METHODOLOGY FOR PREDICTION OF PEDESTRIAN INJURIES UNDER DIFFERENT MOTORCYCLE-PEDESTRIAN IMPACT SCENARIOS

DEVENDRA KUMAR

DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2021

METHODOLOGY FOR PREDICTION OF PEDESTRIAN INJURIES UNDER DIFFERENT MOTORCYCLE-PEDESTRIAN IMPACT SCENARIOS

by

DEVENDRA KUMAR

Department of Mechanical Engineering

Submitted
in fulfilment of the requirements of the degree of Doctor of Philosophy
to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2021

Dedicated to parents, family and friends

CERTIFICATE

This is to certify that the thesis titled "Methodology for Prediction of Pedestrian Injuries Under Different Motorcycle-Pedestrian Impact Scenarios" being submitted by Mr. Devendra Kumar to the Indian Institute of Technology Delhi for the award of Doctor of Philosophy in Department of Mechanical Engineering is a record of bonafide research work carried out by him. He has worked under our guidance and has fulfilled the requirements for the submission of thesis, which, in our opinion, has reached the requisite standard.

The results contained in this thesis have not been submitted in part or full, to any University for the award of degree and diploma.

Dr. Anoop Chawla
Volvo Chair & Professor,
Department of Mechanical Engineering
Indian Institute of Technology,
Hauz Khas, New Delhi – 110016. India

Dr. Sudipto Mukherjee
Ford Chair & Professor,
Department of Mechanical Engineering
Indian Institute of Technology
Hauz Khas, New Delhi – 110016. India

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my supervisors **Prof. Anoop Chawla and Prof. Sudipto Mukherjee** for their generous support and encouragement for the past years. Their continued support and visionary thoughts have been a strong motivation for me. The work ethics and discipline learnt from them will help me throughout my academic career. They always provided me with the best opportunities and help whenever I needed it.

I feel privileged and grateful to my parents, Mr. Ram Asare & Mrs. Munni Devi and my siblings for everything that I have achieved is because of their blessings, encouragement and constant support.

I would also like to sincerely thank my Student Research Committee (SRC) – Prof. D. K. Dubey (SRC chairman), Prof. A. K. Darpe (Internal Expert), Prof. Vasant Matsagar (External Expert) - for their critical and valuable suggestions that helped me look at research from a larger perspective, contributing to improvement in my problem understanding skills.

Thanks are also due to the staff members of Mechanical Engineering Department, Mr. S. Babu, Mr. Manish Kumar, Mr. K. K. Sharma, Mr. P. S. Negi, Mr. Kamal Rana, Mr. Rabindra kar for their support and providing the necessary requirements in my work.

A very special thanks to Dr. S. Hariharan, Dr. Piyush Gaur, Dr. Khyati Verma, Dr. Wondwosen Ayelework who helped me in my initial stage of Ph.D. life. I wish to express my gratitude to my well-wishers Dr. Joyjit Mukherjee, Dr, Shabina Ashraf, Dr. Sugeet Sunder for their constant encouragement and turning tea break into brainstorming sessions. I am thankful to all my friends from dramatics club, Amrish Kumar, Pranjal Singh, Rahul

Shubham, Dr. Vandit Vijay, Dr. Anu Kadyan, Punit Gaur, Neelam Chaudhary, Sanchayan Pal, Dr. Nalin Sharma, Dr. Rupyan Roy and Dr. Deepak & Ritu Sharma, with whom I relaxed and enjoyed during my exhausting schedule.

I am also thankful to my fellow lab mates Kuldeep Singh, Sanyam Sharma, Aman Vikram, Pushpendra Prasad Pandey, Mohd. Akhtar sane, Ramakrishnan Iyer, Vivek Dhimole, Aditya Chhabra, Srikar Kale, Aditya Sinha, Archan Mehta and Akhilesh Chaudhary and all the members of impact lab who helped in directly or indirectly.

