6	-0.1000	0.0318	-3.15	0.003

$$Rear\ Door\ Closing\ Effort\ (J)$$
$$= 2.9315 - 0.1954X_2 - 0.1030X_3 - 0.1396X_5 + 0.4841X_6$$
$$+ 0.3805X_7 + 0.3112X_6X_6 - 0.0770X_2X_6 - 0.0797X_3X_6$$
$$- 0.1000X_5X_6 \qquad \text{.........................} (64)$$

Figure 55 illustrates the residual plot for the front and rear door closing efforts. The term "residual" with respect to the DOE is defined as the difference between the value of the measured output and the predicted value. The closer the two values are to each other, the smaller the residual; this is a desirable outcome. Residuals are important as they are used to assess whether a model complies with the underlying assumptions of the DOE. In addition, the normal probability plot means the closer the individual points lie to a straight line, the higher the degree of normality. The second key assumption for a DOE to be valid is that the variance of the residuals is constant. The plot that is created is used to detect non-linearity, unequal variance. In general, if the plot shows the residuals scattered around the zero line in a random manner. The third key assumption is independence of the residuals. If the plot does not reveal any pattern or sequence, either above or below the zero line, then this assumption is validated. In another word, independence of the residuals is a plot and the randomness in the residual data validates this assumption [65].

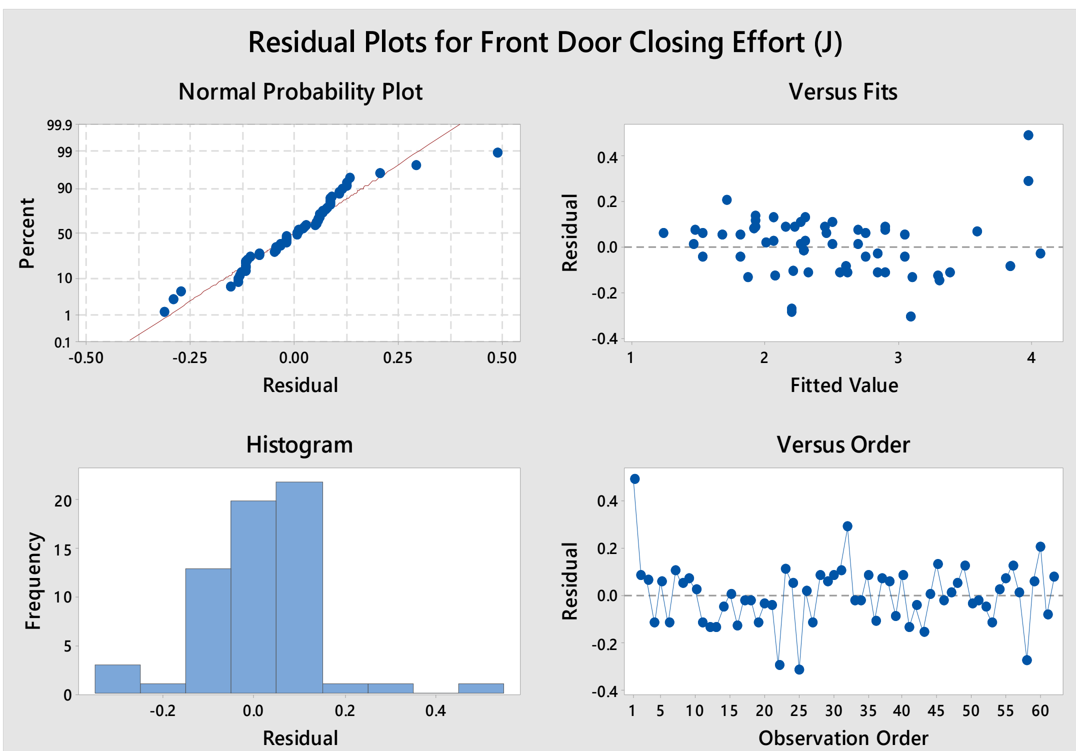


Figure 55. Residual Plots for Front Door Closing Effort

Figure 55 and 56 residual plots do not reveal violations of the underlying assumptions of zero means and constant variance of the random errors. The histograms illustrate normal distributions of the residuals indicating that the measurement errors in the response variables are normally distributed. The normal probability plots of the residuals validate the normality assumption. The points in the “versus fits” plots fluctuate randomly around zero [65].

