COPYRIGHT© INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

OPTIMIZATION OF VEHICLE FRONT END GEOMETRY FOR ADULT AND CHILD PEDESTRIAN PROTECTION

BY

KAUSALYAH VENKATASON

A thesis submitted in fulfilment of the requirement for the degree of Doctor of Philosophy in Engineering

Kulliyyah of Engineering
International Islamic University Malaysia

JULY 2015

ABSTRACT

Motor Vehicle Crash statistics globally indicate that pedestrians make up the second largest category of fatalities after vehicle occupants. Pedestrian kinematics during the crash event with the vehicle has been shown to significantly affect the injury mechanism contributing to severe injuries to the head in particular. The paediatric population stands at significantly higher risk of sustaining heavy casualties during pedestrian vehicle impact compared to adults as they face an additional fatal risk of the vehicle running over them following the initial impact. This work aims to achieve an optimized vehicle front end profile which caters for improved protection for both adult and child pedestrian groups and simultaneously avoiding the Run-over scenario. A hybrid vehicle front end model is developed, and subjected to extensive validation. It is found that despite the simplified structure, the model's deformability provides excellent kinematic accuracy to better capture vehicle-impact, pedestrian fall patterns and corresponding injury values. The hybrid case model records similar impact locations with the verification models for the three tested speeds of 40,32 and 25 km/h. The HIC values for these three cases showed an error margin of $\pm$ 200.The fall pattern of the case model closely conforms to the PHMS verification model. The model offers the distinct advantages of relatively fast processing speed as well as ease of modifications due to its simple profile, which satisfy the criteria necessary for a multi-parameter optimization study. The processing speed is reduced approximately by 705 times achieving 99.85% efficiency in CPU time in comparison to a full FE vehicle model using the similar processing capacity. Design of Experiments (DoE) using the Central Composite Design (CCD) is initially utilized in which, a total of 100 computational runs are generated. The Head Injury Criteria (HIC) results from the simulations are tabulated as the response functions. Polynomial Response Surface Method (RSM) is used to generate mathematical models. Thereafter, the Latin Hypercube Sampling (LHS) design is used with 80computational runs and the mathematical models are generated using the Radial Basis Function (RBF). A comparison is made between the CCD-RSM models and the LHS-RBF models. The CCD-RSM models fitness is at 82.66% with a RMSE of 0.058 and the LHS-RBF has a fitness of 99.91% and a RMSE of 0.044. This clearly indicates that the LHS-RBF pair is best suited for optimization work. Optimization is performed using Genetic Algorithm. Unconstrained optimization is carried out separately for adults and for 6 year old child. A combined Adult-Child optimization is carried out as well. The individual adult optimized design and the child optimized design are shown to be not mutually applicable to each other i.e., HIC for Adult-Opt is 115.09 and using the similar optimized vehicle for the child records a HIC of 1797.4. The combined optimized profile however indicates high probability of Run-over scenario occurring for the child pedestrian, which invalidates the design. Thus, the Run-over occurrences from the DoE data are mapped using Logistic Regression and the resultant mathematical model is introduced as a constraint for the combined optimization. The final optimized model is shown to achieve a safe vehicle front-end profile with Combined-opt showing an observed HIC of 181.92, and Adult and Child-opt each respectively record a HIC of 209.34 and 195.47 successfully addressing both adult and child pedestrians, while simultaneously avoiding Run-over scenarios.

ملخص البحث

علم الحركة للمشاة أثناء الحدث تحطم يؤثر تأثيرا كبيرا على إصابة آلية تسهم في إصابات الرأس الشديدة التي تكون فيها الهندسة الأمامية السيارة يلعب دورا حيويا. تم تطوير نموذج أمامي سيارة هجينة، وتعرض لإثبات واسعة النطاق. استنادا إلى سبعة التصميم. على الرغم من تبسيطها، وسهلة الأمامية نهاية المعلمات لتعديل هيكل، ويوفر التشوه للنموذج دقة حركية ممتازة لالتقاط أفضل سيارة للتأثير، وأنماط سقوط المشاة والإصابات. بالإضافة إلى ذلك، فإن النموذج يضم سريعة نسبيا سرعة المعالجة. يستخدم تصميم لدراسة زارة (LHS) اللاتينية المكعب الزائدي أخذ العينات الطاقة. يتم إنشاء النماذج الرياضية باستخدام وظيفة أساس شعاعي يتم تنفيذ غير المقيدة. وتظهر تصميم الكبار الأمثل .(RBF) الفردية وتصميم طفل الأمثل لتكون غير قابلة للتطبيق بصورة متبادلة لبعضها البعض. ومع ذلك الشخصي الأمثل جنبا تمال كبير لطفل السيناريو الدهس التيإلى جنب يشير اح تحدث. لذلك، يتم تعيين حوادث الدهس من بيانات وزارة الطاقة باستخدام الانحدار اللوجستي وتقديم موديل رياضي الناتجة كعائق لتحسين مجتمعة. هذا النموذج الأمثل النهائي يحقق آمن كبارلمحة السيارة الأمامية، والتصدي بنجاح كل من المشاة ال .كثرأ والأطفال، مع تجنب تشغيل في وقت واحد بين