I am sincerely thankful to my friends from school, graduation and post-graduation; Ravi Kumar, Mayank Dixit, Deepika Soni, Prashant Upadhyay, Sushank Mishra, Ajay Sharma, Nitin Kumar Sahu, Ankur Chaudhary, Rakesh Verma, Ram Mohan Gupta, Nitesh Dabre and Sandeep Kumar who have been continuously listening to me, planning trip with me, making me feel special and pushing me to go to next level.

Finally, I thank all those people, who knowingly or unknowingly inspired me in many ways throughout these years.

Devendra Kumar

ABSTRACT

Variation in pedestrian kinematics in motorcycle pedestrian crashes leads to different kinds of injuries. The speeds of the pedestrian and motorcycle have been estimated from videos showing clear motorcycle-pedestrian crashes. The kinematics of the pedestrian head, chest, pelvis and knees has been extracted from the crash videos and compared with the finite element simulations. Evaluation of THUMS model for injury predicting capabilities in real-life motorcycle-pedestrian cases is carried out. This has been done in two steps; estimating pre-impact crash parameters and evaluating the model for injuries using these parameters. For pre-impact parameters estimation, five orientations (0, 15o CW, 15o CCW, 30o CW, 30o CCW), five positions (0, 20, 40, 60, 80 mm), and five speed variations have been used to iterate and match the known throw distance by performing MADYMO simulations. For evaluation of THUMS, five real-life crashes have been selected from a hospital database. These cases have been simulated and injuries have been estimated and compared with the known clinical data. Injuries have been estimated for five offset positions (-100mm, -50mm, 0mm, +50mm and +100 mm), five angular orientations (0-deg, 45-deg, 90-deg, 135-deg and 180-deg) and three impact speeds (30 kmph, 35 kmph and 40 kmph), resulting in a total of 75 different crash configurations. For angular variations, the maximum and the minimum number of injuries have been observed in 45-deg and 90-deg configuration, respectively. While in offset variation, the maximum and the minimum number of injuries have been observed in 0mm and +100mm configurations. For skeletal injuries corresponding to the sagittal plane, symmetric pedestrian injuries for 225-deg, 270-deg and 315-deg crash configurations have been estimated, which resulted in data for 120 configurations. The data of 120 crash configurations shows that the probability of fracture of bones is highest for the head, followed by Humerus, Ribs, Clavicle, and Tibia.

सार

मोटरसाइकिल पैदल यात्री दुर्घटनाओं में पैदल यात्री की गति में भिन्नता विभिन्न प्रकार की चोटों की ओर ले जाती है। मोटरसाइकिल-पैदल यात्री दुर्घटनाओं को स्पष्ट दिखाने वाले वीडियो से पैदल यात्री और मोटरसाइकिल की गति का अनुमान लगाया गया है। पैदल चलने वाले के सिर, छाती, श्रोणि और घुटनों के काइनेमटिक्स को क्रैश वीडियो से निकाला गया है और फाइनाइट एलीमेंट सिमुलेशन के साथ तुलना की गई है। वास्तविक जीवन मोटरसाइकिल-पैदल यात्री मामलों में चोट की भविष्यवाणी करने की क्षमताओं के लिए THUMS मॉडल का मूल्यांकन किया जाता है। यह दो चरणों में किया गया है; प्रीक्रैश मापदंडों का अनुमान लगाना और इन मापदंडों का उपयोग करके चोटों के लिए मॉडल का मूल्यांकन करना। प्रीक्रैश मापदंडों के अनुमान के लिए, पांच ओरीएन्टेशन (0, 15° CW, 15° CCW, 30° CW, 30° CCW), पांच ऑफ्सेट (0, 20, 40, 60, 80 मिमी), और पांच गति भिन्नताओं का उपयोग किया गया है और MADYMO सिमुलेशन प्रदर्शन करके ज्ञात थ्रो दूरी का मिलान किया गया। THUMS के मूल्यांकन के लिए, अस्पताल के डेटाबेस से पांच वास्तविक जीवन दुर्घटनाओं का चयन किया गया है। इन मामलों का सिमुलेशन किया गया है और चोटों का अनुमान लगाया गया है और ज्ञात रियल लाइफ डेटा के साथ तुलना की गई है। पांच ऑफसेट स्थितियों (-100mm, -50mm, 0mm, +50mm और +100mm), पांच कोणीय स्थितियों (0-डिग्री, 45-डिग्री, 90-डिग्री, 135-डिग्री और 180-डिग्री) के लिए चोटों का अनुमान लगाया गया है और तीन प्रभाव गति (30 किमी प्रति घंटे, 35 किमी प्रति घंटे और 40 किमी प्रति घंटे), जिसके परिणामस्वरूप कुल 75 अलग-अलग क्रैश कॉन्फ़िगरेशन होते हैं। कोणीय भिन्नताओं के लिए, चोटों की अधिकतम और न्यूनतम संख्या क्रमशः 45-डिग्री और 90-डिग्री कॉन्फ़िगरेशन में देखी गई है। ऑफसेट भिन्नता में, 0 मिमी और +100 मिमी कॉन्फ़िगरेशन में अधिकतम और न्यूनतम संख्या में चोटें देखी गई हैं। धनु तल से संबंधित कंकाल की चोटों के लिए, 225-डिग्री, 270-डिग्री और 315-डिग्री क्रैश कॉन्फ़िगरेशन के लिए सममित पैदल यात्री चोटों का अनुमान लगाया गया है, जिसके परिणामस्वरूप 120 कॉन्फ़िगरेशन के लिए डेटा प्राप्त हुआ है। 120 क्रैश कॉन्फ़िगरेशन के डेटा से पता चलता है कि हड्डियों के फ्रैक्चर की संभावना सिर के लिए सबसे अधिक है, इसके बाद ह्यूमरस, रिब्स, क्लेविकल और टिबिया हैं।