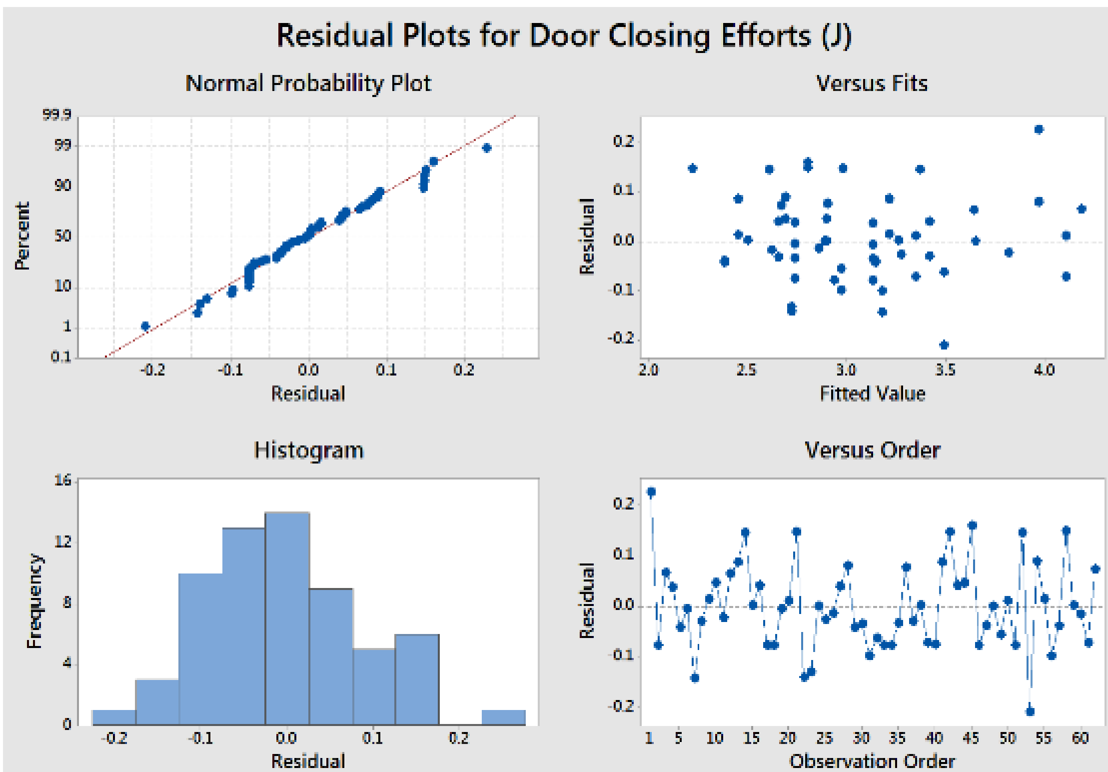


Figure 56. Residual Plots for Rear Door Closing Effort

4.2 Analysis the variable for Door Closing Effort in Meta Model equation

The contour plots of the fitted models are used for the characterization of the response surfaces.

Figure 57 illustrates contour plots for the front door closing effort. The secondary seal CLD with higher CLD value X_6 will have a major effect on the closing effort on the B pillar seal gap area $X_4$with tight seal gap value as shown in violet color. In addition, when seal CLD for both seals is high, then the closing effort will be high too. The secondary impact on the closing effort caused by the secondary seal CLD X_6 bundled with X_1, X_2 *and* X_3 as shown in light blue and it shows the closing effort reduced when the seal gap is wider.

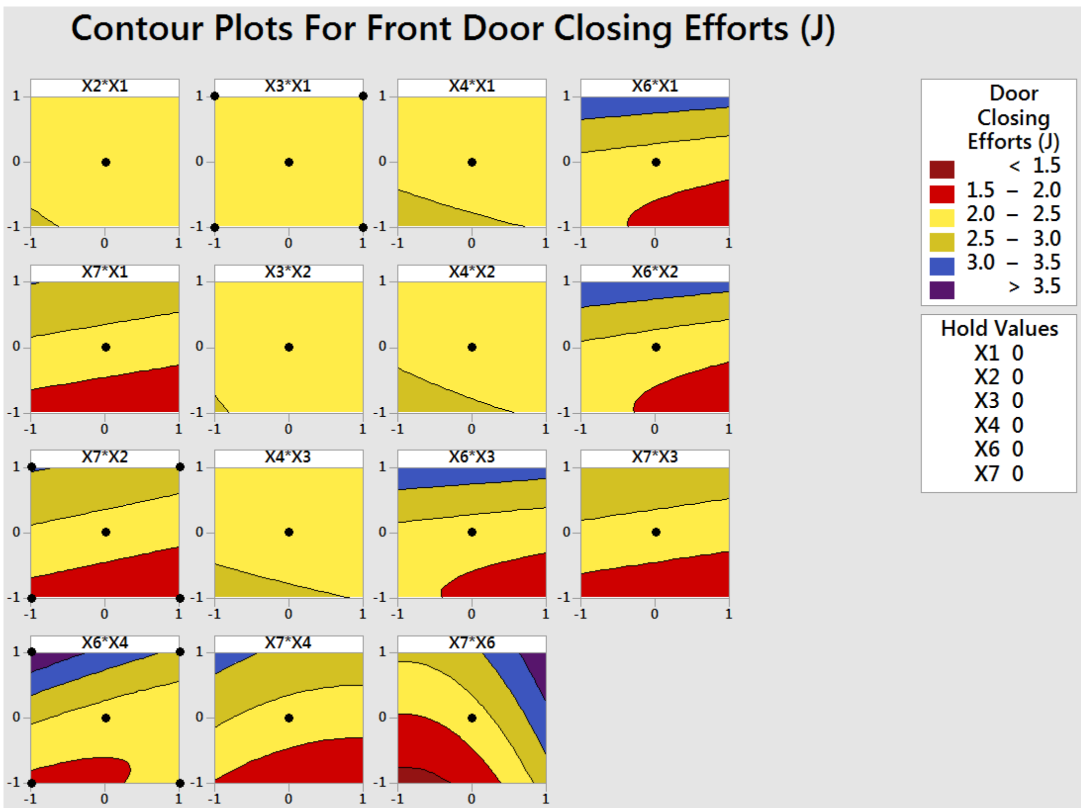


Figure 57. Contour Plots of the Surfaces Generated by the Prediction Equations for Front Door Closing Effort

Figure 58 illustrate contour plot for the rear door closing effort. The secondary seal CLD with higher CLD value X_6will have a major effect closing effort on the header seal gap area $X_2$with tight seal gap value as show in purple color. In addition, when seal CLD for both seals is high, then the closing effort will be high too. The secondary impact on the closing effort caused by the secondary seal CLD X_6 bundled with X_3 *and* X_5 as shown in light blue and it shows the closing effort reduced when the seal gap is wider.

