

**MODIFIED KAMAL MODEL FOR CRUMPLE
ZONE BEHAVIOR AND CONTROL OF ACTIVE
FRONT BUMPER SYSTEM FOR HEAD-ON
COLLISION**

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**MASTER OF SCIENCE
(MECHANICAL ENGINEERING)**

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**MODIFIED KAMAL MODEL FOR CRUMPLE ZONE BEHAVIOR AND
CONTROL OF ACTIVE FRONT BUMPER SYSTEM FOR HEAD-ON
COLLISION**

AMRINA RASYADA BINTI ZUBIR

Thesis submitted to the Centre for Graduate Studies, Universiti Pertahanan Nasional
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(Mechanical Engineering)

ABSTRACT

The development of an active front bumper system arose from the realization that the conventional bumpers are insufficient in absorbing impact energy during frontal collisions. This system utilizes magnetorheological elastomers (MREs), which can adjust its stiffness and damping properties in response to a magnetic field, thus significantly enhancing the impact absorption capabilities. The objective of this project is to model the dynamics of crumple zone, to model the impact behavior of the dual-acting MRE damper and to develop a control strategy for active front bumper system that can reduce the effects of impact force due to collision. The methodology of this study is started with developing a 6 degree-of-freedom (DOF) vehicle crash model based on Kamal approach that represent the actual vehicle crumple zone. Next, the fabrication of dual-acting MRE damper takes place where the impact behavior of the MRE is modelled using 4th order polynomial to study for its force-displacement characteristics. Furthermore, the collision test rig is developed for evaluating the performance of the active front bumper system by conducting the experiment at different levels of collisions including light (83.25 kN), medium (333.02 kN) and hard (749.28 kN). Besides, the combination of proportional-integral-derivative controller (PID) and skyhook controller are chosen to be implemented in the active front bumper system. The proposed method has effectively reduced the impact of frontal collision by 63.78%, 44.16% and 30.06% in terms of acceleration. While, for displacement the reduction are 55.56%, 37.54% and 19.33% for light, medium and hard impact respectively.

ABSTRAK

Pembangunan sistem bampar hadapan yang aktif adalah disebabkan oleh kekurangan bampar lazim dalam menyerap tenaga hentaman semasa perlanggaran hadapan. Sistem ini menggunakan magnetorheological elastomer (MRE), yang boleh melaraskan sifat kekakuan dan redamannya sebagai tindak balas kepada medan magnet, dengan itu meningkatkan keupayaan penyerapan impak dengan ketara. Objektif projek ini adalah untuk memodelkan dinamik zon renyuk, memodelkan tingkah laku impak peredam MRE dwi-tindakan dan membangunkan strategi kawalan bagi sistem bampar hadapan aktif untuk mengurangkan kesan daya hentaman akibat perlanggaran. Metodologi kajian ini bermula dengan membangunkan model perlanggaran kenderaan 6 darjah kebebasan (DOF) berdasarkan pendekatan Kamal yang mewakili zon hancur kenderaan sebenar. Seterusnya, peredam MRE dwi-tindakan direka dan dimodelkan tingkah laku impaknya menggunakan polinomial darjah ke-4 untuk mengkaji ciri-ciri daya-anjakan. Pelantar ujian perlanggaran dibangunkan untuk menilai prestasi sistem bampar hadapan aktif dengan menjalankan eksperimen pada tahap perlanggaran yang berbeza termasuk ringan (83.25 kN), sederhana (333.02 kN) dan kuat (749.28 kN). Gabungan PID dan pengawal skyhook dilaksanakan dalam sistem bampar hadapan aktif. Kaedah yang dicadangkan telah mengurangkan kesan perlanggaran hadapan secara berkesan sebanyak 63.78%, 44.16% dan 30.06% dari segi pecutan. Manakala, anjakan dikurangkan sebanyak 55.56%, 37.54% dan 19.33% untuk hentaman ringan, sederhana dan keras.

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APPROVAL

The Examination Committee has met on **27 February 2024** to conduct the final examination of **Amrina Rasyada Binti Zubir** on his degree thesis entitled ‘**Modified Kamal Model for Crumple Zone Behavior and Control of Active Front Bumper System for Head-On Collision**’.

