Texas A&M Transportation Institute

Development and Evaluation of Roadside Safety Systems for Motorcyclists—FY25

Technical Report 9-1531-R4

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16. Abstract

Motorcycle fatalities have continued to rise in the United States over the past decade. The design of roadways and roadside safety hardware often neglects consideration for the safety of motorcycle road users. Under fiscal year 2025 of TPF-5(482), two research tasks were prioritized for evaluation and consideration of motorcycle safety.

The first research task evaluated four roadway design elements and their effect on motorcycle safety. This consisted of evaluating raised crosswalks, speed bumps, vertical drop-offs, and roundabouts using an exploratory analysis in BikeSim. Computer simulations were performed to evaluate the potential for loss of motorcycle vehicle stability when engaging these roadway design elements in different conditions and scenarios. Interaction with these roadway design elements with low roadway friction values was found to be the primary source of loss of motorcycle vehicle stability.

The second research task developed and evaluated two design concepts for terminating a rubrail element in a motorcycle-friendly guardrail system. Both design concepts were modeled for finite element analysis and evaluated through computer simulations. Manual for Assessing Safety Hardware (MASH) Test 3-10 and 3-11 computer simulations were performed to evaluate the performance of the design concepts according to MASH Test Level 3. Both systems were found to indicate satisfactory crashworthy performance in the computer simulations.

17. Key Words
Motorcycle safety, guardrail, roadway design, raised crosswalk, roundabout, drop-off, speed bump, computer simulations, MASH, finite element analysis.

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DISCLAIMER

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CHAPTER 1. INTRODUCTION

The objective of this project was to conduct research addressing roadside safety issues specifically related to improving motorcyclist safety. Specific research tasks were prioritized by the project panel members for the research team to address. This report summarizes the methodologies, results, and conclusions for two research tasks. The two research tasks were as follows:

- Feasibility Study to Investigate Roadway Element Design Characteristics and Their Effects on Motorcycle Safety through BikeSim Computer Simulations.
- Further Development and Refinement of the Anchor Cap for the Motorcycle Rubrail System.

The report is structured such that the results for each research task are contained in an individual chapter. Each chapter contains the research objectives, design and methodologies, analyses, results, and conclusions for a specific research task.

CHAPTER 2. GEOMETRIC ROADWAY DESIGN EFFECTS ON MOTORCYCLE SAFETY

Motorcycle safety continues to be a primary concern for state departments of transportation (DOTs). According to the National Highway Traffic Safety Administration (2023), motorcycle fatalities continue to rise and represented 15 percent of all traffic fatalities in 2023. There are several factors that can contribute to severe and fatal motorcycle crashes. One factor is the design of the roadway. Research and new technologies have improved the design of our roadways and increased safety. However, these advances are often focused on standard passenger vehicles. Motorcycle vehicles are often not considered when designing and implementing roadway elements and not discussed in most roadway design guides.

This chapter presents a study focused on evaluating roadway design elements and their effect on motorcyclists. Four roadway design elements were considered: raised crosswalks, speed bumps, vertical drop-offs, and roundabouts. These roadway elements may present unique safety concerns for motorcycle vehicles if they are encountered in certain situations and/or environments.

Computer simulations were used as the primary tool for evaluating the effect of these roadway design elements on motorcycle safety. Specifically, the potential loss of motorcycle vehicle stability was the primary evaluation factor. Computer simulations were performed in the BikeSim environment.

BACKGROUND

This section provides an overview of the four geometric elements and outlines any previous research related to evaluation of these geometric elements for motorcycle safety.

Raised Crosswalk

Raised crosswalks were one of the recent pedestrian countermeasures promoted by the Federal Highway Administration (FHWA) through Safe Transportation for Every Pedestrian. A raised crosswalk elevates the crossing area for pedestrians to the level of the nearby sidewalk. This raised elevation increases the visibility of pedestrians to drivers. In addition, the approach ramp to the raised crosswalk may reduce vehicle speeds and improve driver yielding. This countermeasure has been noted to reduce pedestrian crashes by 45 percent (FHWA 2018). However, these raised crosswalks may present unique challenges to motorcycle riders. The geometry and placement of raised crosswalks could lead to challenges in safely traversing the raised crosswalk for motorcyclists.

