RETROFIT DESIGN OF GUARD FENCE SYSTEM TO ACCOMMODATE MOTORCYCLE SAFETY

A Thesis

by

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ABSTRACT

Among all users of the road system, motorcyclists are the most vulnerable. Roadside safety systems and its design play an important role in the severity of motorcycle crashes.

Data shows that from 2004, the number of fatalities related to motorcycle impact against safety barriers was greater than the number of fatalities recorded from the impact of passenger car users against same roadside safety devices.

Although there are no guiding principles providing proper use and testing of motorcycle friendly retrofit barriers, there is a need to develop an appropriately designed guardrail system retrofit to address motorcycle-rider fatalities associated with barrier impacts, which can happen with the rider being either in a sliding or upright position. Retrofit system for placement on appropriate high speed roadways at locations that are more likely to be associated with motorcycle impact fatalities and severe injuries shall be considered. Hence an appropriate “motorcycle-friendly” retrofit guard fence system will be developed for evaluation to determine its compliance with the 2016 American Association of State Highway and Transportation Officials (AASHTO) Manual for Assessing Safety Hardware (MASH), per Federal Highway Administration (FHWA) requirement. This project is funded by Texas Department of Transportation (TxDOT).

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Contributors

This work was supervised by a thesis committee consisting of Dr. Stefan Hurlebaus and Dr. Arash Noshadravan of the Zachry Department of Civil and Environmental Engineering, Dr. Jeffrey Falzarano of the Department of Ocean Engineering, and Dr. Chiara Silvestri Dobrovolny from Texas A&M Transportation Institute.

All work conducted for the thesis was completed by the student independently.

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NOMENCLATURE

A2LA - American Association for Laboratory Accreditation

AASHTO - American Association of State Highway and Transportation Officials

ATD - Anthropomorphic Test Device

BASt - Bundesanstalt für Straßenwesen

CIP - Critical Impact Point

CRIS - Crash Record Information System

FARS - Fatality Analysis Reporting System

FE - Finite Element

FEMA - Federation of European Motorcyclist's Associations

FHE - First Harmful Event

FHWA - Federal Highway Administration

GES - General Estimates System

ISO - International Standards Organization

Km/h – Kilometers per hour

LON - Length of Need

MAG - Motorcycle Action Group

MASH - Manual for Assessing Safety Hardware

MC - Motorcycle

MHE - Most Harmful Event

Mph - Miles per Hour

MPS - Motorcycle Protection System

NHTSA - National Highway Traffic Safety Administration

RHiNO - Roadway Highway Inventory Network Offload

ROR - Run-Off-Road

SVM - Single Motor Vehicle

TL – Test Level

TRB – Transportation Research Board

TRIS - Transportation Research Information Service

TxDOT - Texas Department of Transportation

US Dot - United States Department of Transportation

TABLE OF CONTENTS

Page

ABSTRACT ii

Acknowledgements iii

contributors and funding sources iv

Nomenclature v

Table of Contents vii

List of Figures xi

List of Tables....xiv

1. INTRODUCTION....1

2. LITERATURE REVIEW....6

2. 1 Motorcycle Full-Scale Testing Protocols and Standards....6
2.1.1 L.I.E.R. (1998) Protocol: Motorcyclist Safety Evaluation Regarding Safety Barriers. 6
2.1.2 UNE – 135900 Spanish Standard Protocol: AENOR (2005) Standard UNE 135900:2005, AENOR (2008) Standard UNE 135900:2008rev.01. 8
2.1.3 EN1317-8 (2011) Road Restraint Systems - Part 8: Motorcycle Road Restraint Systems which Reduce the Impact Severity of Motorcyclist Collisions with Safety Barriers....10
2.1.4 ISO 13232 (1996) Motorcycles-Test and Analysis Procedures for Research Evaluation of Rider Crash Protection Devices Fitted to Motorcycles....14
2.1.5 FEMA (2010) Final report of the Motorcyclists & Crash Barriers Project, Federation of European Motorcyclist's Associations 16
2.1.6 Australian/New Zealand Standard (AS/NZS 3845:2015). 17
2.2 Test Conditions and Evaluation Criteria 20
2.2.1 Motorcycle Impacts with Guardrail, Institute National de Recherche sur les Transports et leur Securite, INRETS, France. 20
2.2.2 Motorcycle Crash Test Modelling....22
2.2.3 Motorcycle Impacts into Roadside Barriers – Real-World Accident Studies, Crash Tests and Simulations Carried Out in Germany and Australia....24

2.2.4 Technical bases for the development of a test standard for impacts of powered two-wheelers on roadside barriers 25
2.2.5 Motorbiking - on Safe Roads 27
2.2.6 Infrastructure Improvements to Reduce Motorcycle Casualties 29
2.2.7 Motorcycle-Friendly Guardrails: FEMA is granted the Liaison Status with CEN/TC 226 (2007)....................31
2.3 Motorcycle Crashes and Studies with Mitigation Measures 33
2.3.1 Motorcycle Crash Tests Conducted Inside U.S. 33
2.3.2 Studies Conducted Inside the U.S. 41
2.4 Devices to Retrofit Roadside Barriers for Motorcycle Safety 48
2.4.1 Punctual Energy Absorbers (Crash Barrier Protectors (CBP)) 49
2.4.2 Continuous Systems to Redirect Riders 50
2.4.3 V – Beam Guardrail 53
2.4.4 W-Beam Guardrail Equipped with Lower Motorcycle Barrier (FHWA, 2012) 54
2.4.5 Euskirchener Model – 'Safety outside Build-Up Areas' 56
2.4.6 Spanish Guardrail 57
2.4.7 Other Devices for Roadside Barrier Retrofit for Motorcycle Safety 58
2.5 International Survey for Existing Guardrail Design Options 63
2.5.1 Introduction 63

3. CRASH DATA ANALYSIS 65

3.1 Summary 65
3.2 Introduction 65
3.3 Determining Variables Using Google Earth 67
3.4 Crash Reports 71
3.5 Vehicle Identification Number (VIN) Decoding 74
3.6 Descriptive Statistical Analysis 74
3.6.1 Environmental Crash Characteristics 75
3.6.2 Location 77
3.6.3 Speed Limit 85
3.6.4 Roadway Alignment 86
3.7 Narrative and Diagram Review Data 87
3.7.1 Upright or Sliding Position 87
3.7.2 Impact Location on Guardrail 88
3.7.3 Guardrail Type 89
3.7.4 Ejection 92
3.8 Conclusion 92

4. CONCEPTS DEVELOPMENT AND DESIGN SELECTION 94

4.1 Introduction 94
4.2 Design Options 95

4.2.1 Protection on Top 96
4.2.2 Protection on Bottom 103
4.3 Conclusions 111

5. DEVELOPING DESIGN DETAILS AND PERFORMING ENGINEERING ANALYSIS 114

5.1 Introduction 114
5.2 Model Calibration 115
5.3 Predictive Simulations 124
5.3.1 Retrofitted Option 124
5.3.2 Upright Motorcycle with Dummy 127
5.3.3 Pick Up Truck – Retrofitted MGS 134
5.3.4 Passenger Car – Retrofitted MGS 138
5.3.5 Sliding Dummy 141
5.4 Conclusion 153

6. TEST PLAN 154

6.1 *MASH* Test Requirements 154
6.2 Motorcycle Testing Impact Characteristics from the Previous Testing 155
6.3 Motorcycle Testing Impact Conditions 155
6.4 Motorcycle Testing and Specifications 157
6.5 Motorcycle Testing - Dummy Specifications 157
6.6 Recommendations for Testing 159
6.6.1 Recommendations for MASH Passenger Car and Pickup Truck Testing 159
6.6.2 Test Facility 160
6.6.3 Anthropomorphic Dummy 160
6.6.4 Recommended *MASH* Impact Conditions 160
6.6.5 Critical Impact Points for *MASH* Tests 3-10 and 3-11 for the Retrofitted Guard Fence System 160
6.6.6 Evaluation Criteria for *MASH* Testing 161
6.7 Recommendations for Upright Motorcycle Testing 163
6.7.1 Motorcycle Type 164
6.7.2 Anthropomorphic Dummy 165
6.7.3 Motorcycle Impact Conditions 165
6.7.4 Critical Impact Points for Upright Motorcycle Testing for Retrofitted Guard Fence System 166
6.7.5 Evaluation of Motorcycle Tests 166
6.8 Recommendations for Sliding Dummy Testing 167
6.8.1 Anthropomorphic Dummy 167
6.8.2 Critical Impact Points for Sliding Dummy Tests for Retrofitted Guard Fence Systems 168
6.8.3 Sliding Dummy Impact Conditions 168

6.8.4 Evaluation of Sliding Dummy Tests - Recommendation 168
6.9 Summary of Recommendations 169

7 CONCLUSIONS, LIMITATIONS AND FUTURE RESEARCH 173

7.1 Conclusion 173
7.2 Limitations and Future Research 173

REFERENCES 176

APPENDIX 179

LIST OF FIGURES

Page

Figure 1.1 Passenger Vehicle Occupant Deaths and Motorcyclist Deaths in U.S. from 1975 – 2013 (NHTSA, 2015). 3

Figure 2.1 ISO 13232-2 Impact Configurations (Rogers and Zellner, 1998). 15

Figure 2.2 Hybrid III Modifications According to ISO 13232 (Franco et al., 2018). 16

Figure 2.3 Metal Beam Standard Guardrail Designs. 20

Figure 2.4 Motorcycle Trolley (Nieboer et al., 1993). 22

Figure 2.5 Test Sled in (a) Inclined Position and (b) Upright Position 26

Figure 2.6 Motorcycle Tow System (Adamson et al., 2002). 34

Figure 2.7 Motorcycle and Concrete Barrier used in Tests (Adamson et al., 2002). 34

Figure 2.8 Crash Test Image Showing Rider-Motorcycle Barrier Impact (Dobrovolny et al., 2018). 36

Figure 2.9 Impact Details of Rider-Motorcycle and Barrier Interaction. 37

Figure 2.10 Punctual Energy Absorbers (FEMA, 2010; Palacio et al., 2011). 49

Figure 2.11 V-Beam Guardrail System and Cross Section (Tan et al., 2008). 54

Figure 2.12 Modified W-Beam Guardrail System for Control Purpose (Tan et al., 2008). 54

Figure 2.13 Section Drawing of W-Beam Guardrail Equipped with Lower Motorcycle Barrier (FHWA, 2012) 55

Figure 2.14 Euskirchener Model including Cap at Top (FHWA, 2012). 57

Figure 2.15 Conforming Barrier – Spanish Guardrail (FHWA, 2012). 58

Figure 3.1 Motorcycle Crash Severity per Year 67

Figure 3.2 Motorcycle Crash Fatality (2010 – 2017) 67

Figure 3.3 Street View from Google Earth Pro Software 71

Figure 3.4 Satellite View from Google Earth Pro Software 71

Figure 3.5 Map of Fatal and Suspected Serious Injury Motorcycle Crashes Involving Guardrail Contact, 2010-2017 78

Figure 3.6 Percentage of Crashes under Review per Different Types of Guardrail, 2010-2017 90

Figure 3.7 Estimated Angle of Impact w.r.t Guardrail System from Crash Narratives, 2010-2017 91

Figure 4.1 Option 1 Concept Drawing. 97

Figure 4.2 Option 2 Concept Drawing. 101

Figure 4.3 Option A Conceptual Drawing. 104

Figure 4.4 Option B Conceptual Drawing. 107

Figure 4.5 Option C Conceptual Drawing. 110

Figure 5.1 Finite Element Computer Models. 115

Figure 5.2 Guardrail System with Test Vehicle Before Testing (Kovar et al., 2019).... 116

Figure 5.3 Guardrail System with Test Vehicle After Testing (Kovar et al., 2019). 117

Figure 5.4 Summary of Results for MASH 3-11 Compliant TxDOT Modified Round Wood Post Guardrail System (Kovar et al., 2019). 118

Figure 5.5 (a) Side View, (b) Perspective Front View and (c) Perspective Rear View of the LS DYNA Calibration Guardrail System Model. 120

Figure 5.6 Sequential Images of Pickup Truck – Guardrail System Impact Simulation for Calibration 121

Figure 5.7 Comparison of Actual Crash Test and LS DYNA Simulation (Pictures on Left Adapted from Kovar et al., 2019). 122

Figure 5.8 Different Views of LS Pre-Post Developed Retrofitted MGS for Motorcycle Safety. 124

Figure 5.9 Retrofitted MGS – Motorcycle-Dummy Model Setup. 127

Figure 5.10 Sequential Images of Motorcycle-Dummy Impact Event Against MGS Retrofitted System. 128

Figure 5.11 First Point of Contact of Motorcycle with ATD and MGS. 130

Figure 5.12 Sequential Images of ATD Interaction with MGS from the Predictive Simulation. 131

Figure 5.13 Maximum Dynamic Deformation of Retrofitted MGS During the Motorcycle-Dummy Impact Event. 133

Figure 5.14 Maximum Deformation of Different Guardrail Components After Impact 133

Figure 5.15 Sequential Images of Pickup Truck impact simulation against retrofitted MGS system (Without tire disengagement) 135

Figure 5.16 Sequential Images of Pickup Truck Impact Simulation Against Retrofitted MGS System... 136

Figure 5.17 Sequential Images of Small Car Impact Simulation Against Retrofitted MGS System 139

Figure 5.18 Impact conditions for dummy representing errant sliding rider 142

Figure 5.19 Sequential Pictures for Discrete Post Dummy Impact Condition (Side View) 144

Figure 5.20 Sequential Pictures for Discrete Post Dummy Impact Condition (Top View) (continued) 145

Figure 5.21 Sequential Pictures for Between Posts Dummy Impact Condition (Side View) 147

Figure 5.22 Sequential Pictures for Between Posts Dummy Impact Condition (Top View) 148

Figure 5.23 Sequential Pictures for Rigid Bottom Protection Impact Condition (Side View) 150

Figure 5.24 Sequential Pictures for Rigid Bottom Protection Impact Condition (Top View) 151

LIST OF TABLES

Page

Table 2.1 L.I.E.R. Test Impact Configurations (Reprinted from Page and Bloch, 2010). 7

Table 2.2 Test Specifications 8

Table 2.3 UNE – 135900 Test Impact Configurations (Reprinted from Page and Bloch, 2010) 9

Table 2.4 Test Specification 9

Table 2.5 Test Specification (Continued) 10

Table 2.6 EN 1317-8 Impact Configurations for Test (Reprinted from EN 1317-8) 11

Table 2.7 EN 1317-8 Test Specifications. 11

Table 2.8 EN 1317-8 Severity Levels Specification (Reprinted from EN 1317-8). 12

Table 2.9 EN 1317-8 Determination of Wd Specification (Reprinted from EN 1317-8). 13

Table 2.10 ISO 13232-2 Impact Conditions (Reprinted from ISO 13232, 1996). 15

Table 2.11 Summary Table for Motorcycle Full-Scale Testing Protocols and Standards. 19

Table 2.12 Dummy Test Results Reprinted from Quincy et al. INRETS (Quincy et al., 1988). 21

Table 2.13 Test Specifications 21

Table 2.14 Test Specifications. 23

Table 2.15 Test Configurations and Dummy Load Results (Reprinted from Bert et al., 2005). 24

Table 2.16 Test Specifications. 25

Table 2.17 Rider – Motorcycle Condition after Tests. 25

Table 2.18 Test Specifications 26

Table 2.19 Load Impact Data of Upright Test (Reprinted from Peldschus et al., 2007). 27

Table 2.20 Load Impact Data of Inclined Test (Reprinted from Peldschus et al., 2007). 27

Table 2.21 ARRB Audit Results. 29

Table 2.22 Infrastructure Elements Influencing Likelihood Risk Factors for Vehicles and Motorcycles (Reprinted from Milling et al., 2016). 30

Table 2.23 Summary Table for Various Studies Considered in Section 2.2. 32

Table 2.24 Impact Configurations for Tests (Reprinted from Adamson et al., 2002). 34

Table 2.25 Test Specifications. 35

Table 2.26 Test Specifications. 36

Table 2.27 Test Specifications. 39

Table 2.28 Summary of various tests conducted inside U.S. 40

Table 2.29 Continuous Systems for Rider Redirection (Reprinted from FEMA, 2010). 52

Table 2.30 Continuous Systems for Rider Redirection (Reprinted from FEMA, 2010). 59

Table 2.31 Summary table of roadside barrier retrofit protection devices for Motorcycle Safety. 60

Table 2.32 Barrier Class Based on Collision Friendly Features. (Reprinted from Definition of a Safe Barrier for a Motorcyclist- a Literature Study, May 2015) 64

Table 3.1 Single Vehicle Motorcycle Crashes Involving Guardrail Contact, 2010-2017 66

Table 3.2 Single Vehicle Motorcycle Crashes Involving Guardrail Contact by Lighting Condition, 2010-2017 75

Table 3.3 Single Vehicle Motorcycle Crashes Involving Guardrail Contact by Hour of the Day, 2010-2017 76

Table 3.4 Single Vehicle Motorcycle Crashes Involving Guardrail Contact by Weather Condition, 2010-2017 77

Table 3.5 Count of Single Vehicle Motorcycle Crashes Involving Guardrail Contact by County, 2010-2017 79

Table 3.6 Count of Crashes by County and Control Section, 2010-2017 80

Table 3.7 Count of Crashes Not Associated with a Control Section in the CRIS Database, 2010-2017 83

Table 3.8 Count and Percentage of Reported Speed Limit for Fatal and Suspected Serious Injury Single Motor Vehicle Motorcycle Crashes Involving Guardrail Contact, 2010-2017 86

Table 3.9 Count and Percentage of Reported Alignment for Fatal and Suspected Serious Injury Single Motor Vehicle Motorcycle Crashes Involving Guardrail Contact, 2010-2017 87

Table 3.10 Motorcycle Position at Impact in Fatal and Suspected Serious Injury Single Motor Vehicle Crashes, 2010-2017 88

Table 3.11 Impact Location on Guardrail in Fatal and Suspected Serious Injury Single Motor Vehicle Crashes, 2010-2017 88

Table 3.12 Guardrail Type in Fatal and Suspected Serious Injury Single Motor Vehicle Crashes, 2010-2017 89

Table 3.13 Percentage of Fatal and Suspected Serious Injury Crashes by Guardrail Type, 2010-2017 90

Table 3.14 Estimated Angle of Impact in Fatal and Suspected Serious Injury Single Motor Vehicle Crashes, 2010-2017 91

Table 3.15 After Impact Rider Conditions in Fatal and Suspected Serious Injury Single Motor Vehicle Crashes, 2010-2017 92

Table 4.1 Option 1 Perceived Advantages and Disadvantages. 97

Table 4.2 Option 2 Perceived Advantages and Disadvantages. 101

Table 4.3 Option A Perceived Advantages and Disadvantages 104

Table 4.4 Option B Perceived Advantages and Disadvantages 107

Table 4.5 Option C Perceived Advantages and Disadvantages. 110

Table 4.6 Proposed Designs for Top Protection. 112

Table 4.7 Proposed Designs for Bottom Protection. 113

Table 5.1 Events During Test No. 469688-5-1 (Reprinted from Kovar et al., 2019). ... 117

Table 5.2 Comparison between Full-Scale Crash test and Impact Event Computer Simulation 123

Table 5.3 Guardrail System Components Maximum Deformation. 134

Table 5.4 Occupant Risk and Vehicle Stability Predicted from Simulations with Pickup Truck Vehicle 137

Table 5.5 Occupant Risk and Vehicle Stability Predicted from Simulations with Pickup Truck Vehicle. 140

Table 5.6 Bottom Protection Deflection Values for Sliding Dummy Impacting on Post 145

Table 5.7 Bottom Protection deflection Values for Sliding Dummy Impacting Between Posts 149

Table 5.8 Post Processing Dummy Values Comparision 152

Table 6.1 Motorcycle Testing: Nominal Impact Conditions from the Previous Testing. 156

Table 6.2 Motorcycle Testing: Motorcycle Specifications from the Previous Testing. 158

Table 6.3 Motorcycle Testing: Dummy Specifications from the Previous Testing. 158

Table 6.4 *MASH* TL-3 Testing Conditions (adapted from AASHTO MASH 2016). 170

Table 6.5 Upright Motorcycle Testing Recommendations. 171

Table 6.6 Sliding Dummy Testing Recommendations. 172

1. INTRODUCTION

Past years have witnessed a significant rise in the use of motorcycles as a vehicle to commute due to various reasons. With an increase in the number of motorcycles on the road, there is an urgent need to consider motorcycle safety as one of the important aspects while designing roadside safety systems. Motorcyclists being the most vulnerable users of road safety systems, the severity of motorcycle crashes is essentially affected by these systems. Data suggests that the fatalities related to motorcycle impact against safety barriers are greater than those from impact of passenger car users against the same roadside safety devices.

This project is intended to develop a motorcycle-friendly retrofit design of guard fence system so as to accommodate motorcycle safety. No guidelines are available which can provide proper testing and use of retrofit barriers. Despite this fact, it is important to develop a design of guardrail system to limit the fatalities due to rider – barrier impacts in upright or sliding positions. Guard fence systems are designed to be compliant with 2016 *Manual for Assessing Safety Hardware* (*MASH*), (AASHTO 2016) per Federal Highway Administration (FHWA) requirements.

According to data collected in 2013 by the European Commission, the motorcyclists killed on roads account for 15 percent of all road deaths. Also, 11 motorcyclists per 100,000 registered two-wheelers as compared to five car driver victims per 100,000 registered cars are involved in a fatal accident as per the data collected. According to an analysis done by Stock et al. (2011) in different parts of Germany, one in seven people killed in a roadway accident were motorcyclists in 2008. Also, motorcycles involved around 10 percent of the accidents with injuries.

According to NHTSA 2013's data in the United States, 4,668 motorcyclists died in traffic crashes. Also, 59 motorcyclists per 100,000 registered two wheelers as compared to ten car driver victims per 100,000 registered cars were involved in a fatal accident which shows that motorcycle safety is an important issue to be considered in the U.S. when compared to data by the European commission. Furthermore, as estimated by federal government, motorcyclist deaths occurred 26 times more frequently than car occupant fatalities in road accidents as per vehicle mile traveled.

Florida, with 467 motorcyclists killed, had the highest data of 2013's fatalities in the U.S., followed by Texas, where the rider deaths were 457. Alcohol consumption is one of the leading factors for motorcycle accidents. The percentage of motorcycle riders killed with higher BAC of 0.08 was 37 percent in Texas which supports this fact.

Figure 1.1 illustrates how motorcycle deaths have remained almost constant over the years 1975-2013 in the U.S. (According to National Highway Traffic Safety Administration (2015) Traffic Safety Facts 2013 Data).

Based on a study conducted in 2015, as per data received from the Fatality Analysis Reporting System (FARS) and the General Estimates System (GES) in the U.S., there were 4,976 motorcyclists killed in 2015, which accounts for an increase of 8 percent since 2014. Six percent of these motorcyclists killed were passengers which shows the passenger risk due to such accidents. Also, approximately 88,000 motorcyclists received injuries in 2015 which is 3 percent less than the previous year. It was also found that in 2015 a fatality involving a passenger car was 29 times less frequent than a motorcyclist fatality and the fatality rate was six times for a motorcyclist than that for an occupant of passenger car.

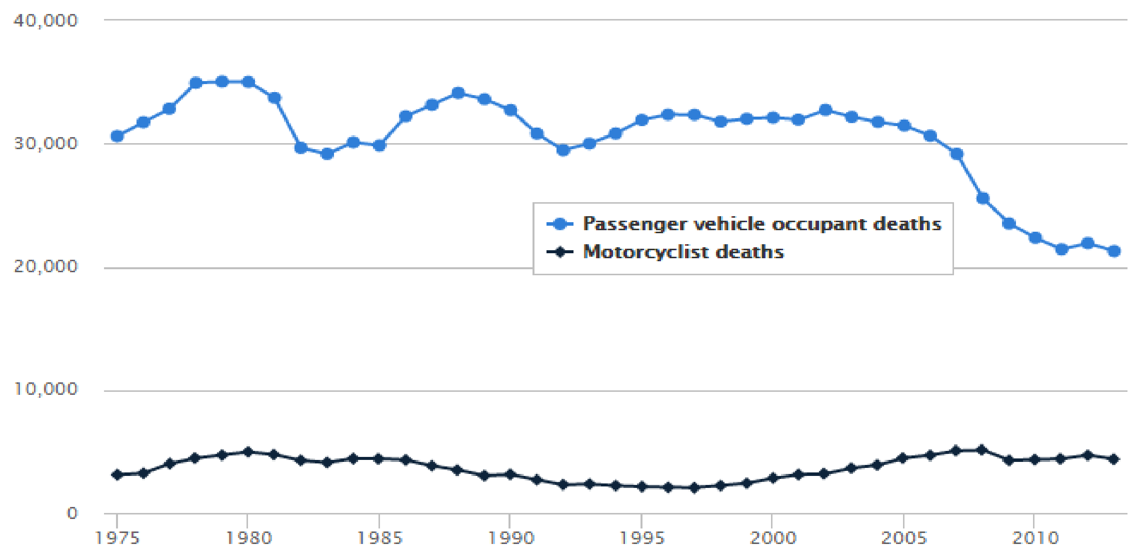


Figure 1.1 Passenger Vehicle Occupant Deaths and Motorcyclist Deaths in U.S. from 1975 – 2013 (NHTSA, 2015).

According to a study conducted by FHWA, after analyzing data obtained from 351 crashes and 702 control rider interviews, it was found that the number of motorcycle rider fatalities was more than twice the amount recorded in 1997 as compared to 2009. In this same time period, there was a 27 percent decrease in the number of passenger car and light truck fatalities.

Nabors et al. (2016) observed through studies that there was a 43 percent increase in motorcycle fatalities from 2003 to 2008 while it decreased from 2008 to 2009, after which it again increased from 2009 to 2012. Also, it was found that the ratio of motorcycle fatalities has increased from 1 in every 20 to 1 in every 7 of motor vehicle fatalities from 1997 to 2004, which clearly indicates the increase in risk to motorcyclists.

Thus, according to given data, a motorcyclist is more vulnerable and fully exposed to risk of injuries during a barrier or other vehicle impact accident.

Based on role the infrastructure elements in motorcycle safety, a two year study done by Milling et al. (2016) in Australia shows that motorcycle fatalities occurred most frequently on curves (39 percent), intersections (38 percent), and straight roadways (23 percent). Roadside hazards and roadside conditions account for 75 percent of single vehicle collisions with some of the most commonly struck objects being trees (24-31 percent), fences/safety barriers (10-12 percent), street lights or traffic light poles (9 percent), and drainage and drain pipes (5 percent).

Regarding the position of the rider during impact of motorcycles with barriers, Berg et al. (2005) reported that by evaluation of 57 real world accidents motorcycles impacted the barriers in an upright position in 51 percent of the cases, while 45 percent of them struck barrier in a sliding position. Peldschus et al. (2007) after performing tests showed that in about 75 percent of cases, the motorcycle was in the same position during impact with fixed objects. However, as stated above, currently there are no standards or guidelines that consider this type of scenario and provide proper testing of the system. Hence, rider impact for both upright and sliding position will be considered in this research.

In order to address these issues, this research is aimed to design and evaluate a retrofit system which is more motorcycle-forgiving and assures rider safety when the motorcycle-rider and barrier impact event takes place.

Structure of the Thesis

Chapter one of this thesis gives an intorduction about the problem statement and research basis. Chapter two deals with the literature review conducted on an international level to refer relatable sources and previous studies pertaining to the research topic. Chapter three talks about the crash datat analysis conducted to determine variables to be considered while coming up with the design concepts. Chapter four discusses about the developed design concepts and proposed options for this study. Chapter five deals with the computational part of the project including FE simulations and detailed analysis of the selected option. Chapter six talks about the test plan recommendations to conduct the full scale crash tests with the proposed option. Chapter seven provides conclusion of the study with limtations and future research scope. Last chapter provides the references for all the sources being used in the entire research study.

2. LITERATURE REVIEW

The objective of this literature review is to take into consideration the most up-to-date national and international studies, standards, system designs, protocols, implementations, and suggested measures which can be employed to provide a motorcycle-friendly retrofit designed guard fence system. Specific attention is given to devices which are used or were proposed to be used for retrofitting roadside barriers for motorcycle safety. An overview containing results and conclusions from various research across the globe focusing on motorcycle safety, guidelines, and different crash test approaches is reported.

This review can be summarized in four parts as follows.

2. 1 Motorcycle Full-Scale Testing Protocols and Standards

This section deals with standards, protocols, and criteria to be met for motorcycles and test execution.

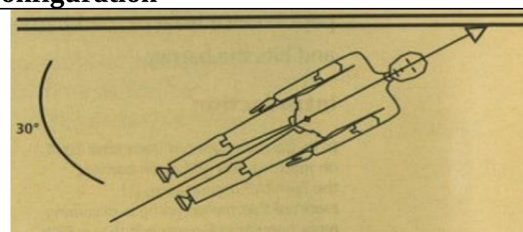
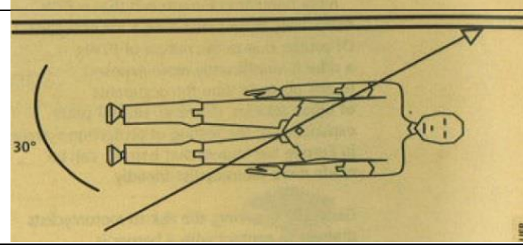
2.1.1 L.I.E.R. (1998) Protocol: Motorcyclist Safety Evaluation Regarding Safety Barriers.

Crash Testing Agency: Laboratoire d'essais INRETS Equipment de la Route Laboratory, France.

Test Protocol:

The L.I.E.R procedure consists of two tests with the dummy impacting the protection system with different configurations, but with same impact conditions as shown in Table 2.1. The test specifications are given in Table 2.2. Point of impact of the dummy with the system is approximately in the middle of the system and opposite to the barrier post (rigid element). The dummy is equipped with sensors to measure acceleration of the head and calculate forces and moments.

Table 2.1 L.I.E.R. Test Impact Configurations (Reprinted from Page and Bloch, 2010).

Impact Configuration	
Test 1. Dummy aligned w/ launch path	
Test 2. Dummy parallel to the test item	

However, many changes are necessary to make the dummy suitable for this impact configuration. Also, full-scale vehicle crash tests must be done according to European Standard EN 1317 Part 2 (EN 1317-2) of the complete system (safety barrier with included motorcyclist protection system).

Table 2.2 Test Specifications

Impact Speed	60 km/h - 37.3 mph
Impact Angles	Test 1 - 30° Test 2 - 30°
ATD	Standard Dummy Model
Dummy Helmet	Standard Motorcycle Helmet
Dummy Clothing	Standard Motorcyclist Clothing
Approval Criteria	Dummy head acceleration, forces, and moments should be within biomechanical limits. The dummy must not pass through the system nor remain trapped within.
Impact Speed	60 km/h - 37.3 mph
Impact Angles	Test 1 - 30° Test 2 - 30°
ATD	Standard Dummy Model
Dummy Helmet	Standard Motorcycle Helmet
Dummy Clothing	Standard Motorcyclist Clothing
Approval Criteria	Dummy head acceleration, forces, and moments should be within biomechanical limits. The dummy must not pass through the system nor remain trapped within.

2.1.2 UNE – 135900 Spanish Standard Protocol: AENOR (2005) Standard UNE 135900:2005, AENOR (2008) Standard UNE 135900:2008rev.01.

Crash Testing Agency: Spanish Ministry of Public Works.

Test Protocol: This test protocol was undertaken to further develop the L.I.E.R procedure, and hence is similar with some differences. Table 2.3 and Table 2.4 show these differences in the form of test configurations and specifications. Further, the revised UNE-135900 standard included an additional test speed of 70 km/h (AENOR, 2008). In this procedure, the protection system which is locally around the post (discontinuous systems) are also taken into account and tested with post-centered test, in addition to a head-first test where point of impact is at an offset with reference to the post. Opposed to the LIER protocol, the second impact is conducted between two posts and not opposite to a post (rigid element). Also, based on biomechanical measurements, two different performance classes are determined for the protection system.

Table 2.3 UNE – 135900 Test Impact Configurations (Reprinted from Page and Bloch, 2010)

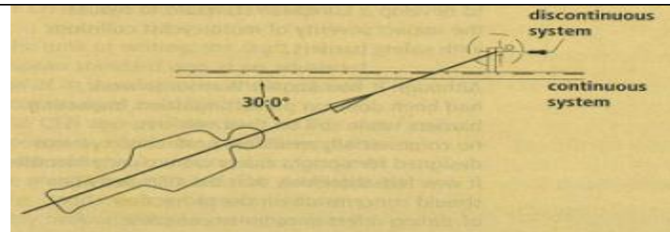
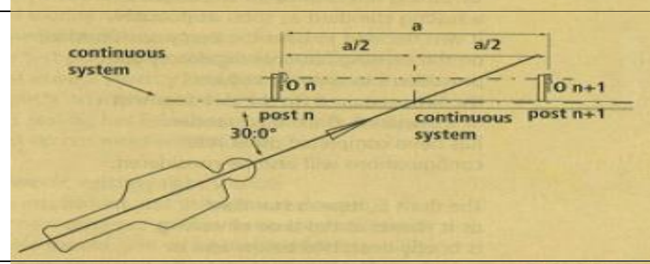
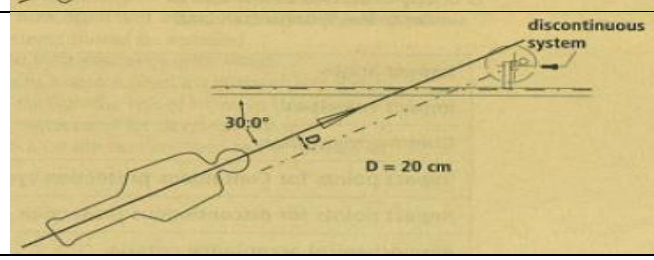
Impact Configuration	
Test 1. Dummy aligned w/launch path - post centered	
Test 2. Dummy aligned w/ launch path - mid-span	
Test 3. Dummy aligned w/the launch path - post offset	

Table 2.4 Test Specification

Impact Speed	Test (1) 60 km/h (37.3 mph) Test (2) 60 km/h (37.3 mph) Test (3) 70 km/h (43.5 mph)
Impact Angles	Test 1 - 30° Test 2 - 30° Test 3 - 30°
ATD	Hybrid III 50^{th} percentile male
Dummy Helmet	Standard Motorcycle Helmet
Dummy Clothing	Standard Motorcyclist Clothing

Table 2.5 Test Specification (Continued)

Approval Criteria	• Protection or safety system should not have yielded with elements or debris weighing more than 2 kg. • Dynamic deflection and working width of the protection device should not be more than the UNE EN 1317 – 2 defined values for 4- wheel vehicle impact. • ATD should not have any intrusions or breakage (except the clavicle). Dummy clothing must be free from any damage.

2.1.3 EN1317-8 (2011) Road Restraint Systems - Part 8: Motorcycle Road Restraint Systems which Reduce the Impact Severity of Motorcyclist Collisions with Safety Barriers

Crash Testing Agency: Comité Européen de Normalisation (CEN) Technical Committee on Road Equipment (TC226).

Test Protocol:

This specification was proposed to further add to the EN 1317 standard for testing motorcyclist protection systems to address motorcyclist safety. This specification was one of its kind during the time of proposal to consider the rider position during impact for testing of the system. The CEN thus concentrated on developing a standard to improve the safety of sliding motorcyclists and considered impact configurations and specifications as given in Table 2.5 and Table 2.6. Initially this standard was adopted as compulsory throughout the European Community, but due to lack of experience of some countries with this test specification, it was decided to accept the standard as a technical specification. Thus, this standard is not compulsory for any country to follow, and each country is free to install a barrier which is considered to provide safety. However, in this case the particular country would be responsible for the decision and not the National Road Authority.

Table 2.6 EN 1317-8 Impact Configurations for Test (Reprinted from EN 1317-8)

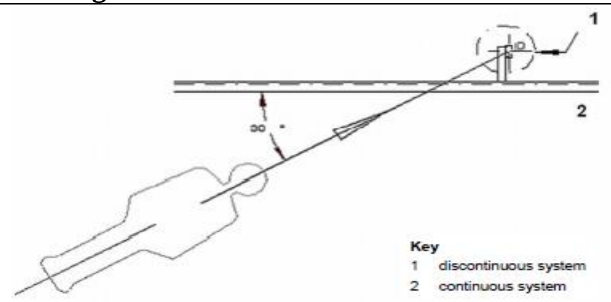
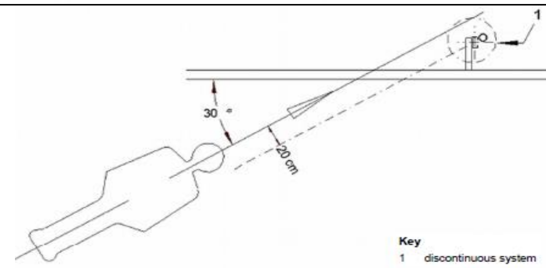
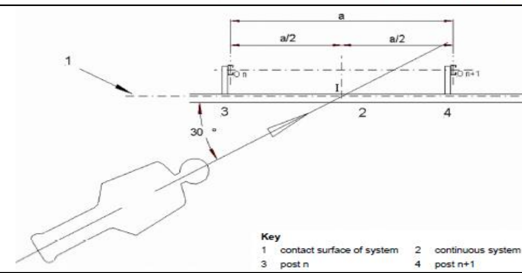
Impact Configuration	
Test 1. Launch Configuration1: Post-Centered Impact	
Test 2. Launch Configuration 2: Post-Offset Impact	
Test 3. Launch Configuration 3: Mid-Span Impact	

Table 2.7 EN 1317-8 Test Specifications.

Impact speed	Test 1, 2 and 3: 60 km/h (37.3 mph) or 70 km/h (43.5 mph)
Impact Angles	Test 1, 2 and 3: 30°
ATD	Modified Hybrid III 50th percentile male
Dummy Helmet	Motorcycle Helmet (polycarbonate shell) satisfying Regulation 22 of ECE/TRANS/505 requirements.
Dummy Clothing	Complying EN 1621 – 1 requirements Motorcyclist Clothing
Approval Criteria	MPS: Any longitudinal element of the test item must not have complete rupture. ATD**:** the ATD shall not remain trapped in the test item. Parts of dummy shall not be completely detached (except the upper extremity which can be detached due to rupture of the frangible screws in the shoulder assembly).

Full scale tests with ATD impacting the barrier with a motorcycle protection system (MPS) is carried out with the ATD sliding on its back. Motorcycle performance is evaluated based on two classes:

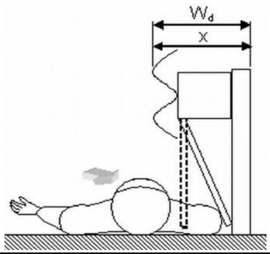
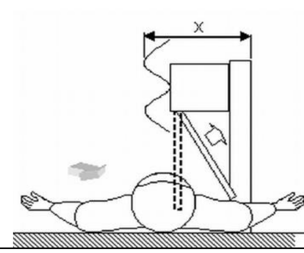
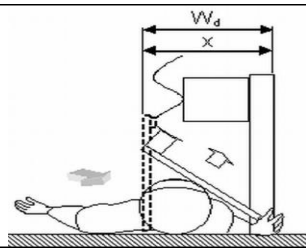
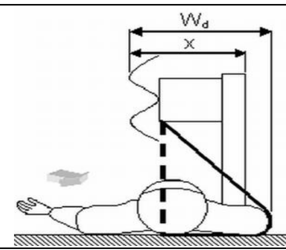
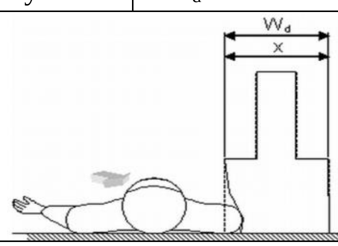
1) Speed class – based on impact speed of tests.
2) Severity level – based on biomechanical values obtained from ATD test measurements.

Table 2.7 adapted from EN 1317-8 gives the severity level for known biomechanical values of ATD, and Table 2.8 adapted from EN 1317-8 gives determination of the dummy working width.

Table 2.8 EN 1317-8 Severity Levels Specification (Reprinted from EN 1317-8).