TABLE OF CONTENTS

Certificate i

Acknowledgement iii

Abstract v

Table of contents ix

List of figures xiii

List of tables xxi

Abbreviation xxiii

Chapter 1. Introduction 1

1.1 Traffic Fatalities Worldwide 1

1.2 Traffic Fatalities in India 1

1.3 Need for Crash Reconstruction 4

1.4 Need for Finite Element Simulations 4

1.5 Thesis Organization 6

Chapter 2. Literature review 9

2.1 Introduction 9

2.2 Road Accidents in India 9

2.2.1 Pedestrian Accidents 11

2.2.2 Motorcycle Accidents 12

2.2.3 Motorcycle Sales in India 13

2.3 Pedestrian Accidents Worldwide 14

2.3.1 The Pedestrian Crash Database Study 14

2.3.2 Pedestrian Casualties in UK 1979 - 2013 15

2.3.3 Pedestrian Accidents in New Zealand 16

2.4 Epidemiology of Pedestrian Injuries 16
2.5 Motorcyclist Accidents and Injuries 20
2.6 Pedestrian Simulation 21
2.7 Motorcycle Simulations 23
2.7.1 Motorcycle Models 23
2.7.2 Pedestrian Models 25
2.7.3 Rider Model 26
2.8 Conclusion 27
Chapter 3. Research Question and Methodology 29
3.1 Introduction 29
3.2 Research Question 30
3.3 Objectives and Scope 30
3.3.1 Pedestrians kinematics validation using THUMS 30
3.3.2 Validating THUMS for Pedestrian injuries 31
3.3.3 Pedestrian's injuries prediction in various impact scenarios 31
3.4 Methodology 31
3.5 Conclusion 34
Chapter 4. Pedestrian Kinematics in real-life crashes 35
4.1 Introduction 35
4.2 Model setup 35
4.3 Selection of cases 37
4.4 Analysis of the cases 38
4.4.1 Case 1 40
4.4.2 Case 2: 49