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Academic session : 2023/2024

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TABLE OF CONTENTS

	TITLE	PAGE
	ABSTRACT	ii
	ABSTRAK	iii
	ACKNOWLEDGEMENTS	iv
	APPROVAL	v
	APPROVAL	vi
	DECLARATION OF THESIS	vii
	TABLE OF CONTENTS	viii
	LIST OF TABLES	xi
	LIST OF FIGURES	xii
	LIST OF ABBREVIATIONS	xv
	LIST OF SYMBOLS	xvii
	LIST OF APPENDICES	xviii
CHAPTER 1	INTRODUCTION	1
	1.1 Background of Study	1
	1.2 Problem Statement	3
	1.3 Research Objective	4
	1.4 Scope and Limitation of Study	5
	1.5 Research Methodology	6
	1.6 Contributions of Study	10
	1.7 Thesis Organization	11
CHAPTER 2	LITERATURE REVIEW	13
	2.1 Introduction	13
	2.2 Analysis of Road Accident Scenarios and Impact Dynamics	13
	2.2.1 First stage: Vehicle collision	16
	2.2.2 Second stage: Human collision	16
	2.2.3 Third stage: Internal collision	17
	2.3 Vehicle Safety Systems	18
	2.3.1 Active Safety Systems	19
	2.3.2 Passive Safety Systems	20
	2.4 Vehicle Front Bumper System	21
	2.4.1 Passive Front Bumper	22
	2.4.2 Active Front Bumper	23
	2.5 Magnetorheological Elastomer (MRE)-Based Devices and Their Modelling Approaches	25
	2.6 Optimization of Model Parameters Using Gravitational Search Algorithm (GSA)	28
	2.7 Control Strategy for MRE-Based Devices	31
	2.8 Designation of Impact Testing: SAE vs ASEAN NCAP Parameters	34

2.9	Research Gap	36
2.10	Chapter Summary	38
CHAPTER 3	VEHICLE CRUMPLE ZONE MODELLING AND MODEL PARAMETER OPTIMIZATION USING GRAVITATIONAL SEARCH ALGORITHM	40
3.1	Introduction	40
3.2	Kamal Model	41
3.3	Modified Kamal Model	43
3.3.1	Equation of Motion for Modified Kamal Model	44
3.3.2	Development of Modified Kamal Model in Matlab-Simulink	46
3.4	Optimization of Model Parameter using GSA	48
3.5	Effect of Varying GSA Parameter	50
3.5.1	Number of Agents (N)	50
3.5.2	Beta Parameter (β)	53
3.5.3	Gravitational Constant (G)	56
3.6	Validation of Result	58
3.6.1	Comparison with Original Kamal Model	59
3.6.2	Comparison with Other Model	62
3.7	Chapter Summary	64
CHAPTER 4	DESIGN, MODELLING AND CHARACTERIZATION OF DUAL-ACTING MRE DAMPER UNDER IMPACT LOADING	66
4.1	Introduction	66
4.2	Design of Dual-Acting MRE Damper for Impact Mitigation	67
4.3	Experiment Setup for Dual-Acting MRE Damper	70
4.4	Impact Behavior Modelling Based on 4 th Order Polynomial Model	75
4.5	Optimization of 4 th Order Polynomial Model with GSA	78
4.6	Effect of Varying GSA Parameter	82
4.6.1	Number of Agents (N)	82
4.6.2	Number of Iterations (T)	83
4.7	Interpolation Model for Prediction of Intermediate Current	84
4.8	Validation of Result	86
4.8.1	Simulation of Polynomial Model at Different Input Current	86
4.8.2	Simulation of Interpolation Model for Intermediate Current	91
4.8.3	Verification of MRE Model by Integrating Input Currents with Intermediate Currents	95
4.8.4	Comparison with Other Model	98