Severity Level	**Maximum Admissible Values**						
		Neck					
	Head	**F_x (N)**	**$F_{z\ ten}$ (N)**	**$F_{z\ comp}$ (N)**	**M_{OCx} (Nm)**	**$M_{OCy\ ext}$ (Nm)**	**$M_{OCy\ flex}$ (Nm)**
	HIC_{36}						
I	650	Table 1.5(a)	Table 1.5(b)	Table 1.5(c)	134	42	190
II	1,000	Table 1.5(d)	Table 1.5(e)	Table 1.5(f)	134	57	190

Table 2.9 EN 1317-8 Determination of Wd Specification (Reprinted from EN 1317-8).

	
(a) Example: barrier + MPS No protrusions rearward of complete system	(b) Example: barrier + MPS Arm protrudes rearward of complete system
-> ACCEPTABLE PERFORMANCE	-> SYSTEM FAILS TEST
	
(c) Example: barrier + MPS Hand protrudes rearward of complete system but is not trapped in system after test	(d) Example: barrier + flexible MPS ATD contained by MPS and MPS protrudes behind barrier
-> ACCEPTABLE PERFORMANCE	-> ACCEPTABLE PERFORMANCE
W_d determined by rearmost part of system	W_d determined by rearmost part of deformed MPS
	
(e) Integrated MPS or MPS on modular or wall-type barrier No protrusions rearward of complete system	
-> ACCEPTABLE PERFORMANCE	
W_d determined by rearmost part of system	
*W_d = Dummy Working Width	

2.1.4 ISO 13232 (1996) Motorcycles-Test and Analysis Procedures for Research Evaluation of Rider Crash Protection Devices Fitted to Motorcycles

Crash Testing Agency: International Organization for Standardization

Test Protocol:

In order to develop an international standard for physical crash testing of a motorcycle impacting against a vehicle, International Organization for Standardization (ISO), appointed a group of motorcyclist safety experts for the development of guidelines in 1996, resulting in the ISO 13232 standard (ISO 13232, 1996).

This standard consists of eight parts:

- Part 1: Definitions, symbols, and general considerations.
- Part 2: Definition of impact conditions in relation to accident data.
- Part 3: Motorcyclist anthropometric impact dummy.
- Part 4: Variables to be measured, instrumentation, and measurement procedures.
- Part 5: Injury indices and risk/benefit analysis.
- Part 6: Full-scale impact test procedures.
- Part 7: Standardized procedure for performing computer simulations of motorcycle impact tests.
- Part 8: Documentation and reporting.

Figure 2.1 illustrates the seven impact configurations as specified by ISO 13232-2 to determine severity of motorcycle (MC) impact against an opposing vehicle (OV). Table 2.9 gives the details of the seven configurations.

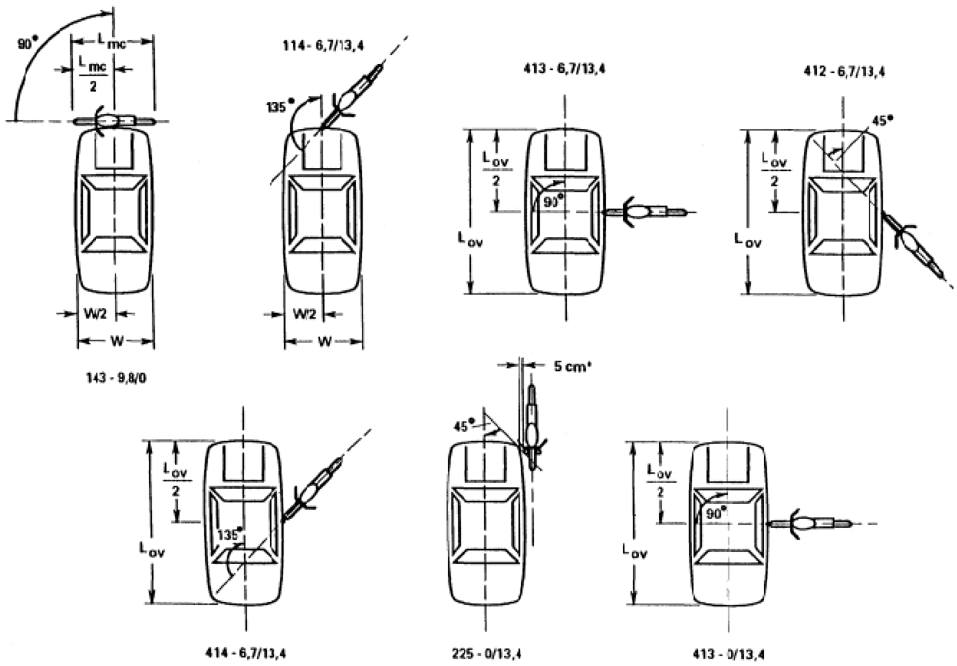


Figure 2.1 ISO 13232-2 Impact Configurations (Reprinted from Rogers and Zellner, 1998).

Table 2.10 ISO 13232-2 Impact Conditions (Reprinted from ISO 13232, 1996).

OV contact location	Relative heading angle (deg)	OV/MC speeds (m/s)	OV/MC speeds (mph)
Front	90	9.8 / 0	22 / 0
Front	135	6.7 / 13.4	15 / 30
Front Corner	*180*	*0 / 13.4*	*0 / 30*
Side	*90*	*0 / 13.4*	*0 / 30*
Side	135	6.7 / 13.4	15 / 30
Side	90	6.7 / 13.4	15 / 30
Side	45	6.7 / 13.4	15 / 30

ISO 13232-2 recommends a Hybrid III 50th percentile male dummy with sit/stand construction, standard non-sliding knees, and head/neck assembly compatible with either a 3- or a 6-axis upper neck load cell. Also, the dummy requires some additional modifications (Figure 2.2), such as sit/stand pelvis, modified elbow bushing, frangible upper-leg components, and leg retaining cables (Zellner et al., 1996).

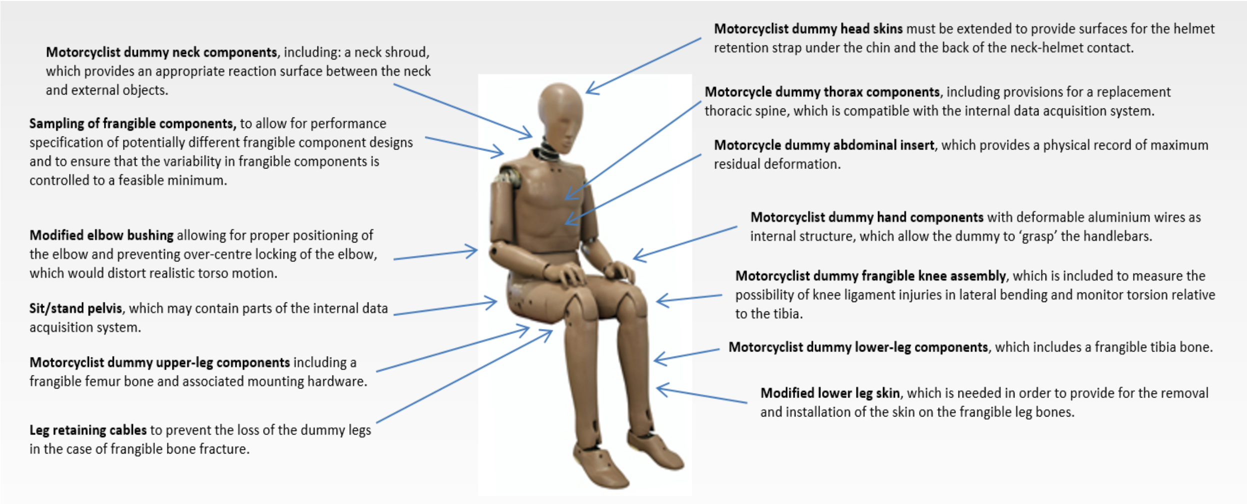


Figure 2.2 Hybrid III Modifications According to ISO 13232 (Reprinted from Franco et al., 2018).

2.1.5 FEMA (2010) Final report of the Motorcyclists & Crash Barriers Project, Federation of European Motorcyclist's Associations

Bundesanstalt für Straßenwesen (BASt - Germany) defined a homologation procedure for impact protectors (FEMA, 2010) which evaluates the deceleration value during the impact against the protector. Evaluation criteria is to limit this value to 60 g peak value, and 40 g over a 3 millisecond interval. Further, the report classifies two different classes of devices as follows:

- Class 1 - tested with impact speed of 12.4 mph (20 km/h).
- Class 2 - tested with impact speed of 21.7 mph (35 km/h).

No more details are reported regarding the classes or general procedure information.

2.1.6 Australian/New Zealand Standard (AS/NZS 3845:2015).

This standard consists of two parts:

1) AS/NZS 3845.1:2015 provides requirements for permanent and temporary safety barrier systems, including longitudinal road safety barriers, terminals, crash cushions, interfaces including transitions, and longitudinal barrier gates.
2) Part 2 provides requirements for permanent and temporary road safety devices such as bollards, pedestrian fences and channelizers, truck or trailer mounted attenuators, and sign support structures and poles.

The AS/NZS 3845 series of standards and the Austroad research regarding road design and safety barrier assessment processes are similar to each other, except that the Austroad guidelines specify the road and roadside configurations that identify the location where road safety barriers may be required to be installed, while the standards set out requirements for road safety barrier systems.

Three other standards which are commonly adopted are described in this standard. However, the AS/NZS standard suggests that apart from the Head Injury Criteria (HIC) as considered by other standards, additional thorax compression criterion testing should be conducted. This is due to the fact that many riders suffer critical injuries in the thorax region. Australian coronial files data reveal that out of half of the motorcyclists who crashed into the barrier in an upright position on the motorcycle, about half suffered from serious thorax-related injuries.

Also, this standard states that previous standards, such as the Spanish standard, LIER testing protocol, and the EN1317 Part 8, involved a dummy sliding into the barrier, and thus motorcyclists impacting roadside barriers in an upright position are not taken into consideration. Thus, the barriers suggested by other standards are less effective in preventing rider injuries while impacting barriers in the upright position.

These newly retrofitted devices should also be crash tested with cars as these motorcycle protection system devices which are provided around critical posts and beams can prove to be less effective during barrier-car impacts. The standard suggests further research and development regarding understanding the risk of riders impacting barriers in an upright position and contacting the barrier on the top.

Summary: This section dealt with different standards, protocols and criteria followed for testing such as ISO 13232, LIER protocol, UNE 135900 protocol, EN 1317 – 8, FEMA (2010) and AS/NZS 3845-2015. Table 2.10 gives a summary for this section based on different test conditions and evaluation criteria.

Table 2.11 Summary Table for Motorcycle Full-Scale Testing Protocols and Standards.

Table:A1.10 Summary table for MOTORCYCLE FULL - SCALE TESTING PROTOCOLS AND STANDARDS							
		ISO 13232 (1996)	**LIER (1988)**	**UNE – 135900 Spanish (2005)**	**FEMA (2010)**	**EN1317-8 (2011)**	**AS/NZS 3845:2015**
Test details and Impact Conditions	**Test type**	MC* - OV**	Dummy - MPS***	Dummy - MPS	MC - Barrier	Dummy - MPS	MC - Barrier
	Impact condition	Seven OV contact location with different heading angle	1)Dummy inclined to MPS 2)Dummy parallel to MPS	1)Dummy aligned - Post centered 2)Dummy aligned - mid span 3)Dummy aligned - Post offeset	MC impacts barier with two different impact speeds	1)Dummy aligned - Post centered 2)Dummy aligned - Post offeset 3)Dummy aligned - Mid span	Suggests barrier design with MC rider - barrier impact in upright postion
	Number of Tests	Seven Impact configuration tests	2 tests (inclined and parallel)	3 tests with above condition	2 tests (class 1 and 2)	3 tests with above condition	N/A
	Impact speed	Variable OV/MC speed combinations	60 km/h (37.3 mi/h)	Test (1) 60 km/h (37.3 mi/h) Test (2) 60 km/h (37.3 mi/h) Test (3) 70 km/h (43.5 mi/h)	12.4 mph (20km/h) 21.7 mph (35km/h)	Test (1) 60 km/h (37.3 mi/h) or 70 km/h (43.5 mi/h) Test (2) 60 km/h (37.3 mi/h) or 70 km/h (43.5 mi/h) Test (3) 70 km/h (43.5 mi/h) or 70 km/h (43.5 mi/h)	N/A
	Impact Angle	Ranging from 45° to 180° for different configuraitons	Test A) 90° , 90° and 67° respectively Test B) 45° and 90° respectively	Test 1 - 30° Test 2 - 30° Test 3 - 30°	No details available	Test 1 - 30° Test 2 - 30° Test 3 - 30°	N/A
	ATD	Hybrid III 50th percentile male dummy (Modifications recommended)	Standard Dummy Model	Hybrid III 50th percentile male	No details available	Modified Hybrid III 50th percentile male	N/A
Evaluation Criteria	**ATD Response**	-	-	• ATD should not have any intrusions or breakage (except the clavicle). • Dummy clothing must be free from any damage	-	•ATD shall not remain trapped in the test item •Parts of dummy shall not be completely detached (Except the upper part)	-
	Head acceleration	-	Should be within biomechanical limits.	-	Deceleration limited to 60 gas peak value and 40 g (3ms interval)	Should be within biomechanical limits.	-
	Interaction with system	-	Must not pass through the system nor remain trapped in it.	•System should not have yielded with elements or debris weighing more than 2 kg. •Wd of the system should not be more than the UNE EN 1317 – 2 defined values for 4- wheel vehicle impact.	-	Any longitudinal element of the test item must not have complete rupture	System should dissipate energy, however not in an uncontrolled way.
	Moments and Force	-	Should be within biomechanical limits.	-		Should be within biomechanical limits.	-
	HIC (36)	-	-	-	-	Should be within biomechanical limits.	Suggests use of Thorax compression criterion apart from HIC.

* MC = MotorCycle ** OV = Opposing Vehcile
***MPS = Motorcycle Protection System

2.2 Test Conditions and Evaluation Criteria

Section 2 provides literature on crash tests with different configurations, measures to reduce impact severity and criteria considered by other countries (outside US) for motorcycle safety.

2.2.1 Motorcycle Impacts with Guardrail, Institute National de Recherche sur les Transports et leur Securite, INRETS, France.

Quincy et al. (1998) conducted research aiming to develop guardrail designs to reduce the aggressiveness of a metal beam standard guardrail. The study revealed severe head injuries due to impact against a barrier post.

Performing Agency: INRETS (France).

Tests Conducted: Three tests were performed: two with the first design and one with the second design (Figure 2.3).

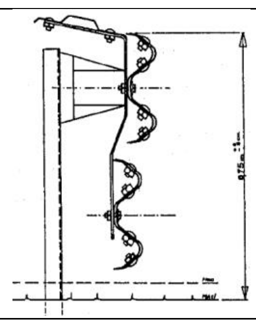
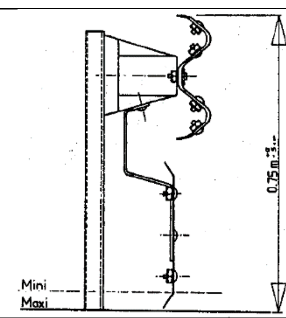
	
Design 1	Design 2

Figure 2.3 Metal Beam Standard Guardrail Designs.

Test Configuration: Tests were performed with a dummy placed on a platform lying on its back (head forward) and ejected with a sled. The sled was stopped at a 2-m distance before impact. Refer to Table 2.12 for test specifications.

Test Results: Head acceleration for tests conducted for given configurations were obtained as shown in Table 2.11.

Table 2.12 Dummy Test Results Reprinted from Quincy et al. INRETS (Quincy et al., 1988).

Test No.	Head Acceleration	
	at 3 ms (g)	**HIC**
504	66	325
506	40	175
566	80	365
505	110	110

Table 2.13 Test Specifications

Impact Speed	34.2 mph (55 km/h)
Impact Angles	Design 1 - 32° Design 2 - 30°
Trolley Type	N/A
Dummy Type	Not specified in paper
Vehicle Used	N/A

Conclusion: The deceleration levels and HIC criteria registered on different parts of the dummy were lower than the limit values. This shows that motorcycle restraint was good. After conducting this research, the motorcycle barrier was approved by the French Transportation Ministry and some highways were provided with these barriers. However, sufficient accident data were not available to evaluate the system.

2.2.2 Motorcycle Crash Test Modelling

Nieboer et al. (1993) conducted a study to obtain data for implementation and validation of MADYMO motorcycle model. Later extended with a rider and passenger car model to asses real-life crash performance.

Performing Agency: TNO Crash Safety Research Center (The Netherlands).

Tests Conducted: Three motorcycle-barrier crash tests were conducted. Two motorcycle (with rider)-passenger car (Mazda 323) were additionally conducted.

Test Configuration: A special trolley (Figure 2.4) was used to guide the motorcycle supported at the handlebar at upper spring damper element with the dummy. Refer to Table 2.13 for test specifications. The dummy was provided with triaxial (chest, pelvis, head, and knees) and uniaxial accelerometers (longitudinal direction) to obtain dummy accelerations. The three-dimensional motorcycle with rider model was developed. MADYMO version 4.2 was used for modeling.

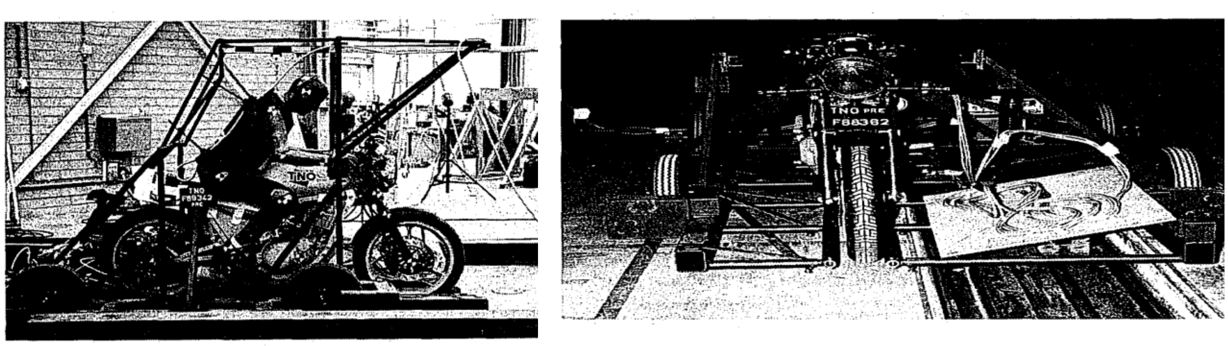


Figure 2.4 Motorcycle Trolley (Reprinted from Nieboer et al., 1993).

Table 2.14 Test Specifications.

Impact Speed	Motorcycle-Barrier tests 1) 20 mph (32.2 km/h) 2) 30 mph (48.3 km/h) 3) 37 mph (59.5 km/h) Motorcycle – Passenger car test: 1) 20 mph (32.3 km/h) 2) 30 mph (48.3 km/h)
Impact Angle	Motorcycle – Barrier tests • 90° • 90° • 67° Motorcycle – Passenger car tests • 45° • 90°
Trolley Type	Special Trolley was use to eject rider in upright and inclined position.
Dummy Type	50% percentile Part 572 Dummy with pedestrian pelvis and legs and feet.
Vehicle Used	YAHAMA SRX -600

Conclusion: Because of the complex nature of motorcycle rider behavior, computer simulation of the same during collision is more difficult than the simulation of passenger car occupants. From results, time-histories of dummy and motorcycle accelerations show an acceptable correlation. Computer simulation of motorcycle and rider response during a crash is an important research activity, from which motorcycle riders involved in a collision event can directly benefit.

2.2.3 Motorcycle Impacts into Roadside Barriers – Real-World Accident Studies, Crash Tests and Simulations Carried Out in Germany and Australia

Berg et al. (2005) conducted research to have better understanding of real world motorcycle-barrier accidents.

Performing Agency: DEKRA Automobil GmbH (Germany) and Monash University (Australia).

Tests Conducted: The study suggested conducting crash tests with two impact situations: Motorcycle in (a) upright and (b) sliding conditions while impacting the barrier. Four tests were conducted with a combination of different impact scenarios. The road surface was kept wet.

Test Configuration: Table 2.14 shows test and impact configurations with dummy load results. Refer to Table 2.15 for test specifications.

Test Results: Table 2.16 gives the test results describing conditions of rider and motorcycle after impact.

Table 2.15 Test Configurations and Dummy Load Results (Reprinted from Bert et al., 2005).

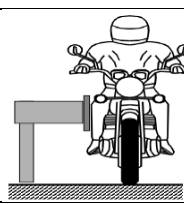
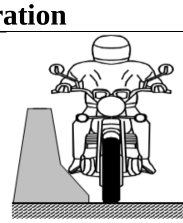
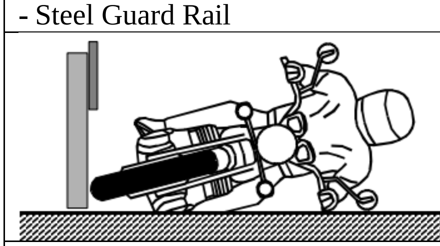
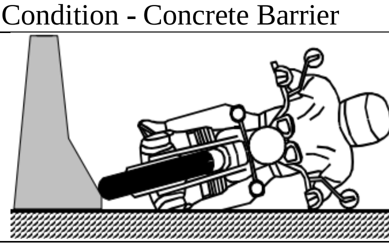
Impact Configuration		Dummy loads
		Loads did not indicate a high level injury risk. But snagging and aggressive contacts of rider with barrier parts can result in severe injuries.
Test 1. Upward Driving Condition - Steel Guard Rail	Test 2. Upward Driving Condition - Concrete Barrier	
		Head loads were above biomechanical limits.
Test 3. Motorcycle Skidding on Side - Steel Guard Rail	Test 4. Motorcycle Skidding on Side - Concrete Barrier	

Table 2.16 Test Specifications.

Impact Speed	37.3 mph (60 km/h)
Impact Angle	Upright - 12° Skidding on side - 25°
Trolley Type	N/A
Dummy Type	Hybrid III (50th percentile male)
Vehicle Used	Kawasaki ER 5 Twister Motorcycle

Table 2.17 Rider – Motorcycle Condition after Tests.

Upward driving condition (Guardrail)	Rider would have severe injuries due to aggressive contacts.
Sliding driving condition (Guardrail)	Motorcycle stuck in system and dummy separated impacting sigma post.
Upward driving condition (Concrete Barrier)	Dummy flew over the barrier landing on other side of barrier.
Sliding driving condition (Concrete Barrier)	Motorcycle and dummy decelerations were less rapid then in case of steel guardrail

Following Tests and Conclusion: Berg at al. modified the system with sigma posts and a closed box-shaped profile at the top with an underrun protection board near the ground to avoid direct impact and rider movement underneath the barrier. Two additional full-scale crash tests were carried out with the same impact configurations for test 1 and 3 with modified guardrail. Results indicated a decrease in injury risk for the modified system. However, Berg at al. questioned the biofidelity of the dummy Hybrid III in simulating all human injury risks after impact.

2.2.4 Technical bases for the development of a test standard for impacts of powered two-wheelers on roadside barriers

Peldschus et al. (2007) did research to design a motorcycle-friendly safety barrier that could easily be adapted to existing barriers in Germany. Data analysis was conducted to observe the nature of motorcyclist crashes into barriers and results were obtained.

Performing Agency: German Federal Highway Research Institute (Germany).

Tests Conducted: Two tests were performed with different configurations. Data was divided into primary and secondary data as follows:

- Primary data - Denotes data specific to the impact with guardrails.
- Secondary data - Reveals data specific to impact of the head to the ground.

Test Configuration: Two impact configurations: Upward driving and motorcycle with the rider inclined to cause sliding. Refer to Table 2.17 and Figure 2.5 for test specifications.

Test Results: Table 2.18 and Table 2.19 give the load impact data for upright and inclined tests, respectively.

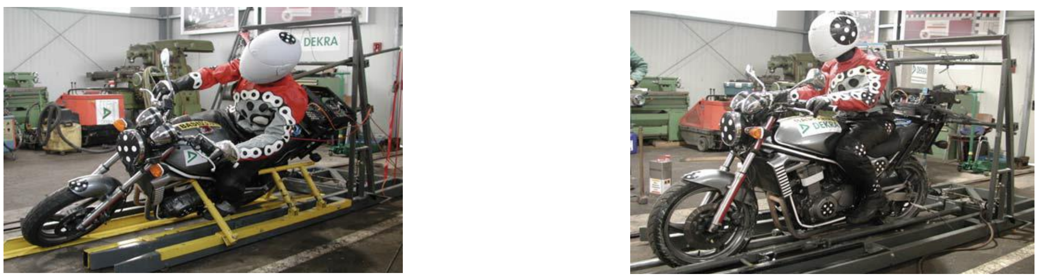


Figure 2.5 Test Sled in (a) Inclined Position and (b) Upright Position (Reprinted from Peldschus et al.,2007)

Table 2.18 Test Specifications

Initial Velocity	60 km/h
Impact Angle	Upright - 12° inclined - 25°
Trolley Type	Test Sled used in upright and inclined position.
Dummy Type	Motorcyclist Anthropometric Test Device (MATD)

Table 2.19 Load Impact Data of Upright Test (Reprinted from Peldschus et al., 2007).

	Limit	Primary	%	Secondary	%
Head					
$a_{res\ 3ms}$	80 g	33,2	**42**	101	127
$HIC_{36\ ms}$	1000	69,0	**7**	584	**58**
Neck	**Neck**				
$M_{b\ y}$	57 Nm	11,5	**20**	18	**31**
$F_{x\ max}$	3100 N	175,8	**6**	243	**8**
$F_{z\ max}$	4000 N	31,6	**1**	1283	**32**
Chest	**Chest**				
$a_{res\ 3ms}$	60 g	11	**19**	9	**16**
Pelvis	**Pelvis**				
$a_{res\ 3ms}$	60 g	12	**20**	14	**24**
Femur	**Femur**				
$F_{z\ right}$ * max	9070 N	-2764	**30**	776	**9**
$F_{z\ left\ max}$	9070 N	401	**4**	-774	**9**

Table 2.20 Load Impact Data of Inclined Test (Reprinted from Peldschus et al., 2007).

	Limit	Primary	%	Secondary	%
Head					
$a_{res\ 3ms}$	80 g	10	**13**	84	**106**
$HIC_{36\ ms}$	1000	5	**1**	383	**38**
Neck					
$M_{b\ y}$	57 Nm	26	**45**	56	**98**
$F_{x\ max}$	3100 N	144	**5**	317	**10**
$F_{z\ max}$	4000 N	391	**10**	3406	**85**
Chest					
$a_{res\ 3ms}$	60 g	13	**21**	51	**85**
Pelvis					
$a_{res\ 3ms}$	60 g	18	**30**	12	**20**
Femur					
$F_{z\ right}$ max	9070 N	-6744	**74**	-590	**7**
$F_{z\ left\ max}$	9070 N	-2960	**33**	-815	**9**

: neg. values = compression, pos. values = tension* *: % of the limit*

Conclusion: The rider is more likely to be in an upright position than sliding after separation from the motorcycle. Injury mechanisms and criteria should be investigated with more details in the future. Additional measurement for lateral loading of the thorax is suggested for the sliding position by dummy modification.

2.2.5 Motorbiking - on Safe Roads

Stock et al. (2011) conducted a study with the objective of enhancing safety of riders by making roads safer. To better manage intersections and treat roads better for motorcyclists. Studies found the primary reasons causing high motorcycle fatalities included reduced safety of roads, such as damaged pavements, lack of underrun protection, unsafe roadway conditions, low visibility, etc.

Location: Germany.

Analysis Conducted: An analysis was carried out focusing on motorcycle accidents in different areas of Germany (Stock et al., 2011). Important findings included:

1) In 2008, motorcyclists accounted for nearly one in seven people that were killed in a roadway accident.
2) 10 percent of accidents resulting in injuries involved motorcycles.
3) Inexperienced riders had higher risk of injuries and fatality.
4) Incorrect right of way maneuvering and improper rider-driving skills while navigating corners are some primary reasons for the high number of motorcycle accidents.

Analysis Suggestions:

1) Earth berms can serve as a good alternative to guardrails by preventing impact of the rider with any sharp objects.
2) Reinforced shoulders and widening of shoulders provide better accommodation to motorcyclist.
3) Implementation of railing systems at high-risk roadway sections can make bends in roads less threatening.
4) Focus on areas like man, machine, and road in greater detail can provide excellent results in road infrastructure safety.

Analysis Conclusion: These six major points were suggested by experts to enhance motorcyclist safety (Stock et al., 2011):

1) Increase awareness among authorities regarding motorcycle safety.
2) Urge authorities to make MVMot guidelines “state of art”.
3) Analyze and discuss accident figures, causes, and facts.
4) Thorough maintenance of roads.
5) Train and inform road users.

6) Implementation of road construction and traffic engineering measures for improved road safety.

2.2.6 Infrastructure Improvements to Reduce Motorcycle Casualties

Milling et al. (2016) conducted research with an objective to reduce motorcycle crash risk and severity by effective infrastructure improvements. Data reveals most motorcycle fatalities occurred on curves (39 percent), intersections (38 percent), and straight roadways (23 percent). Roadside hazards and conditions like poor grip, unsealed shoulders, etc. account for 75 percent of single-vehicle collisions.

Performing Agency: Austroads Ltd, Sydney, Australia.

Analysis Conducted: A crash analysis was carried out that categorized crashes on the basis of week days (commuting period crashes) or holidays (recreational period crashes). ARRB group carried out many safety audits to obtain a comparative study between vehicles and motorcycles which showed how infrastructure elements can influence the likelihood and severity of crashes represented by Risk Factors.

Analysis Results: For crash analysis obtained by considering days and periods as governing factor:

Table 2.21 ARRB Audit Results.

Criteria	Commuting Period (Mon to Friday excluding holidays)	Recreational Period (Saturday, Sunday or Holidays)
Crashes	Majority of total crashes	Higher proportion of motorcycle only crashes.
Crashes on infrastructure elements	Higher on straights and intersections	Higher on curves
Crashes on curves	Higher with open view curves	Higher with obstructed view curves

Table 2.22 Infrastructure Elements Influencing Likelihood Risk Factors for Vehicles and Motorcycles (Reprinted from Milling et al., 2016).

Elements	Description	Likelihood risk factors (rural and urban)		Differences between vehicle and motorcycle risk factors
		Vehicle	Motorcycle	
Curvature	Moderate curvature	1.8	2	0.2
	Sharp curve	3.5	3.8	0.3
	Very sharp	6	6.5	0.5
Quality of curve	Poor	1.25	1.4	0.15
Road condition	Medium	1.2	1.25	0.05
	Poor	1.4	1.5	0.1
Skid resistance / grip	Sealed – medium	1.4	1.6	0.2
	Sealed – poor	2	2.5	0.5
	Unsealed – adequate	3	4	1
	Unsealed – poor	5.5	7.5	2
Intersection type	Roundabout	15	30	15
	3-leg (unsignalised) driver – side turn lane	13	17	4
	3-leg (unsignalised) no driver – side turn lane	16	20	4
	3-leg (signalized) no driver – side turn lane	12	14	2
	4-leg (unsignalised) no driver – side turn lane	23	26	3
	4-leg (signalized) no driver – side turn lane	15	16	1
Intersection Quality	Readability of layout, approach signage, delineation and line marking	0	1	1

Analysis Conclusion: To summarize, as per the report, the following measure should be kept in mind for motorcycle safety enhancement:

1) Motorcyclists should be recognized as a unique road user group and have specific needs with regards to road infrastructure.
2) With more focus on treating road infrastructure elements that affect the likelihood, crash reductions can be achieved.

3) It is more economical to treat road infrastructure elements that effect the likelihood of a crash occurring.
4) As the proposed mitigation measures are road infrastructure based treatments, over time they can be integrated into existing practice and therefore existing funding.
5) Motorcycle crash risk should be proactively identified and a remedial action program developed through motorcycle focused network safety assessments or road safety audits.

2.2.7 Motorcycle-Friendly Guardrails: FEMA is granted the Liaison Status with CEN/TC 226 (2007)

The **Federation of European Motorcyclists (FEMA)** was granted liaison status with the European Committee for Standardization (CEN) Technical Committee (TC) 226 "Road Equipment" as representative of motorcycle riders. FEMA will follow the work of Working Group (WG) 1 "Crash barriers, safety fences, guardrails, and bridge parapets" based on FEMA's experience with numerous accidents where guardrails were the cause of severe injuries to the rider. FEMA will also be involved in APROSYS – an Integrated European Research project on the advanced protection system – in developing a new test procedure for motorcycle-road infrastructure interaction. Guidelines to design motorcycle-friendly infrastructure should be a result of this sub-group. FEMA will now work on convincing CEN members and the European Union to define guardrails which will take motorcyclists into account by modifying current European standards or adopting new standards for devices to be added to existing guardrails.

Summary: This section dealt with different test conditions and evaluation criteria. A summary of this section is given in Table 2.22 based on different test conditions and evaluation criteria.

Table 2.23 Summary Table for Various Studies Considered in Section 2.2.

Table:A2.12: Summary table for various studies considered in A2							
		Study 1 **Quincy et al. (1988)**	**Study 2** **Nieboer et al. (1993)**	**Study 3** **Berg et al. (2005)**	**Study 4** **Peldschus et al. (2007)**	**Study 5** **Stock et al. (2011)**	**Study 6** **Milling et al. (2016)**
Test details and Impact Conditions	**Test type**	Dummy - Guardrail impact	Obtain data for: Test (A) Motorcycle - Barrier impact Test (B) Motorcycle - Passenger car impact	(A) Motorcyle with rider - Steel Guardrail (B) Motorcycle with rider - Concrete Barrier	(A) Motorcyle with rider -Guardrail impact(Primary data) (B) Rider - Ground Impact (Secondary data)	Crash Analysis	Crash Analysis report
	Impact condition	Dummy on Platform	Upright and Inclined	Upright and Skidding for Both tests	Upright and Sliding	N/A	N/A
	Number of Tests	2 with each design	3 for Test (A) and 2 for Test (B)	4 tests with combination of above conditions	2 tests (upright and sliding)	N/A	N/A
	Impact speed	34.2 mph (55 Kmph)	Test (A) 20, 30 ,37 mph respectiviely Test (B) 20, 30 mph respectively	37.3 mph (60 km/h)	60 kmph	N/A	N/A
	Impact Angle	Design 1 - 32° Design 2 - 30°	Test A) 90° , 90° and 67° respectively test B) 45° and 90° respectively	Upright - 12° Skidding on side - 25°	Upright - 12° Inclined - 25°	N/A	N/A
	Trolley	N/A	Special Trolley to eject rider	N/A	Test Sled used in upright and inclined position.	N/A	N/A
Evaluation Criteria	**HIC (head Injury Criteria)**	Lower than Limits	-	No high level injury risk for Upward condition Above Biochemical Limits for skidding condition	Limit = 1000 for all tests and data Lower than limits for both tests and data	-	-
	Head acceleration (3ms (g))	Lower than Limits	-	No high level injury risk for Upward condition Above Biochemical Limits for skidding condition	Limit = 80g for all tests and data Lower than limits for primary data and higher than limits for secondary data for both tests	-	-
	Interaction with system	-	-	Dummy flew over the concrete barrier in upward condition Dummy left shoulder joint was broken while skidding against guardrail	-	-	-
	Moments and Force (neck and femur)	-	-	-	Lowe than limits for all tests and data	-	-
	Other Variables	-	-	-	-	Roadway and Driver Characteristics	Crash days (Commuting or recreational period)
	Infrastructure elements	-	-	-	-	-	Curvature, Quality of curve, Road condition, Skid Resistance/grip, Intersection type and quality.

2.3 Motorcycle Crashes and Studies with Mitigation Measures

This section consists of literature on motorcycle crashes and studies with mitigation measures to be adopted inside the U.S.

2.3.1 Motorcycle Crash Tests Conducted Inside U.S.

2.3.1.1 Seventeen Motorcycle Crash Tests into Vehicles and a Barrier

Adamson et al. (2002) conducted this research to evaluate the post-impact characteristics of a heavy motorcycle involved in collisions with stationary targets.

Performing Agency: TTI Proving Ground, Roadside Safety & Physical Security Division at Texas A&M Transportation Institute.

Tests Conducted: Seventeen staged motorcycle crash tests were performed at the World Reconstruction Exposition 2000 (WREX2000). Seven crash tests conducted as Kawasaki-concrete barrier crash tests while others included Kawasaki-1989 Ford Thunderbirds impact tests.

Test Configuration: Tests were performed with a motorcycle tow system (Figure 2.7). Motorcycles were towed by a Ford Expedition vehicle and stabilized initially until they gained sufficient speed to remain in an upright position. Refer to Table 2.24 for test specifications.

Table 2.24 Impact Configurations for Tests (Reprinted from Adamson et al., 2002).

M/C No.	Target	Impact Location and Comments	Speed (mph)
1	Block	Vertical face	42
2	Block	Vertical face (MC leaning left 30 deg at impact)	10
3	Block	Vertical face	31
4	Block	Vertical face	20
5	Block	Vertical face	24
6	Block	Vertical face	21
7	Block	Vertical face	35
8	Car (M)	Body between B-post and LR wheel well	46
9	Car (M)	Body LR, between wheel well and bumper	39
10	Car (M)	Rear bumper, 17 inches left of right end	34
11	Car (M)	Right side, between front wheel well and door	25
12	Car (M)	Right front wheel	30
13	Car (S)	Right door, center	42
14	Car (M)	Front bumper, 6 inches right of centerline	30
15	Car (S)	No target impact	--
16	Car (S)	Right front fender between wheel well and bumper	41
17	Car (S)	No target impact	--
18	Car (S)	Front bumper, right of center	45
19	Car (S)	Body left rear fender, between wheel well and bumper	49

Figure 2.6 Motorcycle Tow System (Reprinted from Adamson et al., 2002).

Figure 2.7 Motorcycle and Concrete Barrier used in Tests (Reprinted from Adamson et al., 2002).

Table 2.25 Test Specifications.

Impact Speed	10 mph (16.1 km/h) to 49 mph (78.9 km/h)
Impact Angles	90°
Trolley Type	Motorcycle tow system (Figure A3.1)
Dummy Type	N/A
Vehicle Used	Four-cylinder air-cooled Kawasaki 1000 police motorcycles

Test Results and Conclusion: Car damage photographs, motorcycle crush measurements, and car crush measurements obtained from these tests were considered to provide a useful database for future reconstruction of motorcycle collisions.

2.3.1.2 Development and Evaluation of Concrete Barrier Containment Options for Errant Motorcycle Riders

Dobrovolny et al. (2018) conducted this research with the objective of designing and evaluating a containment barrier system with the capability of:

- Containing and redirecting errant upright motorcycle riders during the impact event.
- Avoiding impacted system debris that could potentially result in hazardous conditions to other road vehicles on lower roadways.
- Reducing injury risk for the errant motorcycle rider by controlling the interaction with the impacted system.

Performing Agency: Roadside Safety & Physical Security Division at Texas A&M Transportation Institute.

Tests Conducted: Researchers developed design alternatives of containment systems and then tested each with engineering analysis, finite element simulations, pendulum testing, and full scale crash testing.

Test Configuration: Full-scale impact tests were performed with a motorcycle rider. A permanent 32-inch high and 75 ft long New Jersey concrete barrier was constructed with a radius of curvature of 500 ft. The containment and redirection capability of the final containment system design was evaluated through an upright motorcycle full-scale crash test. Refer to Table 2.25 for test specifications.

Figure 2.8 Crash Test Image Showing Rider-Motorcycle Barrier Impact (Reprinted from Dobrovolny et al., 2018).

Table 2.26 Test Specifications.

Impact Speed	35 mph ± 2.5 mph
Impact Angles	18° ± 1.5° (w.r.t barrier tangent)
Trolley Type	Motorcycle tow system
Dummy Type	A Hybrid H-III 50th percentile male
Vehicle Used	2012 Kawasaki 250 Ninja motorcycle

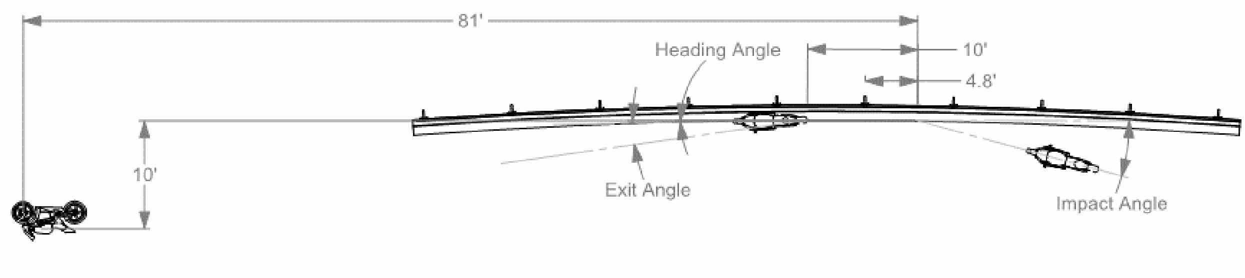


Figure 2.9 Impact Details of Rider-Motorcycle and Barrier Interaction (Reprinted from Dobrovolny et al., 2018).