4.4.3 Case 3: 54
4.4.4 Case 4: 61
4.4.5 Case 5: 65
4.4.6 Case 6: 71
4.5 Validation of method used for speed estimation 74
4.6 Conclusion 76
Chapter 5. Validation of THUMS for Injuries 77
5.1 Introduction 77
5.2 Selection of cases 77
5.3 Crash Reconstruction 79
5.3.1 Multi-body motorcycle model 79
5.3.2 Estimating impact speed using MADYMO Simulations 81
5.4 Injury Validation 89
5.5 Conclusion 96
Chapter 6. Estimating spread of injuries in motorcycle-pedestrian crashes 97
6.1 Introduction 97
6.2 Variation in angle, offset and impact speed 97
6.2.1 Range of Angle of impact 97
6.2.2 Variation in Offset Position 98
6.2.3 Variation in impact speed 99
6.3 Combined Angular-Offset Impact Scenario 99
6.3.1 Overall Pedestrian Injury Pattern 100
6.3.2 Trends of Injuries at 30 kmph 105
6.3.3 Trends of Injuries at 35 kmph 109

6.3.4 Trends of Injuries at 40 kmph 112
6.4 Conclusion 115
Chapter 7. Contributions and Conclusions 117
7.1 Contributions 117
7.2 Limitations 119
7.3 Future Scope 120
References 121
Appendix 134
A. Code for obtaining frames from crash video 134
B. Code for extracting pedestrian kinematics from images 134
C. Code for creating slow motion video for tracked the pedestrian kinematics 137
D. Code for calculating unknown distance, travelled by motorcycle 138
E. Severity of Injury and AIS 140
Brief Bio-data of the Author 141

LIST OF FIGURES

Figure 1.1 Fatalities of different road users in India....2

Figure 1.2 Fatalities of different road users in India....3

Figure 2.1 Increase in number of fatalities with the year (NCRB, 2019)....9

Figure 2.2 Comparison in fatalities of pedestrian and Motorcyclist (NCRB, 2019)...10

Figure 2.3 Increase in registered motor vehicles(Open Government Data, 2016) 11

Figure 2.4 Trend in the fatalities of pedestrians in India 12

Figure 2.5 shows the trend of number of deaths of Motorcyclists with year....12

Figure 2.6 Comparison of injured body region (AIS ≥ 2) 17

Figure 3.1 Flow chart....33

Figure 4.1 Motorcycle model....36

Figure 4.2 Helmet model 36

Figure 4.3 Rider model 36

Figure 4.4 Pedestrian model 36

Figure 4.5 Cross ratio in projective transformation....39

Figure 4.6 The front tire of SUV enters the zebra crossing....40

Figure 4.7 The front tire of SUV exiting the zebra crossing 40

Figure 4.8 The frame at which the sedan car enters the zebra crossing....41

Figure 4.9 The frame at which the sedan car leaves the zebra crossing 41

Figure 4.10 The frame at which the small segment car enters the zebra crossing....41

Figure 4.11 The frame at which the small segment car leaves the zebra crossing 41

Figure 4.12 The frame at which motorcycle touches the stooping line....42

Figure 4.13 The frame at which motorcycle touches the zebra 42

Figure 4.14 The frame at which the pedestrian enters the lane 43

Figure 4.15 The frame at which the pedestrian completes the lane of 3.6m width 43
Figure 4.16 Known distances on the road.....44
Figure 4.17 Location of four collinear points on the image 44
Figure 4.18 Position of pedestrian on the road at the time of impact 45
Figure 4.19 Pixel position of the pedestrian on image.....45
Figure 4.20 Distance traveled by motorcycle 45
Figure 4.21 Car Height 46
Figure 4.22 Pedestrian Height.....46
Figure 4.23 Marked color patches 46
Figure 4.24 Head height variation 47
Figure 4.25 Pelvic height variation.....47
Figure 4.26 Chest height variation.....48
Figure 4.27 Knee height variation 48
Figure 4.28 Comparison of pedestrian kinematics 49
Figure 4.29 Image showing the road markings.....50
Figure 4.30 Speed recorded by Nexar App.....50
Figure 4.31 Motorcyclist entering the street light pole.....51
Figure 4.32 Motorcyclist exiting the street light pole.....51
Figure 4.33 Pedestrian entering the right lane shown in red.....51
Figure 4.34 Pedestrian impacts the motorcycle 51
Figure 4.35 Estimation of pedestrian height.....52
Figure 4.36 Markers on pedestrian 52
Figure 4.37 Head height variation 53
Figure 4.38 Pelvis height variation 53