Raised crosswalks typically comprise of a 6 ft long ramp section and a 10 ft long flat top (Figure 1). There are other variations which can include a sloped top and/or a parabolic ramp section. The height of the crosswalk will vary depending on the sidewalk height and typically ranges from 3 to 6 inches. Raised crosswalks are typically used on roads with speed limits 30 mph or less and an annual daily traffic below 9,000. Figure 2 shows an example of a raised crosswalk.

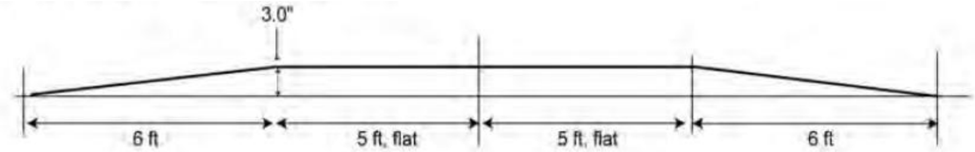


Figure 1. Cross-Section View of Raised Crosswalk (MassDOT 2006).

Figure 2. Example of Raised Crosswalk (FHWA 2018).

Speed Bump

Speed bumps are similar to raised crosswalks but are not intended for pedestrian crossing. The objective is to reduce vehicle speeds at certain locations. Historically, these have not presented significant safety concerns for motorcyclists. However, if not designed or maintained properly, then there may be potential for loss of motorcycle stability when traversing over the speed bump. Common range for speed bump heights is 3 to 4 inches.

Vertical Drop-Off

Vertical drop-offs may exist between lanes during pavement projects where staged paving is utilized. This can present a height differential between nearby lanes, creating a risk to any road users who traverse over it. The height differential is often limited to 1 to 2 inches and may incorporate a slight taper. State DOT agencies have implemented strategies to mitigate this risk such as advanced warning signs and channelizing devices. However, concerns still exist about these situations and how they may affect motorcyclist safety. No research has been conducted that has investigated the effects of these vertical drop-offs on motorcyclist safety.

Roundabout

A roundabout is an unsignalized circular intersection where traffic flows counterclockwise around a central island. These are designed for lowering traffic speed upon entry and act as an efficient alternative to traffic signals. There are four main types of roundabouts: mini-roundabout, compact roundabout, single-lane roundabout, and multi-lane roundabout. National Cooperative Highway Research Program Report 1043 (2023) provides guidance for planning, designing, and implementing roundabouts. There is minimal discussion in this guide regarding the consideration of motorcycle users when designing roundabouts. A study by Hermanus et al. (2015) found that motorcycles were overrepresented in severe crashes at roundabouts compared to standard intersections. Specifically, there was a significant number of crashes that involved motorcyclist interaction with curbed elements in the roundabout. Thus, investigation of these curb elements was the primary consideration design element under this research project. Some key details regarding current roundabout design are discussed below.

Design Speed

The typical design speed for roundabouts depends on the lane configuration and ranges from 15 to 25 mph. The entry speed will depend on the connecting roadway, but recommended entry speeds are 20 to 30 mph.

Geometry

There are several common features for roundabouts that vary in usage and design depending on the type of roundabout. These consist of:

- Central island—Center of the roundabout.
- Splitter island—Raised or traversable area that separates entering traffic from exiting traffic.
- Truck apron—A raised area around the central island that is traversable by large vehicles.
- Circulatory roadway—Roadway path vehicles use to travel counterclockwise around the central island.
- Buffer strip—Separate vehicular and pedestrian traffic.
- Bicycle ramp—Allow bicyclists to exit the roadway in advance of the circulatory roadway.

The presence of these features depends on the traffic volume, number of lanes, and urban/rural roadway setting. Figure 3 shows an example of a two-lane roundabout.