Test Results:

Material: Chain link fence, tubular posts, on to concrete barrier

Exit Conditions: Speed – 28.1 mph, Angle – 8.3°

Post Impact: Stopping Distance – 81 ft.

HIC 15, Value: 92

Conclusion: During the impact event, the system successfully prevented the rider/dummy from ejecting over the barrier. The dummy did not interact with the system's support posts. Thus, this system would prevent riders from ejecting over the barrier, reducing injury severity to the rider during the impact event. Hence, modified "U" shaped posts and a mesh fence containment system is considered suitable for implementation at locations where an upright motorcycle rider containment option is desired. The system can be retrofitted on existing cast-in place roadside concrete barriers.

Crash Data Analysis:

A crash data analysis was developed in support of this research project which aimed to determine relevant factors involved with motorcycle accidents with the bike impacting roadside safety barriers on flyovers/connectors or on curves. The primary focus of this analysis was on fatal and incapacitating motorcycle injuries that occurred in Texas on flyover-connectors in the time interval between 2014 and 2016. Distribution of injuries of riders injured by safety barrier impact such as concrete barrier was taken into account. For both the analysis done (flyovers-connectors and on curves) only motor vehicle accidents were looked at where the driver of the motorcycle was the one that received the injury. It was found that the total number of fatal and incapacitating injury cases that took place on curves was quite larger than the amount of fatal and incapacitating injuries on flyovers-connectors. The outcome of this analysis suggests that retrofit options for existing roadside safety systems are important, although incapacitating injuries can take place due to various other factors, to:

1) Contain the motorcycle rider after impact,
2) Reduce severity of rider injuries during the event of impact.

2.3.1.3 Design and Assessment of a New Roadside Safety Barrier System for Consideration and Mitigation of Upright Motorcycle Impacts

Franco et al. (2018) conducted a study with the objectives as follows:

1) To design a more motorcycle-friendly concept of roadside safety barrier.
2) To evaluate the robustness of the finite element (FE) motorcycle model and, with the improvements introduced, conduct some numerical validation tests.
3) To assess the operation of the new barrier system through numerical impact simulations.

Performing Agency: Roadside Safety & Physical Security Division at Texas A&M Transportation Institute.

Tests Conducted: The first phase of research includes selecting a system from a range of alternatives and creating a model. The second phase includes conducting FE analysis to determine strength and perform impact simulations on the model. The final phase will confirm if the proposed design satisfies *MASH* impact performance requirements. To assess the FE models and verify the dummy-motorcycle system, a motorcycle full-scale crash test performed at TTI was simulated by FE analysis. Refer to Table 2.26 for test specifications.

Table 2.27 Test Specifications.

Impact speed	45 mph
Impact Angles	15°
Trolley type	Motorcycle tow system
Dummy type	A Hybrid H-III 50^{th} percentile male
Vehicle used	Kawasaki 500R Ninja motorcycle

Test Results: The proposed combination rail contained and redirected both test vehicles and they did not penetrate, override, or underride the test article.

Conclusion: After conducting benefit analysis of the proposed systems, the system with screening of the steel rail with an acrylic panel is considered as the most suitable. Motorcycle impact simulations with an ATD shows that the selected barrier system provides excellent results in preventing motorcyclist injuries. The designed roadside device meets all *MASH* evaluation safety criteria. However, the researchers suggest conducting a full scale crash test to validate the proposed FE model. Also, the researchers question if the dummy can simulate real life response of the rider because of the fixed pelvis which prevents the dummy from ejecting off the motorcycle.

Summary: A short summary for this section is given in Table 2.3 summarizing main points of crash tests inside the U.S.

Table 2.28 Summary of various tests conducted inside U.S.

Table:A2.12: Summary table for various crash test studies in US				
		Adamson et al. (2002)	**Dobrovolny et al. (2018)**	**Franco et al. (2018)**
Test details and Impact Conditions	**Test type**	Motorcycle - Barrier test and Motorcycle - Car Test	Motorcycle with rider - barrier impact	Study pertaining to motorcycle friednly safety barrier
	Impact condition	Upright	Upright	Upright Simulation of actual test
	Number of Tests	17 tests in total	3 for Test (A) and 2 for Test (B)	FEA simulation Test
	Impact speed	10 mph to 49 mph	35 mph ± 2.5 mph	45 mph
	Impact Angle	90°	18° ± 1.5° (w.r.t barrier tangent)	15°
	Trolley	Motorcycle tow system	Motorcycle tow system	Motorcycle tow system
Evaluation Criteria	**HIC (head Injury Criteria)**	-	HIC 15, Value: 92	-
	Head acceleration (3ms (g))	-	-	-
	Interaction with system	Motorcycle and car crush measurements were used for future reconstruction	Exit Conditions: Speed – 28.1 mi/h, Angle – 8.3° Post Impact: Stopping Distance – 81 ft. System successfully prevented rider from ejecting over the barrier	Contained and redirected both test vehicle and did not penetrate, override or underride test article
	Moments and Force (neck and femur)	-	-	-
	Other Variables	-	-	-
	Infrastructure elements	-	-	-

2.3.2 Studies Conducted Inside the U.S.

2.3.2.1 Leading Practices for Motorcyclist Safety

Shaffer et al. (2011) conducted research to improve the planning and organization of infrastructure advancements for motorcyclists.

Key points of Study:

1) The research team included a small number of transportation professionals who met motorcycle rider advocacy group leaders from different states. The team chose some experts from infrastructure manufacturing for motorcycle safety from different states to find out which states were most proactive towards motorcycle safety and had high motorcyclists.
2) After consideration, the team decided to focus on the states of Florida, Maryland, and Wisconsin.
3) To increase awareness for motorcycle safety and the need for safety devices, the team wanted to create motorcyclist safety advocacy groups within the states.
4) Primary concerns and focus area for infrastructure improvements include signage and lineage of roads, design of motorcycle-friendly infrastructure systems, and maintenance of roadway systems.
5) The report provides some mitigation measures for drainage, shoulders, communication of upcoming road conditions, traffic control devices, pavement and surface conditions, and even curves and roundabouts.
6) One focus of this study was on the annual bike rallies in different states. Florida, South Dakota, and Wisconsin are looked at in greater depth to understand the situation as these states have recorded a large number of attendees during annual bike rallies. Study

emphasis on the need of government agencies and advocacy groups to coordinate during such events to ensure its safety and orderly working.

7) Another focus of the study was with the inconsistency from state to state in quality of crash reporting. It was found that most states experienced difficulty in considering vehicle miles traveled (VMT) which is mandatory to find risk factors involved in accidents.
8) Recommendations and implementation plans were made to review previous successful cases from different organizations across the states. The plan is to reach out to the members of these agencies via various activities.
9) A few recommendations are the need to create Motorcycle Safety Coalitions, improve data collection methods, communicate roadway condition information, and share successful strategies with other states to increase the common effectiveness.
10) The steps of implementation suggested are as follows: conduct outreach to critical national organizations, develop official guidelines, outreach to states encouraging the creation of MSCs, and a few others not mentioned here.

2.3.2.2 Infrastructure Countermeasures to Mitigate Motorcyclist Crashes in Europe

Nicol et al. (2012) conducted study inside US to assess and evaluate infrastructure improvements, maintenance practices, and traffic operation strategies to enhance motorcycle safety in Germany, Belgium, France, England, and Norway (Nicol et al., 2012).

Key points of Study:

1) A team of 12 transportation engineers conducted this study to attain the required objective.

2) Infrastructure safety measure types used were those that improved safety for all vehicle classes. Areas of behavioral safety were the only major difference between the United States and other countries.
3) There is an increase in the number of motorcyclists in both countries with fatalities in each country being consistently around 15 to 20 percent. Although there were some roadside and median barriers that were designed for motorcycle safety, there was no conclusive data on their effectiveness.
4) For findings and recommendations, the research team concluded that agencies in Europe are working to address the motorcycle safety problems.
5) Standards and guidelines are developed by the European countries to enhance motorcycle safety, yet no single infrastructure change was identified to reduce motorcycle injury.
6) The research team proposed that the United States agencies should establish goals to reduce motorcycle injuries through roadway design, operations, and maintenance practices. New barrier systems are currently being tested and evaluated for effectiveness.
7) Promoting motorcycle awareness and developing a motorcycle research agenda are some ways by which these goals can be accomplished.

2.3.2.3 Traffic Safety Facts for Motorcycles: Based on Fatality Analysis Reporting System (FARS) and General Estimates System (GES) data (2015).

A study based on FARS and GES data (2015) focused on fatal motorcycle crashes with regards to general motorcycle safety.

Important Findings of Study:

1) There was an increase in the number of motorcyclists killed by 8 percent since 2014. Motorcyclist injuries were reduced by 3 percent than the previous year (2014). The number of people being killed in motorcycle accidents has been slightly decreasing since 2008. However, when looking at the number of registered vehicles the fatality rate for a motorcyclist was six times that for an occupant of a passenger car.
2) Passenger injuries were also recorded in this study, which allows the analysis of passenger risk to be calculated. Out of the 4,976 motorcyclists killed, six percent were passengers.
3) In 2015, a fatality involving a passenger car was 29 times less frequent than a motorcyclist fatality with regard to Vehicle Miles Traveled (VMT).
4) Based on environmental and human characteristics, the study reflected the following statistics:
    - 55 percent of the motorcycle fatalities occurred in urban areas compared to 45 percent in rural areas.
    - 67 percent occurred on non-intersection locations compared to 33 percent on intersections.
    - 57 percent occurred during daylight compared to 38 percent in the dark, 4 percent during dusk, and 1 percent during dawn.
    - 97 percent occurred in cloudy/clear conditions compared to 2 percent in the rain and 1 percent in other conditions.
5) Based on crash involvement, 54 percent of the 5,076 fatal motorcycle crashes were due to collisions with motor vehicles in transport. In two-vehicle crashes, 74 percent of the

cases were considered "frontal collisions" and only 7 percent were considered "struck in the rear."

6) Collision with fixed objects (24 percent) was the leading cause of fatalities for motorcyclists.
7) With regard to speeding, 33 percent of all motorcycle riders involved in fatal crashes were speeding.
8) With regard to alcohol consumption, 27 percent of 4,684 motorcycle riders killed in motor vehicle traffic crashes in 2015 were alcohol impaired (BAC of 0.08 g/dL or higher). Additionally, there were 337 (7 percent) fatally injured motorcycle riders who had lower alcohol levels (BACs of 0.01 to 0.07 g/dL).
9) Helmets are estimated to be 37-percent effective in preventing fatal injuries to motorcycle riders and 41 percent for motorcycle passengers.

2.3.2.4 Motorcycle Road Safety Audit Case Studies (Nabors et al., 2016).

Nabors et al. (2016) conducted research to look into road safety issues and find the locations that pose the greatest opportunity for improvement and to try and better understand different conditions that influence the overall safety of motorcyclists.

Key Points of Study:

1) This document consists of three Road Safety Audits (RSAs), each of which focus on various roadside facilities. The RSAs took place between 2012 and 2014. This project as a whole and each of the three audits were funded by FHWA to show how using RSAs can improve motorcyclist safety.
2) Findings of these studies show that nationally, there was a 43 percent increase in motorcyclist fatalities and injuries from 2003 to 2008. There was a significant decrease

in both fatalities and injuries of motorcyclists from 2008 to 2009. However, there was an increase again in both fatalities and injuries to motorcyclists from 2009 to 2012.

3) An interesting finding that relates to all motor vehicle accidents over the year was that in 1997 one in every 20 motor vehicle fatalities occurred on a motorcycle. Then in 2014, one out of seven motor vehicle accidents took place on a motorcycle. This clearly shows an increasing risk through the years to motorcycle riders and drivers.
4) According to the study, motorcyclists composed just 3 percent of all registered vehicles in the United States in 2012. Still, there are 15 percent of fatalities of motorcyclists of the whole vehicle fatality amount.
5) Variables like human factors and characteristics were considered, including the age, rider experience, purpose of travel, and frequency of bike usage.
6) 27 percent of the fatal motorcyclist crashes in 2012 were found to have a blood alcohol concentration (BAC) of at least 0.08g/dL at the time the crash. Also, it was found that in many cases there were trends between the type of motorcycle that was involved and the severity of the crash.

2.3.2.5 Motorcycle Crash Causation Study (Tan C.H., 2017)

This study conducted by Tan C.H. (2017) aimed to increase the awareness of the need for improvement of motorcycle safety and to offer a one-of-a-kind perspective to the role of different crash causation factors.

Key Points of Study:

1) The team that conducted this study consisted of some of the most experienced professionals on crash data analysis. Oklahoma State University, Southern Plains

Transportation Center, and various other companies and research teams were involved in this study.

2) This study was conducted by the Federal Highway Administration (FHWA) and is the most extensive data collection effort in the United States in over 30 years (Tan C.H., 2017). It contains data from 351 crash investigations and 702 control rider interviews.
3) The goal of this data analysis is to show the role of different crash causation factors which in turn will allow for effective countermeasures to be put in place according to the new recommendations.
4) Findings from the report indicate that the number of motorcycle rider fatalities was more than twice that in 2009 than the amount recorded in 1997. Also, in this same time period, a 27 percent decrease in the number of passenger car and light truck fatalities was recorded.

2.3.2.6 Factors Related to Serious Injury and Fatal Motorcycle Crashes with Traffic Barriers

Gabler C.H (2018) conducted study in USA to identify factors contributing to serious injury and fatal motorcycle collisions with traffic barriers.

Performing Agency: Virginia Polytechnic Institute and State University

Key Points of Research:

1) Motorcycle crashes are difficult to analyze for various reasons:
    - Motorcycle usage, roadway design, and crash data collection practices are different among states.
    - Actual sequence of events and cause of injury can differ from typical coding on crash reports. It may be unclear if both the motorcycle and the motorcyclist

impacted the barrier, or if the motorcyclist separated from the motorcycle prior to striking the barrier.

- Uncertainty of exact situation such as impact with the barrier may not have been the most harmful event.

2) There is lack of data with in-depth analysis of motorcycle-traffic barrier crashes in the U.S., which is an obstacle in understanding the injury mechanisms in such crashes.
3) Thus, there is a need to determine factors which cause serious injury and fatal motorcycle crashes with traffic barriers.

Tasks to be conducted:

PHASE I The first phase of research includes literature review, crash characteristics report, developing a revised work plan for Phase II, which will quantify the factors contributing to serious injury and fatal motorcycle collisions with traffic barriers, meet with NCHRP panel to review report with Phase 1 results.

PHASE II The second phase includes execution of the approved plan and submit a final report containing entire research work with future research and injury mitigation recommendations.

The final report of this research is not available due to the research being in progress at the time of writing this literature review.

2.4 Devices to Retrofit Roadside Barriers for Motorcycle Safety

This section deals with motorcycle safety devices used to retrofit barriers to accommodate motorcycle safety.

Different Strategies for Motorcyclists Protection

Three most recent methods to provide protection to a rider by improving barrier safety includes:

1) The replacement of traditional IPE-100 commonly used in guardrail systems with the more forgiving Sigma-Posts.
2) Covering the existing posts with additional W-beams on the lower section of the guardrail system.
3) Covering exposed posts with specifically designed impact attenuators (Koch and Schueler, 1987; Sala and Astori, 1998).

A variety of new devices are being developed by companies across the globe which can be added to existing barrier systems to make them more motorcycle friendly. Succeeding sections give information about such devices and various measures taken with regard to this topic.

2.4.1 Punctual Energy Absorbers (Crash Barrier Protectors (CBP))

Reported Use: Germany, Austria and Luxembourg (FEMA, 2000).

Main Scope of the Device: Protecting the impacting rider from the sharp edges of a barrier post and of absorbing the motorcyclist's kinetic energy.

Device Description: Foam or plastic crash barrier impact attenuators (Figure 2.10).

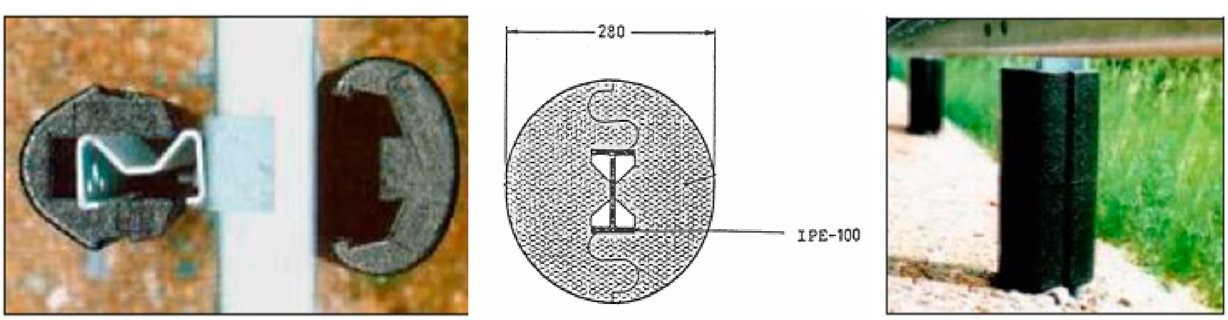


Figure 2.10 Punctual Energy Absorbers (Reprinted from FEMA, 2010; Reprinted from Palacio et al., 2011).

FEMA reports some initiatives by riders' groups in Portugal where they installed used tires on metal barrier posts with the purpose of protecting the impacting rider from the sharp edges of the post. Additionally, Palacio et al. (2011) reports the existence of some systems consisting of a metallic pipe surrounding the post and filled with sand.

Advantages:

1) Easy installation.
2) Durability around four years (FEMA, 2010).

Disadvantages:

1) According to Palacio et al. (2011), these punctual energy absorbers are effective for posted speeds up to 37 mph (60 km/h).
2) The positive effect of the device is reduced with the increasing of the impact speed, considering that the absorbed energy is limited by the device size.

2.4.2 Continuous Systems to Redirect Riders

Reported Use: France (FEMA, 2010).

Main Scope of the Device: Redirect the impacting riders on the road and to absorb energy during the impact by flexion.

Device Description: Four continuous system devices (Table 2.28) were homologated and approved for use on French roads as follows (FEMA, 2010):

1) The Metal "Shield."

   Since the early 1980s, a device consisting of a flat metal beam fixed under the rail to prevent contact with the barrier posts and to absorb impact kinetic energy has been designed and is used in France (sold by the company SEC-Envel). This device absorbs kinetic energy due to its flexibility. Nearly 100 km of motorway was equipped with such devices in the Paris region in 1997.

2) The Plastrail.

   A new device has been recently developed by the French ‘Sodilor’ company. This device consists of soft plastic fence covering barrier posts and aims at combining CBP energy absorption properties with the impact spreading property of the metal sheet.

3) Motorail.

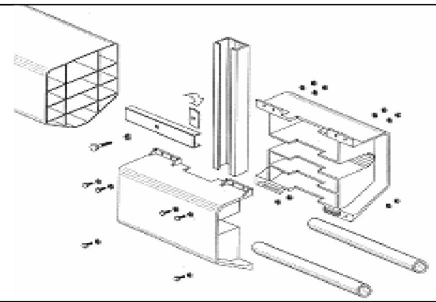
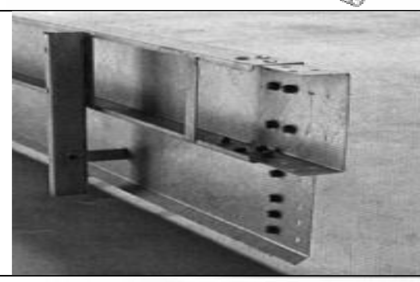
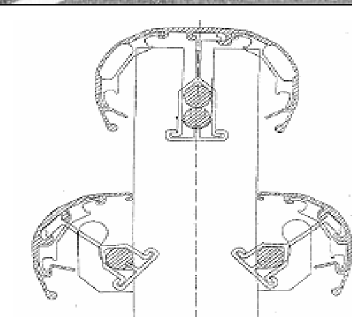
   The device is a built-in secondary rail with shapes reduced to minimal and turned in edges.

4) Mototub.

   This device is similar to “Plastrail”, but comprising 70 percent recycled material, and is also presumably adaptable to cable barriers.

Additionally, Mr. Johannson in Sweden invented a cable cover for wire rope safety fences which consists of aluminum covers for cable barriers. However, it does not provide protection against the posts.

Table 2.29 Continuous Systems for Rider Redirection (Reprinted from FEMA, 2010).

Description	Barrier Protection Device
(a) Metal Shield Metal Plate sold by SEC-Envel (France).	
(b) Plastrail Soft plastic fence covering barrier posts sold by Sodilor (France).	
(c) Motorail Built-in secondary rail sold by Solosar (France).	
(d) Mototub Similar approach as (b) "Plastrail", but comprising 70% recycled material, sold by Sodirel (France).	
(e) Cable Cover Cables cover for wire rope safety fence, invented by Mr. Johannson (Sweden).	

2.4.3 V – Beam Guardrail

Main Scope of the Device: To improve the safety features of an existing guardrail system with regard to motorcyclists so as to reduce the severity of injuries sustained by the motorcyclists during the event of impact (Tan et al., 2008).

Device Description: The new V-beam guardrail system is made up of three V-profile rails. Polypropylene (PP) has been chosen as the material for the V-beam, C-block, and C-post since PP possesses better deflection and energy-absorption properties than steel. The folding edges at the bottom and the top of the 'V' shape are not perfectly sharp but were filleted with radii of 10 mm and 20 mm, respectively. (Figure 2.11).

In order to compare performance of the V-beam guardrail system in terms of deflection and energy absorption, two other types of guardrail systems were designed. These two designs of guardrail systems were simply minor modifications from the existing W-beam system with one made of PP and the other AISI 1020 steel (Figure 2.12). The heights of these two types of guardrail systems are same as the V-beam guardrail system (1390 mm), for control purposes, having three rows of W-beam and a clearance of 80 mm between the ground and the lower edge of the lowest W-beam.

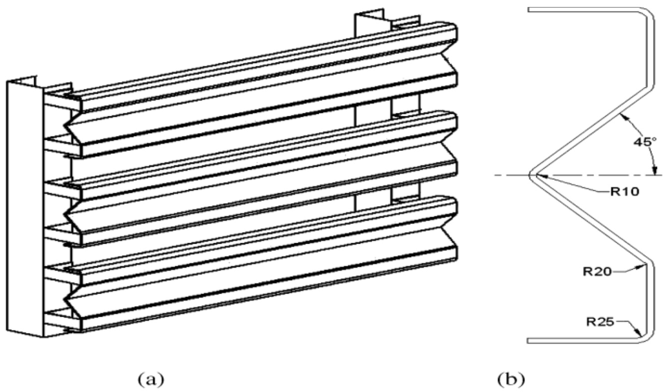


Figure 2.11 V-Beam Guardrail System and Cross Section (Reprinted from Tan et al., 2008).

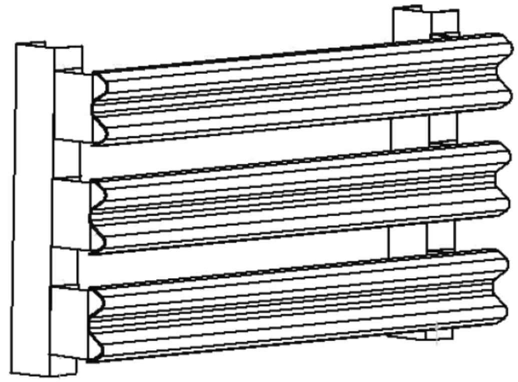


Figure 2.12 Modified W-Beam Guardrail System for Control Purpose (Reprinted from Tan et al., 2008).

Advantages:

1) Double protruding curves of W-beam pose a significant risk to riders, which is eliminated in case of V beam.
2) Clearance of lowest V-beam from the ground is designed to be 80 mm, which would obstruct the fallen motorcyclists from hitting the sharp-edged posts.
3) The height of the present V-beam guardrail system is 1.39 m, which is slightly greater than the rider's center of gravity (generally 1.37 m), thus preventing the rider from falling over the top sharp edges of C-post and C-block.
4) The PP V-beam guardrail is expected to absorb more impact energy than the existing steel W-beam guardrail.

2.4.4 W-Beam Guardrail Equipped with Lower Motorcycle Barrier (FHWA, 2012)

Main Scope of the Device: To dissipate impact energy through deformation or alternate mechanisms so as to induce less injury risk to motorcyclists.

Device Description: This device covers the existing posts with additional W-beams on the lower section of the guardrail system, also covering exposed posts with special impact attenuators.

Moreover, the device also protects victims from directly impacting the guardrail posts. Impact attenuators are fitted to the existing guardrail posts to increase the impact surface and energy absorption on impact, and have been tested to effectively reduce the Maximum Abbreviated Injury Scale (MAIS). But its effectiveness decreases with speed and is generally only acceptable within 50 to 60 km/h (Figure 2.13).

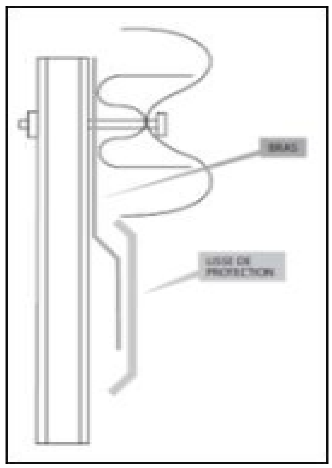


Figure 2.13 Section Drawing of W-Beam Guardrail Equipped with Lower Motorcycle Barrier (Reprinted from FHWA, 2012)

Advantages:

1) Studies indicate that an additional W-beam at the lower section of the conventional guardrail system effectively reduces the severity of injuries sustained by motorcyclists by distributing the energy of impact over a larger surface.
2) The device protects victims from directly impacting the guardrail posts.
3) Impact attenuators on posts increase the impact surface and energy absorption on impact and helps to reduce the Maximum Abbreviated Injury Scale (MAIS).

Disadvantages:

1) Effectiveness of this device reduces with speed, and is generally only acceptable within 50 to 60 km/h.

2.4.5 Euskirchener Model – 'Safety outside Build-Up Areas'

Reported Use: Germany.

Main Scope of the Device: Reduce fatality injuries of motorcyclists.

Project Description: 'Euskirchener Model' is an outcome of an integrated research and safety improvement project 'Safety outside Build-Up Areas'. More than 12 000 meters of the secondary rail have been installed in the district of this respective authority alone (Landesbetrieb Straßenbau -Niederlassung Euskirchen). Figure 2.14 shows a Euskirchener Model with top cap (FHWA, 2012).

The project includes the following measures:

1) Intervention with selective road construction measures;
2) Fitting the existing crash barriers with a second, flat rail called 'Unterfahrschutz Typ Euskirchen'. This product was first used in France and 'reimported' to Germany and forwarded to type approval process;
3) Mounting of 'Direction Panels' (Chevrons);
4) Introduction of 'Double Line', separating the lanes;
5) Creating a 'Forgiving Road Side';
6) Solving problems of where to place roadside furniture, like reflector posts and direction panels. These must be in the field of vision of the rider as well as at a safe distance. Possible solutions are: flexible mountings and mounting outside the most likely crash area;

7) Implementation of behavioral changes with motorcyclists.

This project is a big success as the implementation of the described measures has prevented fatal motorcycle injuries.

Figure 2.14 Euskirchener Model including Cap at Top (Reprinted from FHWA, 2012).

2.4.6 Spanish Guardrail

Reported Use: SPAIN (FHWA, 2012).

Main Scope of the Device: Reduce fatality injuries of motorcyclists.

Project Description: Spain began to work in 2003 on a performance-based standard for evaluating safety barriers against full-scale motorcyclist impact. The Spanish standard defines two types of Motorcyclist Protecting Systems (MPS): punctual systems, or post absorbers, and longitudinal systems, or continuous systems. By 2007, more than 300 km of MPS on guardrails had been installed in Spain. Figure 2.15 shows an example of conforming barrier (FHWA, 2012).

Figure 2.15 Conforming Barrier – Spanish Guardrail (Reprinted from FHWA, 2012).

2.4.7 Other Devices for Roadside Barrier Retrofit for Motorcycle Safety

Apart from these devices, a few countries have adopted different measures with regards to rider safety. In Belgium, a free area of several meters is provided between the side of the road and the barrier so as to give more chance to the errant motorcyclists to decelerate before impacting against the road safety barrier. Also, planted shrubs on sides appear to offer an additional kinetic energy absorbing cushion for the fallen rider. In Holland, some urban areas have cycle lanes on the side of the road, acting as a fixed-obstacle-free safety zone where a rider falling can land without hitting a roadside device. Suggestions of reducing aggressiveness of certain sidewalk shapes are also suggested.

The following table shows some other devices commonly used as a retrofit option for motorcycle safety.

Table 2.30 Continuous Systems for Rider Redirection (Reprinted from FEMA, 2010).

Description	Barrier Protection Device
(a) Motorcycle Specific Guardrail A solid flat lower beam is provided to prevent motorcyclist from direct post impact after a crash. It is made of metal or a series of horizontal polyurethane tubes.	 
(b) Flexible Rub Rail This system is attached to W beam barriers to provide protection for motorcyclists in sliding position during impact.	
(c) Flexible bollards Provides guidance to rider on curves. It is made of flexible materials	
(d) Reflective White and Red Sheeting This guardrail is provided with reflective red and white sheeting on curved roads to provide better visibility to rider.	
(e) Underrun Protection in Bends Barriers are provided with underrun protection in bends for minimizing rider injury.	
(f) Earth Walls Provided on the side of the roads on curves to act as cushion for rider.	

Table 2.31 summarizes all devices mentioned in section 4.

Table 2.31 Summary table of roadside barrier retrofit protection devices for Motorcycle Safety.

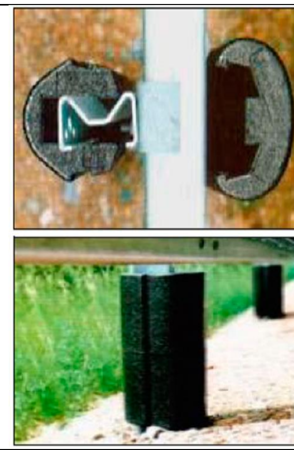
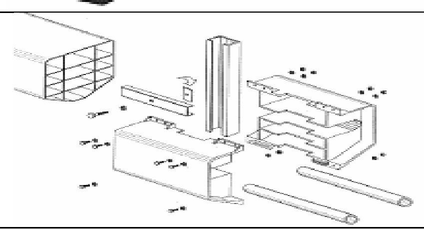
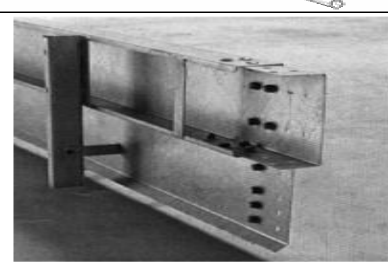
Description	Barrier Protection Device
(1) Punctual Energy Absorbers Foam or plastic crash barrier impact attenuators.	
(2) Metal Shield Metal Plate sold by SEC-Envel (France).	
(3) Plastrail Soft plastic fence covering barrier posts sold by Sodilor (France).	
(4) Motorail Built-in secondary rail sold by Solosar (France).	
(5) Mototub Similar to Plastrail. Sold by Sodirel (France). Comprises of 70% of recycled material.	

Table 2.31 Summary table of roadside barrier retrofit protection devices for Motorcycle Safety (Continued).

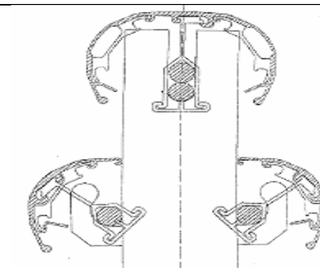
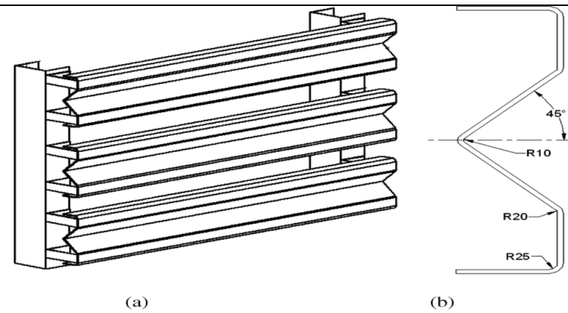
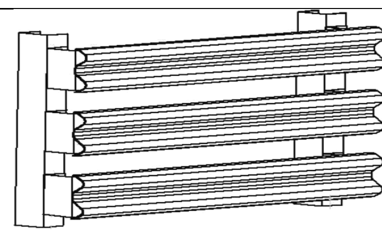
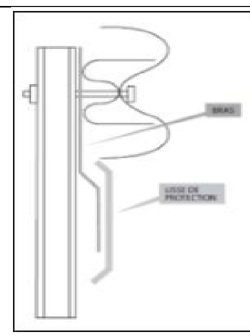
Description	Barrier Protection Device
(6) Cable Cover Cables cover for wire rope safety fence, invented by Mr. Johannson (Sweden).	
(7) V- Beam Guardrail System Consists of 3 V-Profile rails.	
(8) Modified W-Beam Guardrail System for Control Purpose W-beam system made of PP and the other AISI 1020 steel	
(9) W-Beam Guardrail Equipped with Lower Motorcycle Barrier Designed to shield bodies sliding on pavement from posts.	
(10) System Euskirchen Plus Guardrail Includes a cap at top to prevent upper-body injuries from sliding along the top of the rail.	 

Table 2.31 Devices for Roadside Barrier Retrofit for Motorcycle Safety (Continued).

Description	Barrier Protection Device
(11) Spanish Guardrail An example conforming barrier.	
(12) Motorcycle Specific Guardrail A solid flat lower beam is provided to prevent motorcyclist from direct post impact after a crash. It is made of metal or a series of horizontal polyurethane tubes.	 
(13) Flexible Rub Rail This system is attached to W beam barriers to provide protection for motorcyclists in sliding position during impact.	
(14) Flexible bollards Provides guidance to rider on curves. It is made of flexible materials	
(15) Reflective White and Red Sheeting This guardrail is provided with reflective red and white sheeting on curved roads to provide better visibility to rider.	
(16) Underrun Protection in Bends Barriers are provided with underrun protection in bends for minimizing rider injury.	
(17) Earth Berms Provided on the side of the roads on curves to act as cushion for rider.	

2.5 International Survey for Existing Guardrail Design Options

2.5.1 Introduction

This section provides the information obtained from different sources with regards to exisiting guardrail design options which are designed to enhance motorcycle safety. Different international laboratories and agencies were contacted who are involved with the design of guadrails for motorcycle safety. Reseachers around the world who have worked on the same were contacted to get additional information about existing systems. The information obtained was very useful to obatin design ideas and system requirements to ensure minimum injuries. Table A1 attached in the appendix summarizes the information obtained from around the globe with regards to retrofit of guardrail systems for motorcycle safety

Apart from this, one of the studies by Ms Maria Nordqvist entitled "Definition of a Safe Barrier," was referred in which Ms. Nordqvist has classified different systems into barrier class depending upon the protection (collision friendly features) provided by the system to motorcyclist and injury risk. Table 2.32 shows such classification from the paper where class "5" refers to the most protective system in terms of injury risk while "-1" refers to the least protected system. This was done with the intent to explore more design options with recent advances to reduce injury risk of the rider.

Further an Australian study entitled "A Crash Testing Evaluation of Motorcylist Protection Systems for use on Steel W-Beam Safety Barriers" was referred. Key findings of this study indicate that Motorcycle Protection Systems can reduce fatality risk for sliding motorcyclists. Another study, “Development of a Continuous Motorcycle Protection Barrier System using Computer Simulation and Full-Scale Crash Tesitng,” was also referred to gain more inforamtion related to the FEA simulation part of the project.

Table 2.32 Barrier Class Based on Collision Friendly Features. (Reprinted from Definition of a Safe Barrier for a Motorcyclist- a Literature Study, May 2015)

Class	Positive barrier properties	Examples of typical barriers
5 **	** Smooth side with energy-absorbing MPS, smooth top, overrun protection fitted	Non existing
4	Overrun possible ** smooth barrier profile, energy absorbing MPS smooth top	Euskirchen Plus
3	Uneven top, top of post accessible, overrun possible, ** smooth barrier profile, energy-absorbing MPS	W-beam with MPS according to TS 1317-8
2	Uneven upper surface, overrun possible ** smooth barrier profile, existing MPS function with smooth side but not energy-absorbing, no unprotected poles	Concrete barriers
1	Accessible posts cc <4 m, sharp edges, large openings in horizontal and vertical directions, overrun possible ** smooth barrier profile with smooth / dividing box beam guard rail (“roofed W-beam”) with smooth steel profile both side and top	“roofed W-beam” with smooth profile on both side and top
0	Accessible posts cc <4 m, sharp edges, large openings in horizontal and vertical directions, uneven top, overrun possible ** smooth barrier profile	W-beam, kohlswa
-1	Protruding parts on the barrier side and top, accessible posts cc <4 m, sharp edges, large openings in horizontal and vertical directions, uneven side and top, overrun possible	Cable barriers with supporting hooks

The table A2 attached in the appendix provides the list of MPSs obtained from Federation of European Motorcyclists Association (FEMA) website (www.mc-roadsidebarriers.eu). The table provides information such as the name of the manufacturer and product with its testing standards or protocol. The website further provides more details on the webpage about the product and testing.

3. CRASH DATA ANALYSIS

3.1 Summary

This section of the thesis deals with the descriptive statistical analysis of Crash Record Information System (CRIS) data pertaining to a motorcycle making contact with various manmade or placed objects; for example, guard fence systems, along public roadways.

Following crash characteristics were focused:

- Vehicles identified as motorcycles
- Single motor vehicle (SMV) crashes
- Run-off-road (ROR) crashes
- First harmful event (FHE) and most harmful event (MHE), both depicted as Hit guardrail
- Injury severity: fatal, suspected serious injury (K+A in KABCO scale)

3.2 Introduction

From years of 2010 to 2017, 68,838 TxDOT reportable, motorcycle involved crashes are available in CRIS. A crash that occurs on a public roadway and results in a fatality, injury, or $1,000 or more in damage due to the crash is considered as a “TxDOT reportable” crash. Out of all these crashes, 689 crashes were identified which involved a motorcycle making contact with a guardrail. Among them. 646 SMV crashes constituted the majority (94%) of all. Among the SMV crashes, 109 crashes (17%) resulted in a fatality (K) while 215 (33%) resulted in a suspected serious injury (A) which involved contact with a guardrail.

Fatal and the suspected serious injury crashes were focused upon and available crash coordinates from the CRIS data were used to collect guardrail data for 325 crashes from satellite imagery which included 300 of the single vehicle motorcycle (SVM) crashes involving guardrail contact.

Table 3.1 Single Vehicle Motorcycle Crashes Involving Guardrail Contact, 2010-2017

Crash Severity	Count of Crash Severity	Percentage of Total
FATAL	109	17%
SUSPECTED SERIOUS INJURY	215	33%
NON-INCAPACITATING	211	33%
POSSIBLE INJURY	74	11%
NOT INJURED	25	4%
UNKNOWN	12	2%
Grand Total	**646**	**100%**

24 of the crashes did not have crash coordinates associated with them. The Texas Peace Officer's Crash Reports were also reviewed to obtain crash details from the narrative available with illustration on the reports. This was done for the 350 fatal and suspected serious injury crashes with guardrail involvement, including the SMV crashes.

Fatality Number

From the analysis, it can be deduced that the fatality number for the SVM impacting guardrails has remained fairly constant from the years 2010 to 2017 (Figure 3.1 and 3.2). Further, it can be recalled from the literature review that the motorcyclist deaths over 1975 to 2013 (Figure 1.1) was also nearly constant (NHTSA, 2015). Hence, it can be said that the data obtained is in line with what was observed from 1975 to 2013 on a national level and supports the fact that the tendency of the motorcycle deaths is nearly same over these range of years.