Figure 4.39 Chest height variation 53
Figure 4.40 Knee height variation 53
Figure 4.41 Comparison of pedestrian kinematics 54
Figure 4.42 Image shows the dimensions of a zebra crossing 55
Figure 4.43 Vehicle crossing the stopping line 55
Figure 4.44 The front tire of vehicle exiting the zebra crossing 55
Figure 4.45 Pedestrian entering the zebra crossing 56
Figure 4.46 Motorcyclist hits the pedestrian 56
Figure 4.47 Pedestrian position on the road 57
Figure 4.48 Pixel distance of pedestrian 57
Figure 4.49 Pedestrian position on the road 57
Figure 4.50 Pixel distance traveled by motorcycle 57
Figure 4.51 Position of pedestrian on the road 58
Figure 4.52 Pedestrian position in simulation 58
Figure 4.53 Distance traveled by motorcycle 58
Figure 4.54 Car height 58
Figure 4.55 Pedestrian’s height 58
Figure 4.56 Marked color patches 58
Figure 4.57 Head height variation 59
Figure 4.58 Left knee height variation 59
Figure 4.59 Chest height variation 59
Figure 4.60 Right knee height variation 59
Figure 4.61 Comparison of pedestrian kinematics 60
Figure 4.62 Entry of motorcycle 61

Figure 4.63 Motorcycle at the time of crash 61
Figure 4.64 Pedestrian before crash 62
Figure 4.65 Pedestrian at the time of crash 62
Figure 4.66 The height of the car 63
Figure 4.67 The height of pedestrian 63
Figure 4.68 Head height variation 64
Figure 4.69 Pelvis height variation 64
Figure 4.70 Chest height variation 64
Figure 4.71 Knee height variation 64
Figure 4.72 Comparison of pedestrian kinematics 65
Figure 4.73 Vehicle's end entering the zebra crossing 66
Figure 4.74 Vehicle's end leaving the zebra crossing 66
Figure 4.75 Motorcycle entering 66
Figure 4.76 Motorcycle almost exiting 66
Figure 4.77 Pedestrian entering the pedestrian crossing 67
Figure 4.78 Motorcyclist contacts the pedestrian 67
Figure 4.79 Kinematics of pedestrian on the road 68
Figure 4.80 kinematics of pedestrian in simulation 68
Figure 4.81 Car height 68
Figure 4.82 Pedestrian's height 68
Figure 4.83 Marked color patches 68
Figure 4.84 Head height variation 69
Figure 4.85 Pelvic height variation 69
Figure 4.86 Chest height variation 70

Figure 4.87 Knee height variation 70
Figure 4.88 Comparison of pedestrian kinematics 70
Figure 4.89 Scenario just before the crash 71
Figure 4.90 Speed of other road user 71
Figure 4.91 Three wheeler Auto height 72
Figure 4.92 Pedestrian's height 72
Figure 4.93 Marked color patches 72
Figure 4.94 Head height variation 73
Figure 4.95 Pelvis height variation 73
Figure 4.96 Chest height variation 73
Figure 4.97 Knee height variation 73
Figure 4.98 Comparison of pedestrian kinematics 74
Figure 4.99 (a) & (b) shows the initial and final frame of motorcycle 75
Figure 4.100 (a) & (b) shows the initial and final frame of motorcycle 75
Figure 5.1 Motorcycle Joints (Canaple et al., 2002) 80
Figure 5.2 MADYMO Motorcycle model 80
Figure 5.3 Comparison of wall forces 81
Figure 5.4 Offset variation 82
Figure 5.5 Angular Variation 82
Figure 5.6 THUMS FE models 88
Figure 6.1 Top view of cases of angular impact scenario 98
Figure 6.2 Offset impact scenario 99
Figure 6.3 Number of cases with different bone fracture 101
Figure 6.4 Probability of fracture of bones with speed 103
Figure 6.5 Variation of injuries with speed 104