APPROVAL PAGE

The thesis of Kausalyah Venkatason has been approved by the following:

Kassim Abdulrahman Abdullah
Supervisor

Qasim H Shah
Co-Supervisor

Mouneb M Idres
Co-Supervisor

Meftah Hrairi
Internal Examiner

Rozli Zulkifli
External Examiner

Jamaluddin Mahmud
External Examiner

Saim Kayadibi
Chairman

DECLARATION

I hereby declare that this thesis is the result of my own investigation, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Kausalyah Venkatason

Signature………………. Date …..................

INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

DECLARATION OF COPYRIGHT AND AFFIRMATION OF FAIR USE OF UNPUBLISHED RESEARCH

Copyright © 2015 by International Islamic University Malaysia. All rights reserved.

OPTIMIZATION OF VEHICLE FRONT END GEOMETRY FOR ADULT AND CHILD PEDESTRIAN PROTECTION

No part of this unpublished research may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise without prior written permission of the copyright holder except as provided below.

1. Any material contained in or derived from this unpublished research may be used by others in their writing with due acknowledgement.

2. IIUM or its library will have the right to make and transmit copies (print or electronic) for institutional and academic purposes.

3. The IIUM library will have the right to make, store in a retrieval system and supply copies of this unpublished research if requested by other universities and research libraries.

Affirmed by Kausalyah Venkatason

……..……..……………	…………………..
Signature	Date

ACKNOWLEDGEMENT

All glories to the Supreme Lord Sri Krsna by whose mercy and sanction I was able to complete this PhD journey. I would like to thank my spiritual master, His Holiness B.V.V. Narasimha Swami who gave his priceless blessings and encouragement to complete this arduous task.

I would like to acknowledge my sincere gratitude to my supervisor, Asst. Prof. Dr. Kassim A. Abdullah for bearing with me throughout this PhD journey. There were many downs which I had to face and he was very understanding and encouraging in these periods. Having tolerated my difficult moments, his invaluable guidance, enthusiasm and untiring inspiration and support made the completion of this PhD possible. Thank You Dr Kassim for believing that this PhD was possible and enforcing the belief in me.

I would like to also express my gratitude and indebtedness for the kind cooperation from my co-supervisors Asst. Prof. Dr Moumen M. Idres, Assoc. Prof. Dr. Qasim H. Shah and Prof. Dr. Wong Shaw Voon. A special thanks to Dr. Moumen for his contribution and suggestions which helped me overcome many errors and showed me the right path during the course of this work.

I would like to express my special appreciation to my husband, Mr. Shasthri Sivaguru who was also my course mate in this PhD journey. His tireless assistance in both technical and non technical matters, his cooperation, his kindness and optimism and his sacrifice during my study period is very highly appreciated, without which the completion of this thesis would not be possible. I thank him from the bottom of my heart.

Thank You to my parents who were a great help during this journey. I would like to thank my mother who sacrificed a lot in caring for my children while I was studying despite this taking the toll her health and thank you to my father for being very supportive. I would like to thank my sister, Padmaa for assisting and being there to listen to my grouses and cheering me up. I would like to thank my two darling children Prahlad and Jhahnavi for bearing with me throughout this 4 years and tolerating the lack of attention and mood swings. I am truly blessed to have a very supportive family.

I would like to also extend my appreciation to Cik Hidayah and Puan Marina from the Post Graduate office of Kulliyah of Engineering for their kind assistance. Thank You also to Pn Siti Zainab from RMC who assisted in the grant management. I would like to thank The Ministry of Higher Education (MOHE) for the FRGS funding and IIUM for the Endowment fund.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Adult-Opt	Adult Optimization
AIS	Abbreviated Injury Scale
ANOVA	Analysis of Variance
AOP	Adult Occupant Protection
ATD	Anthropomorphic Test Dummies
BCH	Bumper Centre Height
BL	Bumper Lead
BLE	Bonnet Leading Edge
CCC	Central Composite Design Circumscribed
CCD	Central Composite Design
CCF	Central Composite Design Faced
CFC	Channel Frequency Class Filters
Child-Opt	Child Optimization
COP	Child Occupant Protection
C-Opt	Combined Optimisation
DoE	Design of Experiments
DRL	Day Running Lights
EA	Evolutionary Algorithm
EEVC	European Experimental Vehicles Committee
FE	Finite Element
GA	Genetic Algorithm
GIDAS	The German In-Depth Accident Study