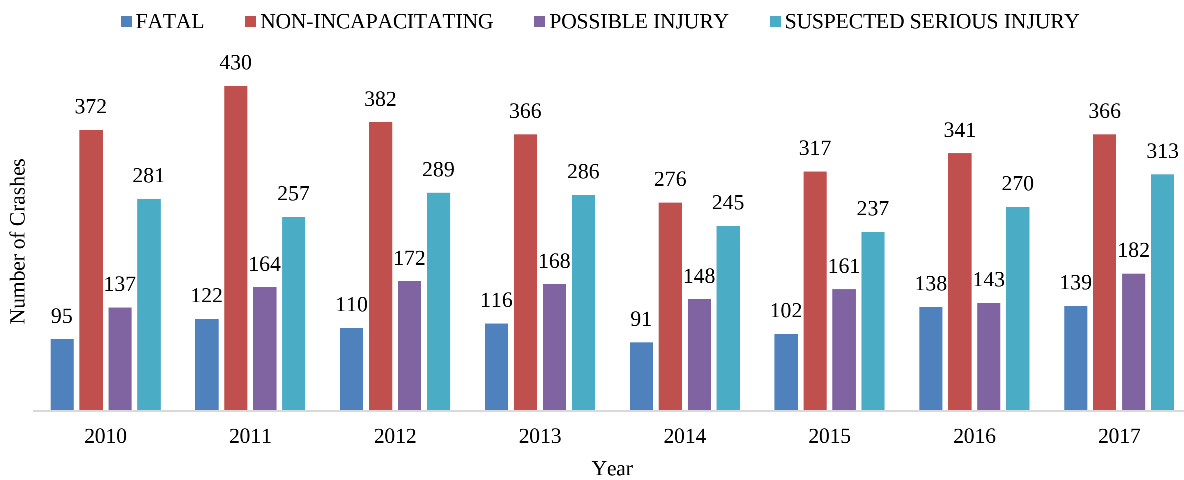


Figure 3.1 Motorcycle Crash Severity per Year

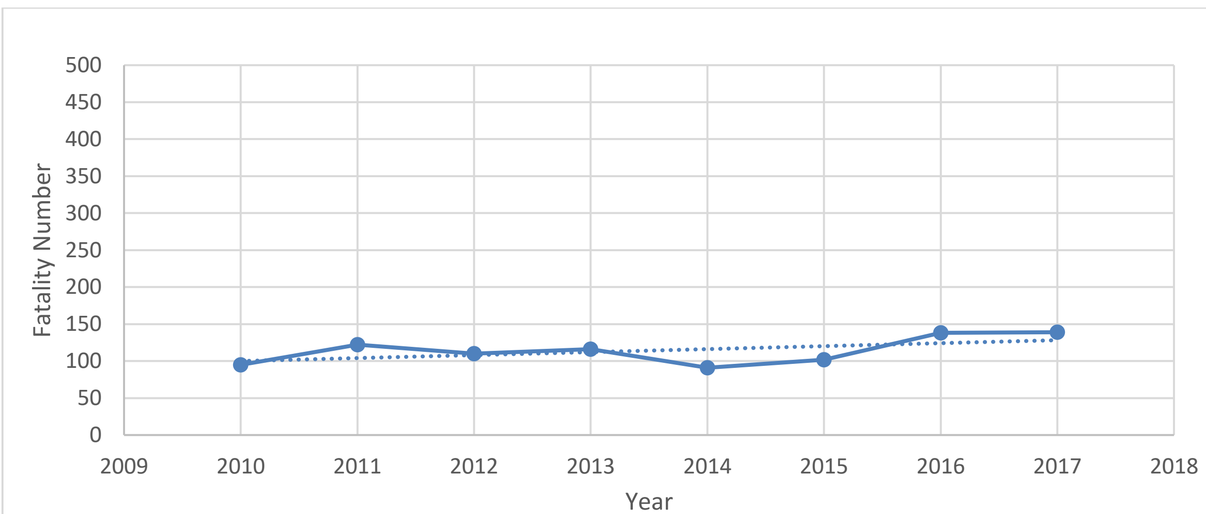


Figure 3.2 Motorcycle Crash Fatality (2010 – 2017)

3.3 Determining Variables Using Google Earth

Google Earth program was used to determine some of the variables considered for the analysis. These variables were decided after consideration of different aspects and suggestions with regard to motorcycle crashes and guardrail design. With the latitude and longitude data available from the crash data, it was possible to actually look up to the crash site and note the guardrail type, road conditions, retrofit to guardrails, and type of street. This was done with the street view facility (Figure 3.3 and 3.4) available in the Google Earth Pro software. Also, the historical satellite imagery option was used to match the satellite view with the crash year for some reports.

All 692 crash reports with motorcycle crashed into guardrail were analyzed with the Google Earth. These cases included Fatal, Suspected Serious Injury, Non–Incapacitating, and not Injured and Possible Injury crash severity. Crash data with crash year, crash severity, county, city, crash latitude, crash longitude, crash road speed limit, first harmful event, collision manner and object struck information were available.

By inputting crash latitude and longitude into Google Earth, we were able to retrieve approximate location of the crash. By street view feature, we determined the following variables:

1) **Curve**: It is important to know if the road section on which the crash took place had a curve or not. It is generally observed that curved sections have more fatal injuries as compared to other sections.
2) **Type of Street**: This variable was used to segregate between two way and one way street with motorcycle crashed into a guardrail. Also, this field is marked as intersection if the crash location is at an intersection. This variable helps us to know if street type has any effect on the crash severity and frequency of crash.
3) **Guardrail**: Google Earth Street View made it possible to clearly look at the type of guardrail. Guardrail type can have significant effect on the crash severity. Most of the guardrail were W beam type with either wooden or steel I beam posts. However, there were few cases with exception such as cylindrical rails or double steel rail. Determining guardrail type is a very important factor to be considered for the crash data analysis part of

the project as it would help us decide the retrofit or guardrail option according to the crash severity associated with specific type.

4) **Retrofit to Guardrail**: Through the street view feature on Google Earth, it was checked if the impacted guardrail already had retrofit option available. This was necessary to determine as it would directly signify if a retrofit option has any effect on motorcycle crashes over time. However, there were very few cases with a retrofit available over the length of guardrail. Most common type of retrofit observed was end terminal cushion provided at ends of guardrail. However, they were ineffective as they were only provided at ends and were not motorcycle friendly.

All crash severity types were analyzed with Google Earth and above mentioned variables were determined. However, there were some assumptions taken into consideration while incorporating these variables as follows:

1) Crash latitude and longitude gives approximate location of the crash. Thus the google earth street view for a particular set of coordinates would not show the exact crash site. This would sometimes lead to a location which might not have a guardrail at all but with guardrail at some distance from the coordinates. Hence during inputting guardrail type, it was assumed that crash site (which is very near to the coordinates given) would have the same guardrail type as that on the street view obtained by crash coordinates.
2) Some guardrails were provided with wooden posts for major portion of the rail and steel I beam posts for initial and terminating portion or vice versa. We have classified such type of guardrail with posts as one occupying the major portion of the guardrail length. Such

guardrails were again verified with the cash reports data and checked if there is any specific detail about the posts available. Necessary corrections were made for any changes.

3) Many guardrails have initial portion with wooden posts cut at the top level. Thus the protruding part of the post has a square cross section. However, there is no segregation done for such type of post and all such wooden post are simply classified as wood post. This is again due to the fact that major portion of the guardrail were occupied by the cylindrical top wooden posts.
4) End terminal cushion is considered as a retrofit to the guardrail as it is an addition to normal rails. However, terminal cushions do not really contribute to reduction of the crash severity for motorcycle crashes. Hence, for crashes taking place in the middle portion of the guardrail, where the end terminal cushion is not visible anywhere near to the crash coordinates, the retrofitting field is marked as 'NO'. Hence the retrofit variable is concerned only with the crash site and not for whole length of the guardrail.
5) Exceptional cases with no information available about variable were marked with 'No Info' in the variable field.

Each crash analyzed by Google Earth was linked with a crash ID. After analyzing all cases and inputting variable as per above mentioned assumptions in an excel file, the actual crash reports with crash IDs were analyzed. Exceptional cases were again checked with the crash reports and information was confirmed with the data and report drawings available. Necessary changes were made after checking.

Figure 3.3 Street View Screenshot from Google Earth Pro Software

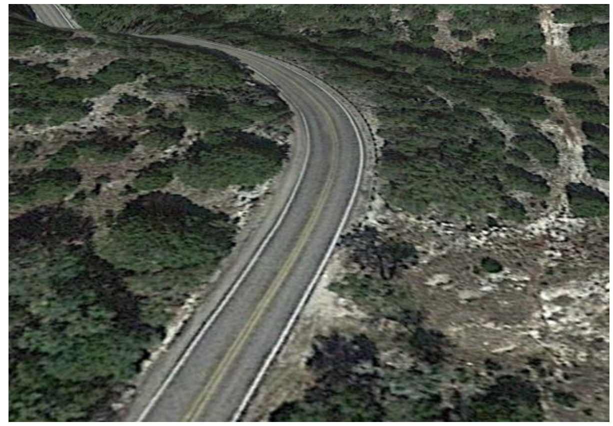


Figure 3.4 Satellite View Screenshot from Google Earth Pro Software

3.4 Crash Reports

After completing the Google Earth Analysis, the crash reports of fatal and suspected serious injury crash severity were analyzed. Fatal crash reports accounted for a total of 122 reports while Suspected Serious Injury accounted for 228 crash reports. These Police crash reports provided valuable information such as crash ID, number of units involved in crash, vehicle make and model, rider and passenger (if any) details, road on which crash occurred, investigator's narrative opinion about the incident and a field diagram representing the crash.

The variables considered while analyzing crash reports included:

1) **Direction of travel**: This field was obtained from the field diagram showing the north sign or from Investigator's narrative. Hence this field was marked with either of North bound, South Bound, East Bound or West Bound. This variable was determined to obtain travel direction of the rider with motorcycle when the crash happened. This would give us information about rider trajectory before crash and relative location of rider and guardrail before crash especially for a two way street with guardrail on one side of the road.

2) **Impact location of the road section**: This variable was determined from the field diagram and investigator's narrative. It specifies if the motorcyclist was entering, leaving or was at the middle of the road section just before the crash. This would give information about the effects of changes in road sections on the crashes and its severity.

3) **Crash in an Upright or Sliding Position**: This is an important variable with regards to the objective of this project. This information was obtained from field diagram and narrative available in the report. Although there were comparatively less cases where narrative clearly described the sliding position before crash, field diagrams were used to judge and fill this variable field. This variable would help us know the percentage of crashes in upright or sliding position, its frequency and crash severity associated with it. Thus it would be a very important consideration to be kept in mind while designing guardrail. Also this would help us associate crash position with road sections.

4) **After Impact**: This information was available from the field diagram and narrative given by investigator. It is used to provide information about after impact condition of the rider. Thus, it determines if the rider was ejected, ejected on same side of guardrail or on the other side of guardrail, or if no information is available from crash report. This would help us know whether containment criteria of guardrail is satisfied. Guardrail should be designed so as to contain rider after impact and prevent from ejecting rider to other side which can cause severe or fatal injuries.

5) **Angle of Impact**: This field is obtained from field diagram. Although no definite angle is mentioned on crash reports, an arbitrary angle as per researcher's judgment is assigned based on diagram point of impact line. This variable can help us determine if collision was

head on or rider sideswiped the guardrail causing injuries. This variable can also be used to decide full scale crash test configuration.

6) **On Post/Middle**: This field was obtained from diagram and narrative given in crash reports. It is used to determine if motorcycle with rider directly hit the post or hit the guardrail between two posts. Majority of the reports did not mention clearly if rider hit the post or not. However, some field diagrams indicated clear impact with posts and some narrative defined if rider hit post. Generally direct impact with post results in fatal injuries, hence this variable would be important to show how protruding elements in a guardrail can be fatal.

7) **Driver Characteristics**: This variable is determined from investigator's narrative. It shows driver behavior before crash. This field shows if rider was intoxicated, over speeding, distracted, rash driving, normal, lost control, was an amateur rider or combination of these factors. This variable can help us know if rider behavior had any effects on the crash severity. Note that rider behavior is stated as normal if rider himself is not responsible for the crash but other units have role in the crash, for example motorcycle being hit from behind or animal suddenly hitting the rider on road. Similarly, driving vehicle at an unsafe speed for weather conditions at the time of crash is marked as an over speeding case.

8) **Other**: This field provides a short description or keywords describing actual crash scenario and important factors resulting in crash. This data is obtained from narrative provided in the report. This is just a supplementary information provided along with other data to have a better understanding of the crash situation.

Thus, all variables were determined from investigator's narrative and the field diagram. Data like crash year and crash ID from these reports were used for the Google Earth part of this analysis. Exceptional cases with no information available about variable were marked with 'No Info' in the variable field. Other crash severity reports were not analyzed as it would be unreasonable to analyze all cases considering time constraint and labor required.

It is to be kept in mind that some of these variables are determined based on researcher's judgment analyzing the crash report. Exact situation of the crash may vary depending upon the accuracy of data provided in the reports and in field diagram. The aim to choose these variables is to extract maximum information available from the crash reports and include it in the analysis to obtain relation between different factors involved in crash.

Thus, the entire crash data analysis uses a total of 12 variables to obtain important statistical and analytical data and relation between different factors governing crashes. Results obtained can be very useful for retrofitting or design of a guardrail to ensure motorcyclist safety.

3.5 Vehicle Identification Number (VIN) Decoding

349 VIN number were processed using the NHTSA's VIN decoder available online. VIN information is collected by law enforcement on the crash reports. Information for 329 motorcycles were returned from the program.

3.6 Descriptive Statistical Analysis

324 fatal and suspected serious injury, single vehicle, motorcycle crashes were used for this analysis which involved contact with a guardrail. Google Earth and the crash reports data were linked with the CRIS data using the crash ID from CRIS. Unit (i.e. motorcycle) data, crash data and rider level data is available from CRIS. The final data set contains CRIS, Google Earth, and crash report data and VIN data.

3.6.1 Environmental Crash Characteristics

Following analysis was conducted to check if the SMV motorcycle crashes involving guardrails are not a result of environmental characteristics.

Lighting conditions

For this analysis, the crashes were classified according to the lighting conditions under which it took place. For the crashes under consideration, 58% were classified as occurring in daylight conditions while 41% occurring in dark conditions. Table 3.2 gives the number of crashes and percentage as per the lighting condition variables.

Table 3.2 Single Vehicle Motorcycle Crashes Involving Guardrail Contact by Lighting Condition, 2010-2017

Lighting Condition	Count of Light Condition	Percentage of Light Condition
DAYLIGHT	187	58%
DARK, LIGHTED	55	17%
DARK, NOT LIGHTED	74	23%
DARK, UNKNOWN LIGHTING	2	1%
DUSK	5	2%
DAWN	1	0%
Grand Total	324	100%

By considering the crashes occurred by the crash hour, it can be seen that the time of day and the lighting condition do not play a role in occurrence of a guardrail crash. Table 3.3 provides the number of crashes occurring during given hour of the day.

Table 3.3 Single Vehicle Motorcycle Crashes Involving Guardrail Contact by Hour of the Day, 2010-2017

Hour of the Day	Count of Crash Hour	Percentage of Crash Hour
00:00 - 00:59	8	2.5%
01:00 - 01:59	12	3.7%
02:00 - 02:59	21	6.5%
03:00 - 03:59	6	1.9%
04:00 - 04:59	3	0.9%
05:00 - 05:59	1	0.3%
06:00 - 06:59	4	1.2%
07:00 - 07:59	9	2.8%
08:00 - 08:59	10	3.1%
09:00 - 09:59	3	0.9%
10:00 - 10:59	14	4.3%
11:00 - 11:59	24	7.4%
12:00 - 12:59	18	5.6%
13:00 - 13:59	19	5.9%
14:00 - 14:59	22	6.8%
15:00 - 15:59	14	4.3%
16:00 - 16:59	21	6.5%
17:00 - 17:59	15	4.6%
18:00 - 18:59	14	4.3%
19:00 - 19:59	14	4.3%
20:00 - 20:59	18	5.6%
21:00 - 21:59	18	5.6%
22:00 - 22:59	19	5.9%
23:00 - 23:59	17	5.2%
Grand Total	324	100.0%

Weather Condition

It is evident that it can be more challenging to drive a motorcycle in bad weather conditions. However, for the crashes considered in the study, weather conditions listed by law enforcement at the time of the SMV motorcycle crashes resulting in fatal and suspected serious injury crashes was primarily listed as clear, 85%. The following table gives the data as per number and percentage of crashes occurring during different weather conditions.

Table 3.4 Single Vehicle Motorcycle Crashes Involving Guardrail Contact by Weather Condition, 2010-2017

Weather Condition	Count of Weather Condition	Percentage of Weather Condition
CLEAR	278	85.8%
CLOUDY	37	11.4%
RAIN	5	1.5%
SEVERE CROSSWINDS	2	0.6%
FOG	1	0.3%
OTHER (EXPLAIN IN NARRATIVE)	1	0.3%
Grand Total	324	100.0%

Similarly the surface conditions data available during the time of crash is reported to be dry surface conditions for 93% of the crashes. There were very less number (less than 1%) of the crashes in which sand, mud or dirt on the roadway played a role in the crash.

3.6.2 Location

As per the data available and analysis, between 2010 and 2017, fatal and suspected serious injury SMV motorcycle crashes involving guardrails occurred in 77 of the 254 Texas counties.

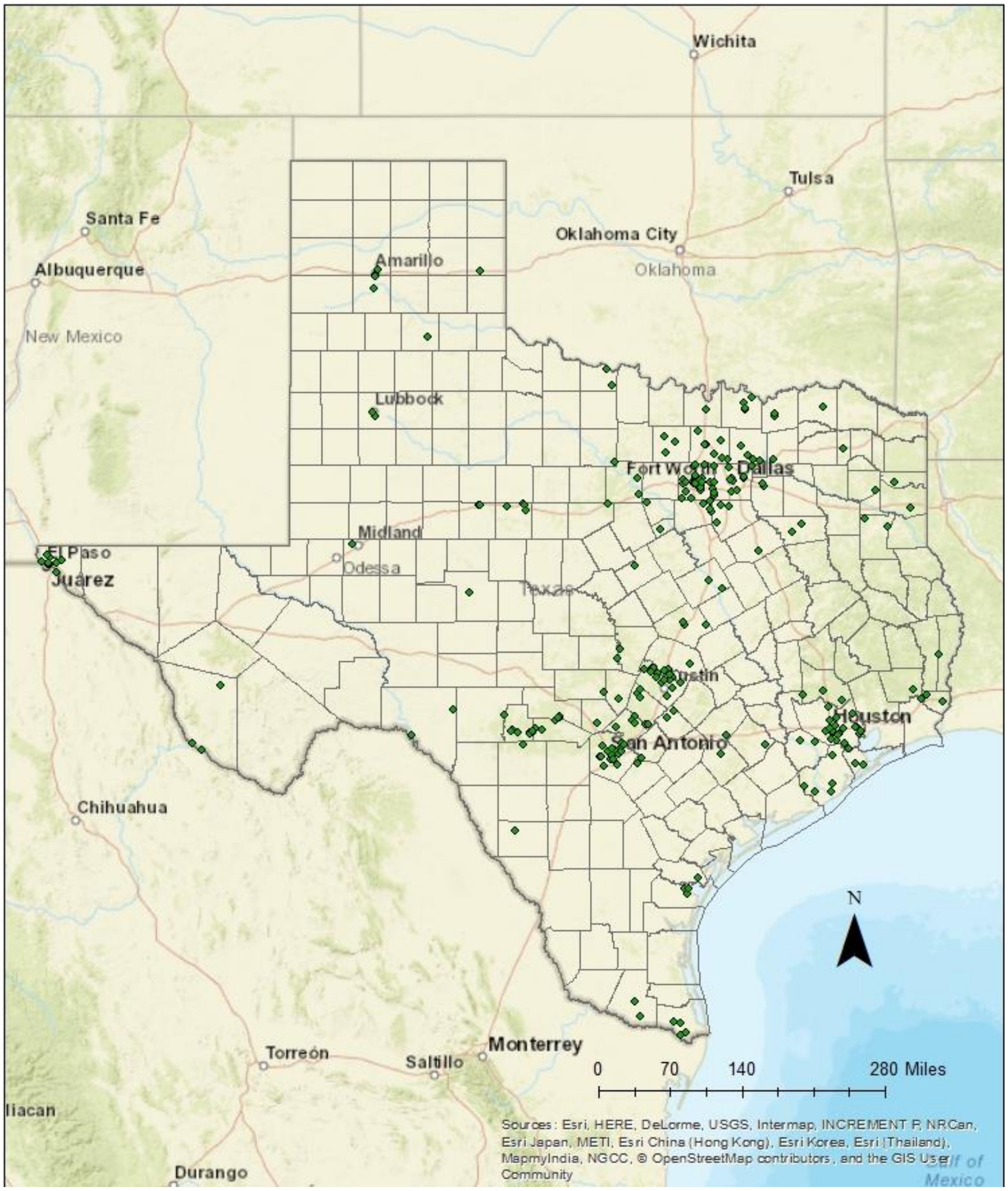


Figure 3.5 Map of Fatal and Suspected Serious Injury Motorcycle Crashes Involving Guardrail Contact, 2010-2017

Out of those counties, Tarrant and Real counties have the 35 crashes each. The data supports the fact that Real County is the location for one of the most popular motorcycle rides in the State and Tarrant County has one of the highest rates of vehicle miles traveled. The following table list the counties by number of crashes. Table 3.5 gives the count of crashes for different counties in Texas.

Table 3.5 Count of Single Vehicle Motorcycle Crashes Involving Guardrail Contact by County, 2010-2017

County	Count of Crash	County	Count of Crash
Tarrant	35	Kerr	5
Real	35	Williamson	5
Harris	27	Hays	5
Bexar	23	Wise	4
Travis	16	Taylor	4
Dallas	15	Bell	4
El Paso	12	Grayson	4
Denton	11	Ellis	4
Nueces	6	Johnson	4
Collin	6	Bandera	3
Brazoria	6	Presidio	3
Comal	5	Potter	3
Cameron	5	Galveston	3
Burnet	3	Starr	1
Montgomery	3	Madison	1
Fannin	2	Wheeler	1
Randall	2	Marion	1
Orange	2	San Patricio	1
Caldwell	2	Hood	1
Val Verde	2	Briscoe	1
Henderson	2	Midland	1
Fort Bend	2	Uvalde	1
Hidalgo	2	Hunt	1
Palo Pinto	2	Lavaca	1
Kaufman	2	Navarro	1
Rusk	2	Harrison	1
Lamar	2	Newton	1
Wichita	2	Somervell	1
Lubbock	2	Hamilton	1
McLennan	2	Edwards	1
Nolan	2	Dimmit	1
Fayette	1	Tom Green	1
Colorado	1	Jefferson	1
Upshur	1	Wilson	1
Gillespie	1	Hardin	1
Blanco	1	Young	1
Franklin	1	Eastland	1
Cooke	1	Kendall	1
Guadalupe	1	Grand Total	324

Between the years 2010 and 2017, fatal or suspected serious injury SMV motorcycle crashes involving guardrails occurred on 174 different roadways. Most number of crashes were identified to take place at RM337 in Real County. The crashes are associated with a control section for crashes that occurred on state-maintained roadways. Of the 324 crashes in this analysis 248 were associated with a roadway control section. This would allow the crash to be linked to the roadway inventory for that section of roadway. Table 3.6 gives the data relating different counties with the crash control section and number of crashes.

Table 3.6 Count of Crashes by County and Control Section, 2010-2017

County	Crash Control Section	Total Number of Crash	County	Crash Control Section	Total Number of Crash
Real	0792-02	18	El Paso	2121-02	3
Real	0792-01	16	Harris	0500-03	3
Bexar	0073-08	6	Bell	0231-04	2
Tarrant	1068-02	6	Bexar	2452-03	2
Nueces	0074-06	5	Burnet	1378-04	2
Tarrant	0008-13	5	Dallas	0092-14	2
Kerr	0291-03	4	Dallas	2374-02	2
Travis	1378-01	4	El Paso	0167-01	2
Bexar	0025-02	3	Galveston	0389-07	2
Bexar	0521-04	3	Harris	0508-07	2
Collin	1392-01	3	Harris	0598-01	2
Dallas	0196-03	3	Nolan	0006-03	2
Denton	0816-02	3	Tarrant	0014-16	2
Bandera	0291-04	1	Tarrant	0172-06	2
Bandera	0678-02	1	Tarrant	0363-03	2
Bandera	0855-04	1	Cameron	0039-10	1

Table 3.6 Count of Crashes by County and Control Section, 2010-2017 (Continued).

County	Crash Control Section	Total Number of Crash	County	Crash Control Section	Total Number of Crash
Bexar	0016-07	1	Cameron	1138-01	1
Bexar	0017-09	1	Collin	0281-02	1
Bexar	0017-10	1	Colorado	0709-01	1
Bexar	1890-01	1	Comal	0511-02	1
Bexar	3508-01	1	Cooke	0195-01	1
Blanco	0253-01	1	Dallas	0047-07	1
Brazoria	0111-08	1	Dallas	0196-07	1
Brazoria	0179-03	1	Dallas	1068-04	1
Brazoria	0586-01	1	Dallas	2374-01	1
Brazoria	1003-01	1	Dallas	2374-03	1
Brazoria	1004-01	1	Denton	0081-13	1
Briscoe	0541-01	1	Denton	0364-03	1
Burnet	0150-05	1	Denton	2979-01	1
Caldwell	0384-04	1	Dimmit	0037-07	1
Caldwell	1776-03	1	Eastland	0007-06	1
El Paso	2552-02	1	Edwards	0830-01	1
El Paso	2552-04	1	El Paso	2552-01	1
Ellis	0048-04	1	Harris	0271-07	1
Ellis	0596-02	1	Harris	0271-14	1
Fannin	0045-05	1	Harris	0271-15	1
Fannin	0279-03	1	Harris	0271-17	1
Fayette	0535-07	1	Harris	0389-12	1
Fort Bend	0027-08	1	Harris	0502-01	1
Fort Bend	0543-02	1	Harris	0508-01	1
Franklin	0610-02	1	Harris	0980-02	1
Galveston	0192-04	1	Harris	1062-04	1

Table 3.6 Count of Crashes by County and Control Section, 2010-2017 (Continued).

County	Crash Control Section	Total Number of Crash	County	Crash Control Section	Total Number of Crash
Grayson	0047-03	1	Hays	0016-03	1
Grayson	0202-08	1	Hays	0113-07	1
Grayson	0728-02	1	Hays	0683-03	1
Guadalupe	2233-02	1	Henderson	1085-01	1
Hamilton	0183-02	1	Henderson	1099-03	1
Hardin	0200-10	1	Hidalgo	1427-01	1
Harris	0110-05	1	Hood	0385-02	1
Johnson	0747-05	1	Hunt	0009-13	1
Johnson	1600-04	1	Johnson	0172-10	1
Johnson	3010-02	1	Palo Pinto	0314-02	1
Kaufman	0495-01	1	Potter	0168-10	1
Kaufman	0751-01	1	Potter	0275-01	1
Kendall	1042-01	1	Presidio	0957-07	1
Lamar	0221-01	1	Presidio	0957-08	1
Lubbock	0067-11	1	Presidio	1283-02	1
Lubbock	0130-05	1	Randall	0168-09	1
McLennan	0015-01	1	Randall	1480-02	1
McLennan	0049-01	1	Rusk	2653-01	1
Midland	1188-02	1	San Patricio	0180-06	1
Montgomery	0523-08	1	Somervell	0259-02	1
Navarro	0166-01	1	Tarrant	0008-14	1
Newton	0627-02	1	Tarrant	0008-15	1
Nueces	0617-01	1	Tarrant	0081-12	1
Orange	0028-11	1	Tarrant	0171-05	1
Orange	0784-04	1	Tarrant	1068-01	1
Palo Pinto	0007-10	1	Tarrant	1068-03	1
Tarrant	2374-06	1	Tarrant	2266-02	1
Taylor	0006-04	1	Tarrant	2374-05	1

Table 3.6 Count of Crashes by County and Control Section, 2010-2017 (Continued).

County	Crash Control Section	Total Number of Crash	County	Crash Control Section	Total Number of Crash
Taylor	2398-01	1	Wichita	0044-01	1
Tom Green	0077-06	1	Wichita	0156-07	1
Travis	0151-06	1	Williamson	0015-09	1
Travis	1186-01	1	Williamson	0204-04	1
Travis	2100-01	1	Williamson	0683-01	1
Upshur	0640-04	1	Wilson	1437-02	1
Uvalde	0036-07	1	Wise	0013-07	1
Val Verde	0022-07	1	Wise	0134-07	1
Val Verde	0160-04	1	Wise	1751-01	1
			Young	0362-01	1

For other crashes which are not provided with a control section in the CRIS database were identified by the crash assigned to county and the roadway. A review of the remaining 76 crashes shows that the majority of the crashes occurred on roadways that would be considered local roads. Table 3.7 gives the count of crashes not associated with a control section as per CRIS database.

Table 3.7 Count of Crashes Not Associated with a Control Section in the CRIS Database, 2010-2017

County	Derived Road	Total Number of Crashes	County	Derived Road	Total Number of Crashes
Bexar	IH0010	2	Comal	FARHILLS DR	1
Harris	IH0045	2	Comal	FM0306	1
Tarrant	WINSCOTT PLOVER RD	2	Comal	RIVER RD	1

Table 3.7 Count of Crashes Not Associated with a Control Section in the CRIS Database, 2010-2017 (Continued).

County	Derived Road	Total Number of Crashes	County	Derived Road	Total Number of Crashes
Bell	N WHEAT RD	1	Dallas	LAKE RIDGE PKWY	1
Bexar	OLD SEGUIN RD	1	Dallas	LIBERTY GROVE RD	1
Bexar	ROADRUNNER WAY	1	Dallas	US0080	1
Brazoria	MASTERS RD	1	Denton	HIGHLAND VILLAGE RD	1
Cameron	E STENGER ST	1	Denton	IH035W	1
Cameron	FM0511	1	Denton	IH2000	1
Collin	HARDIN BLVD	1	Denton	MARSH LN	1
Collin	WATKINS RD	1	Denton	N I 35E	1
El Paso	CARNEGIE AVE	1	Harris	SH0146	1
El Paso	N COPIA ST	1	Harris	SOUTHWEST FWY	1
El Paso	SL 375	1	Hays	QUAIL RUN	1
El Paso	TURNER RD	1	Hays	W FITZHUGH RD	1
Ellis	FM0983	1	Hidalgo	SEMINARY RD	1
Ellis	N WALNUT GROVE RD	1	Jefferson	BIGNER RD	1
Gillespie	LOWER ALBERT RD	1	Kerr	IHIH10	1
Harris	E OREM DR	1	Lamar	US0271	1
Harris	EASTEX FWY	1	Lavaca	FM 957	1
Harris	EVERGREEN DR	1	Madison	FM0978	1
Harris	HOMESTEAD RD	1	Marion	FM 726	1
Harris	MEMORIAL DR	1	Montgomery	CARRIAGE HILLS BLVD	1
Harris	N COMMERCE ST	1	Montgomery	GRAND PKWY	1
Rusk	COUNTY ROAD 156	1	Potter	E HASTINGS AVE	1
Starr	US0083	1	Real	RR0337	1
Tarrant	BLUE MOUND RD E	1	Travis	AIRPORT BLVD	1
Tarrant	LAKE RIDGE PKWY	1	Travis	BULLICK HOLLOW RD	1

Table 3.7 Count of Crashes Not Associated with a Control Section in the CRIS Database, 2010-2017 (Continued).

County	Derived Road	Total Number of Crashes	County	Derived Road	Total Number of Crashes
Tarrant	RANDOL MILL AVE	1	Travis	FM3238	1
Tarrant	S HAMPTON RD	1	Travis	OLD TX 20	1
Tarrant	SH0114	1	Travis	RM 2769	1
Tarrant	SILVER CREEK RD N	1	Travis	WELLS BRANCH PKWY	1
Taylor	OLD ANSON RD	1	Williamson	FM2243	1
			Williamson	US0183	1
			Wise	COUNTY ROAD 3470	1

3.6.3 Speed Limit

The speed limit of the roadway on which a crash occurred is reported by Law enforcement officers. Of the 324 crashes, 71% of the suspected serious injury or fatal SMV crashes involving guardrail contact occurred on roadways with a speed limit range of 45 to 65 miles per hour. 55 miles per hour was the single value with highest percentage (25%) of a reported limit. Table 3.8 gives the count and percentage of reported speed limit for fatal and suspected serious injury SVM crashes.

Table 3.8 Count and Percentage of Reported Speed Limit for Fatal and Suspected Serious Injury Single Motor Vehicle Motorcycle Crashes Involving Guardrail Contact, 2010-2017

Reported Speed Limit	Count of Crash Speed Limit	Percentage of Crash Speed Limit
0	5	2%
20	2	1%
25	2	1%
30	14	4%
35	19	6%
40	19	6%
45	40	12%
50	21	6%
55	81	25%
60	60	19%
65	27	8%
70	11	3%
75	11	3%
No Data	12	4%
Grand Total	324	100%

3.6.4 Roadway Alignment

Road alignment is also reported by officer along with the speed limit. It was found from the CRIS data that 73% of the suspected serious injury and fatal SMV motorcycle crashes occurred on roadways which were identified as curved and 26% of roadways were identified with straight alignment. The following table provides the percentage and count of different road alignments. Table 3.9 gives the count and percentage of reported alignment for fatal and suspected serious injury SMV crashes.

Table 3.9 Count and Percentage of Reported Alignment for Fatal and Suspected Serious Injury Single Motor Vehicle Motorcycle Crashes Involving Guardrail Contact, 2010-2017

Road Alignment	Count of Road Alignment	Percentage of Road Alignment
CURVE, GRADE	128	39.5%
CURVE, LEVEL	92	28.4%
STRAIGHT, LEVEL	69	21.3%
CURVE,HILLCREST	17	5.2%
STRAIGHT, GRADE	13	4.0%
STRAIGHT, HILLCREST	4	1.2%
OTHER (EXPLAIN IN NARRATIVE)	1	0.3%
Grand Total	324	100.0%

3.7 Narrative and Diagram Review Data

324 fatal and suspected serious injury SMV motorcycle crash narratives were reviewed involving contact with a guardrail. Crash narrative is a free form field that allow the reporting officer to give additional information about the events of the crash. Also, there is a diagram section in the report which is a free form field that allows the officer to provide a not to scale drawing to illustrate the crash. Hence, the data collected and reviewed is constrained by the level of detail contained in the narrative and diagram.

3.7.1 Upright or Sliding Position

An important area of focus for the project is the injury sustained by a rider due to interaction with a guardrail during a crash event. However, position of the motorcyclist during such an interaction is not clearly informed in the CRIS database. The narratives and diagrams reveal that majority of the crashes under consideration (79%) occurred with the motorcyclist making a contact with the guardrail system in an upright position while 20% of the riders interacted in a sliding position. In both cases, one third of the total crashes under consideration resulted in a fatality. Table 3.10 shows motorcycle position data at impact in fatal and suspected serious injury for SMV crashes.

Table 3.10 Motorcycle Position at Impact in Fatal and Suspected Serious Injury Single Motor Vehicle Crashes, 2010-2017

Motorcycle Position	Count of Crash	Percentage of Crash
Upright	255	78.7%
Sliding	64	19.8%
Didn't hit	1	0.3%
Skidding opposite direction	1	0.3%
Skidding	1	0.3%
No Info	2	0.6%
Grand Total	**324**	**100.0%**

3.7.2 Impact Location on Guardrail

From the crash narratives available, crashes were classified as per the location at which the motorcycle hit the part of the guardrail system since it is important for the computational part of the project (simulations). From the results, the majority (77.5%) of suspected serious injury or fatal SMV motorcycle crashes occurred with the motorcycle making contact with the middle section of the guardrail. Table 3.11 shows impact location on guardrail data at in fatal and suspected serious injury for SMV crashes.

Table 3.11 Impact Location on Guardrail in Fatal and Suspected Serious Injury Single Motor Vehicle Crashes, 2010-2017

Guardrail Impact Location	Count of Crash	Percentage of Crash
Middle	251	77.5%
Entering	39	12.0%
Leaving	28	8.6%
No Data	5	1.5%
NA	1	0.3%
Grand Total	**324**	**100.0%**

Further, the crash narratives were reviewed to determine if they mentioned any interaction with posts. However, only 49 crashes had any information about contact with a post. Majority of the crashes had no information about post contact. It is important to note that 65% of the crashes that showed interaction with post resulted in fatality.

3.7.3 Guardrail Type

As mentioned, Google Earth was used to determine the type of guardrails involved in the crashes from the crash coordinates available. Results show that majority of the crashes considered (75%) had guardrails constructed of W-beam with wood posts. This is an important result for designing and computational part of the project since the final design of the guardrail system will rely on the type of post to be used in the project. Table 3.12 and Figure 3.6 gives the number and percentage of crashes as per different types if guardrail systems.

Table 3.12 Guardrail Type in Fatal and Suspected Serious Injury Single Motor Vehicle Crashes, 2010-2017

Guardrail Type	Count of Crash	Percentage of Crash
W beam - Wood Post	244	75.3%
No data	34	10.5%
W beam - Steel I Post	31	9.6%
NO Guardrail	6	1.9%
W beam - Steel Posts	1	0.3%
Cable barrier	1	0.3%
W beam - Steel I Post - Concrete	1	0.3%
Concrete barrier	1	0.3%
Cylindrical Steel	1	0.3%
Wire - Steel I Post	1	0.3%
Wooden Double Rail	1	0.3%
Steel Cylindrical railing	1	0.3%
Steel Railing	1	0.3%
Grand Total	**324**	**100.0%**

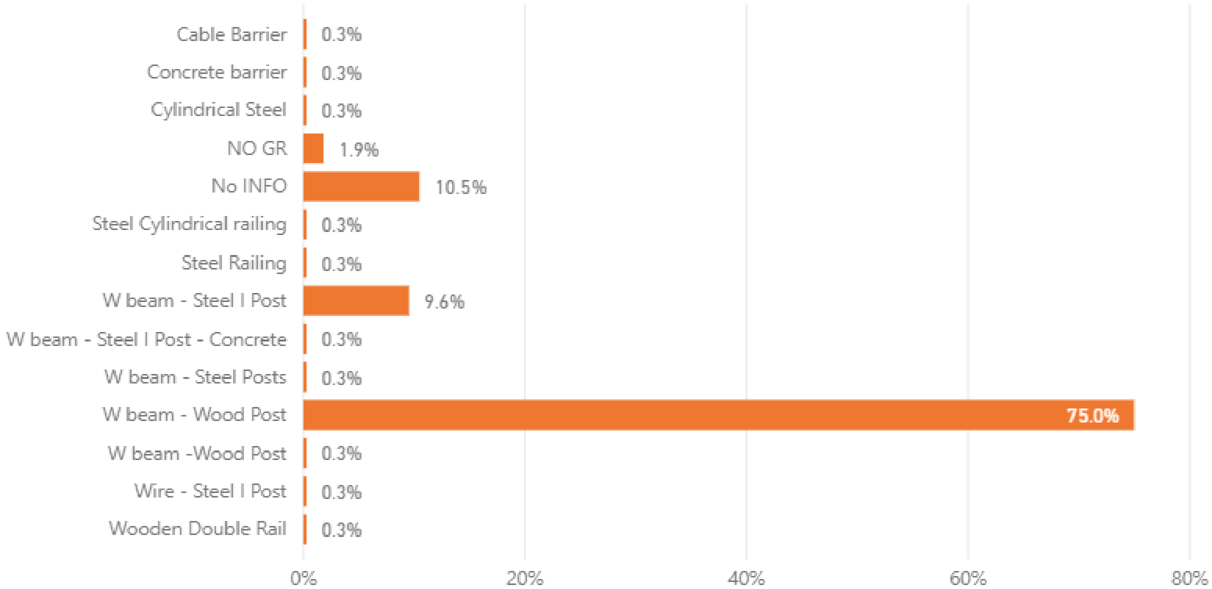


Figure 3.6 Percentage of Crashes under Review per Different Types of Guardrail, 2010-2017

Further, W-beam and wood post when compared to W-beam and steel I post shows that the steel post construction had a higher rate of fatal crashes. Table 3.13 below shows the data to support this fact.