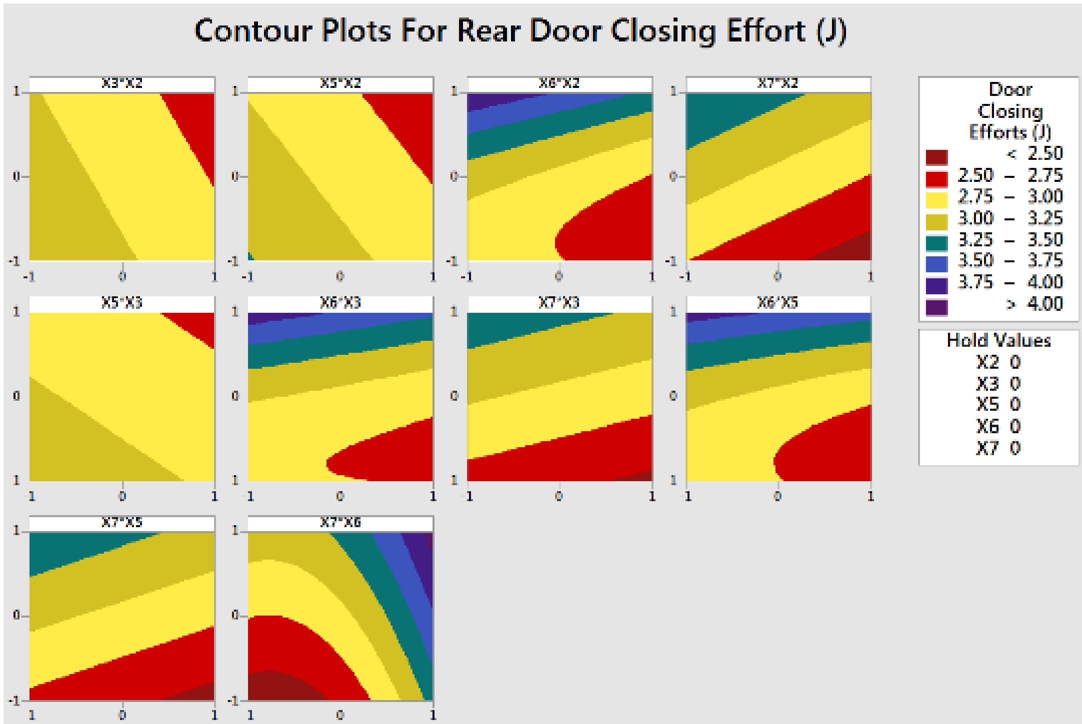


Figure 58. Contour Plots of the Surfaces Generated by the Prediction Equations for Rear Door Closing Effort

Three-dimensional response surface plots in Figure 59 and 60 provide the same conclusions for the front and rear doors contour plot respectively. A 3D surface plot is useful in several ways. First, it reveals if there exists any concavity or convexity in the factor relationships, when there is little topographic variation in the response surface like X_3X_6 in Figure 59 and X_5X_6in

Figure 60, the degree of topographic variation increases; therefore, the degree of interaction between the factors increases as well like X_4X_6 in Figure 59 and X_2X_6 in Figure 60.

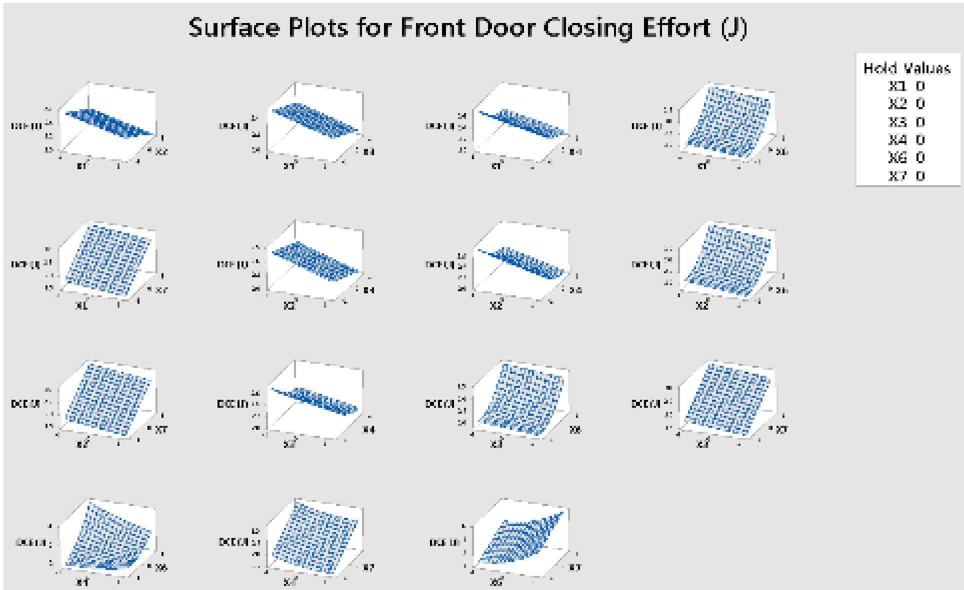


Figure 59. Three-Dimensional Response Surface Plots Generated by the Prediction Equations for Front Door Closing Effort

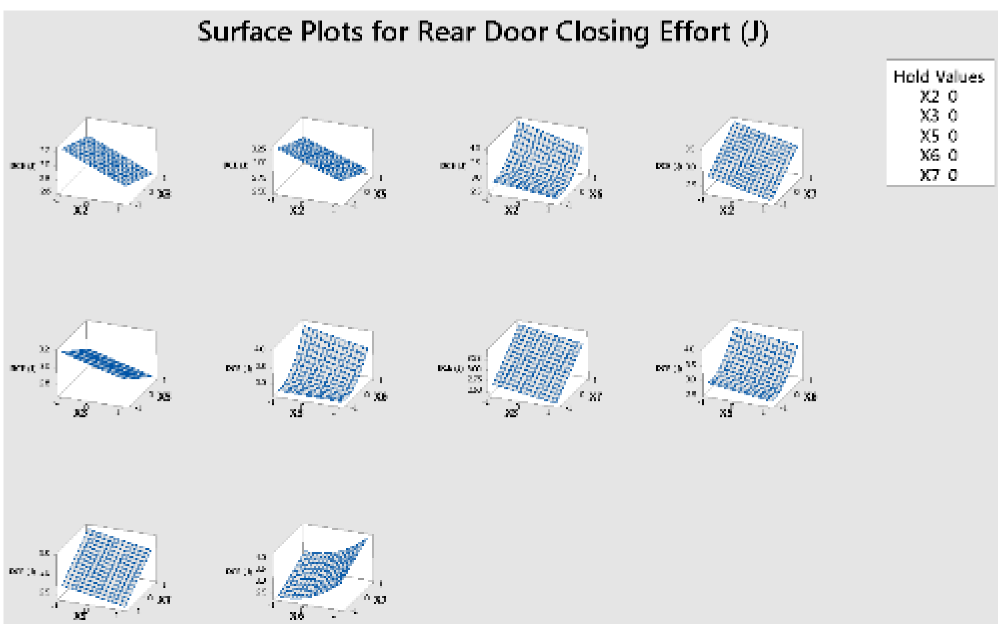


Figure 60. Three-Dimensional Response Surface Plots Generated by the Prediction Equations for Rear Door Closing Effort

Part of the analysis of the variables for door closing effort in regression equation model (61) is studying the interaction for the variable as shown in Figure 61and 62 for front and rear doors, respectively. In Figure 61, there is no significant interaction between the variable. At the same time, it shows the major impact for the variables X_4X_6 and X_6X_7 on the side door closing effort.