HEH	Hood Edge Height
HIC	Head Injury Criteria
HL	Hood Length
HLE	Hood Leading Edge Height
IHRA	International Harmonised Research Activities
ISA	Intelligent Speed Assistance
ISO	International Standards Organisation’s
JARI	Japan Automobile Research Institute
LHS	Latin Hypercube Design
LTV	Light Truck Vehicles
MADYMO	Mathematical Dynamical Models
MB	Multi-body
MIROS	Malaysian Institute of Road Safety Research
MLR	Multi-linear Logistic Regression
MPV	Multi-Purpose Vehicle
MVC	Motor Vehicle Crash
NCAP	New Car Assessment Programme
NHTSA	National Highway Traffic Safety Administration
PCDS	Pedestrian Crash Data Study
PMHS	Post Mortem Human Subjects
PRESS	Predictive Error Sum of Squares
PRESS R2	PRESS Coefficient of Determination R
PRESS RMSE	PRESS Root Mean Square Prediction Error
RARU	Road Accident Research Unit of Adelaide University

RBF	Radial Basis Function
RMSE	Root Mean Square Error
RSM	Response Surface Method
SAE	Society of Automotive Engineers
SSE	Sum Of Square Errors
SSR	Sum of Squared Residuals
SST	Total Sum Of Squares
SUV	Sports Utility Vehicle
TNO	Netherlands Organization for Applied Scientific Research
TRL	Transport Research Laboratory
U.S.	United States of America
VRU	Vulnerable Road Users
WG17	Working Group 17

LIST OF SYMBOLS

t_1	initial time in seconds
t_2	final time in seconds
a	acceleration measured in g's (standard gravity acceleration)
g	standard gravity acceleration
$a_{resultant}$	resultant acceleration
a_x^2	acceleration in x-direction
a_y^2	acceleration in y-direction
a_z^2	acceleration in z-direction
E	Young's Modulus
t	Quadratic Element Thickness
$f(x)$	Response Function / Objective Function
$f'(x)$	Approximation of Response Function / Objective Function
m	Total Number of Design Variables
x	Design Variable
p	Number Of Non-Constant Terms In The RSM Model
n	Number of observations / Sampling Points
R^2	Coefficient Of Determination
f_i	Measured Function Value at the *ith* Design Point
$\bar{f}$	Mean Value of f_i
k_i	Unknown Weighting Coefficient
x_{1-7}	Vehicle Design Parameters
R^2_{adj}	Adjusted R-Squared

r	Euclidean distance
c	Prescribed parameter
α	Axial Values in CCD
$H\alpha$	Hood Inclination Angle
$WS\alpha$	Windshield Inclination Angle
ϕ	Basis Function
β	Coefficients of design variables in RSM equation
ε	Error in RSM equation
ρ	Density
σ_y	Yield Stress
μ	Poisson's Ratio
λ	Coefficient vector in RBF model

CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

Pedestrian injuries pose a significant problem throughout the globe. More than a third of the 1.2 million people killed and the 10 million injured annually in road traffic crashes worldwide are pedestrians (World Bank, 2002). In Malaysia, police statistics show that pedestrians rank third in road fatalities after motorists and motorcyclists (MIROS Report, 2011). In comparison to the injuries sustained by vehicle occupants, pedestrians sustain more multi-system injuries, with concomitantly higher injury severity scores and mortality (Brainard, 1986; Crandall et al., 2002)). This is also true for children who make up one quarter of these figures, where fatality and severity of injury is much more likely (Brainard, 1986). In motor vehicle-pedestrian crashes, head injuries are frequently the most common injury types, often leading to lifelong disabilities. Statistically, they also record the highest fatality occurrence (Otte, 1999; Maki et al., 2003; Pedestrian Safety Working Group 2001). Much effort has been extended in addressing this problem including law enforcement, increasing awareness, active and passive vehicle safety enhancement, and legislation. The existing literature abounds with researches of this nature. In this regard, one effort is the study of the relationship between vehicle front-end shape and the ensuing pedestrian fall pattern and kinematics for improved injury mitigation.