Table 3.13 Percentage of Fatal and Suspected Serious Injury Crashes by Guardrail Type, 2010-2017

Guardrail type	Fatal Crashes	Suspected Serious Injury Crashes	Total Crashes
W beam - Wood Post	36%	64%	100%
W beam - Steel I Post	48%	52%	100%

Angle of Impact

The crash diagrams available from the reports were useful in approximating and estimating the angle of impact of the motorcycle with respect to the guardrail. Results show that majority (68%) of the crashes were estimated to have an angle of impact of approximately in the range of 30 to 45 degrees. Table 3.14 and Figure 3.7 gives data about estimated angle of impact in fatal and suspected serious injury SMV crashes.

Table 3.14 Estimated Angle of Impact in Fatal and Suspected Serious Injury Single Motor Vehicle Crashes, 2010-2017

Row Labels	Count of Angle of Impact	Percentage of Angle of Impact
10	39	12.0%
20	8	2.5%
30	123	38.0%
45	97	29.9%
50	1	0.3%
60	23	7.1%
70	8	2.5%
90	15	4.6%
No Data	10	3.1%
Grand Total	**324**	**100.0%**

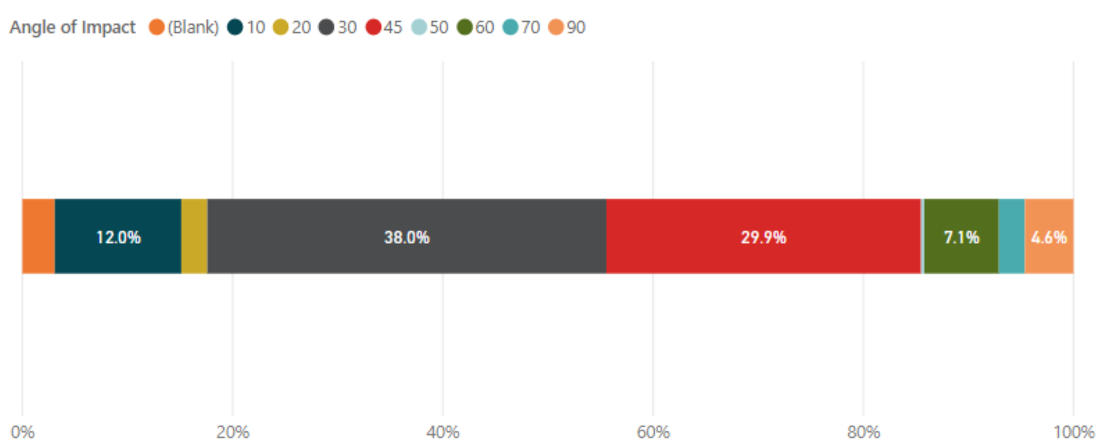


Figure 3.7 Estimated Angle of Impact w.r.t Guardrail System from Crash Narratives, 2010-2017

3.7.4 Ejection

From the available results, 70% of the suspected serious injury and fatal SMV motorcycle crashes resulted ejection of the rider from the motorcycle. Among the total 308 motorcycle operators 25% were ejected on to the other side of the guardrail after the impact while 32% were ejected off their motorcycle onto the roadway. Table 3.15 below gives the number and percentage of rider as per different after impact rider condition.

Table 3.15 After Impact Rider Conditions in Fatal and Suspected Serious Injury Single Motor Vehicle Crashes, 2010-2017

After Impact	Count of Riders	Percentage of Riders
Ejected Same side	97	31.5%
No Info	89	28.9%
Ejected Other side	78	25.3%
Ejected	37	12.0%
Ejected - On post	2	0.6%
Ejected - Slid into Guardrail	1	0.3%
No Impact	1	0.3%
Not Ejected	1	0.3%
Sliding	1	0.3%
No data	1	0.3%
Grand Total	**308**	**100.0%**

3.8 Conclusion

This section provides a descriptive statistical analysis and crash reports narrative and diagrams review. As per the results shown in this section, specific locations can be identified where suspected serious injury and fatal SVM crashes occurred. Further, types of guardrail designs, roadway speed limits and environmental conditions associated with the crashes were identified. Crash data Analysis pertaining to motorcycle crashes in Texas over the years 2010 to 2017 reveal that fatality is nearly constant. This result conforms to previous available data from NHTSA, 2013 (Figure 1.1). The fatal crashes pertaining to the impact can be due to several reasons. However, by providing suitable protection devices to the guardrail systems, the injuries due to such impact can be mitigated. Hence, this bolsters the need for requirement of a motorcycle protection guardrail system. Results related to the guardrail contact reveal that majority (78.7 %) of the crashes took place in an upright condition. Further, conducted literature review suggests almost 50% of motorcycle crashes included rider impacting in sliding position. Hence, it is important to provide satisfactory design to the retrofitted option with both top and bottom protection. Also, 75% of the guardrail posts were identified as wooden as compared to steel. This might be related to the fact that Texas is a wood post guardrail state since it is more commonly used and available. Hence, after the discussion with the committee panel, it was decided that the retrofitted design options should be designed for guardrail system with wood posts. The results of this analysis will be useful for designing potential retrofitted guardrail options.

4. CONCEPTS DEVELOPMENT AND DESIGN SELECTION

4.1 Introduction

The purpose of this chapter is to provide proposed concepts developed for consideration as potential guardrail systems retrofit options for motorcycle safety. There are various W-beam guardrail systems that have been evaluated under the Manual for Assessing Safety Hardware (MASH) standards. These include the Midwest Guardrail System (MGS) with 8-inch and 12-inch wood blockouts, the MGS without blockouts, the MGS system with steel posts, the MGS with wood posts, and a weak post W-beam system. Results from the previous section suggest a need for retrofitting such system with top and bottom protection keeping in mind the fatal and suspected serious injuries of the motorcyclists.

Considering the results obtained from the previous section (crash data analysis) and suggestions from the sponsors of this project, it was decided to specifically develop retrofit options for a wood-post MGS system with 8-inch blockout, considering it represents the system most commonly adopted by the Texas Department of Transportation (TxDOT). The retrofit options were suggested keeping in mind the results obtained from crash data analysis pertaining to upright and sliding motorcycle injuries. There might be the opportunity, however, to adapt the proposed options to other w-beam guardrail systems reported above. The proposed design concepts are not fully engineered and detailed at this stage of the research study, but the proposed concept details are sufficient for an initial feasibility assessment of rail behavior and capability.

The concepts addresses basic requirements for the retrofit guardrail system, including accommodation of service loads, and developed design alternatives with the potential to meet impact performance requirements which provides other desirable functional characteristics. Specifically, the study aimed to develop design options for a motorcycle-friendly guardrail system with the primary intent to limit severe and fatal injuries of impacting errant motorcyclists. The retrofit design considers the impacts of errant riders when occurring in both sliding and upright configurations.

The design options suggested in this section were presented and discussed with the sponsors to develop improved retrofit system concepts. This document also mentions advantages and disadvantages for each design alternative suggested, including any perceived performance benefits and application limitations. Further sections will involve more detailed engineering analysis and design development after selecting the preferred design option to address riders in sliding impact configuration and the preferred design option to address riders in upright impact configuration.

4.2 Design Options

Design options suggested in this section are retrofit options to a standard Midwest Guardrail System (MGS). The standard MGS consists of a post at 32-inch height above ground, a block out 8 inches deep and 6 inches wide, and a top rail (W6×9 beam). The top of the beam and block out are at 32 inches above ground, while the top of the rail is at 31 inches above the ground.

Attachment of the protection system to the MGS is accomplished by bolting. The options suggested give a general idea of the anticipated behavior during an impact event. Future simulations may require modifications to the shape and dimensions of the protection system to further optimize the design to minimize injury severity. Design options are not designed to satisfy containment criteria of the rider, but for minimizing injury severity of the motorcyclist caused due to an impact event.

4.2.1 Protection on Top

Option 1. Bent Plate Top Protection

Figure 4.1 shows a bent plate top protection attached to a standard MGS. The top protector consists of a flat plate bent to form a smooth vertex on top with a bent shape gently sloping down and outwards from the vertex and bent down at ends to provide some vertical distance for attachment to the wood post. The top protection bent plate can be provided with the same material and thickness as that of the W-beam rail. If this option is prioritized and selected for further evaluation through this project, extension of the plate bending would be decided based on finite element computer simulations to provide adequate implementation flexibility and dissipation of energy. Table 4.1 lists the advantages and disadvantage of Option 1.

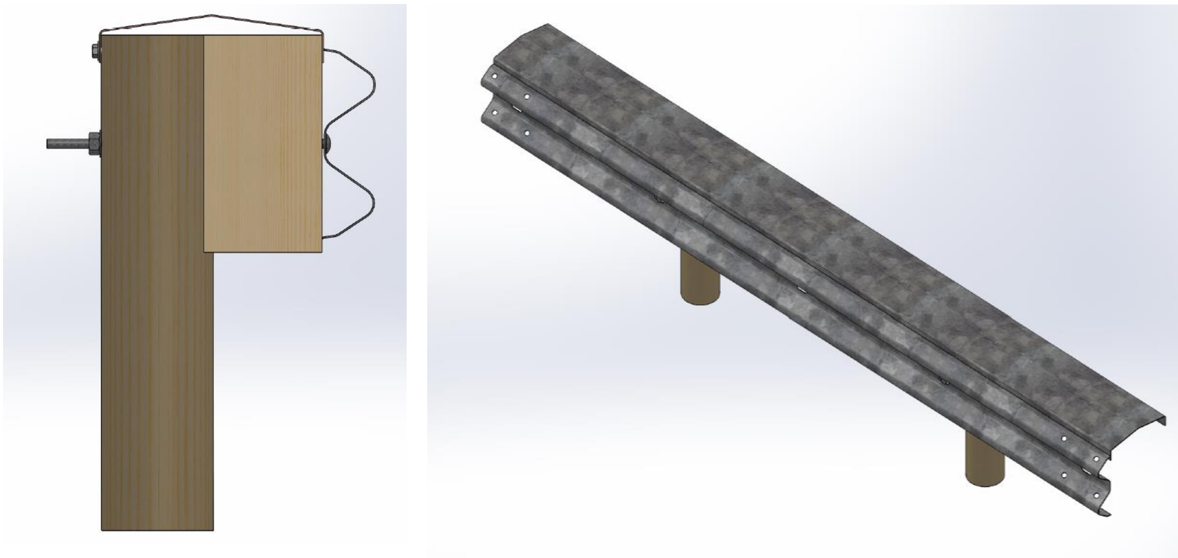


Figure 4.1 Option 1 Concept Drawing.

Table 4.1 Option 1 Perceived Advantages and Disadvantages.

Advantages	Disadvantages
1. The plate is bent at its top. The notched shape provides opportunity for small vertical deformations during impact event with the ATD, which would act as an energy dissipation mechanism.	1. Need post drilling to allow for bolting connection at back of the post.
2. The notch provides adaptation to block out and wood depth tolerances.	2. If new installation, a post with punched hole is already existing – however it is more costly and would require proper inventory.
3. No special material required for the construction of this option. A 12-gauge standard steel material would be considered.	
4. Shape can be formed with minimal effort from manufacturers.	

Table 4.1 Option 1 Perceived Advantages and Disadvantages (Continued).

Advantages	Disadvantages
5. Plate is attached with one bolt to the wood post (back), minimizing the number of bolt drilling through the wood post (on-site /retrofit).	
6. No attachment of the plate to the front W-beam or block out is proposed. Therefore. No interference with W-beam deformation is anticipated during the impact event.	
7. No attachment of the plate to the front W-beam or block out is proposed. Plate is not constrained on one side (W-beam), providing more deformation flexibility during impact event with passenger vehicle.	
8. Provides a continuous post/block out shielding option to the impacting motorcyclist.	
9. It is manufactured as one piece with no sharp edges, preventing severe injuries ("knifing" consequences) to the motorcyclist when sliding on the system during impact event.	
10. Installation can be performed on-site – no need for existing system to be dismantled for application of the suggested plate (just need to loosen existing rail to insert plate, and tighten it back up).	
11. No specific requirements for maintenance are anticipated.	

Table 4.1 Option 1 Perceived Advantages and Disadvantages (Continued).

Advantages	Disadvantages
12. Minimal cost for material /construction and installation (cost-effective).	
13. Being a continuous plate, it minimizes the possibility to have multiple debris scattered during the impact event with a vehicle.	
14. The retrofit option minimally alters the general characteristics of an existing MGS guardrail (e.g., height).	
15. Minimum installation time required on site (limited worker exposure, also no need for workers to be on the traffic side).	
16. It is manufactured as one piece with no sharp edges, preventing severe injuries ("knifing" consequences) to the motorcyclist when sliding on the system during impact event.	
17. Installation can be performed on-site – no need for existing system to be dismantled for application of the suggested plate (just need to loosen existing rail to insert plate, and tighten it back up).	
18. No specific requirements for maintenance are anticipated.	
19. Minimal cost for material /construction and installation (cost-effective).	

Table 4.1 Option 1 Perceived Advantages and Disadvantages (Continued).

Advantages	Disadvantages
20. Being a continuous plate, it minimizes the possibility to have multiple debris scattered during the impact event with a vehicle.	
21. The retrofit option minimally alters the general characteristics of an existing MGS guardrail (e.g., height).	
22. Minimum installation time required on site (limited worker exposure, also no need for workers to be on the traffic side).	

Option 2. Flat Plate Top Protection

Figure 4.2 shows the flat plate top protection attached to a standard wood-post MGS with 8-inch blockout. Option 2 consists of a flat plate bent vertically at one end and sloped at the other end to accommodate attachment to the existing w-beam rail. Attachment is to be provided by a bolted connection at a suitable interval. Bent fillet radius can be determined based on the required smoothness on top with reasonable dimensions. Top protection can be provided with the same material and thickness as that of w-beam rail. Thickness can be reduced to a certain extent to provide adequate flexibility for better rider protection during an impact event.

Table 4.2 lists the advantages and disadvantage of Option 2.

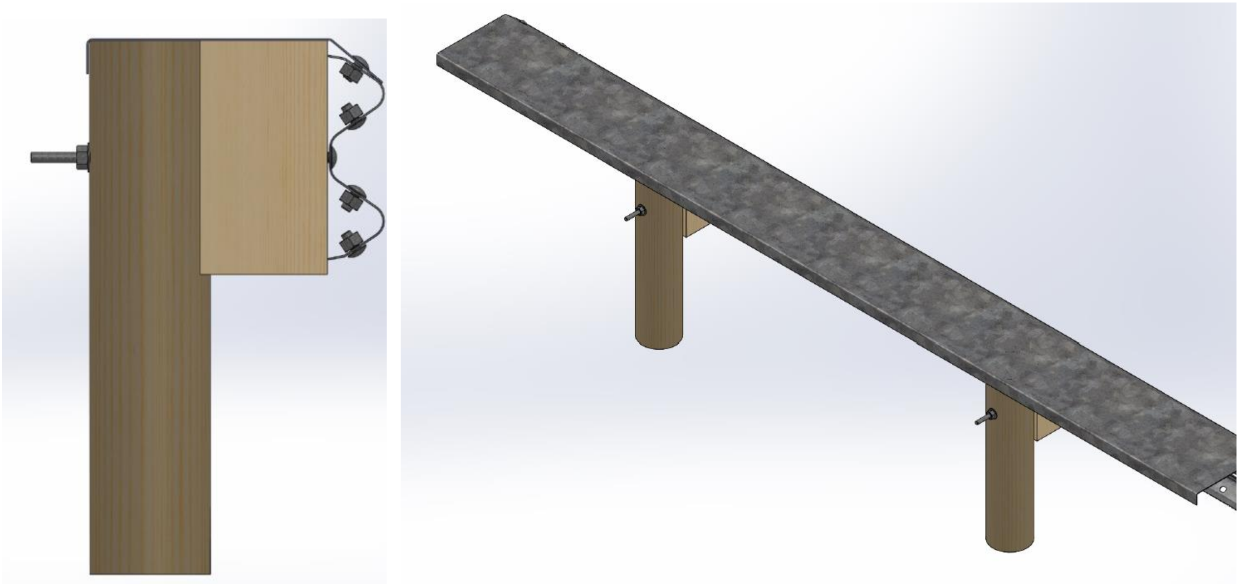


Figure 4.2 Option 2 Concept Drawing.

Table 4.2 Option 2 Perceived Advantages and Disadvantages.

Advantages	Disadvantages
1. It is manufactured as one piece with no sharp edges, preventing severe injuries ("knifing" consequences) to the motorcyclist when sliding on the system during an impact event.	1. Plate is attached with one bolt to the top rail (front) at multiple locations through the existing rail section length. This adds to the total cost as it requires ordering a special type of rail with bolt slots provided on top.
2. No special material required for the construction of this option. A 12-gauge standard steel material would be considered.	2. Punching of the rail is not suggested on site, for cost reasons.

4.2 Option 2 Perceived Advantages and Disadvantages (Continued).

Advantages	Disadvantages
3. Shape can be formed with minimal effort from manufacturers.	3. For retrofit options, the entire rail in consideration will need to be replaced (new rail is going to be more costly because it needs more pre-punched slots).
4. Provides a continuous post/block out shielding option to the impacting motorcyclist.	4. To provide sufficient bonding between top rail and plate, there is a need to provide enough in mid-span connection to prevent buckling.
5. No specific requirements for maintenance are anticipated.	5. Bolted connection of plate with top rail is exposed on the impact side of the system and might result in snagging interaction of ATD with bolts resulting in injuries.
6. Installation can be performed on-site – requires replacement of standard top rail with a special rail (with extra bolt slots) attachment to posts and plate-rail connection on top. It can be a retrofit option, but the rail needs to be changed.	6. Installation time is more as compared to previous option as this option requires a new rail attachment on posts with flat plate connected on top.
7. Being a continuous plate, it minimizes the possibility to have multiple debris scattered during the impact event with a vehicle.	
8. The retrofit option minimally alters the general characteristics of an existing MGS guardrail (e.g., height).	

4.2.2 Protection on Bottom

Option A. Flat Plate for Bottom Protection

Figure 4.3 shows a flat bottom protection for wood-posts MGS. Option A consists of a round-cornered flat bottom plate attached to the posts with two bolts (at the top and bottom of the plate). The plate is spaced at a suitable distance from the post to allow adequate deformation when dummy impacting in sliding condition. The plate is smoothly bent at the ends to provide sufficient length for bolting. Thickness and material of the bottom plate can be the same as that of the standard MGS top rail. However, thickness can be investigated through computer simulations to provide flexibility to dissipate adequate energy after dummy impact to lower injury risk. The distance between the flat bottom rail and the existing w-beam rail should be minimized to prevent any chance for dummy limbs entangling between rail and bottom protection.

Table 4.3 lists the advantages and disadvantages of Option A.

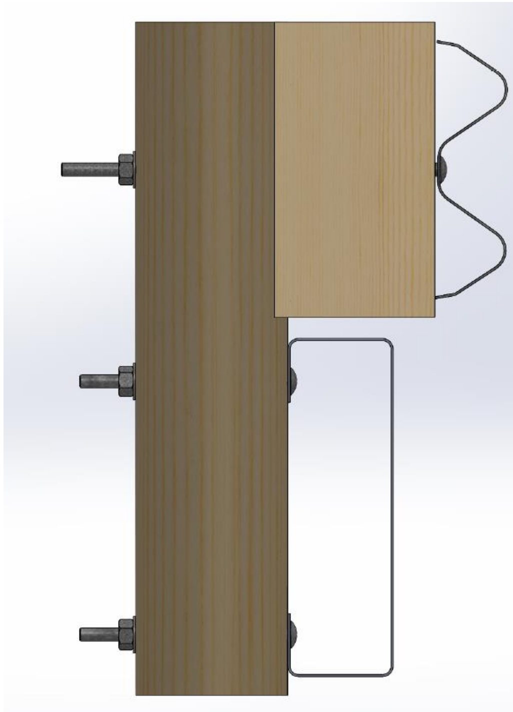


Figure 4.3 Option A Conceptual Drawing.

Table 4.3 Option A Perceived Advantages and Disadvantages

Advantages	Disadvantages
1. The flat shape provides opportunity for dissipation of energy of impacting dummy by accommodating small deformations during impact event.	1. Need post drilling to allow for bolting connection at front to the post. Two bolted connections are required at each post to provide bottom protection.
2. Provides a continuous post shielding option at bottom to the sliding motorcyclist.	2. Post drilling on site requires workers to be exposed on the traffic lane.

Table 4.3 Option A Perceived Advantages and Disadvantages (Continued).

Advantages	Disadvantages
3. Flat plate is flexible to length criteria hence can be made available in different lengths to take care of height tolerances at different sites.	3. Although plate might acts as rub rail and limit vehicle snagging potential, it is unknown vehicle behavior during impact event (tendency for vehicle climbing?)
4. No special material required for construction. A 12-gauge standard steel material would be considered.	
5. Shape can be formed with minimal effort from manufacturers.	
6. It is manufactured as one piece with no sharp edges, preventing severe injuries ("knifing" consequences) to the motorcyclist sliding on the system during impact event.	
7. Installation can be performed on-site – no need for existing system to be dismantled for application of the suggested plate.	
8. No specific requirements for maintenance are anticipated.	
9. Minimal cost for material /construction and installation (cost-effective).	

Table 4.3 Option A Perceived Advantages and Disadvantages (Continued).

Advantages	Disadvantages
10. Flat plate acts like a rub rail at bottom. This minimizes risk of vehicle snagging after impacting system especially in a no block out condition when vehicle snagging is a major risk.	
11. Being a continuous plate, it minimizes the possibility to have multiple debris scattered during the impact event with a vehicle.	

Option B. Inclined Plate Attached to Connection Plates

Figure 4.4 shows an inclined bottom protection for wood-posts MGS. Option B consists of a continuous rubrail attached to discrete connection plates. The plates are inserted between the top rail and the block out through a single bolt connection. The rubrail could be inclined at an angle. Thickness and material of plates and rubrail can be the same as that of standard w-beam. However, thickness can be reduced based on computer simulations to provide flexibility and therefore energy dissipation during dummy impact. The distance between the flat bottom rail and the existing w-beam rail should be minimized to prevent any chance for dummy limbs entangling between rail and bottom protection.

Table 4.4 lists the advantages and disadvantages of Option B.

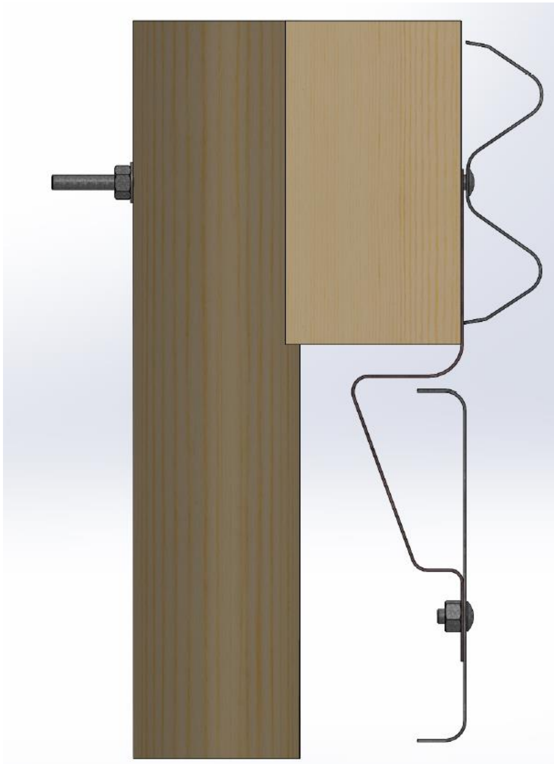


Figure 4.4 Option B Conceptual Drawing.

Table 4.4 Option B Perceived Advantages and Disadvantages

Advantages	**Disadvantages**
1. The plate is bent to form an inclined shape in front. This shape provides opportunity for dissipation of energy of impacting dummy by accommodating small deformations and rotation during impact event.	1. Installation requires existing rail to be dismantled for attachment of the suggested plate to block out or post.

Table 4.4 Option B Perceived Advantages and Disadvantages (Continued).

Advantages	Disadvantages
2. Provides a continuous post shielding option at bottom to the sliding motorcyclist.	2. Although plate might acts as rub rail and limit vehicle snagging potential, it is unknown vehicle behavior during impact event (tendency for vehicle climbing?)
3. No need of post drilling for bolting connection as bolting can be done through the previously available bolt hole for block out/post.	
4. No special material required for the construction of this option. A 12-gauge standard steel material would be considered.	
5. Shape can be formed with minimal effort from manufacturers.	
6. It is manufactured as one piece with no sharp edges, preventing severe injuries ("knifing" consequences) to the motorcyclist sliding on the system during impact event.	
7. No specific requirements for maintenance are anticipated.	
8. Inclined plate acts like a rub rail at bottom. This minimizes risk of vehicle snagging after impacting system especially in a no block out condition when vehicle snagging is a major risk.	

Table 4.4 Option B Perceived Advantages and Disadvantages (Continued)

Advantages	Disadvantages
9. Minimal cost for material /construction and installation (cost-effective).	
10. Flat plate acts like a rub rail at bottom. This minimizes risk of vehicle snagging after impacting system especially in a no block out condition when vehicle snagging is a major risk.	

Option C. Inclined Plate for Bottom Protection Attached to Posts

Figure 4.5 shows the inclined plate for bottom protection for wood-post MGS. Option C is similar to option B except that the continuous plate connection is provided directly to posts below the rail attachment. This option consists of a continuous plate attached to front of the posts of the MGS system and then bent to form an inclined protection at the bottom to accommodate a sliding rider during an impact event. Thickness and material of the plate can be the same as that of the standard MGS top rail. However, thickness can be reduced based on computer simulations to provide flexibility and therefore energy dissipation during dummy impact. The bottom end of the plate should be at a suitable height from the ground to prevent accumulation of any debris at bottom.

Table 4.5 lists the advantages and disadvantages of Option B.

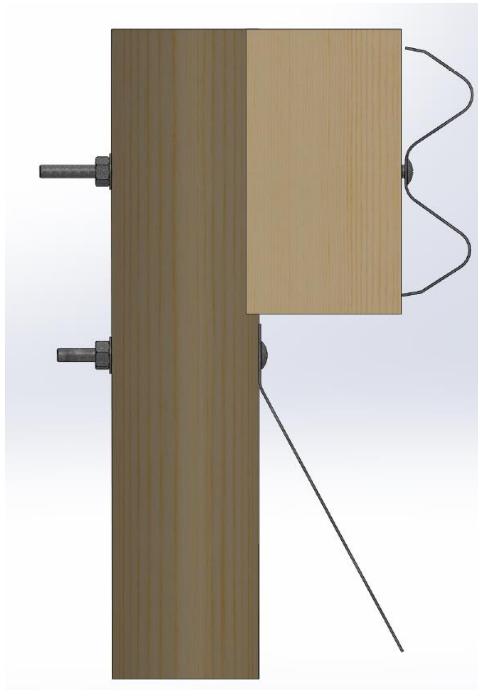


Figure 4.5 Option C Conceptual Drawing.

Table 4.5 Option C Perceived Advantages and Disadvantages.

Advantages	**Disadvantages**
1. All advantages stated in Table 4.4, expect point 2 for Option B hold true for this option.	1. Need post drilling to allow for bolting connection at front to the post. Single bolted connection is required at each post to provide bottom protection.
2. No need for existing system to be dismantled for application of the suggested plate.	

4.3 Conclusions

Tables 4.6 and 4.7 summarizes the proposed design options for protection on the top and bottom for a standard wood-post MGS with 8-inch blockouts. Considering the advantages and disadvantages for all the mentioned options and as per the detailed discussion with the project sponsors, it was decided to adopt option 1 for top protection (Bent Plate) while a combination of option B and option C for bottom protection in that, and additional mounting bracket is provided attached to the post to which the bottom plate is attached. Next chapter discusses in detail the model adopted for testing and informs about the FEA simulations conducted to check the adequacy of the proposed model.

Table 4.6 Proposed Designs for Top Protection.

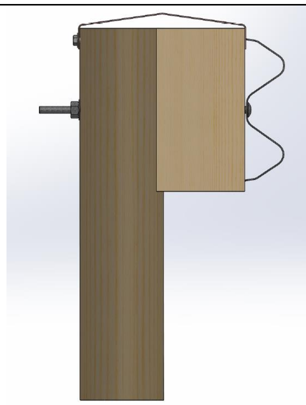
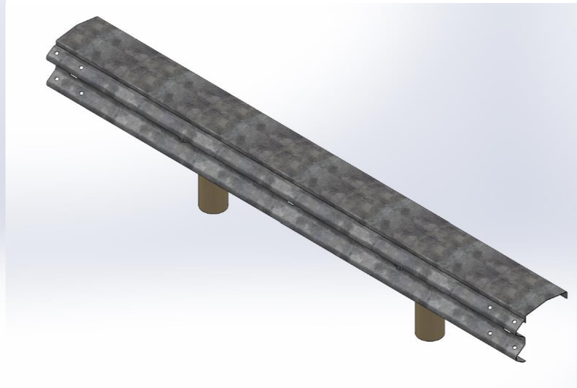
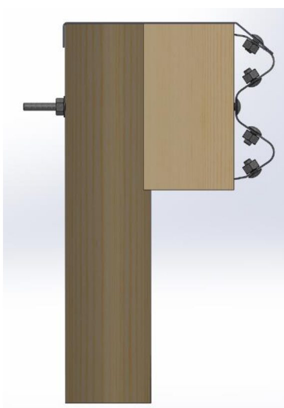
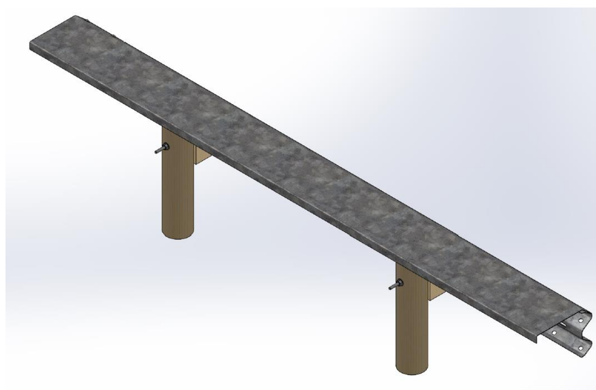
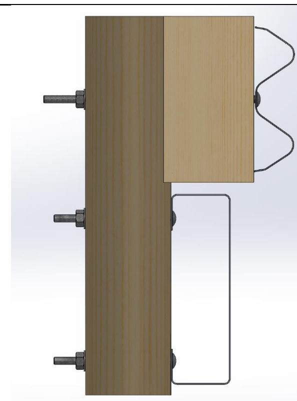
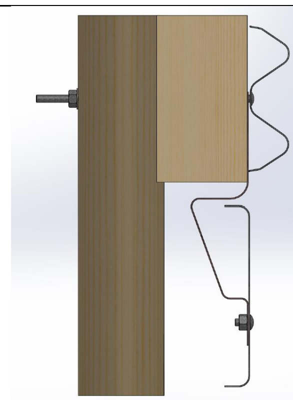
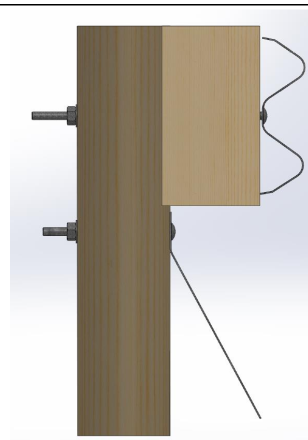
Retrofit Option	Images
Option 1	 
Option 2	 

Table 4.7 Proposed Designs for Bottom Protection.

Retrofit Option	Images
Option A	
Option B	
Option C	

5. DEVELOPING DESIGN DETAILS AND PERFORMING ENGINEERING ANALYSIS

5.1 Introduction

The purpose of this chapter is to inform the design details of the design option that was selected by considering previous design concepts and crash data analysis to address riders in sliding impact and upright impact configuration. The performance of the developed mitigation strategies to reduce the impact severity of the motorcycle rider's impacts was investigated. Engineering analyses through finite element applications was performed to determine the appropriate size and connection of the retrofit components for both design concepts, and verify if the design can accommodate service load requirements. Hence, this chapter of the thesis deals with the computational part of the project.

The ability of the design system to meet impact performance requirements and provide desirable functional characteristics was evaluated by engineering analyses. The evaluation involved the use of finite element models and impact simulations.

A finite element model of the selected design was developed and LS-DYNA was used to perform impact simulations with the inclusion of the developed model, available vehicles and motorcycle models (Figure 5.1a), available Hybrid III 50% anthropomorphic test device (ATD) (dummy) model (Figure 5.1b), as well as available rider helmet model. The results were analyzed to satisfy the Manual for Assessing Safety Hardware standard Test Level 3 impact performance requirements and checked if any other desirable functional characteristics can be provided. Simulation results were used to evaluate whether any design modification(s) are required to the developed design system to improve the probability of meeting the project objectives before proceeding with full-scale crash testing. Further sections will discuss the simulation results and conclusion obtained after analyzing each model testing. The developed model was calibrated by comparing the results of the developed FE barrier system model against available full-scale crash tests data. Once the FEA model was calibrated, the same model was used to apply the proposed design retrofit changes and conduct predictive simulations.

(a) Motorcycle FEA Model (b) ATD as Motorcycle Rider

Figure 5.1 Finite Element Computer Models.

5.2 Model Calibration

Full Scale Crash Test

A MASH compliant W-beam guardrail system with round wood posts tested by the Texas Department of Transportation (TxDOT) was used for calibration (Kovar et al., 2019). TTI researchers conducted MASH Test 3-11 on this W-beam guardrail system with round wood posts with a reduced post embedment of 36 inches. The results of the full-scale crash test were used to calibrate the developed guardrail computer model system by comparing vehicle impact behaviour and stability, as well as occupant risks and guardrail system performance upon vehicle impact.

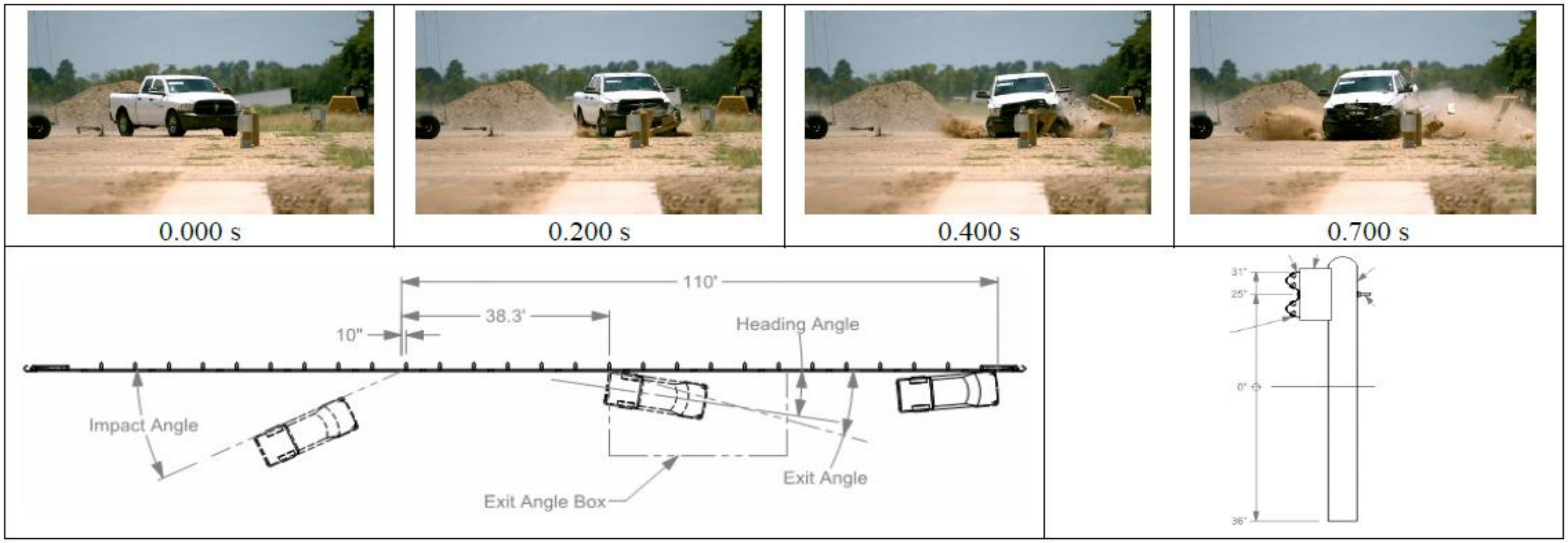
The 2013 RAM 1500 pickup truck used in the test which weighed 5018 lb. Actual impact speed and angle were 62.7 mph and 25.5°, respectively. The actual impact point was 0.8 ft upstream of post 12. Figure 5.2 and 5.3 illustrate vehicle and guardrail system before and after the full-scale crash test event. Table 5.1 describes the most notable events recorded through review of the full-scale crash test. Figure 5.4 summarizes full-scale crash test results.

Figure 5.2 Guardrail System with Test Vehicle Before Testing (Reprinted from Kovar et al., 2019).

Figure 5.3 Guardrail System with Test Vehicle After Testing (Reprinted from Kovar et al., 2019).

Table 5.1 Events During Test No. 469688-5-1 (Reprinted from Kovar et al., 2019).

Time (sec)	**Event (Actual Crash Test)**
0	Vehicle makes contact with the guardrail
0.043	Vehicle begins to redirect
0.079	Post 14 broken at ground and detached from rail element
0.132	Post 15 broken at ground and separated from rail element
0.135	Rail detached from posts upstream of impact point
0.169	Post 16 detached from guardrail and broken at ground
0.249	Post 17 broken at ground
0.3	Post 17 detached from rail element
0.396	Vehicle becomes parallel with guardrail
0.418	Post 18 detached from rail with broken blockout
0.655	Vehicle loses contact with guardrail while traveling at 27.1 mph



General Information	
Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard Test No.	MASH Test 3-11
TTI Test No.	469688-5-1
Test Date	2018-07-06
Test Article	
Type	Longitudinal Barrier – Guardrail
Name	TxDOT Round Post Guardrail System
Installation Length	181.2 ft
Material or Key Elements	W-Beam rail, round wood posts embedded 36 inches in soil at 75 inch spacing
Soil Type and Condition	AASHTO M147-65(2004), grading B Soil (crushed limestone), Damp
Test Vehicle	
Type/Designation	2270P
Make and Model	2013 RAM 1500
Curb	5006 lb
Test Inertial	5018 lb
Dummy	No dummy
Gross Static	5018 lb

Impact Conditions	
Speed	62.7 mi/h
Angle	25.5°
Location/Orientation	10.0 inches upstream of post 12
Impact Severity	122 kip-ft
Exit Conditions	
Speed	27.1 mi/h
Exit Traj./Heading Angle	16.2° / 8.9°
Occupant Risk Values	
Longitudinal OIV	15.4 ft/s
Lateral OIV	14.4 ft/s
Longitudinal Ridedown	11.0 g
Lateral Ridedown	6.8 g
THIV	20.3 ft/s
PHD	11.3 g
ASI	0.62
Max. 0.050-s Average	
Longitudinal	-5.5 g
Lateral	5.1 g
Vertical	2.0 g

Post-Impact Trajectory	
Stopping Distance	110 ft downstream adjacent to rail
Vehicle Stability	
Maximum Yaw Angle	34°
Maximum Pitch Angle	4°
Maximum Roll Angle	7°
Vehicle Snagging	No
Vehicle Pocketing	Moderate
Test Article Deflections	
Dynamic	44.1 inches
Permanent	37.0 inches
Working Width	62.2 inches
Height of Working Width	57.4 inches
Vehicle Damage	
VDS	11-LFQ-X
CDC	11FLEWX
Max. Exterior Deformation	11.0 inches
OCDI	LF0010000
Max. Occupant Compartment Deformation	None

Figure 5.4 Summary of Results for MASH 3-11 Compliant TxDOT Modified Round Wood Post Guardrail System (Reprinted from Kovar et al., 2019).