Figure 6.6 (a) & (b) Variation of injuries with angle and speed, respectively.....104
Figure 6.7 Variation of injuries at different offsets 105
Figure 6.8 Variation of bone fractures with angles at -100-mm offset.....106
Figure 6.9 Variation of bone fractures with angles at -50-mm offset.....106
Figure 6.10 Variation of bone fractures with angles at 0-mm offset.....107
Figure 6.11 Variation of bone fractures with angles at +50-mm offset.....107
Figure 6.12 Variation of bone fracture with offsets at 0-deg angle.....107
Figure 6.13 Variation of bone fractures with offsets at 45-deg angle 107
Figure 6.14 Variation of bone fractures with offsets at 90-deg angle 108
Figure 6.15 Variation of bone fractures with offsets at 135-deg angle 108
Figure 6.16 Variation of bone fractures with offsets at 180-deg angle 108
Figure 6.17 Variation of bone fractures with angles at -100-mm offset.....109
Figure 6.18 Variation of bone fractures with angles at -50-mm offset.....109
Figure 6.19 Variation of bone fractures with angles at 0-mm offset.....110
Figure 6.20 Variation of bone fractures with angles at +100-mm offset.....110
Figure 6.21 Variation of bone fractures with offsets at 0-deg angle 111
Figure 6.22 Variation of bone fractures with offsets at 45-deg angle 111
Figure 6.23 Variation of bone fractures with offsets at 90-deg angle 111
Figure 6.24 Variation of bone fractures with offsets at 135-deg angle 111
Figure 6.25 Variation of bone fractures with angle at -100-mm offset 112
Figure 6.26 Variation of bone fractures with angle at -50-mm offset 112
Figure 6.27 Variation of bone fractures with angle at 0-mm offset.....113
Figure 6.28 Variation of bone fractures with angle at +50-mm offset 113
Figure 6.29 Variation of bone fractures with angle at +100-mm offset 113

Figure 6.30 Variation of bone fractures with offset at 0-deg angle 114

Figure 6.31 Variation of bone fractures with offset at 45-deg angle 114

Figure 6.32 Variation of bone fractures with offsets at 135-deg angle 115

Figure 6.33 Variation of bone fractures with offsets at 180-deg angle 115

LIST OF TABLES

Table 2.2 Distribution of injury sustained by Anatomical Region 18

Table 2.3 Human CAE models summarized from (EURO NCAP v1.4, 2015)..... 26

Table 4.1 Variation in height and weight of pedestrian and rider models 37

Table 4.2 Cases selected from YouTube 37

Table 5.1 Cases considered in the study 78

Table 5.2 Case 1 – Variation in throw distance w.r.t. vehicle speed 83

Table 5.3 Case 2 – Variation in throw distance w.r.t. vehicle speed 84

Table 5.4 Case 3 – Variation in throw distance w.r.t. vehicle speed 85

Table 5.5 Case 4 – Variation in throw distance w.r.t. vehicle speed 86

Table 5.6 Case 5 – Variation in throw distance w.r.t. vehicle speed 87

Table 5.7 Variation in failure strain values with age for cortical bone..... 91

Table 5.8 Variation of injuries with speed and time 91

Table 5.9 Location of bone fracture in simulation and real-life case 94

Table 6.1 Simulation Matrix 100

ABBREVIATION

FE	-	Finite Element
HBM	-	Human Body Model
RTI		Road Traffic Injuries
NCRB	-	National Crime Record Bureau
PCDS	-	Pedestrian Crash Data Study
AIS	-	Abbreviated Injury Scale
THUMS	-	Total HUman Model for Safety
GHBMC	-	Global Human Body Models Consortium
VRU	-	Vulnerable Road Users
GIDAS	-	German In-Depth Accident Study
NCAP	-	New Car Assessment Program
HIC	-	Head Injury Criteria
MATD	-	Motorcycle Anthropometric Test Device
MoRTH	-	Ministry of Road Transport and Highways
CW	-	Clockwise
CCW	-	Counterclockwise
m	-	Meters
mm	-	Millimeters
s	-	Seconds
^{o}	-	Degrees
WHO	-	World Health Organisation