	4.9 Chapter Summary	99
CHAPTER 5	CONTROL STRATEGY AND EXPERIMENTAL TESTING OF THE ACTIVE FRONT BUMPER SYSTEM	101
	5.1 Introduction	101
	5.2 Development of Collision Test Rig	102
	5.2.1 Universal Pendulum Impact Tester	102
	5.2.2 Sled Impactor	105
	5.2.3 Scaled Vehicle	105
	5.3 Dimensional Analysis Between Model and Prototype Using Froude Similarity Criterion	107
	5.4 Control Structure of Active Front Bumper System in Simulation Environment	109
	5.4.1 PID and Skyhook Controller	110
	5.4.2 On-Off Current Generator	111
	5.5 Optimization Parameters	112
	5.6 Optimization Results	113
	5.7 Experimental Setup of Control for Active Front Bumper System	114
	5.7.1 Controller Implementation Using Arduino Mega 2560	115
	5.7.2 Integrating Control Simulation Into Experiment for Impact Testing	117
	5.8 Experimental Result and Analysis	118
	5.8.1 Light Impact Case	119
	5.8.2 Medium Impact Case	121
	5.8.3 Hard Impact Case	123
	5.9 Chapter Summary	126
CHAPTER 6	CONCLUSION AND RECOMMENDATIONS	127
	6.1 Conclusions	127
	6.2 Future Works	129
REFERENCES		131
APPENDICES		141
BIODATA OF STUDENT		150
LIST OF PUBLICATIONS		151

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 2.1	The classification of collision (Tucker,1995)	18
Table 3.1	Initial spring-mass-damper parameters (Perodua, 2023; Pawlus et al., 2011)	47
Table 3.2	The optimized parameters for all number of agents	52
Table 3.3	The optimized data for all beta parameters	55
Table 3.4	The optimized data for all gravitational constants	58
Table 3.5	The optimal c and k values	59
Table 3.6	The maximum percentage error for each model	64
Table 4.1	Comparison of dual-acting MRE damper and crash box	70
Table 4.2	Percentage of MRE samples (Sobri et al., 2021)	71
Table 4.3	Experimental parameters set of for impact test	73
Table 4.4	Initial simulation parameters for GSA	80
Table 4.5	Optimized model parameter for each input current	81
Table 4.6	Force prediction error for input current	91
Table 4.7	Force prediction error for the interpolation current	95
Table 5.1	Physical parameter for real and scaled vehicles	108
Table 5.2	Simulation parameters for control	113
Table 5.3	Comparison of light impact cases	121
Table 5.4	Comparison of medium impact cases	123
Table 5.5	Comparison of hard impact cases	125
Table 5.6	Classification of impact loading	146
Table 5.7	Classification of collision (half of the actual value)	146

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 1.1	Comparison between present bumper structure and active front bumper system	4
Figure 1.2	Flowchart of research work	8
Figure 2.1	Road traffic fatality rates per 100 000 by WHO region	14
Figure 2.2	Different types of collision (Sierra, 2020)	15
Figure 2.3	Structure of active safety systems (European Automobile Manufacturers' Association, 2019)	20
Figure 2.4	Structure of passive safety systems (European Automobile Manufacturers' Association, 2019)	20
Figure 2.5	Front bumper systems (Rusch, 1990)	22
Figure 2.6	Active front bumper system (Davoodi et al., 2012)	24
Figure 2.7	Schematic diagram of MRE-based isolator with its model (Li et al., 2013; Yu et al., 2021)	27
Figure 2.8	Schematic diagram of MRE isolator device (MREID) with its model (Rahmat et al., 2021)	27
Figure 2.9	Block diagram of a model reference adaptive control system (Choi et al., 2016)	32
Figure 2.10	Basic structure of Fuzzy-PID control system (Wahid et al., 2012)	33
Figure 3.1	Mathematical model of a barrier impact (Kamal, 1970)	42
Figure 3.2	The dynamic forces acting on the front crumple zone (Kamal, 1970)	43
Figure 3.3	Free-body diagram of the crumple zone modelling	44
Figure 3.4	Schematic diagram of the modified Kamal model	47