Computer Model Simulation

LS Pre-Post was used to develop a round wood post modified guardrail system model (Figure 5.5) with 36-inch embedment in soil. A guardrail system with 16 wood posts model was developed with MAT 001- ELASTIC to define wood post material properties. Further, MAT 000-ADD EROSION was used to provide erosion to wood post to incorporate the failure of the post due to vehicle impact. The maximum principal stress at failure for the erosion of 43.0 MPA was determined by iteration through model simulation testing and comparing the results with actual crash test values. MAT 025-GEOLOGIC CAP MODEL material was used to define material properties for soil. Elastic springs were provided in form of discrete element with specified elastic stiffness at the ends of the rail to incorporate the effect of guardrail terminals. Figure 5.5 shows the LS DYNA model guardrail system used for calibration.

Available validated Silverado pickup truck model was used as the test vehicle with a similar weight as the actual crash test RAM model. Test vehicle actual impact speed and angle orientation were implemented in the computer simulation. Figure 5.6 illustrates the sequential images of the simulated computer model impact event, and Figure 5.7 compares frames from the actual full-scale crash test and the calibrated computer model impact simulation.

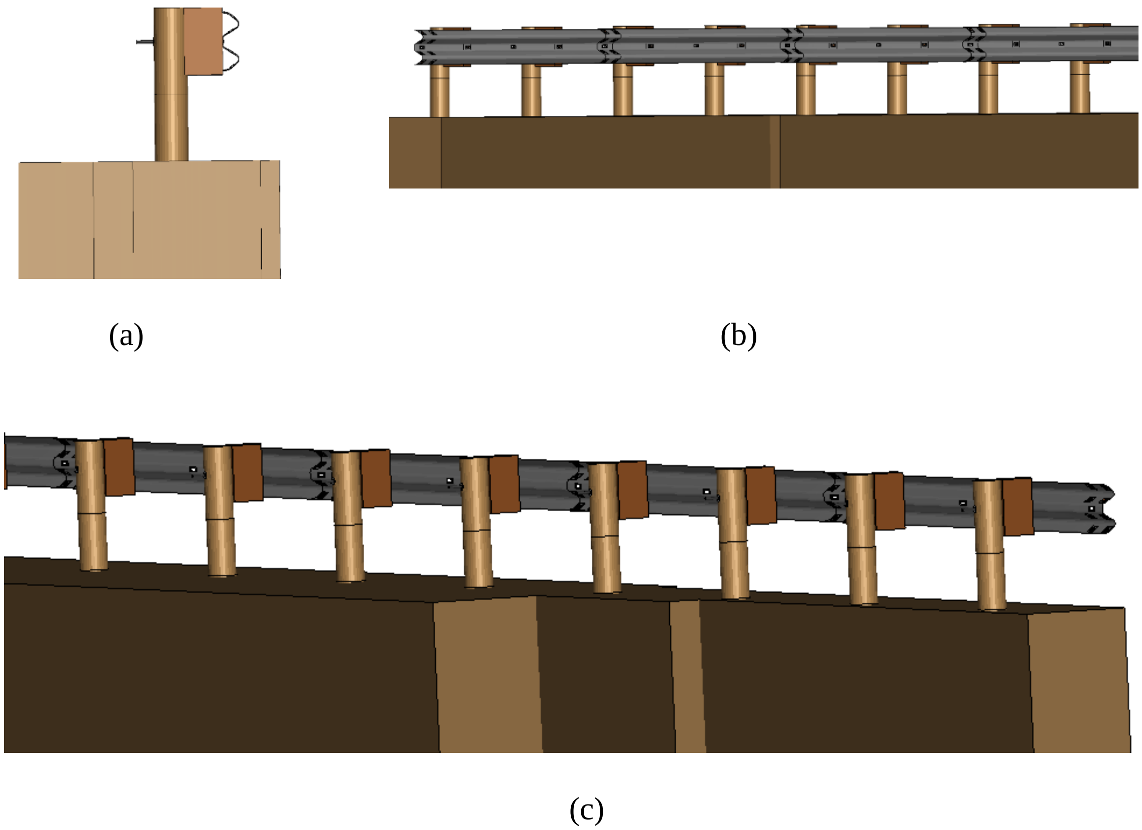


Figure 5.5 (a) Side View, (b) Perspective Front View and (c) Perspective Rear View of the LS DYNA Calibration Guardrail System Model.

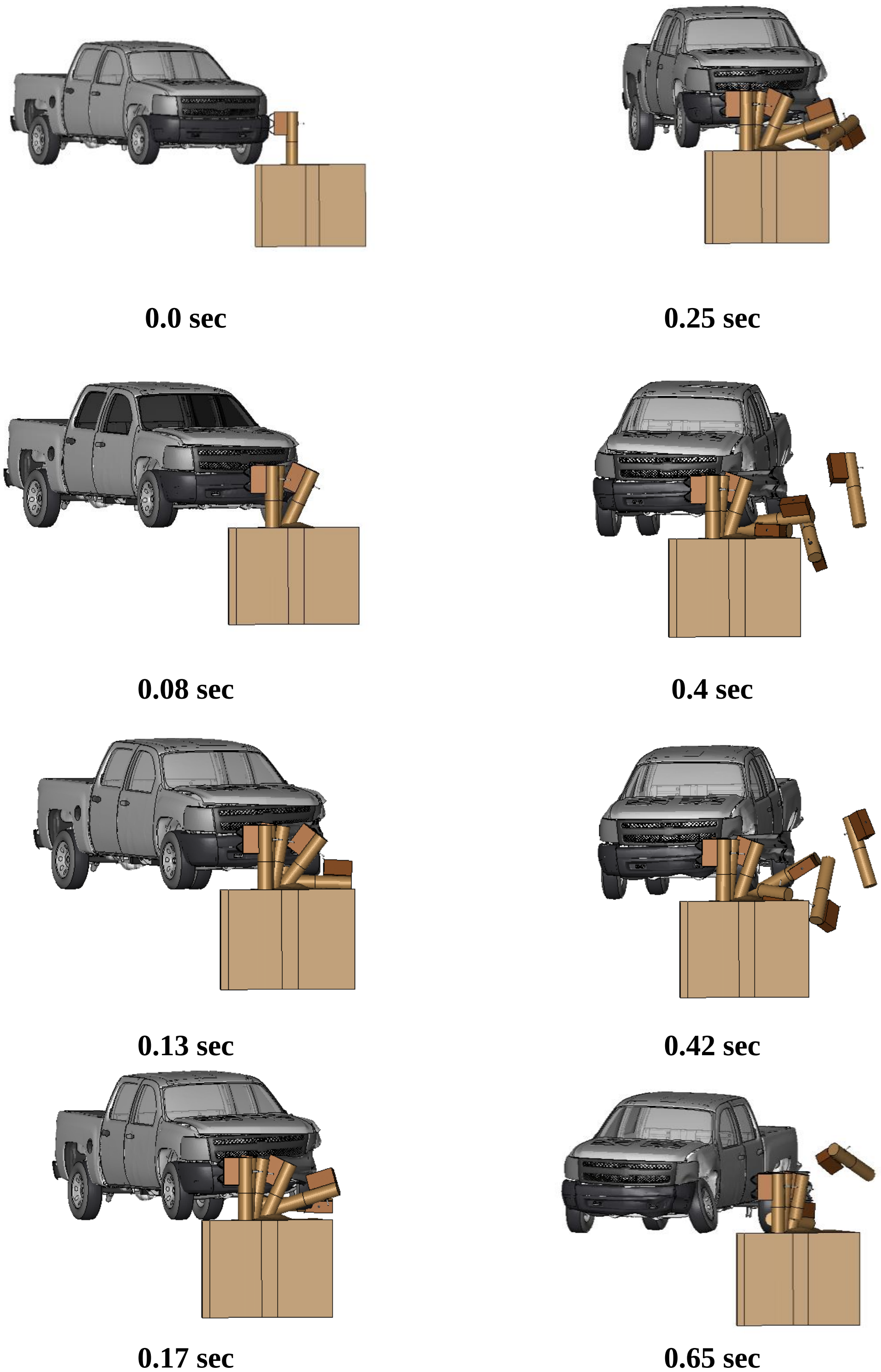


Figure 5.6 Sequential Images of Pickup Truck – Guardrail System Impact Simulation for Calibration

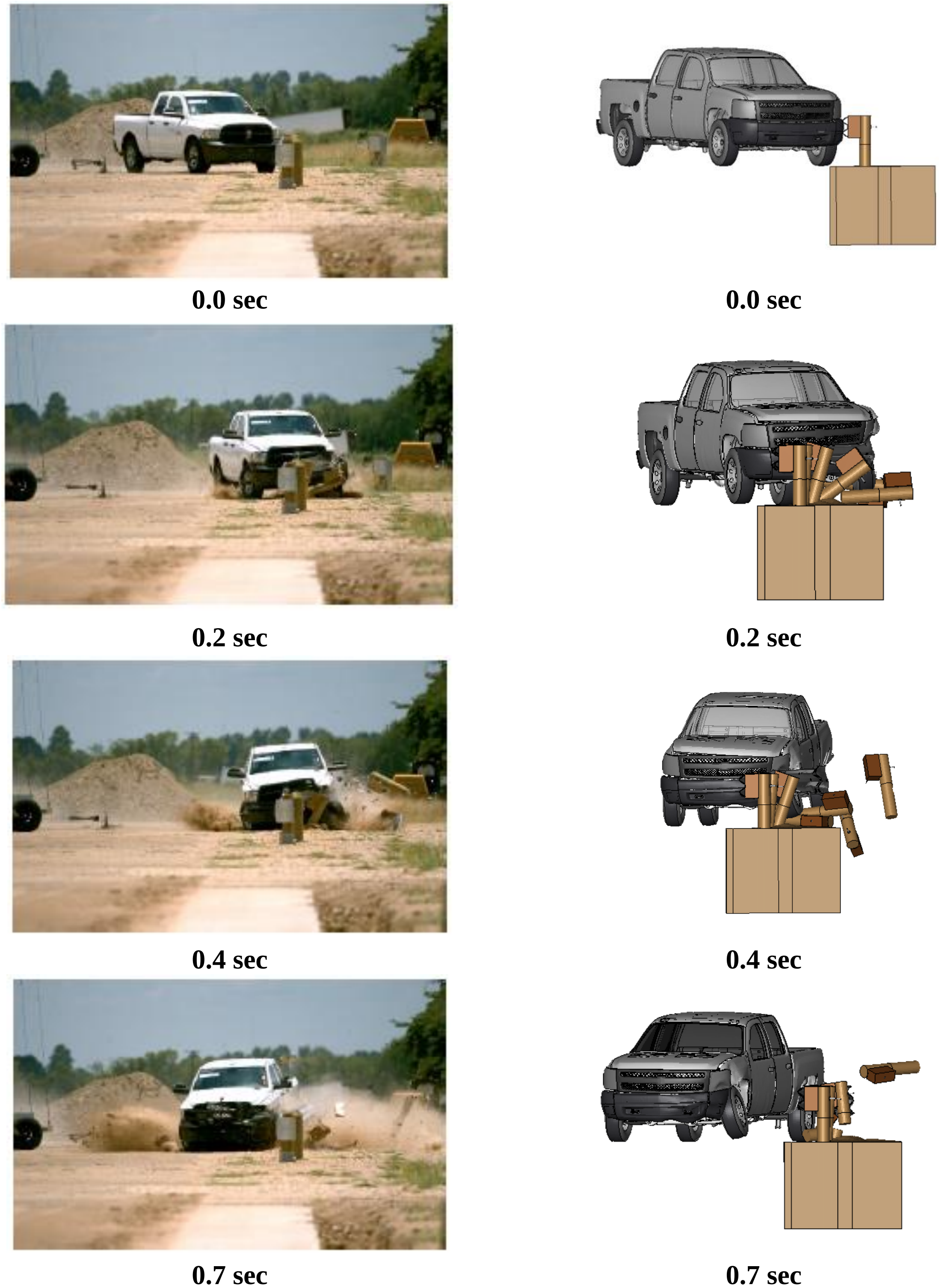


Figure 5.7 Comparison of Actual Crash Test and LS DYNA Simulation (Pictures on Left Reprinted from Kovar et al., 2019).

Table 5.2 summarizes occupant risk, vehicle stability information, and system deflection values from the comparison between the actual crash test values and the simulated impact event.

Table 5.2 Comparison between Full-Scale Crash test and Impact Event Computer Simulation

	Actual Crash Test Values (Reprinted from Kovar et al., 2019).	**FEA Simulation Values**
Longitudinal OIV **Lateral OIV**	15.4 ft/sec 14.4 ft/sec	17.0 ft/sec 16.0 ft/sec
Longitudinal Ridedown **Lateral Ridedown**	11.0g 6.8g	5.3g 7.1g
THIV	20.3 ft/sec	22.3 ft/sec
PHD	11.3g	7.9g
ASI	0.62	0.69
Max 0.050-s Average **Longitudinal** **Lateral** **Vertical**	 -5.5g 5.1g 2.0g	 -4.5g 5.5g 3.5g
Maximum Roll **Maximum Pitch** **Maximum Yaw**	7° 4° 34°	5.0° 3.6° 41.4°
Maximum deflection **Permanent deflection**	44.1 inches 37.0 inches	52.3 inches 28.3 inches

Conclusion

Comparison of LS DYNA simulation results and actual crash test values reveal that the computer models (system and vehicle) can be considered to be calibrated with respect to the actual crash test. The simulated impact event closely matches with the actual crash test events.

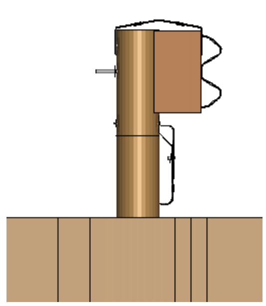
5.3 Predictive Simulations

Testing conditions for the simulations are determined from the available literature review and previous experience with crash testing since crash data did not provide much information for the testing conditions at which the simulations shall be conducted. CRIS data also lacks information and detailed data pertaining to crash testing conditions. Hence, the impact conditions for a pick-up truck and car were determined from previous crash testing experience at TTI while for the upright motorcycle and sliding dummy test, the European standards were followed.

5.3.1 Retrofitted Option

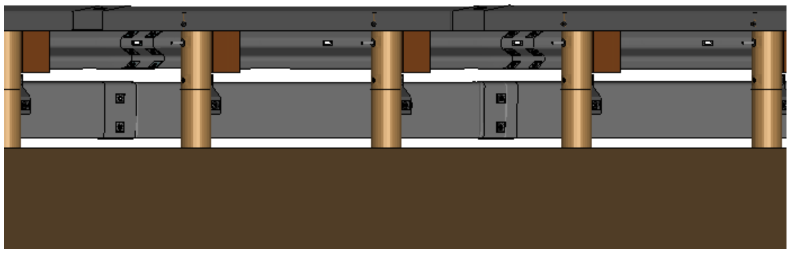
Figure 5.8 illustrates the computer model that was developed to retrofit the existing MGS guardrail system to address errant motorcyclists' safety. Following were the retrofitting options approved for top and bottom protection for further consideration:

1) Top Protection: Notched Plate Top Protection for MGS with Block out
2) Bottom Protection: Inclined Bottom Protection for MGS

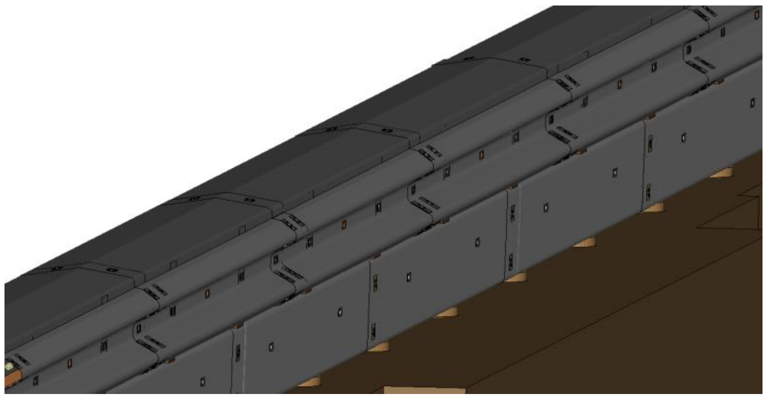


(a) Side View

Figure 5.8 Different Views of LS Pre-Post Developed Retrofitted MGS for Motorcycle Safety.



(b) Perspective Rear



(c) Perspective Front

Figure 5.8 Different Views of LS Pre-Post Developed Retrofitted MGS for Motorcycle Safety (Continued).

Shell elements were used for both the top notched plate and bottom mounting bracket and inclined plate. The values obtained after calibrating the 36-inch embedment TxDOT guardrail system were used in this MGS including the wood erosion keyword values. The thickness of the top and bottom protection plate was kept the same as that of the rail as 2.657 mm (12 gauge). However, the thickness of the mounting bracket was increased to 4.36 mm (8 gauge) from 2.657mm after performing several simulations with varying gauge thickness. This increase in thickness was a result of less load carrying capacity of the mounting bracket which sagged under the load of the 12 gauge bottom plates under gravity. The vertical length of the bottom protection plate was provided to be around 13 inches curved inwards with a bent length of around 1.2 inches at both ends. The distance of the bottom plate from the ground is 2.5 inches while from the block out is 2.3 inches approximately. Eighteen-inch bolts were used for attaching the rail to block out and 11-inch bolts were used to attach the mounting bracket to wood post at the bottom. Short 1-1/4-inch bolts were used for attaching the bottom plate to mounting bracket while 7-inch bolts were used to attach the top plate to the wood post on the rear side of the MGS. Bolt diameter was kept close to 5/8 inches for all bolts.

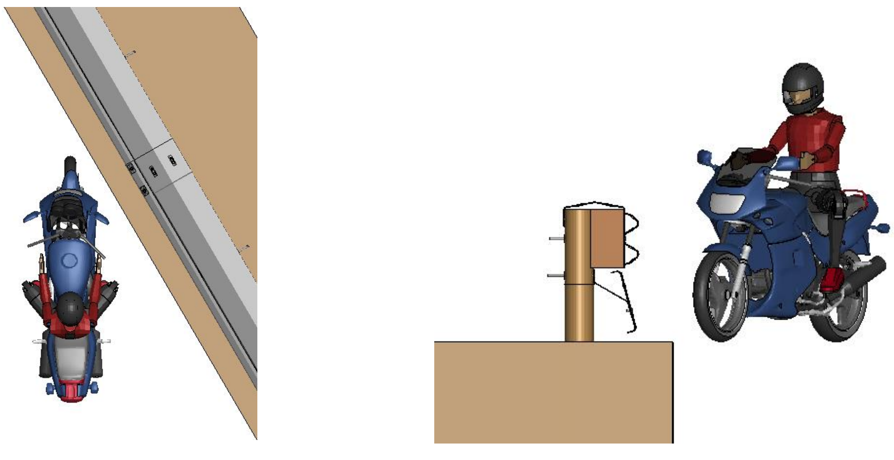
Material and section properties of top and bottom protection along with the mounting bracket (except the increased thickness) was defined with same keyword values as that of the rail. The stiffness of the bottom mounting bracket was varied considering the approximate deflection of the bottom plate after impact. Discrete spring element with small mass was provided at the ends of the rail to incorporate the effect of ground embedment at ends. The stiffness was kept the same as the calibration model spring stiffness values.

AUTOMATIC_SURFACE_TO_SURFACE contact keyword card was used to define contact between different MGS parts like segments of rail and bottom plate while TIED_NODES_TO_SURFACE contact keyword card was used to provide contact between stamps of rails and plates of MGS. AUTOMATIC_SINGLE_SURFACE contact was used to provide a contact for entire MGS as a whole.

After running various simulations of the MGS model acting under gravity with stability, the model was used for other simulations with motorcycle-dummy model and with vehicle models.

5.3.2 Upright Motorcycle with Dummy

The developed retrofitted computer model was used to perform simulations with a Motorcycle-Dummy available model (Figure 5.9). The purpose of this simulation was to verify the general behaviour of the MGS guardrail retrofitted system during a motorcycle-rider impact event, as well as to understand the dummy interaction with the roadside safety hardware during impact. The impact conditions were determined by referring to literature of previous sliding dummy crash tests. The impact angle of the motorcycle with rider was kept approximately 30° with the MGS while the impact velocity was kept as 37 mph approximately. AUTOMATIC_SURFACE_TO_SURFACE contact keyword card was defined to provide contact between the motorcycle with ATD and the MGS.



(a) Top View (b) Side View

Figure 5.9 Retrofitted MGS – Motorcycle-Dummy Model Setup.

FEA computer simulations were performed and Figure 5.10 illustrates sequential images of the simulation results.

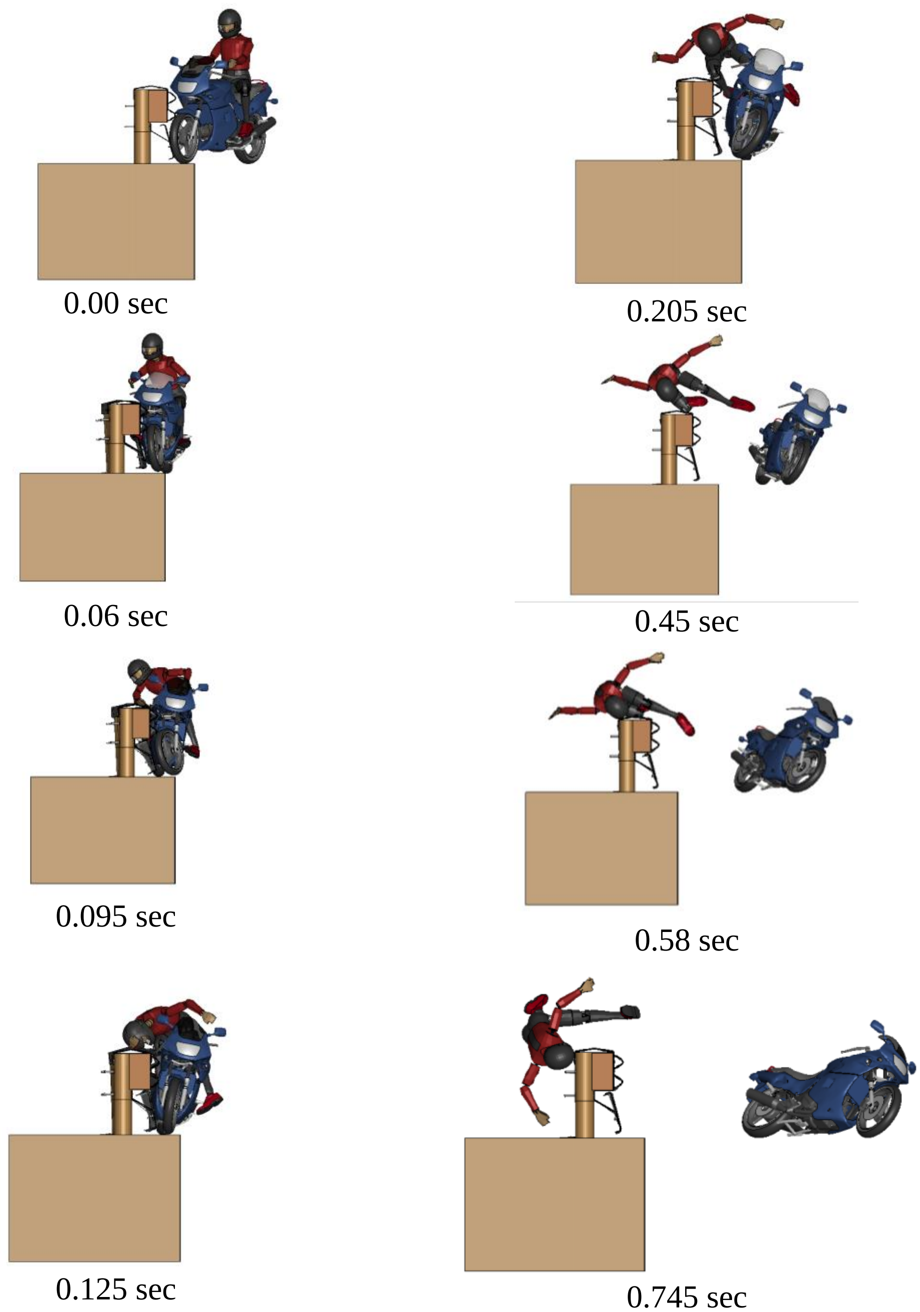
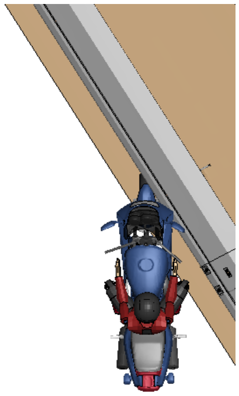


Figure 5.10 Sequential Images of Motorcycle-Dummy Impact Event Against MGS Retrofitted System.

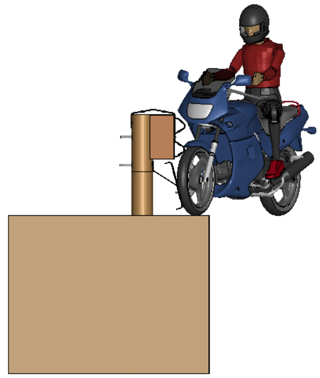
The simulation results were analyzed to investigate rider interaction and determine the maximum dynamic deflection of the system as well as with system permanent deformation. The retrofitted design component attached to the bottom of the post is to account for the rider sliding into the guardrail. This design includes some design details that were later modified for other simulations. It will be noted that further simulations that are reported in this thesis have slightly different retrofit bottom design with less inclined and closely spaced to the post. It is believed that this design is more critical for motorcycle impact than others. This is because as the plate is inclined, it is more likely to provide the ramping action for motorcycle (since the straight plate is not anticipated to provide ramping). Also, as the plate is more spaced from the post, the motorcycle would get in contact with the bottom part earlier than if spaced closer to the post. This would keep the motorcycle farther away from the top rail. Closer spacing would allow more interaction with top rail rather than bottom rail potentially limiting the instability.

Rider Interaction

The first point of contact of the motorcycle with the rider with the MGS was taken as the reference point. This time of the first contact is taken as 0.00 seconds and other time of contacts are measured with respect to the first time of contact. Figure 5.11 shows the first point of contact (POC) with MGS.



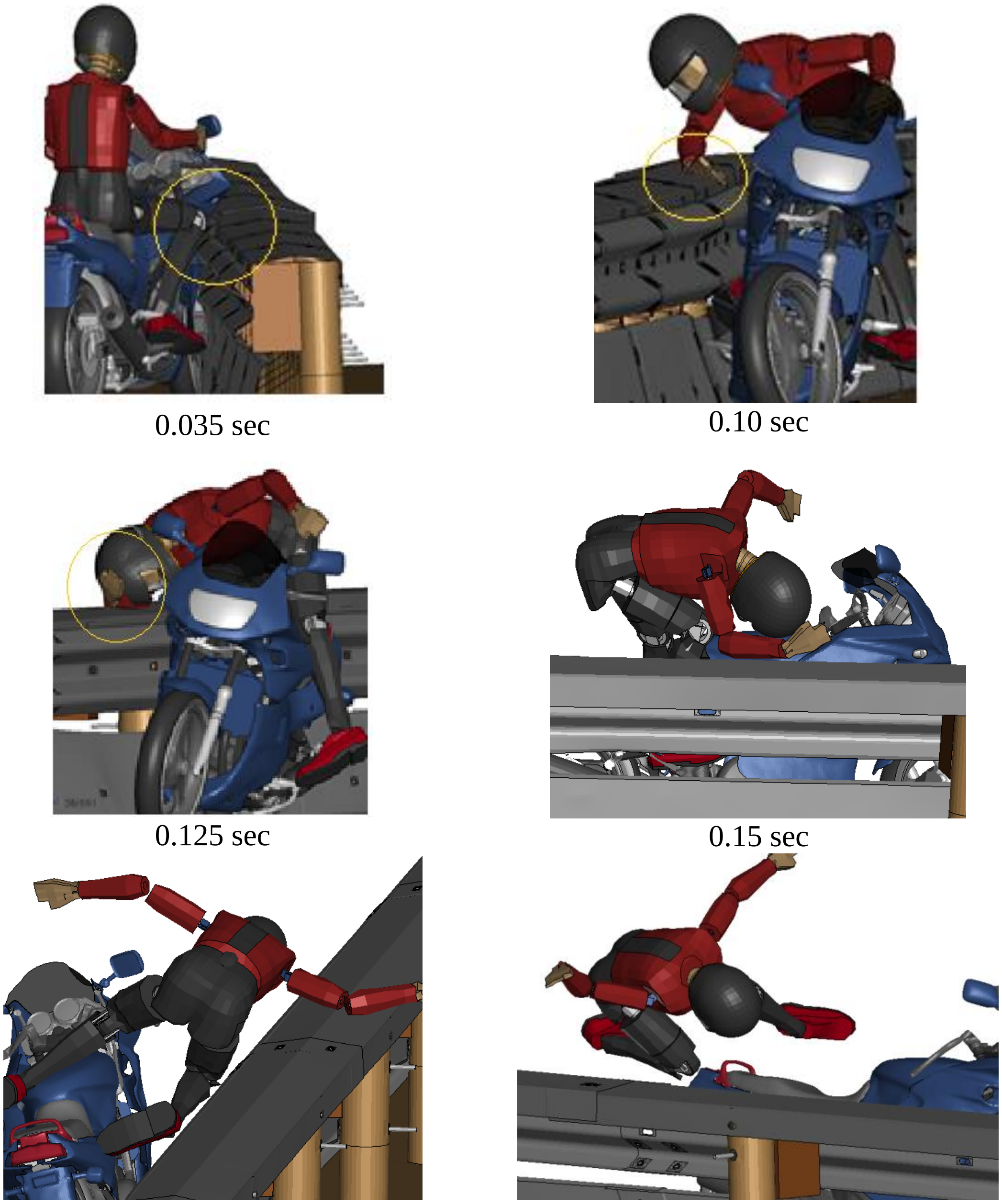
(a) Top View



(b) Side View

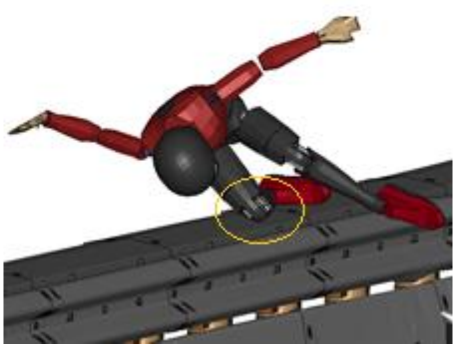
Figure 5.11 First Point of Contact of Motorcycle with ATD and MGS.

The ATD first interacted with the MGS system when its right leg impacted top rail at 0.035 secs after the first POC. Further, the right hand of the ATD contacts the top plate of MGS at 0.10 secs and at approximately 21 inches from first POC. At 0.125 sec and approximately 26 inches from first POC, ATD helmet hits the right arm of ATD already in contact with top plate and bounces back up. After 0.15 secs, the right hand of the ATD loses contact with the top part and after 0.24 secs, the right leg of ATD loses contact with the rail. The ATD remains airborne until next contact of the right leg with the top part at 0.455 secs after the first POC at approximately 12.3 ft. While the right leg of ATD slides on the top plate, ATD helmet hits top plate again at 0.53 secs and approximately 16.7 ft from the first POC. Both ATD helmet and right leg slide on the top part for a distance of 6.5 ft and loses contact with the MGS at 0.72 secs after the first POC. Figure 5.12 shows the sequential images of the ATD interaction with the top part at different time after the first POC. Different views in Figure 5.12 are used so as to show rider interaction more in detail. Yellow circles in the Figure denote the rider body’s part interacting with the MGS at that specific moment during the depicted event.

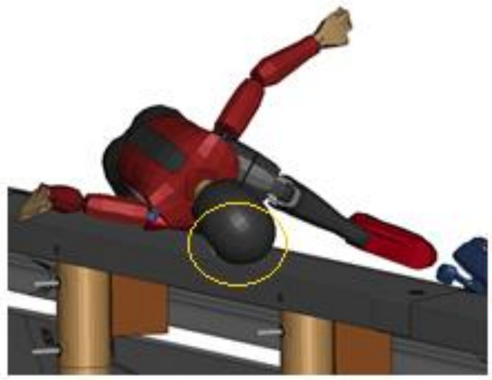


0.035 sec | 0.10 sec
0.125 sec | 0.15 sec
0.24 sec | 0.42 sec

Figure 5.12 Sequential Images of ATD Interaction with MGS from the Predictive Simulation.

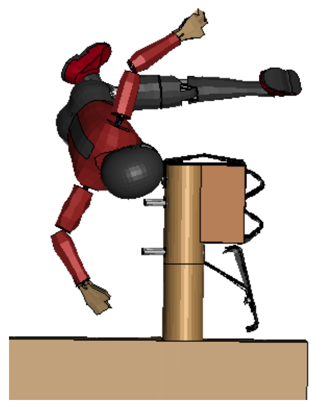


0.455 sec



0.53 sec

0.67 sec

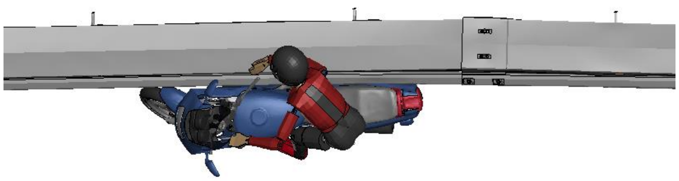


0.72 sec

Figure 5.12 Sequential Images of ATD Interaction with MGS from the Predictive Simulation (Continue).

MGS Behavior

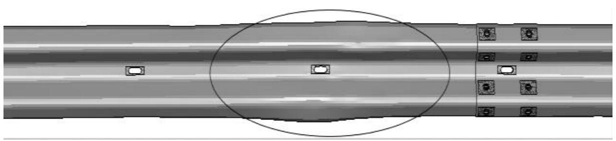
The maximum deflection of the rail and retrofitted options were determined through the simulation results. Figures 5.13 and 5.14 show the maximum deformation of the system obtained at 0.95 sec after the first POC.



(a) Top View

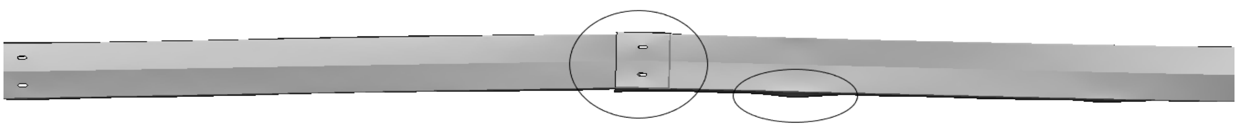
(b) Side View

Figure 5.13 Maximum Dynamic Deformation of Retrofitted MGS During the Motorcycle-Dummy Impact Event.



(a) Front view of the rail

(b) Front view of bottom protection



(c) Top view of top protection

Figure 5.14 Maximum Deformation of Different Guardrail Components After Impact

By measuring the relative displacement of different guardrail components, the approximate deformation for rail, top protection and bottom protection at 0.95 secs after the first POC are given in Table 5.3. This maximum deformation for different parts occur at different location near the impact point. Rail has a maximum deformation near the upstream side of the post while the top and bottom protection have maximum deformation on the downstream side of the impact point. The stress and strain values for the model were analyzed and checked to determine any defects. The values were under limits and system behaviour can be considered satisfactory after impact.

Table 5.3 Guardrail System Components Maximum Deformation.

Rail system component	Deformation (inches)
Rail	2.2
Top protection	4.3
Bottom protection	6.3

Conclusion

Simulation analysis suggests that the retrofitted MGS system is capable of satisfying the required purpose of providing a sliding surface for upright motorcyclist. The predictive simulation seems to indicate the retrofitted system does not present protruding elements that might originate errant rider snagging during the impact event. Further, the predictive simulation suggests that the system deformation during impact is not significant, hence providing minimum damage to the guardrail system. The motorcycle was contained and redirected as evident from the simulation results. Errant rider ejected and slid on the top protection. The purpose of minimizing rider interaction with discrete elements of guardrail system was satisfied.

5.3.3 Pick Up Truck – Retrofitted MGS

The retrofitted MGS was used to predict the behaviour of the system under the impact of the pickup truck vehicle. The vehicle impact angle and speed were kept the same as those from the calibration model. Same erosion value was assigned to obtained from calibration and determined the crashworthiness of the test. Three simulations were conducted with the pickup truck for the mentioned configurations. One with no tire disengagement and other two with tire disengagement of 30,000 and 15,000 unit axial force at failure. Figure 5.15 illustrates sequential images from the conducted predictive computer simulation for the pickup truck with no tire disengagement. Figure 5.16 shows the sequential images from the simulations results for the truck with tire disengagement.

Figure 5.15 Sequential Images of Pickup Truck impact simulation against retrofitted MGS system (Without tire disengagement)

Disengagement failure at 15,000 unit force | **Disengagement failure at 30,000 unit force**

Figure 5.16 Sequential Images of Pickup Truck Impact Simulation Against Retrofitted MGS System

Table 5.4 illustrates the occupant risk values and vehicle stability obtained for the preditive simulation for all three pickup truck simulations.

Table 5.4 Occupant Risk and Vehicle Stability Predicted from Simulations with Pickup Truck Vehicle

	No Tire Disengagement	Tire Disengagement	
		Axial Force at failure = 30,000 units	Axial Force at failure = 15,000 units
Longitudinal OIV **Lateral OIV**	18.3 ft/sec 14.7 ft/sec	16.1 ft/sec 14.1 ft/sec	16.7 ft/sec 14.8 ft/sec
Longitudinal Ridedown **Lateral Ridedown**	9.7 g 7.5 g	10.5 g 10.0 g	8.4 g 9.9 g
THIV	21.9 ft/sec	21.0 ft/sec	21.3 ft/sec
PHD	10.3 g’s	12.4 g’s	10.3 g’s
ASI	0.68	0.76	0.76
Max 0.050-s Average **Longitudinal** **Lateral** **Vertical**	-6.5 g’s 4.9 g’s 4.0 g’s	-5.9 g’s 5.8 g’s 4.1 g’s	-6.0 g’s 6.6 g’s 3.1 g’s
Maximum Roll **Maximum Pitch** **Maximum Yaw**	5.9° 5.2° 46.2°	19.3° 11.3° 46.3°	23.1° 10.5° 43.0°

CONCLUSION

The preliminary results obtained from the predictive simulation of the pickup truck vehicle impacting the proposed retrofitted MGS system indicate that the retrofitted system should be able to contain and redirect the vehicle during the impact event, and should not de-stabilize the vehicle during the impact event. Evaluated occupant risk also seems to indicate the retrofit option does not compromise occupant safety. During the impact event, it was noted that the pickup truck pushed down the added bottom protection rail and seemed to keep riding on top of it. However, it appeared that riding on top of the bottom protection rail did not interfere with the vehicle stability and overall integrity of the hardware system. Further, the simulation results also suggest that there is not much difference in the occupant risk values between the three simulations, indicating that the FEA model appears to be robust for predictive simulations.

5.3.4 Passenger Car – Retrofitted MGS

The performed simulation of the pickup truck impacting the retrofitted MGS system seems to indicate that there should not be reasons of concern for system debris during the impact event. There was an indication of a potential rupture for both top and bottom protection rail components during impact, not indication of potential intrusion into the occupant compartment. It is necessary, however, to confirm this potential outcome through simulation of the impact of a small passenger car against the proposed system, to verify system integrity, vehicle stability, and occupant risk.

The small car impact simulation was conducted with no tire disengagement. It was noted in the pickup truck simulations that the tire disengagement did not substantially affect the occupant risk values. Hence, it was comfortable to investigate the small car impact event without tire disengagement expecting sufficient accuracy and realistic behaviour.

MGS system model was used to determine behaviour of small passenger car after impacting the system. The erosion value of the calibrated system was used to provide post-failure material in LS Pre-Post. The car was angled at 25 degrees with an impact velocity of 62 mph in the simulation model. The impact location was decided based on the parametric evaluation of a few simulations with chosen locations. The parametric simulations results did not yield appreciable different outcomes. Figure 5.17 shows the sequential images of the simulation results.