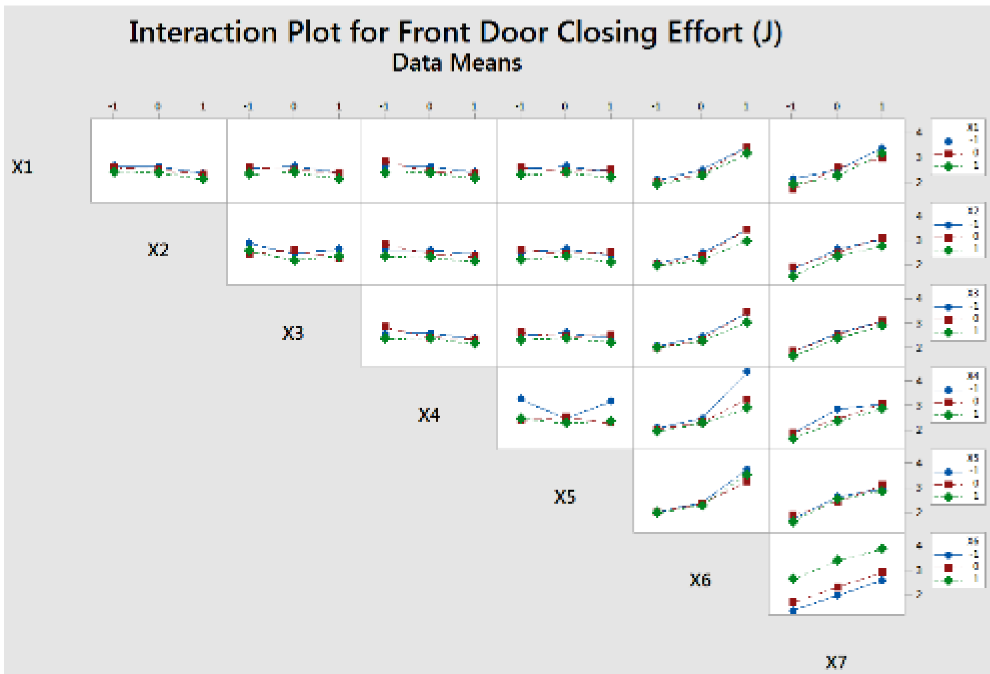


Figure 61. Interaction Plot for Front Door Closing Effort (J)

In Figure 62, there is no significant interaction between the variables. At the same time, it shows the major impact for the variables X_2X_6 and X_6X_7 on the side door closing effort.

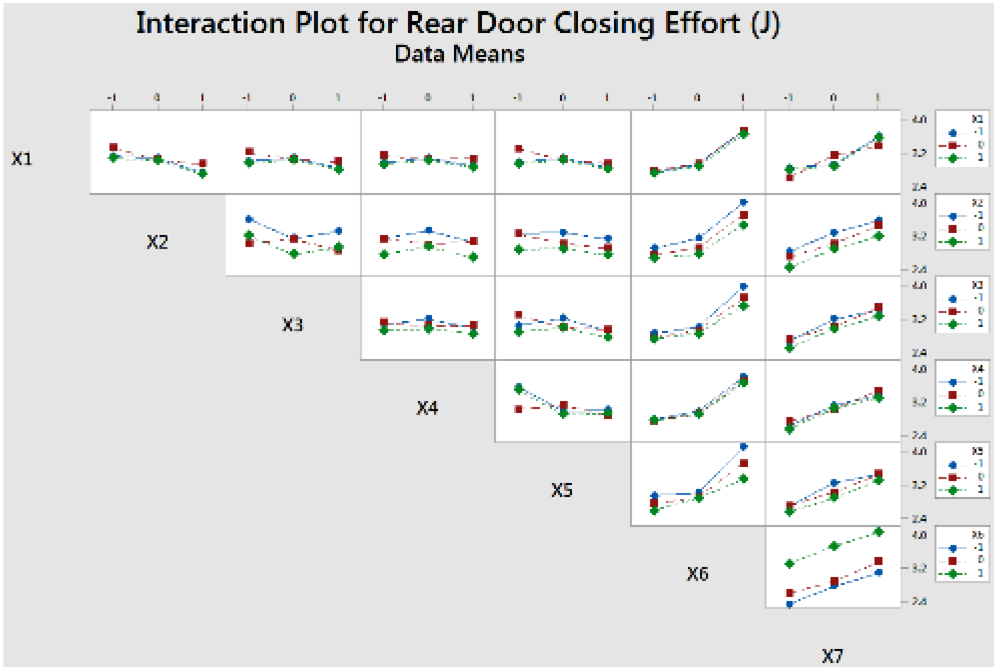


Figure 62. Interaction Plot for Rear Door Closing Effort (J)

Analysis of the variable for door closing effort for Meta Model equations (62) and (64) for front and rear doors respectively by studying the main effect for the Independent variables as shown in Figure 63 and 64 for front and rear doors respectively.