About 84% of all pedestrian fatalities involve frontal impacts and it is found that the vehicle front-end structure plays a key role in the determination of severity of injuries (Crandall et al., 2002; Liu et al., 2003). Literature shows that apart from the impact velocity, the vehicle's front-end contour is considered the most crucial vehicle design related factor in determining pedestrian kinematics (Kuehn et al., 2003; Liu et al., 2003; Carter et al., 2005). The resulting post-impact kinematics of the pedestrian in turn, determines the head impact locations, impact angle and head impact speed which finally influence the injury outcome (Kuehn et al., 2003; Liu et al., 2003; Yong et al., 2012). Although injuries to the lower extremities are generally attached to long term consequences, it is well established that the major cause of pedestrian fatality is due to injuries sustained on the head (Liu et al., 2003; Yao et al., 2007). Due to the non-linear nature of the problem, optimization of the vehicle geometry has not been a direct affair. Nevertheless, the usage of statistical methods and evolutionary optimization techniques has generated efforts in this direction. However, almost all of these are catered for mostly singular groups of adult pedestrians (Liu et al., 2003; Carter et al., 2005). In the determination of injury severity, studies of pedestrian post kinematics show that vehicle front-end geometry affects child and adult pedestrians in a different ways and as such the optimized profiles are shown to be not mutually applicable for safety. Furthermore, Run-over scenario is observed in child pedestrian optimized profiles, where its occurrence invalidates the optimization (ITARDA 2009; Serre et al., 2010; Bronwyn et al., 2011). This is a scenario where following impact, the child is knocked down in front of the vehicle and is run over by it instead of rolling over the vehicle and falling relatively safely to the side. Such an event serves a potentially greater fatality risk than primary impact induced head injuries (Bronwyn et al., 2011). Difficulties therefore are encountered in mitigation efforts involving both pedestrian groups (Kramlich et al., 2002; Peng et al., 1999; Carter et al., 2005; Zhao et al., 2010). Another consideration is that majority of these studies are done using the multi-body dynamics environment which offers the advantage of fast modeling and processing speed coupled with model simplicity (Liu et al., 2003; Dunmore et al., 2006). However, due to the exclusive use of rigid bodies, one major drawback is that multi body modeling method does not consider deformation properties. As local deformations of the vehicle body due to impact may significantly affect the kinematics of the pedestrian fall and hence the corresponding injury, the use of a deformable simplified Finite Element (FE) model is deemed more advantageous than the use of rigid bodies (Liu et al., 2003).

Therefore, this study emphasizes on the development of a deformable vehicle front-end hybrid model built using simple finite element profile shapes and a multi-body plane. This model is designed to be optimization-friendly, i.e., having simple, easily modifiable profile geometry with economical processing time. Multiple optimizations are then performed upon this vehicle front-end profile in the interest of achieving an optimized vehicle front-end profile design which offers mutual safety for both groups while simultaneously avoiding Run-over scenarios for child pedestrians.

1.2 PROBLEM STATEMENT AND RESEARCH SIGNIFICANCE

The shape or contour of a vehicle front end is customarily designed according to aerodynamics, engine packaging, manufacturability, occupant safety, and styling. With the rising concerns over pedestrian safety in the recent years (Niederer et al., 1984; Kuehn et al., 2003; Carter et al., 2005; Zhao et al., 2010), much has been done to create additional safety features onto vehicles to improve and mitigate pedestrian injuries, i.e. deployable airbags at hood and A-pillar, intelligent speed assistants (ISA), laser active night vision and thermal imaging for better visibility and detection, braking optimization such as brake assist etc. (Crandall et al., 2002). Nevertheless, some of these additional features are considerably expensive and highly unlikely to be market friendly and hence do not serve their purpose fully. Thus, a more design inherent approach is required in which the pedestrian protection provided is built-in to the vehicle design. This passive pedestrian-vehicle safety measure involves a two-fold approach. The first approach involves the control of the stiffness of vehicle parts such as the bumper, bonnet and windscreen-A-pillars that will tend to deflect upon impact and in so doing, serve to dissipate shock and thus reduce injury. Liu et al. (2002), Svobodha et al. (2003), Simms et al. (2006) , Lange et al. (2006) and Han et al.(2012), reported that the vehicle stiffness plays a big role on the resultant injury of the struck pedestrian especially on the head and the lower limb regions.

The second approach involves the study of the collision kinematics between the pedestrian and the vehicle whereby the pedestrian size, angle of approach, vehicle speed and vehicle front-end geometry dictate the motion of the human body upon impact and the determination of the likelihood of areas of impact. Ishikawa et al., (1993) and Liu et al., (2003) in their study reported that stiffness properties of the vehicle structure have little influence on the kinematic motion of the pedestrian during an impact. It is also found that the shape of the vehicle's front-end is the most important design related factor in determining pedestrian kinematics which in turn determines the injury outcome (Lange et al., 2006; Liu et al., 2003; Carter et al., 2005). Higuchi et al. (1991), Ishikawa et al., (1993) and Liu et al. (2003) studied the effects of the vehicle front-end structure on adult pedestrian injuries by investigating the relationship between the vehicle front-end profiles such as the bonnet leading edge height, bumper height and bumper lead on the head impact speed but not on combined effects. Liu et al. (2003) did a parametric study to show the interaction between the vehicle parameters on the head impact conditions and injury responses of a child