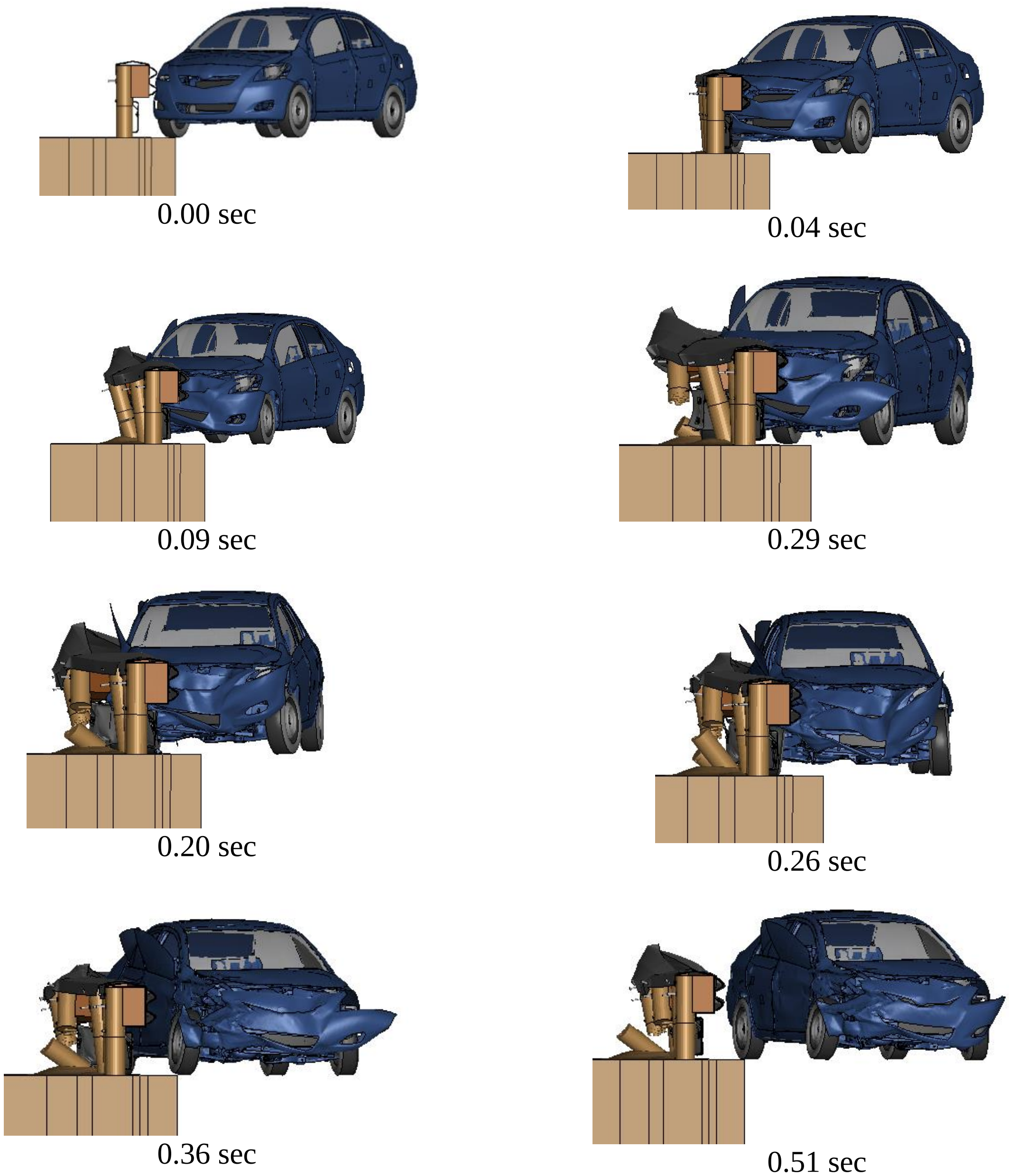


Figure 5.17 Sequential Images of Small Car Impact Simulation Against Retrofitted MGS System

Table 5.5 illustrates the occupant risk values and vehicle stability obtained for the predictive simulation for small car simulations.

Table 5.5 Occupant Risk and Vehicle Stability Predicted from Simulations with Pickup Truck Vehicle.

	FEA simulation results
Longitudinal OIV **Lateral OIV**	23.9 ft/sec 19.0 ft/sec
Longitudinal Ridedown **Lateral Ridedown**	21.7 g 11.4 g
THIV	29.5 ft/sec
PHD	22.4 g
ASI	1.17
Max 0.050-s Average **Longitudinal** **Lateral** **Vertical**	-10.3 g 8.4 g 3.7 g
Maximum Roll **Maximum Pitch** **Maximum Yaw**	1.9° 1.2° 43.2°

The occupant risks values obtained from TRAP are within limits except for the ridedown acceleration which is slightly over the limit value. As per our previous simulation calibration and results, the car model overpredicts the occupant risks especially the ridedown acceleration. Hence, the simulation results can be considered to be realistic looking at the interaction and behaviour of the car with the MGS.

CONCLUSION

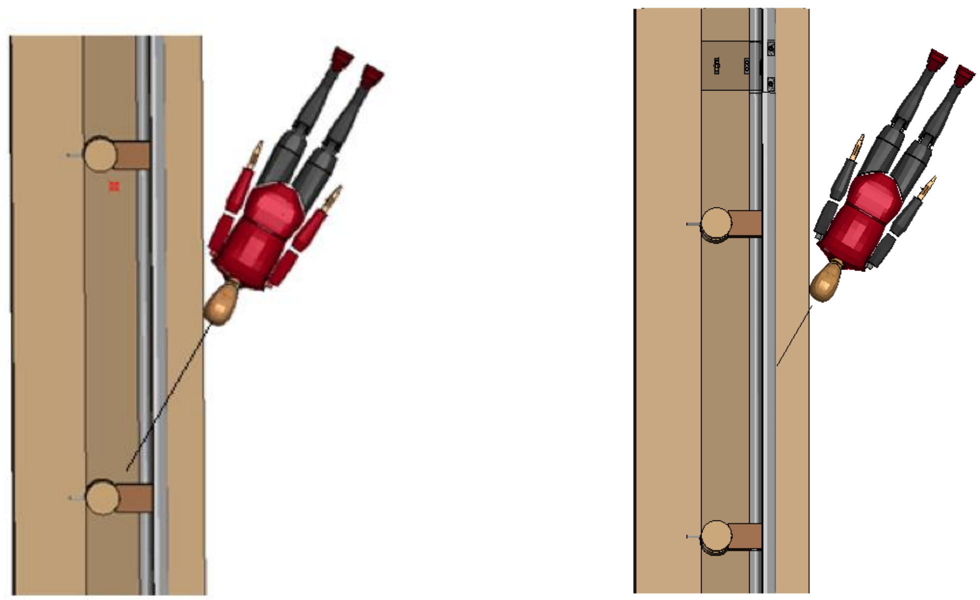
The preliminary results obtained from the predictive simulation of the car impacting the proposed retrofitted MGS system indicate that the retrofitted system should be able to contain and redirect the vehicle during the impact event. Also, the vehicle remained in stable conditions during the impact event. Based on previous experience with this vehicle model, the passenger car seems to tend overpredicting occupant risk values. Therefore, it is anticipated that the obtained ridedown acceleration values from the computer simulation are overpredicted from what is expected in full-scale crash tests.

5.3.5 Sliding Dummy

Predictive computer simulations need to be conducted to verify the retrofitted system crashworthiness once impacted by an errant sliding rider. Two impact conditions are investigated for this specific need (Figure 5.18):

1) Rider (dummy) impacting the system at 30-degree orientation angle aiming at the discrete post;
2) Rider (dummy) impacting the system at 30-degree orientation angle aiming at mid-span between posts.

These simulations results will help understanding how the proposed bottom protection system deflects and generally behaves during the impact of an errant sliding rider. Specifically, there is a need to investigate the ability of the proposed bottom retrofit system to limit the severity of the interaction between the errant rider and the discrete system posts. In addition, these simulations will provide an understanding of the ability of the system to redirect the sliding errant rider without providing snagging locations.



(a) Aiming at discrete post

(b) Aiming at mid-span between posts

Figure 5.18 Impact conditions for dummy representing errant sliding rider

5.3.5.1 Sliding Dummy – Discrete Post Impact

The first impact condition for sliding dummy simulations is to direct sliding rider toward the discrete post at an angle of 30 degrees. The impact speed of the rider was 37.3 mph (60 km/h) to conform to the European standards for testing sliding dummies. The scope was to investigate the rider interaction with the system during the impact event.

To speed up computation time, the top part of the system was removed, given the fact it would have a negligible effect on the simulation results. To account for this modification, the top connection of the mounting bracket with the wood post was fixed by providing restrained boundaries in all directions. This would still allow the flexible movement of the plate and bracket with respect to the connection at the wood post. Further, this would provide a more conservative result as the additional flexibility of the wood post would be ignored and hence the system will be more rigid than actual test conditions. Figure 5.19 and 5.20 shows the sequential images of the simulation results obtained from LS DYNA. Table 5.6 gives the values of maximum and permanent deformation of bottom protection after sliding dummy impacts the bottom protection.

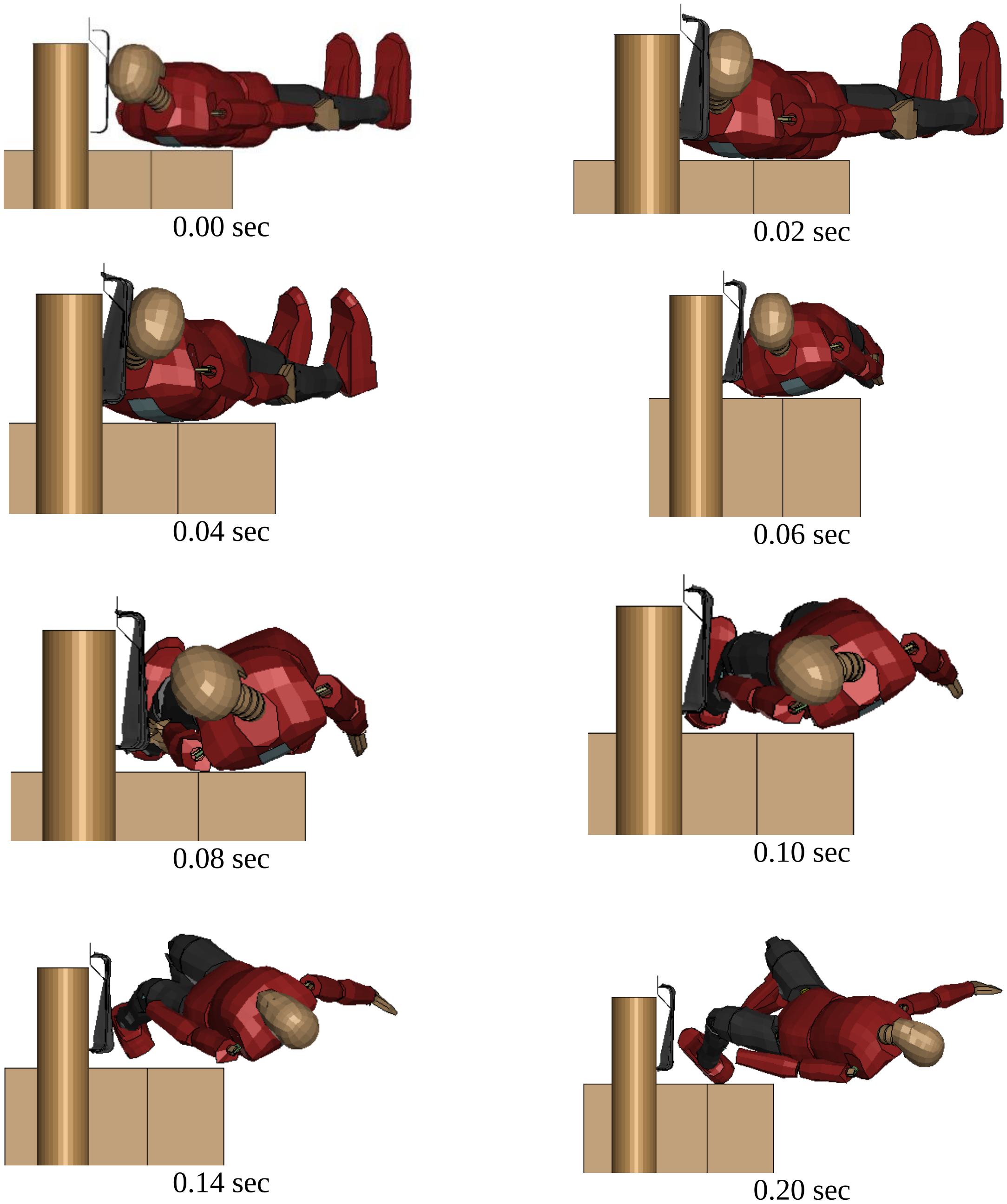


Figure 5.19 Sequential Pictures for Discrete Post Dummy Impact Condition (Side View)

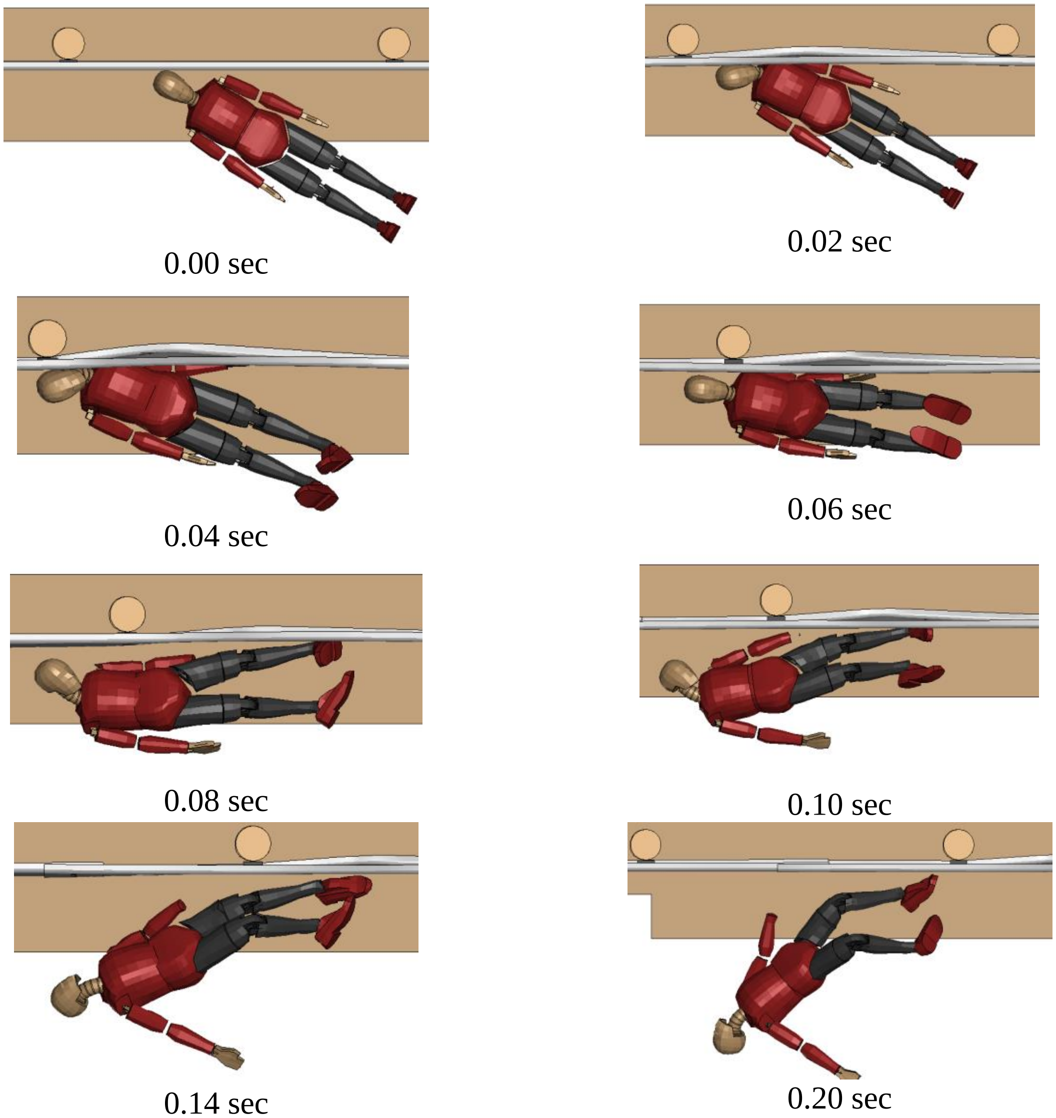


Figure 5.20 Sequential Pictures for Discrete Post Dummy Impact Condition (Top View) (continued)

Table 5.6 Bottom Protection Deflection Values for Sliding Dummy Impacting on Post

Bottom protection deflection	**Deformation (inches)**
Maximum	5.5
Permanent	4.3

As can be seen from the sequential images, the dummy is being redirected from the flexible system at a safe distance from the post without any damage to it. The post-processing dummy values for the simulations were obtained and compared with other simulation results.

5.3.5.2 SLIDING DUMMY – Between Posts Impact

The second impact condition for sliding dummy simulations is to direct sliding rider at midspan of two posts, at an angle of 30 degrees. The speed of impact was 37.3 mph (60 km/h) to conform to the European standards for testing sliding dummies.

Figure 5.21 and 5.22 shows the sequential images of the simulation results. Table 5.7 gives the values of maximum and permanent deformation of bottom protection after sliding dummy impacts the bottom protection.

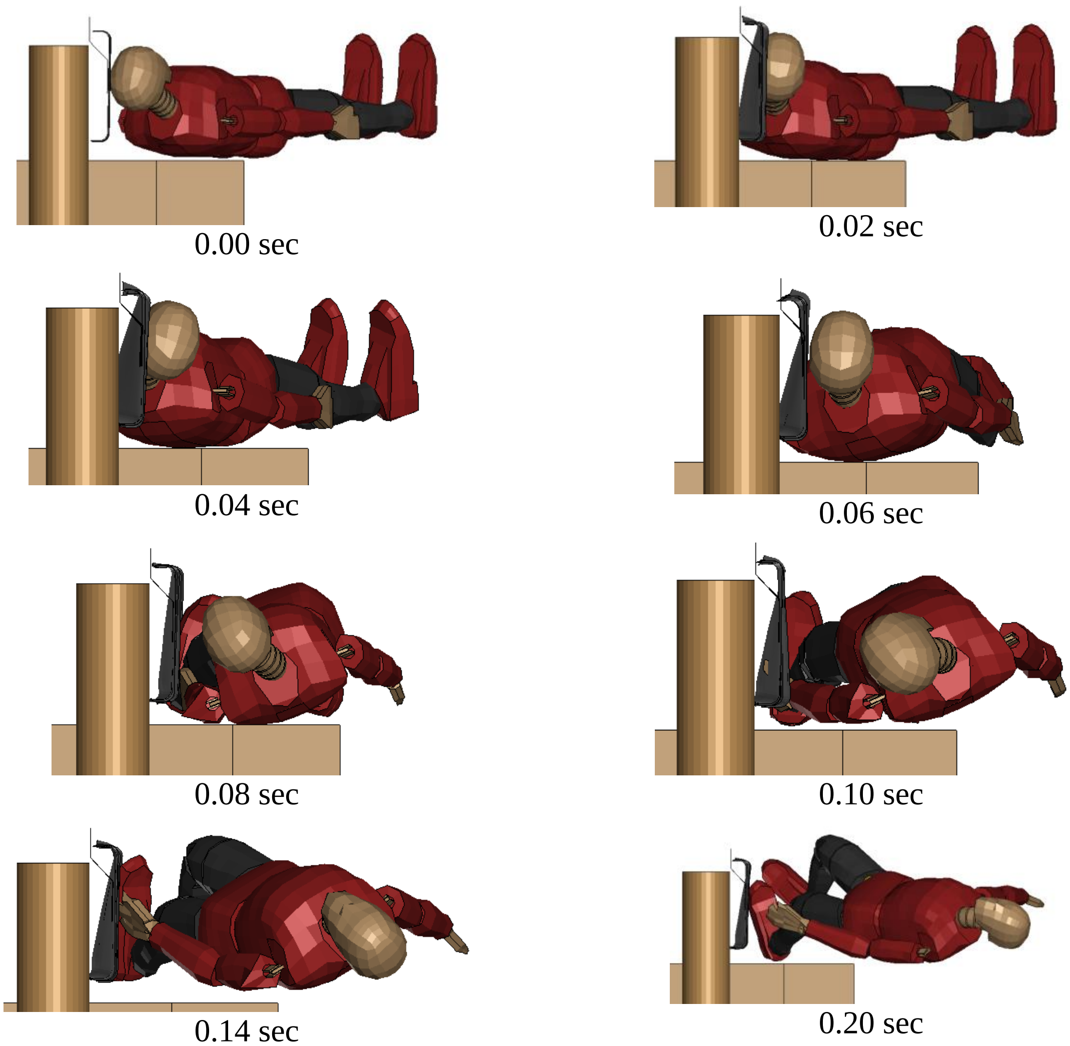


Figure 5.21 Sequential Pictures for Between Posts Dummy Impact Condition (Side View)

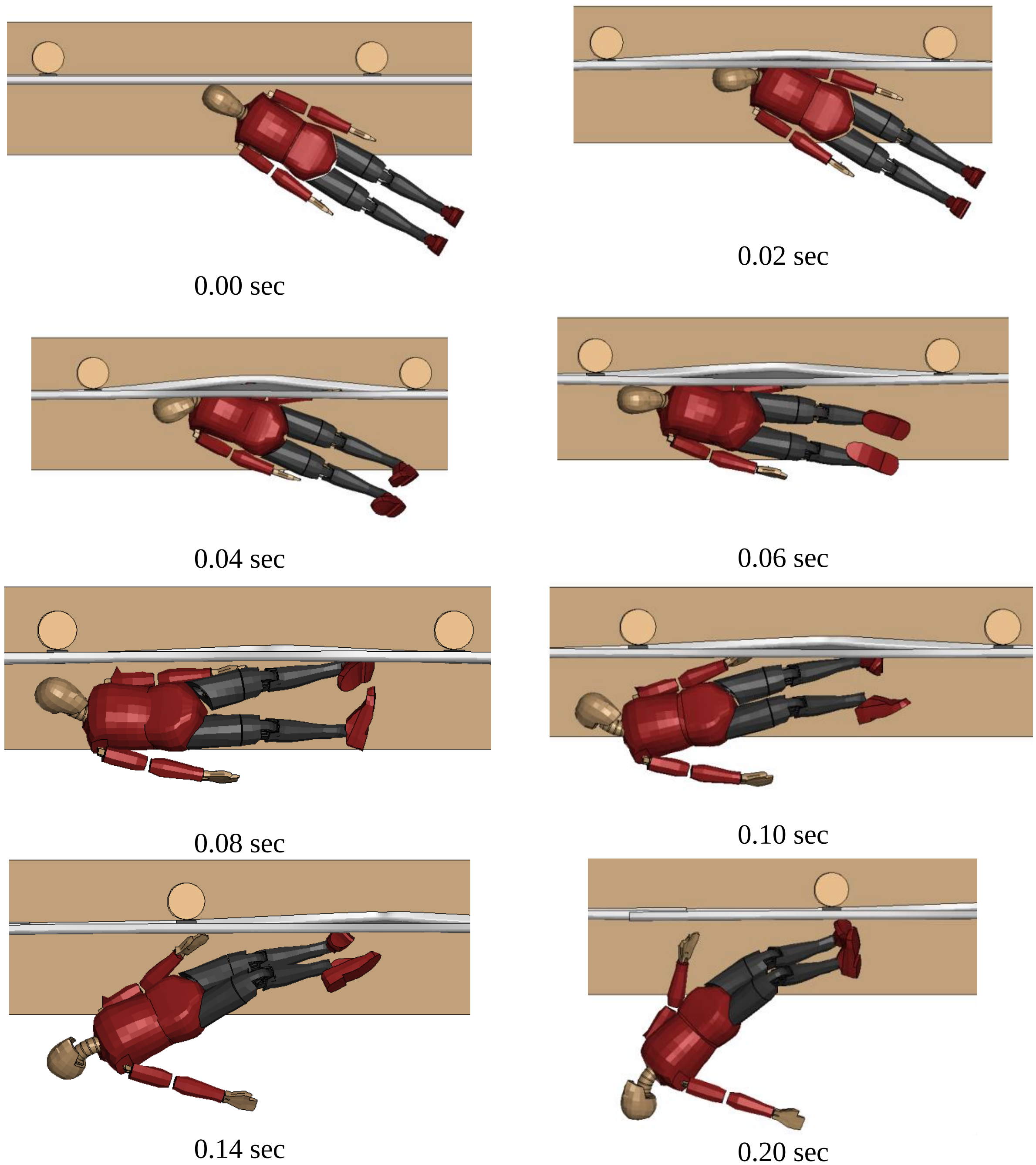


Figure 5.22 Sequential Pictures for Between Posts Dummy Impact Condition (Top View)

Table 5.7 Bottom Protection deflection Values for Sliding Dummy Impacting Between Posts

Bottom protection deflection	Deformation (inches)
Maximum	6
Permanent	3.7

As can be seen from the sequential images, the dummy seems to be smoothly redirected from the flexible system. It is to be noted that the system deflection for this case is higher than the direct post-impact condition due to the fact that the rider is impacting at midspan, which provides the opportunity for higher system flexibility. The post-processing dummy values for the simulations were computed to compare with other simulations results.

3-5-3) SLIDING DUMMY – Rigid Bottom Protection Impact

An additional simulation was conducted to investigate behaviour and results of the dummy impact against fixed-bottom protection and utilize them for comparative analysis with the previous simulated cases. Figure 5.23 and 5.24 shows the sequential images of the simulation results.

The post-processing dummy values for the simulations were computed to compare with other simulation results.

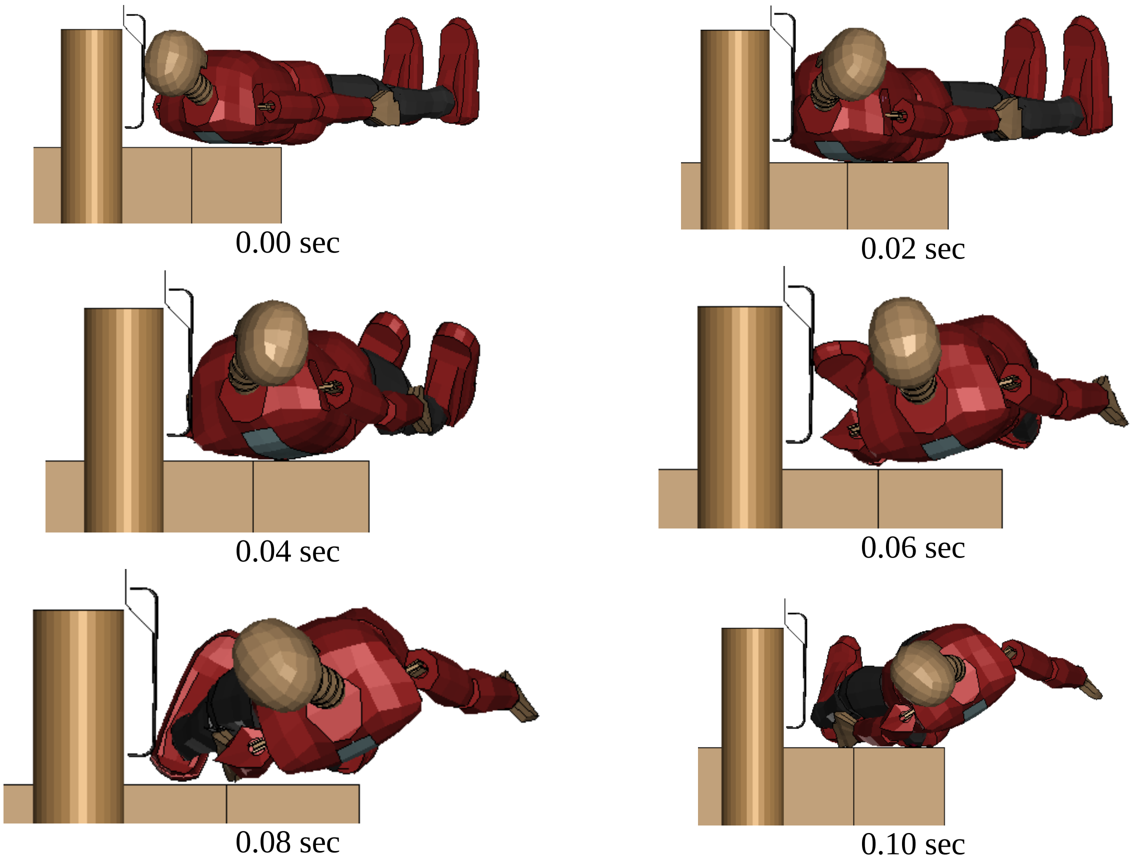


Figure 5.23 Sequential Pictures for Rigid Bottom Protection Impact Condition (Side View)

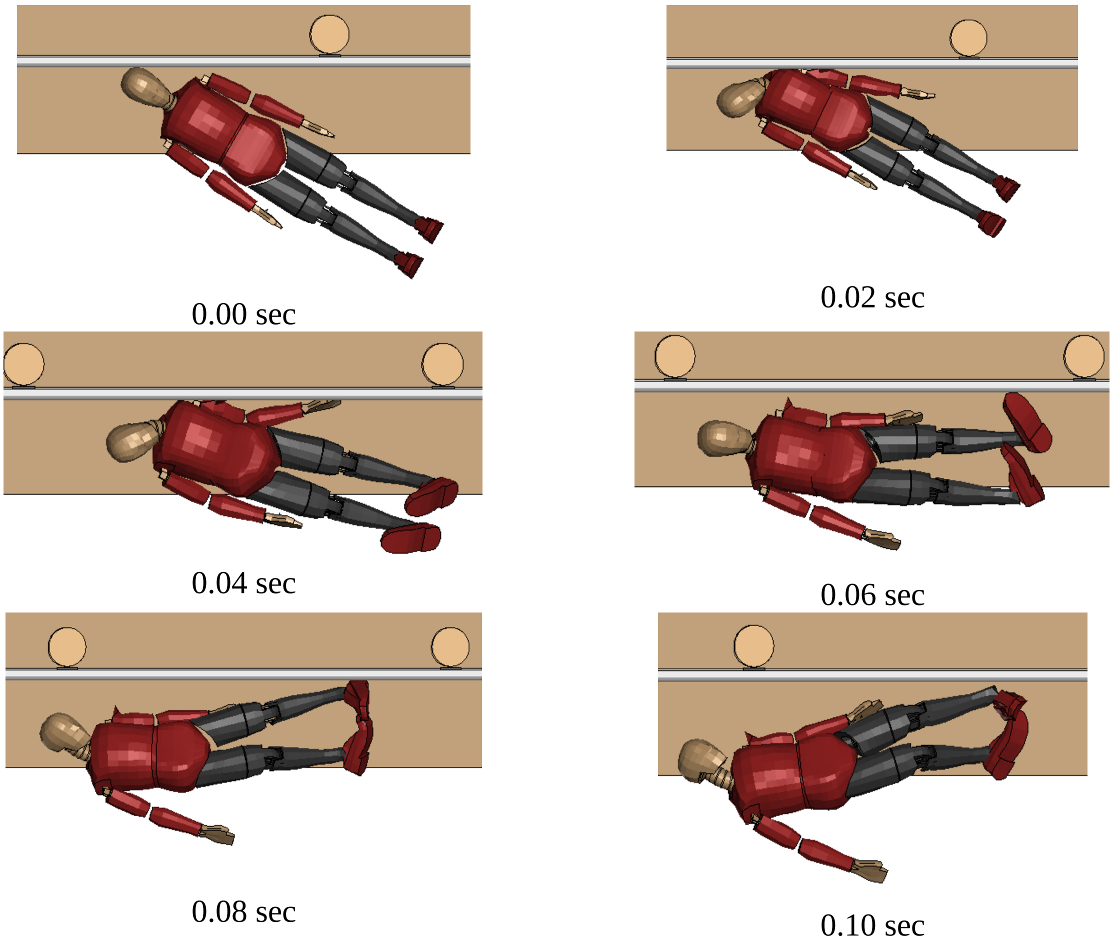
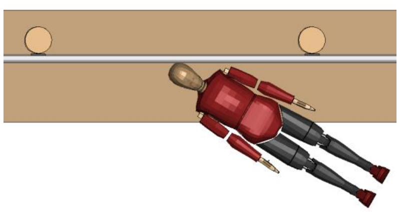
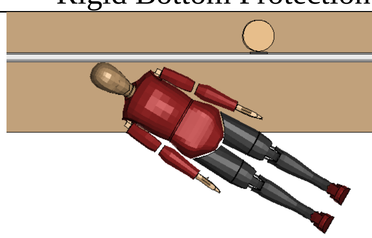
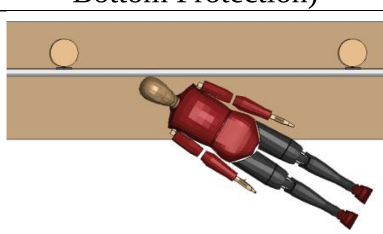


Figure 5.24 Sequential Pictures for Rigid Bottom Protection Impact Condition (Top View)

SLIDING DUMMY – Post Processing Dummy Values Comparision

Results from dummy occupant risk are summarized in Table 5.8. Since the Head Injury Criteria (HIC36), neck forces, neck moment, and chest acceleration values are the highest for the fixed bottom protection simulation, they were considered as reference values for further comparison with results obtained from the simulations with flexible bottom protections. It is to be noted that initial simulation analysis which included rider with helmet were also scrutinized. However, since the helmet was not calibrated for such type of impact, the results obtained were not realistic. Hence, the results shown in this section are for the rider without helmet impact simulations. Future research shall focus on calibrating the hemet model and conducting simulations to verify the results obtained in this chapter. Since this study is more like a research and development study, the purpose of these simulations was to evaluate the performance of the system qualitatively and comparitively. Hence, the dummy with helmet model, is anticipated to give equal or better results than the one without helmet if the system is not altered.

Table 5.8 Post Processing Dummy Values Comparision

Impact Conditions	HIC 36	Chest Deflection	Neck Forces (Shear)	Neck Moment
 Rigid Bottom Protection	100%	100%	100%	100%
 At Posts Midspan (Flexible Bottom Protection)	5.38%	76.5%	14.8%	80%
 At Post (Flexible Bottom Protection)	5.38%	85.2%	11%	83.8%

5.4 Conclusion

Simulation analysis suggests that the retrofitted MGS system is capable of satisfying the required purpose of providing protection to sliding rider from fatal impact with system components. The results show that sliding dummy is effectively contained and redirected. Further, the predictive simulation suggests that the system deformation during impact is not significant, hence providing minimum damage to the guardrail system. There is no snagging of dummy parts with the system during the simulations. Hence, the purpose of minimizing rider interaction with discrete elements of guardrail system was satisfied. It is also seen from the post processing comparison that the system is efficient from injury perspective.

6. TEST PLAN

This chapter provides a recommendation plan for conducting appropriate full-scale crash testing and evaluate the selected retrofit guard fence options. When recommending the test plan, the need to evaluate the efficiency of the retrofit options for upright and for sliding impacts, and the crashworthiness of the modified retrofitted system during vehicular impact was accounted for. A testing program is recommended for the selected retrofit system that involves:

- Two sliding dummy crash tests to evaluate the developed retrofit system when impacted by a dummy representing the rider sliding during the impact event;
- One upright motorcycle with a seated rider crash dummy test to evaluate the retrofit system when impacted in an upright position by a rider on a motorcycle and
- Two full-scale vehicular crash tests per MASH TL3 standard conditions to evaluate MASH compliance of the modified retrofit guard fence system.

6.1 *MASH* Test Requirements

The impact speed and angle of 62 mph and 25 degrees approximate the 85th percentile of real-world impact conditions from the available information obtained by reconstruction of run-off-the-road passenger vehicle crash on high-speed roadways. Hence, these values were selected to represent the design impact conditions for high-speed, high-volume roadways.

The tests will be performed at Test Level (TL) 3 conditions. MASH recommends two tests to evaluate longitudinal barriers at test level three (TL-3).

***MASH* Test Designation 3-10:** A 2420-lb vehicle (1100C) impacting the critical impact point (CIP) of the length of need (LON) of the barrier at a nominal impact speed and angle of 62 mph and 25 degrees, respectively. This test investigates a barrier's ability to successfully contain and redirect a small passenger vehicle, with an emphasis on occupant risk (MASH, 2016).

***MASH* Test Designation 3-11:** A 5000-lb pickup truck (2270P) impacting the CIP of the length of need (LON) of the barrier at a nominal impact speed and angle of 62 mph and 25 degrees, respectively. This test investigates a barrier's ability to successfully contain and redirect light trucks and sport utility vehicles, with an emphasis on structural adequacy and vehicle stability (MASH, 2016).

6.2 Motorcycle Testing Impact Characteristics from the Previous Testing

For developing a testing methodology and for the evaluation of the retrofit barrier system, relevant work was reviewed and evaluated based on usefulness and applicability.

6.3 Motorcycle Testing Impact Conditions

Nominal impact conditions, as mentioned in the literature review of this thesis, of previous motorcycle testing against barriers with the use of a seated rider dummy are summarized in Table 6.1. Testing has also been performed with unseated dummies sliding into the barrier, which reflects the suggested procedure for motorcycle safety testing in certain European countries. The reported testing can be grouped into four major testing configurations: sliding dummy, upright motorcycle-dummy impact, inclined motorcycle-dummy impact and skidding motorcycle-dummy impact.

Nominal impact testing speed and angle conditions vary from 20 to 42 mph, and 12 to 90 degrees, respectively.

Table 6.1 Motorcycle Testing: Nominal Impact Conditions from the Previous Testing.

INITIAL CONDITIONS OF TESTS					
Report	Year	General Information	Impact Speed (mph)	Impact Angle (Degrees)	Sled Orientation
Lier Procedure (France)	1998	Test dummy sliding on its back, impacts protection system head first.	37.3	30	None
		Test dummy sliding on its back, impacts protection system parallel with the test item.	37.3	30	None
UNE-135900 Protocol (Spain)	2005	Test dummy sliding on its back, impacts protection system at 30 degrees angle.	37.3	30	None
Seventeen Motorcycle Crash Tests into a Barrier	2002	Motorcycle impacts concrete target block at an impact angle of 90 degrees. Total of seven tests were conducted	Impacts speeds ranging 20-42	90	Upright-90 Degrees
Motorcycle Impacts into Roadside Barriers	2005	Two different tests of motorcycle and dummy crashing into steel guardrail and concrete barrier in upright position.	37.3	12	Upright-90 Degrees
		Two different tests of motorcycle and dummy skidding on ground impacting steel guardrail and concrete barrier.	37.3	25	Motorcycle Skidding
Motorcycle Crash Test Modelling	1993	Motorcycle and dummy impact crash test 1	20	90	Upright-90 Degrees
		Motorcycle and dummy impact crash test 2	30	90	Upright-90 Degrees
		Motorcycle and dummy impact crash test 3	37	67	Upright-90 Degrees
Motorcycle Impacts with Guardrail	1988	Dummy impact with guardrail at two different impact angles for two different designs of the guardrail.	34.2	30	None
Technical Bases for the Development of a Test Standard for Impacts of Powered Two-Wheelers on Roadside Barriers	2007	Motorcycle and dummy on test sled inclined at 45 degrees with the ground impacts guardrail.	37.3	25	Inclined-45 Degrees
		Motorcycle and dummy configured in upright position on test sled impacts guardrail.	37.3	12	Upright-90 Degrees

6.4 Motorcycle Testing and Specifications

Table 6.2 summarizes motorcycle type (make and model) and key characteristics (including weight, wheelbase, and production year) for tests in which an actual motorcycle was used. There are three types of motorcycle that have been used in previous motorcycle-barrier testing: Kawasaki Police, Kawasaki ER 5, and Yamaha SRX-600.

6.5 Motorcycle Testing - Dummy Specifications

Dummy type used and key dummy characteristics (including weight and major modifications applied to the dummy) have been summarized in Table 6.3 for tests in which a dummy was used. Further, comments regarding the use of helmets for dummies during testing are provided. A Hybrid III was used in all studies that utilized a dummy (note that dummy information was not provided for one test). This is primarily due to the fact that the dummies were instrumented to evaluate different injury criteria such as Head Injury Criteria (HIC) among others. The two major dummy modifications applied were (1) replacement of the curved spine with a straight lumbar spine, and (2) installation of a moveable pelvis structure to allow proper positioning of the dummy on the motorcycle in a seated rider position. The proposed dummy for the motorcycle test shall be Hybrid III 50% male anthropomorphic test dummies (ATD), given its fidelity.

Table 6.2 Motorcycle Testing: Motorcycle Specifications from the Previous Testing.