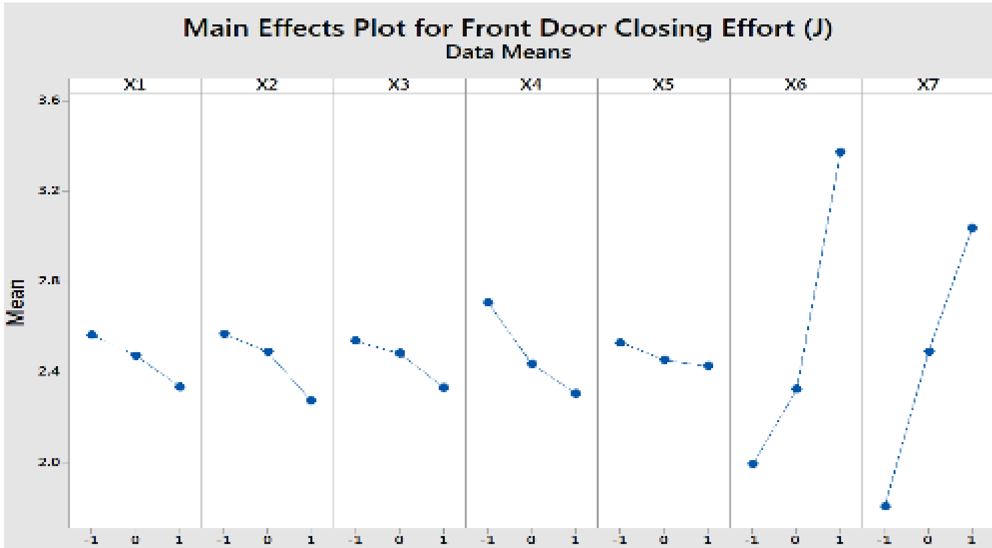


Figure 63. Main Effects Plot for Front Door Closing Effort (J)

Figure 63 for front door closing effort, the secondary seal CLD X_6 is the main variable that has effect on closing effort. The primary seal CLD X_7 is the secondary factor that is causes high closing effort for the front door. The third major variable that will effect the closing effort is the secondary seal gap variation at the B pillar X_4. The other variables are X_1, X_2, X_3 and X_5 have less effect on the closing effort. In other words, one needs to pay more attention in designing the main variables X_6, $X_7 and$ X_4 and working to control these variables.

In Figure 64 for rear door closing effort, the secondary seal CLD X_6 is the main variable that affects closing effort. The primary seal CLD X_7 is the secondary factor that causes high closing effort for the rear door. The third major variable that will affect the closing effort will be the secondary seal gap variation at the header X_2. The fourth variable that affects closing effort is the seal gap variation at the C pillar X_5. In other words, one needs to pay more attention in designing the main variables $X_6, X_7, X_2 and\ X_5$ and working to control these variables.

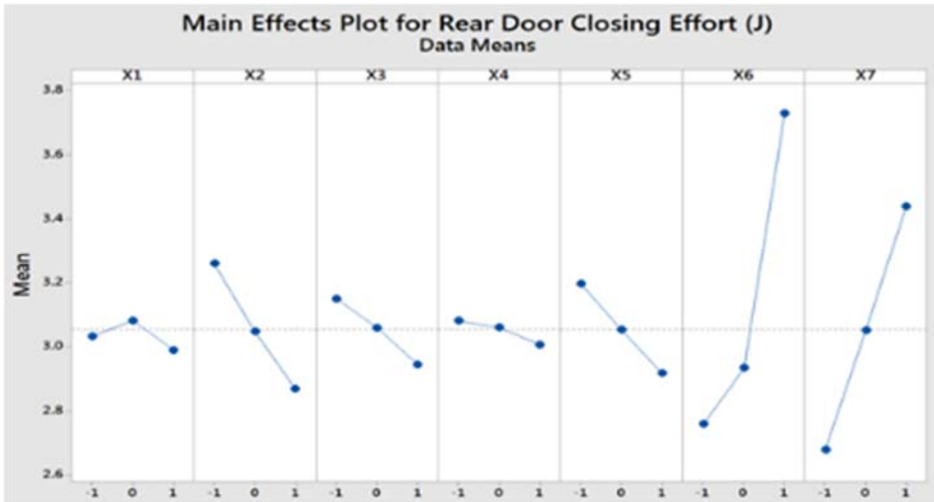


Figure 64. Main Effects Plot for Rear Door Closing Effort (J).

4.3 Sensitivity Analysis

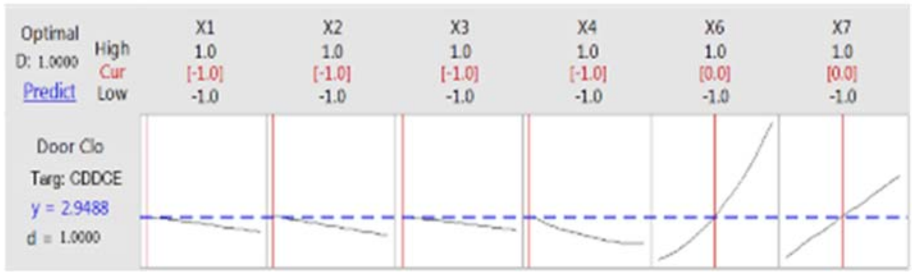
Sensitivity analysis is an essential tool in the process of building models, since most of the independent variables are part of the structures of these models. This model helps to define the optimum seal gap variation with optimum seal CLDs variation so that it can meet the Customer Desired Door Closing Energy (CDDCE). For this reason, many iterations can be summarized for front and rear doors as follows:

- Nominal seal CLDs for the primary and secondary seals with tight seal gap variations as shown in the Figures 64a and 65a for the front and rear doors consecutively. This option can deliver 2.94J and 3.36J for the front and rear door respectively. However, this is not feasible because it doesn't account for the seal's

CLD variation as shown in Figures (65 a and 66 a) for front and rear doors respectively.