Figure 3.5	The outcome of varying the number of agents (N)	51
Figure 3.6	The outcome of varying the beta parameter (β)	54
Figure 3.7	The outcome of varying the gravitational constant (G)	57
Figure 3.8	The optimum model parameters	60
Figure 3.9	Acceleration responses of original Kamal and Modified Kamal models	62
Figure 3.10	Comparison with others model	63
Figure 4.1	Design and prototype of dual-acting MRE damper	68
Figure 4.2	MRE fabrication process	71
Figure 4.3	Experiment setup of MRE drop impact	73
Figure 4.4	Force-displacement graph from drop impact test	74
Figure 4.5	Force-displacement characteristic	75
Figure 4.6	MRE non-parametric polynomial model	77
Figure 4.7	Model identification procedure based on GSA	78
Figure 4.8	Effect of varying the number of agents on the performance of GSA	83
Figure 4.9	Effect of varying the number of iterations on the performance of GSA	84
Figure 4.10	The structure of the interpolation current prediction model	86
Figure 4.11	Force-displacement characteristics of the MRE damper for currents 0 A – 0.5 A	87
Figure 4.12	Force-displacement characteristics of the MRE damper for currents 1 A – 2 A	89
Figure 4.13	Force-displacement curve of the interpolation currents for 0.3 A and 0.7 A	92
Figure 4.14	Force-displacement curve of the interpolation currents for 1.3 A and 1.7 A	93

Figure 4.15	Comparison of the force-displacement curve for simulation 0 A – 1 A	96
Figure 4.16	Comparison of the force-displacement curve for simulation at 1 A – 2 A	97
Figure 4.17	Comparison between Exponential model (EM) and Polynomial model (PM)	99
Figure 5.1	Structure of universal pendulum impact tester (Enkay Enterprises, 2023)	103
Figure 5.2	The weight of pendulum at different cases	104
Figure 5.3	The structure of sled impactor	105
Figure 5.4	Top and side view of scaled vehicle model	106
Figure 5.5	Froude similarity model	108
Figure 5.6	Froude number comparison between model and prototype	109
Figure 5.7	Control structure for simulation	110
Figure 5.8	Structure of skyhook controller	111
Figure 5.9	Structure of on-off current generator model	112
Figure 5.10	Optimization results of active front bumper system with control strategy under high collision force	114
Figure 5.11	Experimental setup for collision test rig	116
Figure 5.12	Full control structure in Matlab-Simulink	117
Figure 5.13	Schematic diagram of connection between simulation with experiment	118
Figure 5.14	Experiment results of collision test rig under light impact	120
Figure 5.15	Experiment results of collision test rig under medium impact	122
Figure 5.16	Experiment results of collision test rig under hard impact	124
Figure 5.17	Position of weight pendulum	145

LIST OF ABBREVIATIONS

ABS	-	Anti-lock Braking System
ACO	-	Ant Colony Optimization
ADAMS	-	Automated Dynamic Analysis of Mechanical Systems
ADAS	-	Advanced Driver-Assistance Systems
AEB	-	Automatic Emergency Braking
ANFIS	-	Adaptive Neuro-Fuzzy Inference System
BPF	-	Band-Pass Filter
CIP	-	Carbonyl Iron Particles
DAQ	-	Data Acquisition
DOF	-	Degree-of-freedom
E&E	-	Elkady and Elmarakbi Model
EM	-	Exponential Model
ESC	-	Electronic Stability Control
FE	-	Finite Element
GA	-	Genetic Algorithm
GMT	-	Glass Mat Thermoplastic
GSA	-	Gravitational Search Algorithm
HGSPSO	-	Hybrid Gravitational Search Particle Swarm Optimization
HPF	-	High-Pass Filter
IPSO	-	Improved Particle Swarm Optimization
KM	-	Kamal Model
LB	-	Lower Boundary

LPF	-	Low-Pass Filter
LVDT	-	Linear Variable Differential Transformer
MAE	-	Magneto-Active Elastomer
MKM	-	Modified Kamal Model
MR	-	Magneto-Rheological
MRE	-	Magnetorheological Elastomer
MREID	-	Magnetorheological Elastomer Isolator Device
PID	-	Proportional-Integral-Derivative
PIDF	-	Proportional-Integral-Derivative Filter
PM	-	Polynomial Model
POM	-	Polyoxymethylene
PSO	-	Particle Swarm Optimization
PWM	-	Pulse Width Modulation
R&D	-	Research and Development
RADAR	-	Radio Detection and Ranging
RCTD	-	Real Crash Test Data
RTV	-	Room Temperature Vulcanized
SLI	-	Speed Limit Information
SMC	-	Sheet Moulding Compound
UB	-	Upper Boundary
UPNM	-	Universiti Pertahanan Nasional Malaysia
USB	-	Universal Serial Bus
WHO	-	World Health Organization