MOTORCYCLE SPECIFICATIONS					
Report	**Year**	**Motorcycle type**	**Motorcycle Weight (lbs.)**	**Motorcycle Wheelbase (in.)**	**Motorcycle Production Years**
Lier Procedure (France)	1998	None	-	-	-
UNE-135900 Protocol (Spain)	2005	None	-	-	-
Seventeen Motorcycle Crash Tests into a Barrier	2002	Kawasaki Police	596	59.3	1975-2005
Motorcycle Impacts into Roadside Barriers	2005	Kawasaki ER 5	395	56.3	1997-2006
Motorcycle Crash Test Modelling	1993	Yamaha SRX-600	328	54.3	1985-1997
Motorcycle Impacts with Guardrail	1988	None	-	-	-
Technical Bases for the Development of a Test Standard for Impacts of Powered Two-Wheelers on Roadside Barriers	2007	Kawasaki ER 5	395	56.3	1997-2006

Table 6.3 Motorcycle Testing: Dummy Specifications from the Previous Testing.

Report	**Year**	**Dummy Type**	**Dummy Weight (lbs)**	**Dummy Modifications**	**Helmet Used?**
Lier Procedure (France)	1998	Hybrid III 50^{th} percentile male	193±5.5	• Straight lumbar spine replaces curved spine. • Pedestrian pelvis to allow positioning of dummy on the motorcycle. • Installation of foam neck shield. • Clavicle replaced with a modified one that employs fusible bolts.	Yes
UNE-135900 Protocol (Spain)	2005	Hybrid III 50^{th} percentile male	193±5.5	• Straight lumbar spine to provide an upright seating position on a motorcycle. • Pedestrian pelvis to allow positioning of dummy on the motorcycle. • Installation of foam neck shield. • Clavicle replaced with a modified one that employs fusible bolts.	Yes
Seventeen Motorcycle Crash Tests into a Barrier	2002	None	-	-	-

Table 6.3 Motorcycle Testing: Dummy Specifications from the Previous Testing.

Motorcycle Impacts into Roadside Barriers	2005	Hybrid III 50th percentile male	Approximately 203	• Straight lumbar spine to provide an upright seating position on a motorcycle. • Pedestrian pelvis to allow positioning of dummy on the motorcycle. • Installation of foam neck shield. • Clavicle replaced with a modified one that employs fusible bolts.	Yes
Motorcycle C-rash Test Modelling	1993	Hybrid III 50th percentile male	Unknown	• Pedestrian (standing) pelvis and pedestrian legs and feet. • Installation of foam neck shield. • Clavicle replaced with a modified one that employs fusible bolts.	No
Motorcycle Impacts with Guardrail	1988	Unknown	-	-	-
Technical Bases for the Development of a Test Standard for Impacts of Powered Two-Wheelers on Roadside Barriers	2007	Hybrid III 50th percentile male	Unknown	• Pedestrian pelvis to allow positioning of dummy on the motorcycle. • Modification of dummy shoulder with frangible shoulder. • Installation of foam neck shield. • Clavicle replaced with a modified one that employs fusible bolts.	Yes

6.6 Recommendations for Testing

6.6.1 Recommendations for MASH Passenger Car and Pickup Truck Testing

The full-scale vehicle crash tests shall be performed in accordance with the guidelines and procedures set forth in *MASH*. Vehicle-mounted accelerometers, angular rate transducers, and high-speed photography can be used to make the measurements necessary to observe occupant kinematics, evaluate occupant risk, and determine compliance with other *MASH* evaluation criteria.

6.6.2 Test Facility

The full-scale crash tests with the passenger car and pickup truck is recommended to be performed at an International Standards Organization (ISO) 17025 accredited laboratory with American Association for Laboratory Accreditation (A2LA) Mechanical Testing certificate 2821.01.

6.6.3 Anthropomorphic Dummy

A crash dummy is recommended to be placed on the impact side of the small passenger car in Test 3-10. An uninstrumented dummy is required in this test by *MASH* guidelines to account for mass distribution and for visualization of occupant kinematics.

According to *MASH*, the use of a dummy in the 2270P vehicle is optional; therefore, the inclusion of a test dummy isn't proposed for the pickup truck test.

6.6.4 Recommended *MASH* Impact Conditions

It is recommended that the passenger car and pickup truck tests will be performed according to *MASH* TL-3 conditions. The impact conditions associated with the two relevant tests are as follows:

- ***MASH* Test 3-10:** 2420-lb passenger car; 62 mph 25 degrees.
- ***MASH* Test 3-11:** 5000-lb pickup truck; 62 mph; 25 degrees.

6.6.5 Critical Impact Points for *MASH* Tests 3-10 and 3-11 for the Retrofitted Guard Fence System

The CIPs for each test are recommended based on previous TTI testing experience and on the suggested results from the conducted FEA computer simulations.

Research suggests a CIP of 4.4 ft ±1 ft upstream of post for Test 3-11.

As for test 3-10, a computer parametric analysis was performed by varying the impact location and comparing the system performance the vehicle stability. The researchers suggest the target CIP for MASH full-scale crash Test 3-10 on the retrofitted system to be 3.1 ft ±1 ft upstream of the post.

In both cases, the CIP was chosen to maximize the vehicle interaction with the retrofitted system and the occupant risk during the impact event.

6.6.6 Evaluation Criteria for *MASH* Testing

The vehicle crash tests are recommended to be evaluated in accordance with the relevant criteria presented in *MASH*. The impact performance of the barrier shall be judged based on three factors: occupant risk, structural adequacy, and post-impact vehicle trajectory. The potential risk of hazard to occupants in the vehicle and, if applicable, to some extent pedestrians, workers or other traffic is evaluated by occupant risk. The barriers ability to contain and redirect the impacting vehicle is evaluated by the structural adequacy. The *MASH* occupant risk criteria include occupant ridedown acceleration and impact velocity, which are computed at the vehicle's centre of gravity using the acceleration-time histories. These criteria are based on a "flail space" model that assumes an unrestrained occupant.

Post impact vehicle trajectory shall be assessed as part of the *MASH* evaluation criteria, although it is not a criterion for pass /fail. It is suggestive of the potential for secondary impact of the vehicle with fixed objects or other vehicles that can create a further risk of injury to occupants of the impacting vehicle and/or risk of injury to occupants in other vehicles.

The specific safety evaluation criteria (adapted and reprinted from *MASH* Table 5-1 "Safety Evaluation Guidelines"*)* that can be used to evaluate the passenger vehicle crash tests are summarized below.

Structural Adequacy

A. *The test article should redirect and contain the vehicle or bring the vehicle to a controlled stop; the vehicle should not underride, penetrate, or override the installation although controlled lateral deflection of the test article is acceptable.*

Occupant Risk

D. *Detached elements, debris, or fragments from the test article should not penetrate or show potential for penetrating the occupant compartment, or personnel in a work zone, or present an undue hazard to other traffic, or pedestrians.*

Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Appendix E and Section 5.3 of MASH. (roof $\leq$102 mm (4.0 inches); windshield = $\leq$76 mm (3.0 inches); side windows = no shattering by test article structural member; wheel/foot well/toe pan $\leq$229 mm (9.0 inches); forward of A-pillar $\leq$305 mm (12.0 inches); front side door area above seat $\leq$229 mm (9.0 inches); front side door below seat $\leq$305 mm (12.0 inches); floor pan/transmission tunnel area $\leq$305 mm (12.0 inches))

F. *During and after the collision, the vehicle should remain upright. The maximum pitch and roll angles are not to exceed 75 degrees.*

H. *Occupant impact velocities should satisfy the following:*

Lateral and Longitudinal Occupant Impact Velocity (OIV)

Preferred	*Maximum*
30 ft/s	*40 ft/s*

I. *Occupant ridedown accelerations should satisfy the following:*

Lateral and Longitudinal Occupant Ridedown Accelerations

Preferred	*Maximum*
15.0 Gs	*20.49 Gs*

Vehicle Trajectory

The vehicle shall exit the barrier within the exit box for redirected devices.

6.7 Recommendations for Upright Motorcycle Testing

Currently, there are neither standards nor procedures developed for upright motorcycle testing with a seated rider. The only standardized procedure that some European countries have elected to adopt and follow involves testing with a sliding dummy to represent the case when the rider is ejected from the motorcycle and slides into the barrier. In this case, however, no motorcycle is included in the test.

Further, there is no crash database in the United States (U.S.) that includes impact conditions (such as impacting speed and angle) associated with real-world motorcycle crashes. A research effort funded by the National Cooperative Highway Research Program (NCHRP) with title "Factors Related to Serious Injury and Fatal Motorcycle Crashes with Traffic Barriers" is currently underway to investigate factors related to serious injury and fatal motorcycle crashes with traffic barriers. This research study, however, is not investigating the types and characteristics of motorcycles involved in crashes against barriers, nor does it include any related human factors analysis. Consequently, impact nominal conditions for upright motorcycle testing is recommended based on very limited previous upright motorcycle testing projects and engineering judgment. Details of these recommendations are described below.

6.7.1 Motorcycle Type

According to the conducted literature review, more than one research project utilized a Kawasaki ER 5 Twister motorcycle for upright testing against barriers. Studies conducted in Europe and Australia employed a nominal impact speed of 60 km/h (37.3 mph) and a shallow impact angle.

No studies were found investigating the relationship between motorcycle rider trajectory and impact conditions. There was very limited testing conducted in Germany with an upright motorcycle with a seated rider crash dummy, impacting guardrail systems. It can be seen after reviewing the video frames that the dummy has the tendency to be ejected from the motorcycle upon impact and then continue sliding on the guardrail top before falling on the ground. This is likely attributable to the shallow impact angle used in the testing, and perhaps to the slight horizontal curvature introduced into the barrier to represent a common real-case scenario of accidents on curves.

The choice of the motorcycle type might also have an influence on the behaviour of the dummy after impact with the barrier. In previous projects, the researchers decided to compare popular types of motorcycles in terms of wheelbase, weight, seat height, and rider posture. The motorcycle types chosen were a Kawasaki ER5 (since it was previously used in multiple testing projects), a Honda CTX700 (since it represents a cruising style motorcycle), and a Harley Davidson Electra Guide Ultra Classic (because it appears that Harley Davidson is a very popular brand with high sales in the U.S.).

Based on a critical review of previous literature, dummy post-impact trajectory for available upright motorcycle tests into barriers, motorcycle popularity and dimensions, and rider posture, the researchers suggest using a Kawasaki Ninja 500R for the upright motorcycle tests under this project. This motorcycle corresponds to the U.S. model of the Kawasaki 250 Ninja. It is the opinion for this study that this is a popular bike style favoured by younger, less experienced riders that are more prone to drive at higher speeds. In addition, it is the opinion for this study that this motorcycle provides a rider posture that is more likely to induce rider ejection during an impact event, with less interference from the bike's body and structure.

6.7.2 Anthropomorphic Dummy

It is recommended for the testing agency to use an instrumented Hybrid III 50th percentile male ATDs for use in the upright motorcycle and the sliding dummy tests. This opinion is based on thorough review of the needs for this research study and consulting with experts in the field of anthropomorphic test devices (ATD).

6.7.3 Motorcycle Impact Conditions

It is suggested from the study that the nominal impact speed and angle for the upright motorcycle testing to be 37 mph and 30 degrees, respectively. A speed of 37 mph was chosen to adhere to the condition included in the already developed and utilized EN1317 European protocol.

There are two primary reasons that lead the study to recommend a 30-degree impact angle. First, there are no standard protocols available to determine a specific impact angle for the test.

The previous testing suggests different angles at which the motorcycle was tested. Since higher angles increase the severity of the crash, the impact angle greater than shallow angles would be a conservative move. Second, the only testing that has a standard protocol for sliding dummy suggest 30 degrees as the impact angle. This is to account for the curvature which is the most common case of motorcycle crashes into guardrails (from crash data analysis). Therefore it is the opinion of the study that the angle should not be too shallow as long as we achieve the sliding interaction of the rider on the top of the guardrail. This would serve the purpose of the retrofit option and also take into account the curvature of the roadway.

6.7.4 Critical Impact Points for Upright Motorcycle Testing for Retrofitted Guard Fence System

The CIP for the motorcycle test was determined based on an engineering evaluation of the dummy trajectory upon the impact of the motorcycle against the barrier during the conducted FE computer simulations. Considering that the rider will be free from any type of restraints, the researchers anticipate that the rider will be ejected from the motorcycle and will likely slide on top of the retrofitted guardrail system until falling on the ground. The study recommends the CIP to be 2ft. upstream of the post.

6.7.5 Evaluation of Motorcycle Tests

The kinematics of the crash dummy and the severity and nature of any contact between the head and limbs of the crash dummy and structural components of the retrofitted guardrail system can be assessed through post-test examination of the crash dummy and by using high-speed photography during the test. This is a key aspect of the evaluation of the effectiveness of the retrofit rail design in mitigating potential limb and head injury.

Collected values from the dummy instrumentation can be revised and compared to the National Highway Traffic Safety Administration (NHTSA) Injury Assessment Reference Values (IARVs). It is important to note, however, that the Hybrid III dummy is an ATD that is calibrated for frontal impacts (0-degree orientation angle).

The computer simulation predicted the dummy to be ejected from the motorcycle and to slide along the retrofitted top component of the guardrail. Interaction between dummy's chest, neck and head with the guardrail top component was noted. Therefore, it is suggested to instrument the dummy to investigate forces and deflection of such body components during the full-scale test.

6.8 Recommendations for Sliding Dummy Testing

The standardized procedure that some European countries have elected to adopt and follow involves testing with a sliding dummy to represent the case when the rider is ejected from the motorcycle and slides into the barrier. In this case, no motorcycle is included in the test.

Further, there is no crash database in the U.S. that includes impact conditions (such as impacting speed and angle) associated with real-world motorcycle crashes. Consequently, the study had to rely on previous testing projects and engineering judgment to develop recommended impact conditions for the sliding dummy tests planned under the current project. Details of these recommendations are described below.

6.8.1 Anthropomorphic Dummy

Research suggests using instrumented Hybrid III 50th percentile male ATDs for use in the sliding dummy tests.

6.8.2 Critical Impact Points for Sliding Dummy Tests for Retrofitted Guard Fence Systems

There are two types of sliding dummy testing that is recommended:

- One sliding crash dummy test to evaluate the retrofit system when impacted by a dummy aiming at the post, to represent impacting the most rigid component of the system; and
- One sliding crash dummy test to evaluate the retrofit system when impacted by a dummy aiming at post midspan, to represent impacting the location where the system defection is expected to be higher.

6.8.3 Sliding Dummy Impact Conditions

The study suggests the nominal impact speed and angle for the sliding dummy testing to be 37.3 mph and 30 degrees, respectively, conforming to the European standards. The impact conditions can be used for both configurations of sliding the dummy between the posts and at the post.

6.8.4 Evaluation of Sliding Dummy Tests - Recommendation

The kinematics of the crash dummy and the nature and severity of any contact between the parts of the crash dummy and structural components of the guard fence system can be assessed using high-speed photography and post-test examination of the crash dummy. This is a key aspect of the evaluation of the effectiveness of the retrofit system design in mitigating rider injury potential.

According to the European criteria, there are two performance indicators that shall be considered: (Refer Table 2.7 EN 1317-8 Severity Levels Specification (EN 1317-8))**.**

1) Severity level. This is represented by the level of biomechanical indices that are calculated from the data collected from the ATD instrumentation during the test (Head Injury Criteria (HIC) and neck forces);

2) During the test, the dummy is not allowed to remain trapped in the test item. Dismantling of the dummy to remove the ATD from the test article is not allowed, after completion of the test. No limb, head or neck of the dummy is allowed to become totally detached from the dummy body during or after impact with the test item, and no lacerations to the dummy flesh resulting from the test are allowed. (Refer Table 2.8 EN 1317-8 Determination of Wd Specification (EN 1317-8)).

6.9 Summary of Recommendations

Tables 6.4 summarize recommendations for *MASH* TL-3, upright motorcycle and sliding dummy testing within this research project.

Table 6.4 *MASH* TL-3 Testing Conditions (adapted from AASHTO MASH 2016).

***MASH* Test 3-10**	***MASH* Test 3-11**
Vehicle Type	
1100C Vehicle (Passenger Car); 2420 lb ± 55 lb	2270P Vehicle (Pickup Truck); 5000 lb ±110 lb
Anthropomorphic Dummy	
Uninstrumented Hybrid II ATD on impacting side	No ATD included
Nominal Impact Conditions	
Nominal Impact Speed (mph)	
62 ± 2.5	62 ± 2.5
Nominal Impact Angle (degrees)	
25 ± 1.5	25 ± 1.5
Critical Impact Point Location	
3.1 feet Upstream of Post	4.4 feet Upstream of Post

Table 6.5 summarizes the recommendations for the upright motorcycle testing to be conducted within this research project.

Table 6.5 Upright Motorcycle Testing Recommendations.

Motorcycle Type	
Kawasaki 250 Ninja (Source of this image: wikipedia.org (2020))	
Anthropomorphic Dummy	
Instrumented Hybrid III ATD; Protective clothing, boots, gloves and helmet (Source of this image: Humaneticsatd.com (2019))	
Nominal Impact Conditions	
Nominal Speed (mph)	37
Nominal Angle (degrees)	30
Critical Impact Point Location	2 feet Upstream of Post

Table 6.6 summarizes the recommendations for two sliding dummy tests to be conducted within this research project.

Table 6.6 Sliding Dummy Testing Recommendations.

Anthropomorphic Dummy	
Hybrid III (Pedestrian – Flexible Pelvis); Protective clothing, boots, gloves and helmet (Source of this image: Humaneticsatd.com (2019)) 	
Nominal Impact Conditions	
Nominal Impact Speed (mph)	
Impact between posts	Impact on post
37	37
Nominal Impact Angle (degrees)	
30	30
Critical Impact Point Location	
The centerline of the dummy head aligned with post midspan	The centerline of the dummy head aligned with the post

7 CONCLUSIONS, LIMITATIONS AND FUTURE RESEARCH

7.1 Conclusion

The research study aimed to develop a retrofitted guardrail system to accommodate the need to address motorcyclist safety by mitigating rider injuries. Through literature review with crash data analysis was employed to determine and propose such guardrail system. A retrofitted guardrail system was developed that satisfies such needs and is compliant with MASH and FHWA criteria. FEA simulations were performed on the proposed design option and results obtained were analyzed. Finally, a test plan with is proposed keeping in mind the obtained results and suggestions for testing from an international literature review.

Simulations results indicate that the system would provide adequate safety and serve the intended purpose while satisfying MASH and FHWA criteria. Further, it shows satisfactory behaviour of vehicular, dummy and motorcycle impacts with the guardrail system. In addition, the retrofit options provide feasibility to be employed for TxDOT MGS.

7.2 Limitations and Future Research

The suggested retrofit system is for the new 31 inches tall TxDOT MGS installation with 7.5 inches wood posts diameter, 36 inches embedment. In Texas as in many other states, such systems (31 inches tall MGS wood post installation) is a relatively new system and proved crashworthy in Texas roads. In Texas State, there are many miles of older guardrail system which might not be 31 inches tall or are less than 31 inches of height which do not have 36 inches embedment. Therefore, the need might arise for proposed retrofit options to accommodate these existing older guardrail systems. In this case, due to dimension constraints such as guardrail height of 27 inches or even less might not make it possible to directly apply the proposed system to an existing system. Hence some kind of modification might be needed. Also, wood posts with W beam guardrail type were considered in this project. However, future research can aim to provide such systems to different post materials i.e. steel posts. The system developed and results obtained in this project can hence be used as a reference for designing such new systems. The top and bottom protection systems can be added to other guardrail types with fewer modifications.

The research is limited to the decided impact conditions which are based on literature review and available data. The conditions are investigated based on limited data and hence the conditions might not exactly replicate real-life conditions. Also, there is no standard protocol developed for motorcycle impacting in an upright condition similar to sliding impact condition. Hence, there is a need to a conduct research study to develop standards and protocol for upright motorcycle impact conditions since the behaviour is quite different than sliding impact against the barriers. Further, a standard or protocol would help compare different tests conducted with such systems.

Further, future research should focus on collecting data and conduct data analysis to understand actual impact conditions of the motorcycle against guardrail systems and to understand motorcycle behaviour during such impact events.

Further studied will need to address how to terminate such motorcycle protection systems on the length of need (LON) of the guardrail. Hence, future studies can suggest suitable end termination designs for the top (with top protection cut at end of the post-block out system?) and bottom (can be curved inside before the last post like normal rub rail?) retrofit option. However, more studies and research can provide better solutions to such ideas.

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9 APPENDIX

Table A1. Summary Table of Information Obtained from International Sources.

Questions	Organization/ Laboratory/ Researchers	Answers
1) Are there any advancements, changes or suggestions for CEN/TS 1317-8 “Motorcycle road restraint system which reduce the impact severity of motorcyclist collisions with safety barrier” technical specification?	FEMA	CEN/TS 1317-8 is just a technical specification. We would like to have a real test standard, which is less non-committal. CEN/TS 1317-8 only deals with under slide protection. About 60% of the crashes of motorcyclists with barriers are in upright position. Therefore we also need a protection of the topside of the barrier to prevent toppling over and to prevent serious injuries or death caused by protruding elements of the barrier. This is especially necessary with barriers that have beams on both sides of the posts. This kind of barriers is e.g. common in the Netherlands and some other European countries.
	CSI	In Europe an inter-laboratories testing has been done in order to verify the reliability of the CEN/TS 1217-8 test protocol. The data are
2) Would you be able to provide us with list of proprietary/non-proprietary systems, companies, organizations, etc. with regards to retrofitting of guardrail or any retrofitting of roadside safety devices for motorcycle safety?	FEMA	Part of our RIDERSCAN research project (finalized in 2015) was to build a website (www.mc-roadsidebarriers.eu) where manufacturers could provide this information. All information we have you can find there. However, most information is over four years old and may be outdated.

Table A1. Summary Table of Information Obtained from International Sources (Continued).

Questions	Organization/ Laboratory/ Researchers	Answers
3) Does your Organization follow any standards/protocols for testing roadside safety systems for motorcycle safety?	FEMA	No, we are not directly involved in testing road restraint systems
	CSI	Yes. In Europe the standard is CEN/TS 1317-8 *"Motorcycle road restraint system which reduce the impact severity of motorcyclist collisions with safety barrier"* technical specification. It is a voluntary specification.
	HORIBA MIRA	EN1317 would be used for the testing of a Vehicle Restraint system. Motorcycle protection systems specifically are covered under TS 1317-8:2012.
	Dr. Tana Tan	I work for a consulting company so we don't perform any testing of roadside barriers for motorcycle safety. However, Austroads (**www.austroads.com.au**) is the federal organization receives test reports from manufacturers and distributors wishing to sell their products in Australia. They then evaluate whether these products meet Australian Standards. If so, they then pass on their assessment outcome on products that meet the Australian Standards to each state road agencies. It is then up to each state road agency to decide whether they will allow or disallow the barrier to be installed within their state.
4) Does your Country require implementation of roadside safety systems for motorcycle safety?	**FEMA**	FEMA works on European level, while the implementation of roadside safety systems for motorcycle safety is a national, provincial or local activity. As far as we know very few countries (e.g. the Netherlands, parts of Switzerland, Germany and France) have these kind of requirements. More about this can be found in "Federation of European Motorcyclists' Associations (2012), New standards for road restraint systems for motorcyclists, designing safer roadside for motorcyclists, Brussels".

	HORIBA MIRA	Not specifically for motorcycles only. All vehicle restraint systems must be tested to EN1317 and assessed by a Notified Body to enable the manufacturer to place a CE mark on the product and be sold.
	Dr. Tana Tan	Australia doesn't have laws which require the implementation of roadside safety systems for motorcyclists specifically. However, there are Australian Standards governing the design and installation of barrier systems for other passenger vehicles. Australian Standard AS3845 is the standard that would be most relevant to your research. We also have a federal organization who evaluates barriers for use in Australia. Some information on this origination's involvement in barriers can be found at: https://austroads.com.au/safety-and-design/barrier-assessment
5) Are there any ongoing non-proprietary research study/testing conducted by your organization/country within the field of roadside safety barriers for motorcycle safety? If so, would you be able to share any information in this regard (study objectives)?	FEMA	No. However, we are in contact with CEN TC226 WG1 about the drafting of new standards for both topside and under slide protection systems. This may lead to new research. Furthermore, a recent developed system to attach solar panels on roadside barriers is still being tested for the solar panel part. This system has in our view potential as a topside motorcycle protection system. We contacted the manufacturer and they are willing to do some testing as MPS after the current test is finished. Article: http://www.fema-online.eu/website/index.php/2018/09/10/solarpanels/
	CSI	No

	HORIBA MIRA	No
	Dr. Tana Tan	Not that I am aware of, but I can certainly see a market for it in Australia.
6) Are you aware of any recently completed research /testing study that resulted in new outcomes for motorcycle-friendly roadside safety	FEMA	No, we are not aware of such.
	CSI	No, Probably you have to contact FEMA association in Brussels.
	HORIBA MIRA	No
	Dr. Tana Tan	Not that I am aware of from an Australian perspective.

Table A2. List Of Systems Obtained from FEMA (www.mc-roadsidebarriers.eu)

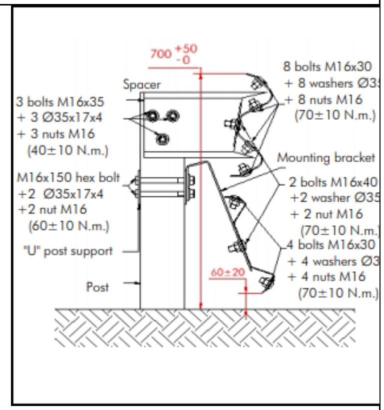
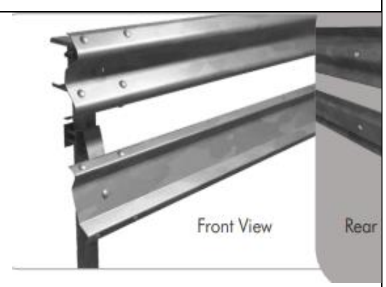
Name of the Manufacturer	Product Name	Country	Test Protocol or Standard	Drawing/Picture
ASEBAL, S.L.	AS-SM6.B (C4)	Spain	UNE 135900 Level 1 60 km/h	
Highway Care Ltd	BikeGuard	United Kingdom	NA	
ASEBAL	AS-SM6.B	Poland	UNE 135900 EN 1317 – 1 and 2 Level 1 60 km/h	

Table A2. List Of Systems Obtained from FEMA (www.mc-roadsidebarriers.eu) Website (Continued).

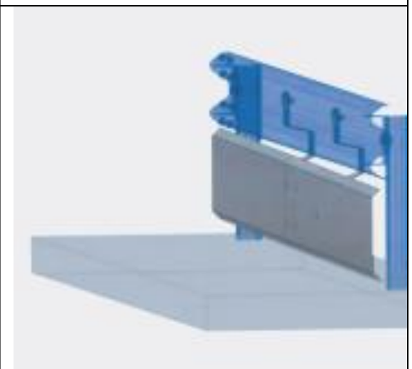
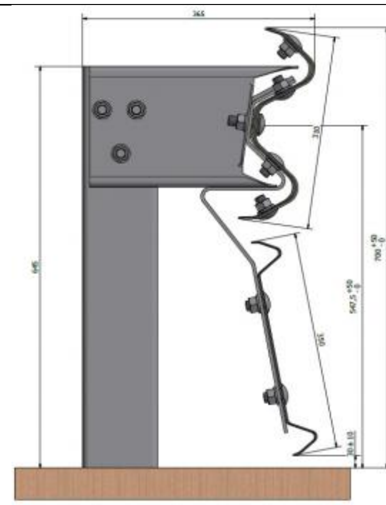
Name of the Manufacturer	Product Name	Country	Test Protocol or Standard	Drawing/Picture
SGGT Strassenausstatt ungen GmbH	Bike-Guard	Germany	BASt 70 km/h	
INDUSTRIAS DUERO	BLM.ID 2-N2/C4	Spain	UNE 135900 Level 1 60 km/h	
CEGASA INTERNACIO NAL, S.A.	Cegasa MPS	Spain	UNE 135900 EN ISO 1421 (Mesh Loads) Level 1 60 km/h	NA

Table A2. List Of Systems Obtained from FEMA (www.mc-roadsidebarriers.eu) Website (Continued).

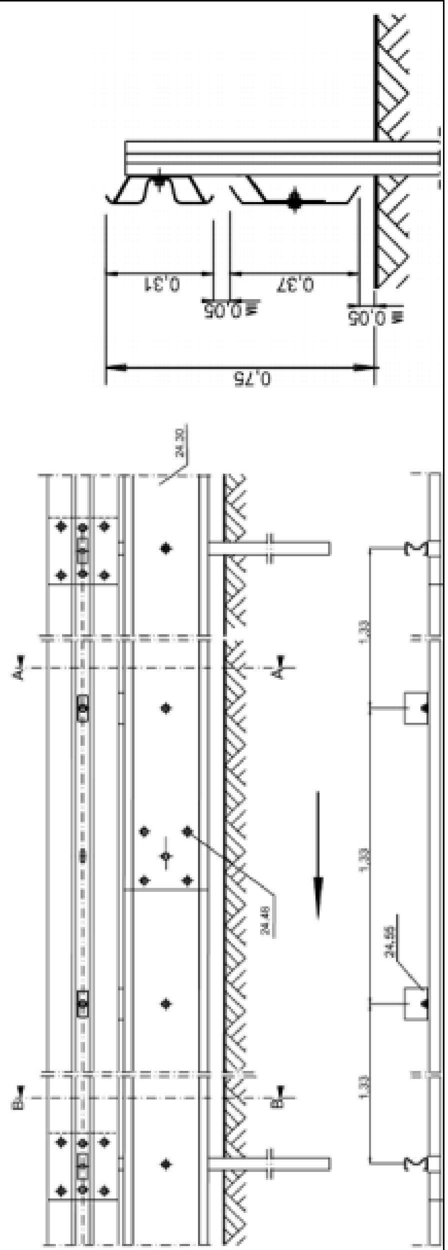
Name of the Manufacturer	Product Name	Country	Test Protocol or Standard	Drawing/Picture
PASS+CO	Einfache Schutzplanke mit Unterfahrschutz (ESP mit UFS)	Germany	BASt EN 1317 RAL-RG 620	

Table A2. List Of Systems Obtained from FEMA (www.mc-roadsidebarriers.eu) Website (Continued).

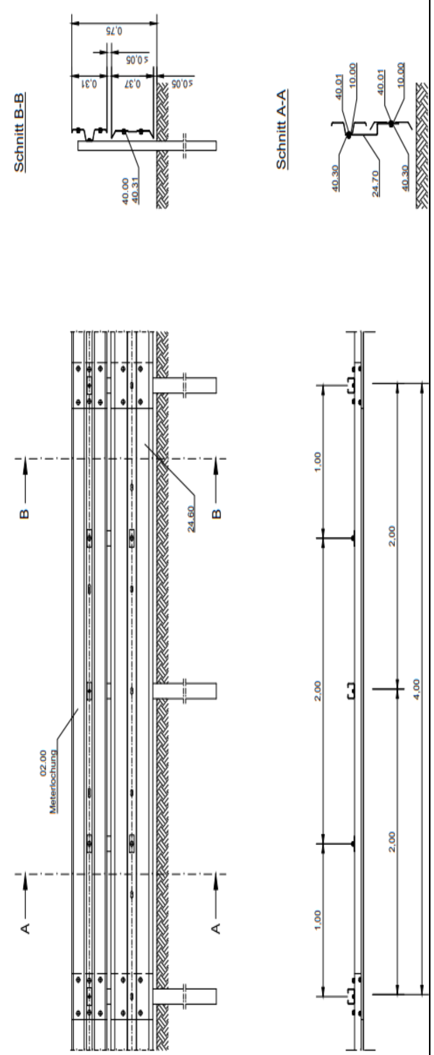
Name of the Manufacturer	Product Name	Country	Test Protocol or Standard	Drawing/Picture
Studiengesellschaft für Stahlschutzplanken e.V.	Eco-Safe MPS	Germany	CEN/TS 1317 – 8 RAL-RG 620 Level 2 60km/h	

Table A2. List Of Systems Obtained from FEMA (www.mc-roadsidebarriers.eu) Website (Continued).

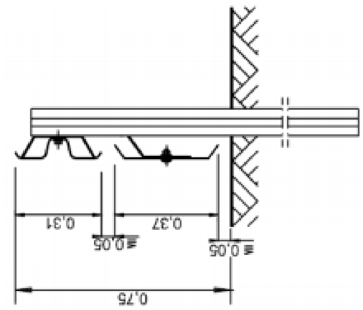
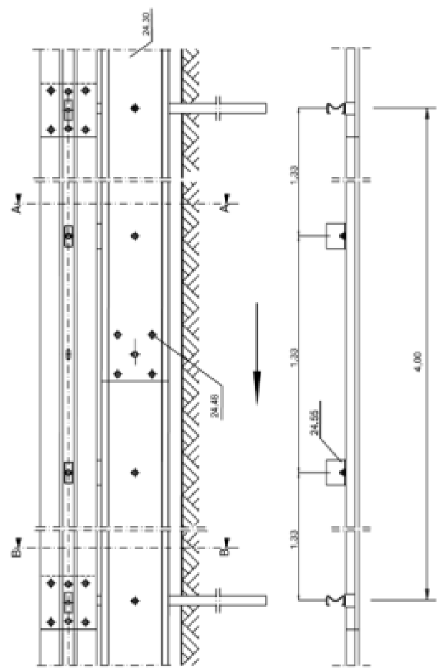
Name of the Manufacturer	Product Name	Country	Test Protocol or Standard	Drawing/Picture
PASS+CO	Einfache Schutzplanke mit Unterfahrschutz (ESP mit UFS)	Germany	BASt EN 1317 RAL-RG 620	 
ASEIM s.l.	Flexible protection for fences	Spain		NA

Table A2. List Of Systems Obtained from FEMA (www.mc-roadsidebarriers.eu) Website (Continued).

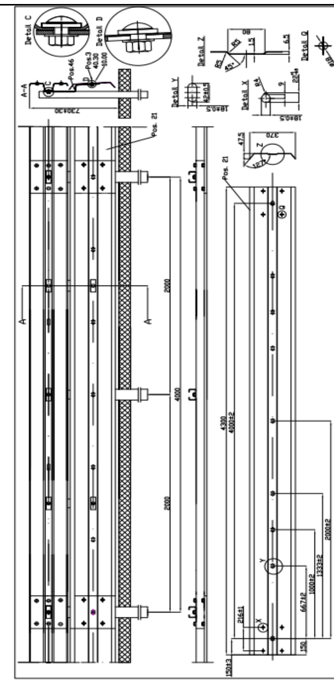
Name of the Manufacturer	Product Name	Country	Test Protocol or Standard	Drawing/Picture
KAUFMANN AG	MOTO-PROTECT	Switzerland	ISO 1461 EN 12767 EN 1317-8 Level 1 60 km/h	
Pass+Co	passco CMPS 60-2-W03 (ES 2.00)	Germany	UNE 135900 ISO 1461 (Durability) EN 1317-8 Level 2 60km/h	

Table A2. List Of Systems Obtained from FEMA (www.mc-roadsidebarriers.eu) Website (Continued).

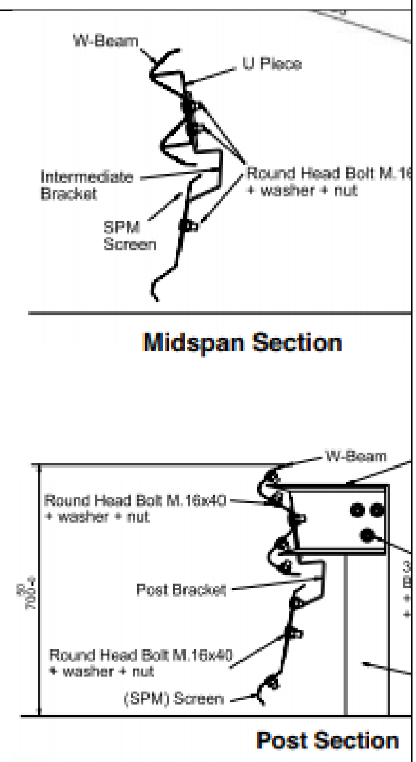
Name of the Manufacturer	Product Name	Country	Test Protocol or Standard	Drawing/Picture
INOXMAR	SEGUR VITAL www.vialmarco.com	Spain	UNE 135900 EN 1317-8 Level 1 60 km/h	
HIERROS Y APLANACIONES S.A. (HIASA)	SPM ES-4	Spain	UNE 135900 Level 1 70 km/h EN 1317-2 EN ISO 1461	

Table A2. List Of Systems Obtained from FEMA (www.mc-roadsidebarriers.eu) Website (Continued).

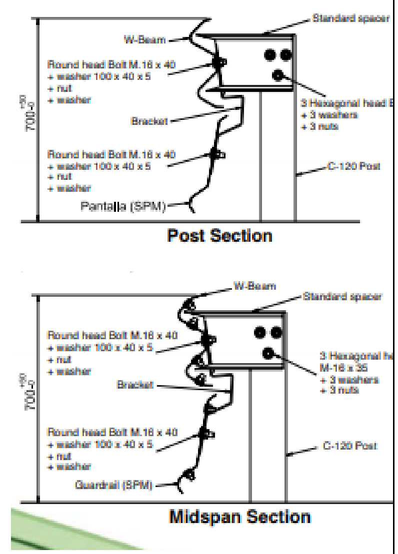
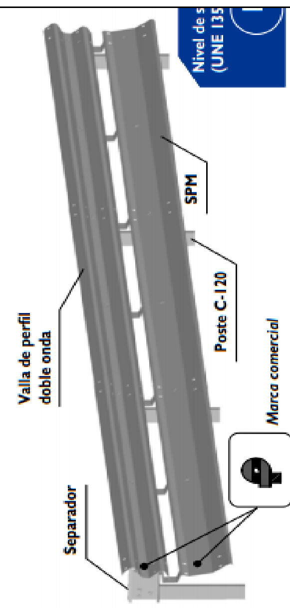
Name of the Manufacturer	Product Name	Country	Test Protocol or Standard	Drawing/Picture
HIERROS Y APLANACIONE S S.A. (HIASA)	SPM-ES2	Spain	UNE 135900 Level 1 70 km/h EN ISO 1461	
Mieres Tubos (Grupo Condesa)	SPM4-MT	Spain	NA	

Table A2. List Of Systems Obtained from FEMA (www.mc-roadsidebarriers.eu) Website (Continued).

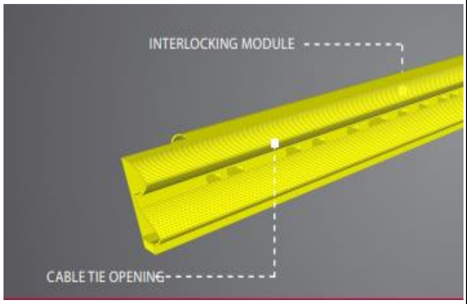
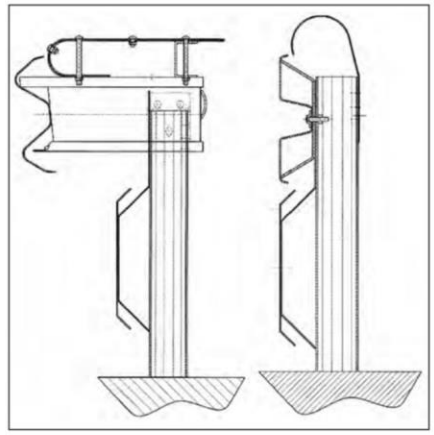
Name of the Manufacturer	Product Name	Country	Test Protocol or Standard	Drawing/Picture
Snoline by Lindsay	DR 46	UK	UNE 135900-1 and 2 EN 1317-2	
Consortium – Heijmans and Solliance Solar Research		Netherlands	Still to be tested	
Barrier Class 1 (Maria's Paper)	Rooftop Barrier	NA	NA	

Table A2. List Of Systems Obtained from FEMA (www.mc-roadsidebarriers.eu) Website (Continued).

Name of the Manufacturer	Product Name	Country	Test Protocol or Standard	Drawing/Picture
Gartner	System Euskirchen Plus nach	Germany	EN 1317	
INGAL CIVIL	Ingal MPR – Ezy-Guard Exploded	Australia	AS/NZS 1594 UNE 139500-1 and 2 UEN/CN 1317-1 and 2 Level 1	
INGAL CIVIL	Ingal Rub Rail	Australia	NA