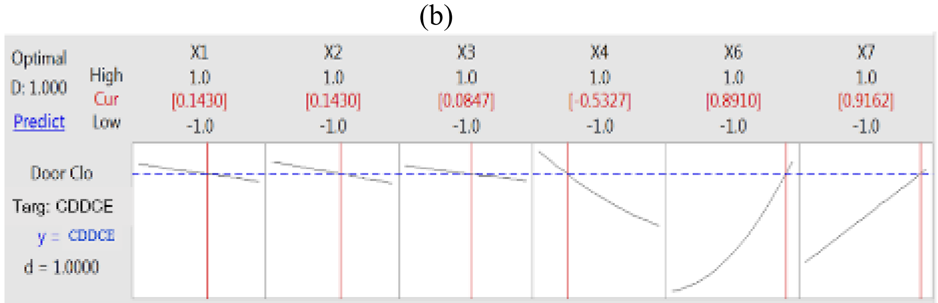
- Propose a seal gap variation ±2.5 and the seals CLD's ±2.0. For the high end seal's CLD's, it shows that one can meet the CDDCE, but with infeasible conditions which is some seal segment's it can't accept any door build inboard condition. This is shown in Figures (65 b and 66 b) for front and rear doors, respectively.
- Propose a seal gap variation ±2.0 and the seals CLD's ±1.5. For the high end seal's CLD's, it shows one can meet the CDDCE. However, infeasible conditions some seal segments can't accept any door build inboard condition. This is shown in Figures (65 c and 66 c) for front and rear doors, respectively.
- Propose a seal gap variation ±2.5 and the seals CLD's ±1.0. For the high end seal's CLD's, it shows one can meet the CDDCE. However, infeasible conditions some seal segments can't accept any door build inboard conditions. This is shown in Figures (65 d and 66 d) for front and rear doors, respectively.
- Propose a seal gap variation ±1.5 and the seals CLD's ±1.0. For the high end seal's CLD's, it shows one can meet the CDDCE. However, it is feasible with worst-case door build inboard conditions. This is shown in Figures (65 e and 66 e) for front and rear doors, respectively.

This technique helps to understand the behavior of all the variables on the door closing effort mode and optimize the variables to meet the CDDCE.

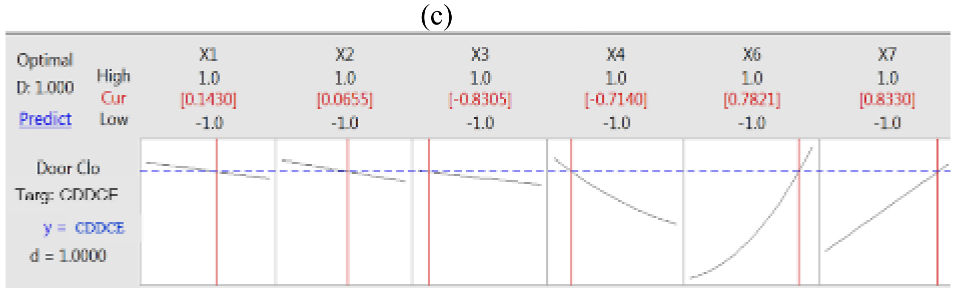


(a)

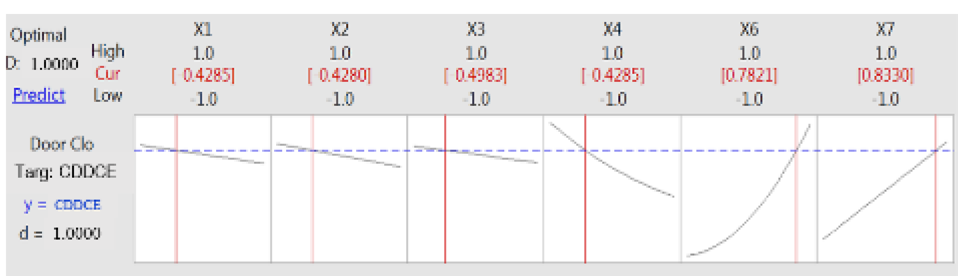
(b)



(c)



(d)



(e)

Figure 65. Optimize Front Door Closing Effort with Respect to the Effective Variables in Mathematical Model