LIST OF SYMBOLS

β	-	Beta Parameter
c	-	Damper Coefficient
C_1	-	Skyhook Damper
D	-	Number of Dimension
F_{coll}	-	Collision Force
F_d	-	Damping Force
F_m	-	Force Model
F_p	-	Force Prototype
F_r	-	Froude Number
g	-	Gravitational Acceleration
G	-	Gravitational Constant
k	-	Spring Constant
K_d	-	Derivative Value
K_i	-	Integral Value
K_p	-	Proportional Value
L	-	Length of Vehicle
N	-	Number of Agent
Q	-	Dissipative Energy
T	-	Number of Iteration
T	-	Kinetic Energy
v	-	Velocity
V	-	Potential Energy

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
	Appendix A : Coding of GSA	141
	Appendix B : Calculation of Weight Pendulum	145

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Conventional bumper design is less efficient in terms of total amount of energy absorbed during front collision because the front bumper is fix directly towards the vehicle body (NHTSA, 2018). They are designed to absorb and disperse energy upon impact but may not actively prevent or mitigate the force of a collision. Moreover, this bumper also unable to perform optimally in low-speed collisions, where the impact forces are minimal (Mo et al., 2018). As a result, this can lead to unnecessary damage to the vehicle.

As time goes by, the conventional vehicle bumper with passive systems that offer limited protection during collisions has evolved into an active front bumper system which made of two main components in the design namely, sensing system and a collapsible structure that extends from the front of the automobile to absorb impact energy where a more advanced system might be able to prevent or reduce damage (First-rate Mold Solution Co., Ltd., 2019).

In this study, an active front bumper system is developed using magnetorheological elastomer (MRE) dampers that is placed between the chassis and front bumper to reduce the effect of frontal collision which can causes crumple zone damage, unwanted acceleration and jerk or even worse fatalities. The main part of the damper is made of a smart material known as MRE that can change it stiffness and damping coefficient when induced with magnetic field.

To function as an effective system against the frontal impact, this study considers modelling the vehicle crash simulation that represents the arrangement of an actual vehicle crumple zone to carefully examine which part of the vehicle that affected during the accident. Furthermore, the impact behavior modelling of the MRE also takes place to identify the force-displacement characteristics when subjected to different stages of collision. Both validated models will be used to implement the suitable control strategy to evaluate the performance of the system.

The control strategy is developed based on the responses of displacement, acceleration, and transmitted force. Next, the collision test rig is developed and tested using a scaled vehicle. The experiment is conducted at different cases such as passive, active, and off state to evaluate the potential benefits of the active front bumper system in reducing the effect of frontal collision.

1.2 Problem Statement

Frontal collisions have been demonstrated to inflict more damage compared to rear collisions, primarily due to the concentration of crucial components such as the engine, transmission system, and radiator in the front of the vehicle (Florin Roebig, 2023). This high-density configuration of the crumple zone leads to less effective energy absorption and a greater transfer of force to the vehicle's structure, thereby contributing to passenger injuries, especially when the vehicle is traveling at higher speeds.

To mitigate these issues, various methods have been developed to minimize the impact of frontal collisions, including the integration of intelligent features into the vehicle's electronic systems, such as Automatic Emergency Braking (AEB) and Advanced Driver-Assistance Systems (ADAS). Utilizing sensors like RADAR and cameras, these systems provide real-time information to the driver and can take automatic actions based on the perceived obstacles (Vargas et al., 2021).

Additionally, an innovative approach involves the implementation of an active front bumper system incorporating magnetorheological elastomer (MRE) technology. This system aims to address the shortcomings of energy absorption in traditional bumper structures. By subjecting MRE samples to a magnetic field, the stiffness and damping properties are altered to enhance impact energy absorption. The front bumper is specifically designed to be sacrificed during frontal collision in order to absorb energy, thereby reducing the transfer of force to the occupant compartment, as illustrated in Figure 1.1 (Wang et al., 2021).