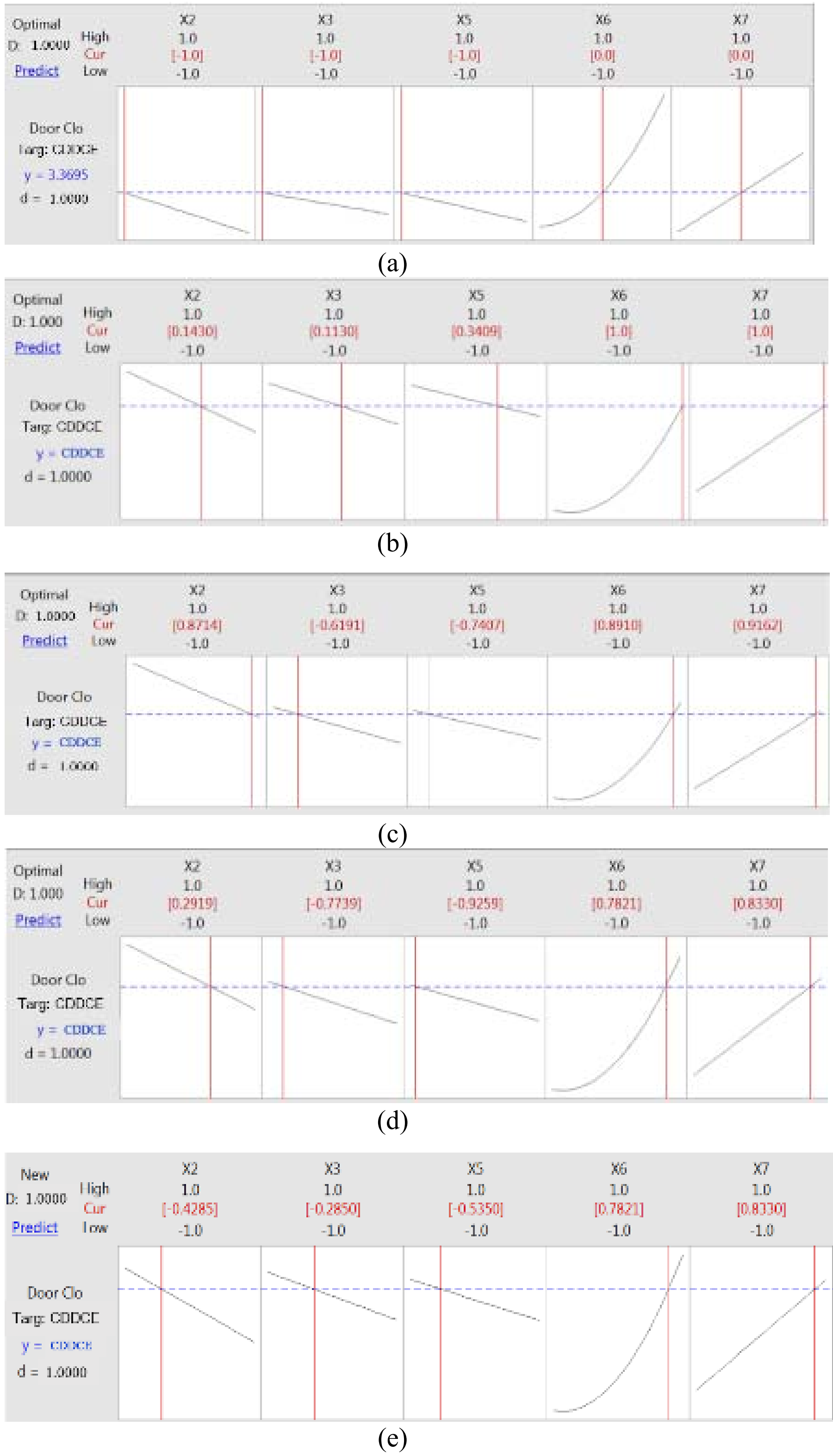


Figure 66. Optimize Rear Door Closing Effort with Respect to the Effective Variables in Mathematical Model

4.4 Results versus Literature Survey

The performed literature survey defined the most relevant resources and current published knowledge related to this research topic. This topic was summarized, interpreted and evaluated as a pretense to side door closing effort and the study conducted on effect of the seal gap segments on side door closing effort. It is prosed to optimize the manufacture tolerance for the seal gap and the seal CLDs for the primary and the secondary seals in order to meet the customer expectations. The study put further emphasis on the need to conduct the research.

Navalkumar et al. (2015) developed a mathematical model to evaluate door closing velocity through calculating energy contribution by each parameter like hinge friction, hinge axis inclination, sealing, latch and air bind effect. The authors previously mentioned, calculated the closing efforts for an existing model in order to improve the existing scenario, then modified the design. These design modifications have been implemented and showed a reduction in door closing velocity by 22.8 %. Experiment validations were conducted and results found in line with the theoretical calculations. The existing scenario design modifications are proposed in the hinge axis inclination, check strap resistance reduction and the latch operating efforts. Changing the hinge tip angle to increase the potential energy will cause a change in the studio surface and the change will effect the cut line for the margin and the class surface. Most of the proposed changes relate to the change in the studio surface, while in this dissertation one can rely on optimizing the side door closing efforts to meet the customer expectations. This is accomplished by modifying in the seal gap manufacture tolerance and the seal CLD manufacture tolerance for the primary and the secondary seals.

Navalkumar et al. (2015) propose improving the closing efforts from 9.4 J to 7.37 J, which is 22.8% improvement. This dissertation illustrates the side door closing efforts can meet the customers' expectations which will be 85% less than the improved model for door closing efforts that the previous author proposed.

Yunkai et al. (2010) developed excel based software with Visual Basic Application programming language as a base for the mathematical models which calculated the energy sink of the subsystems. The energy sink of different factors for the closing effort of a production vehicle door was measured to verify the accuracy of the calculation software developed. Calibration is necessary because some input parameters are difficult to obtain directly. The option has been provided to calibrate the hinge model, the latch model, the seal compression model, and the air bind model. The door weight effect is geometrically exact and does not need calibration. Compared to experiment results, the deviation of the total side swing door closing energy calculated by the software is 7.9%. This is absolutely permitted in engineering and proves the accuracy and efficiency of the software. In this dissertation, the mathematical model was calibrated with a sedan vehicle. If different vehicle size is used, than recalibration is required to reflect the experiment result.

Li et al. (2009) [26] focused on energy sink by the door component, and it is assumed that the check link does not function while we include the check energy as a part of the door system energy.

(Moon et al. 2010) [5] created a design model that calculated the door closing efforts. This compares to the models obtained from the CAE model. The result of Moon's model was a minimum door closing velocity. The model was compared to the CAE and showed minimum error. Most of the error occurred at the primary seal when Moon compared a sedan, a truck and a small car.

In this dissertation, a predicting closing efforts tool was used this tool for the sedan vehicle and it demonstrated a strong correlation between the CAE and the experiments results with the accepted error 13.1 %-3.8 %. Many automotive manufacturers spend considerable effort and much money to predict the seal gap variation. At the same time, automotive industries work to reduce the seal CLD's manufactures tolerance in order to meet the door closing effort to the customers' satisfaction.

Wagner et al. (1997) studied the seal compression load deflection (CLD) behavior by using nonlinear finite element analysis. This study conducted for the primary, secondary and the margin seal. This addresses the weatherstrip seals with the door high/low and fore/aft build variations. The study summarizes the for/aft build variation with a minor effect (approximately 20%) on the calculated CLD response. Door inboard/outboard build variations had the major impact on the door closing effort. In this dissertation, it has been addressed in the in/out seal gap variation. This is the major impact on the closing effort and the primary with the secondary seal contribute around 30% from the whole door closing effort. This results were aligned with Wagner et al. (1997). This defines the primary and the secondary seal which contribute 35-50% of the force or energy to close the door. This study analysis of the build variations demands that the seal models compressions up to 3.0 mm greater than the nominal design compression. Door variations inboard/outboard are modelled as over or under compression along the local normal direction that defines the door closing motion. The effect of door high/low and fore/aft variations are accommodated by displacing the door rigid surface and door mounted seals along the tangential direction up to the ± 2.0 mm tolerance. This dissertation went ahead of Wagner et al. (1997) by adding the overslam to the seal gap variation. Each section had different overslam amounts and that was defined by the physical test. The door was designed to accommodate for the overslam especially at the header section. This overslam amount drives the seal to absorb more energy during the door closing process.

Li, J. (2009) developed a simplified door closing prediction model consisting of approximate models for the energy sinks due to air bind, seal compression, hinge friction, and latch effort. In order to improve the prediction accuracy, the model parameters, and the model error correction factors were estimated using measured data. Li did not calculate the check energy and focused on the system absorb energy. In addition, this study focused on the tool that can predict the closing efforts so it doesn't have a consideration for the manufacture's tolerance, overslam, and the seal gap tolerance as well. This dissertation addressed the check assist energy that adds energy to the system. The study created a mathematical model that can optimize the door closing efforts. This can be accomplished by proposing an accepted seal gap variation which is ±1.5mm and the manufacture tolerance for seal CLDs for the primary and the secondary seal ±1N.

The seal gap segments for the upper and the lower hinges had no impact on the side door closing efforts. This is due to the fact most of the build is going with wide seal gap. This leads to minimize the seal gap impact on the side door closing efforts. These segments represent $X_5$for the front door and rear doors, is represented by X_1 and X_4. For the front door, the most seal gap segment that had the major impact on the closing efforts is located at the latch which is represent by X_2. The reason is most the door are built with tight seal gap. The seal gap for the front door at the B pillar margin seal above the seal had the second impact on the closing efforts. This is represent by X_1. The third seal gap segment that it has impact on the closing efforts was the header. The reason for that was the overslam which directly impact on the closing efforts even if the data show a wider seal gap build. The major seal gap for the rear door that had the most impact on the door closing efforts was the header and is represented by X_2. The reason this is that have most the maximum overslam at the header. The seal gap at the latch for the rear door had the second impact on the door closing efforts. This is because the build variation to outboard side was more than what was expected for the front door. This is caused by door fitting and managed by the craftsmanship specifications for the vehicle. The seven factors have been addressed and define the secondary seal CLD's variation have the major impact on the closing efforts X_6 and the second factor that is impact on the closing efforts was the primary seal CLD's variation. However, to meet the customer satisfaction that will need to tighten the seal gap tolerance to have ±1.5mm and the seal CLD's tolerance to be ±1N.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

One of the customer's initial impressions regarding the quality of the vehicle will be the behavior of the opening and closing of the door and energy that are required to obtain full latching. In order to optimize the closing efforts, the seal gap variations, which are delivered by the assembly plant, must be analyzed. This step will enable one to understand how to best meet the closing efforts with customer satisfaction. It may be necessary to rely on the seal manufacture tolerance to deliver desired door closing efforts. Generating a mathematical model helps to predict the side door closing efforts early in the design phase. It is much easier and cheaper for OEMs to improve the closing efforts in the early design phase.

Response surface methodology enabled the second order models for the side door closing effort. A Meta Model or surrogate model for the front and rear door closing effort is a model of a model with insignificant terms. This is produced a probability (p) value that is greater than 0.05 were eliminated from the models. These created models accurately describe the side door closing effort values. To calculate the second order regression model coefficients, each design variable was studied at three distinct levels and a Box-Behnken design with 3-level. A 7-factor factorial design provided a redundancy factor 35.3%. Sensitivity analyses were performed where in the evaluated input parameters were part of the structures of the door closing effort models. The sensitivity analyses define the major factors that had an effect on the door closing efforts. The secondary seal CLD, with the manufacture tolerance, was the major variable effect on the door closing efforts. The primary seal CLD with the manufacture tolerance was the second variable. In addition, the seal gap manufacture variation defined the seal gap at the upper and lower hinges. This was negligible for both front and rear doors, defined by the variable X_5 for front door and X_1 *and* X_4 for rear door. For the front door, the seal gap variation at the hinge area is defined by X_1. This was the major variable that affected the closing effort then the header area X_2, B pillar margin seal above the belt X_2 and the least affect was the rocker area seal variation X_3. For the rear door seal gap variation, the major variable was the header area X_2, then the seal gap at the latch X_5 was the second variable. The seal gap at the rocker X_3 was the least one.

This applied research focused on the development of an optimization process for the door closing efforts with multiple iterations. The output for this dissertation is meeting the customer satisfaction for side door closing efforts. This was combined by reducing the seal gap variation for all the primary and the secondary seal to ±1N without reducing the nominal seal CLD. In addition, reduce the seal gap variation for the secondary seal to ±1.5mm for both front and rear doors.

5.2 Recommendations and the next step

The mathematical model developed in this applied research is to predict the side door closing efforts with customer satisfaction. The seal gap variation for the secondary seal and the manufacture tolerance for the primary and the secondary seal CLD’s addressed and analyzed to optimize the side door closing efforts. The manufacture build variation for the secondary seal obtained for thirty vehicles sample size for different platforms. This research demonstrates current design can't meet the door closing efforts with customer satisfaction at the worst case door fitting. To reach door closing efforts with customer satisfaction needs the following:

- Improve the seal gap variation for the secondary seal to ±1.5 mm.
- Improve the manufacture tolerance for the primary and the secondary seal to ±1 N.

The next steps are summarized as follows:

- The mathematical model has a potential opportunity for operator error due to the enormous data input for this model. This needs to address a checkpoint that defines the operator error with clear instructions.
- The mathematical model in this research validated for a sedan vehicle, and it requires to verify it with SUVs, trucks, and the compact vehicles as well.
- The sealing system used in this research was level two sealing system, and this mathematical model needs to validate with level one sealing system as well.
- The absorbed energy from the air bind validated with prototype vehicle by using a correction factor of 1.2. The air bind needs correction factor to be optimized with production vehicles.

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