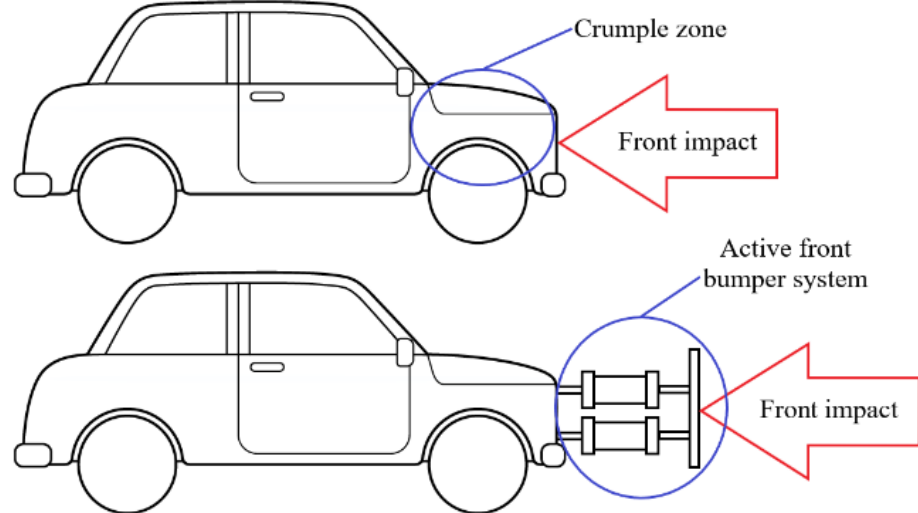


Figure 1.1 Comparison between present bumper structure and active front bumper system

In order to ensure the effectiveness of the active front bumper system, creating a functional control structure according to the actual collision scenario has been a challenge throughout this study. This is to guarantee that the damper is capable of reducing the impact imposed on the vehicle body at different collision stages (light, medium and hard impact energies). Thus, before the experiment is carried out on the scaled vehicle, a vehicle crash model and a MRE model are initially simulated to obtain the accurate model parameters.

1.3 Research Objective

The aim of this study is to reduce the effect of frontal collision including the damage on the vehicle crumple zone, fatalities on the passenger, unwanted acceleration and jerk. The objectives of the research are:

- (a) To model the dynamics of crumple zone during frontal collision using modified Kamal model.

- (b) To model the impact behaviour of the dual-acting MRE damper in the form of force-displacement characteristics using a non-parametric polynomial approach.
- (c) To develop a control strategy for active front bumper system that can reduce the effects of impact force due to collision.

1.4 Scope and Limitation of Study

The scope of this research focused on:

- (a) Only frontal collision is considered in this study by neglecting the lateral impact and rear-end collision.
- (b) Crumple zone modelling for frontal collision is develop based on Kamal model.
- (c) Impact behavior modelling of MRE is based on force-displacement characteristics.
- (d) The method used for controller and model optimization is gravitational search algorithm (GSA).
- (e) The control strategy implemented in this study is developed by considering low computational cost with fast response.
- (f) Experiment is conducted at low, medium and hard impact energies by varying the weight of pendulum.
- (g) The results of the experiment is analyzed based on the displacement and acceleration responses.

However, there are several limitations that need to be overseen on this study such as:

- (a) The characterization of the MRE is tested with the impact velocity of 2.24 m/s due to limitations of the drop impact test.
- (b) The vehicle model is downscaled to 1:10 of the actual vehicle because of the high fabrication cost and limited space in the collision test rig.
- (c) Modelling and control design are performed using Matlab-Simulink software.
- (d) On-off current generator is applied in the inner loop of the controller for active front bumper system.
- (e) Friction between the tire and road surface is neglected in both simulation and experiment.

1.5 Research Methodology

This research project started with the modelling of crumple zone based on Kamal model which has been modified into 6 degree-of-freedom vehicle crash model consists of six lumped masses, ten spring constants and four damper coefficients that represents the crucial parts of an actual vehicle. Each parameter are optimized using the gravitational search algorithm (GSA) until it closely follows the deformation and acceleration responses from the real crash test data (RCTD) obtained from TRL (1995) that is set as the benchmark of this project.

The project continues with the development of a dual-acting MRE damper which acts as an actuator in the active front bumper system. The damper is filled with solid and ring shaped MRE that are arranged along the body and wrapped with enameled copper coils where current is applied to produce magnetic field. A drop