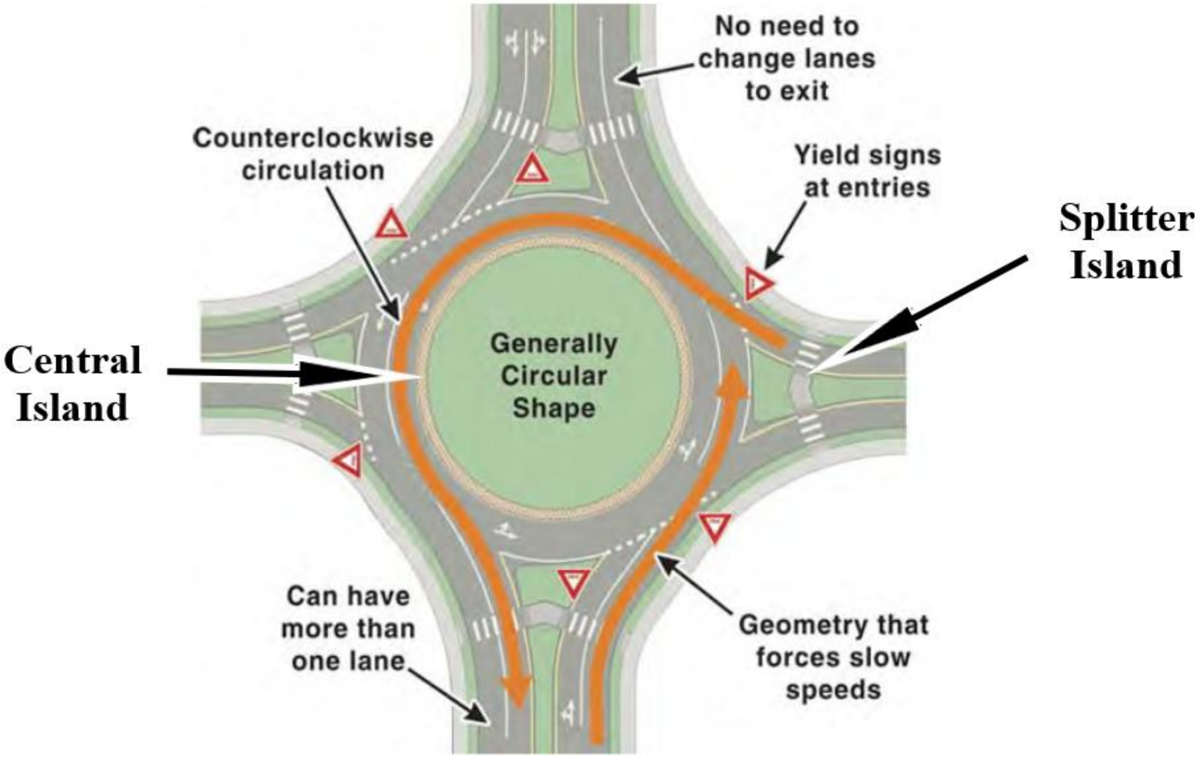
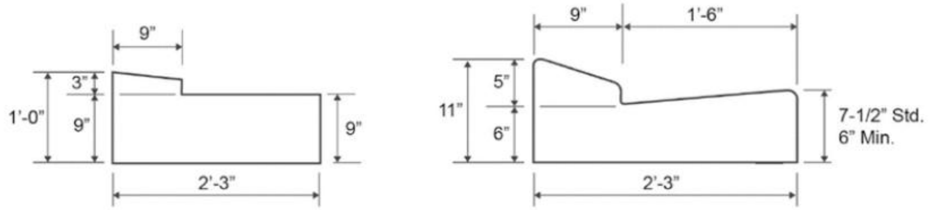


Figure 3. Features of a Two-Lane Roundabout (NAS 2023).

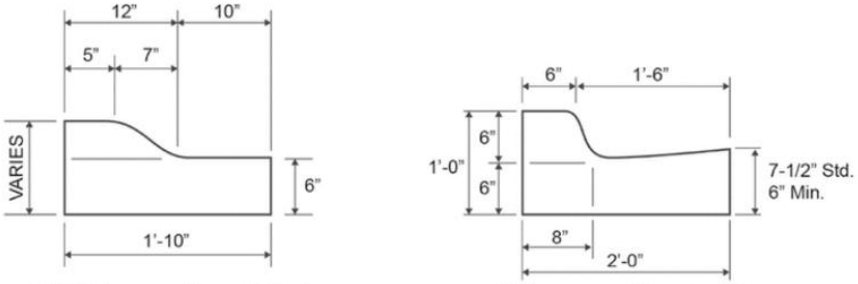
Curbs

Raised elements in the roundabout often have curb structures. The presence of curbs typically applies to the central island and splitter island. There are two types of curbs for these applications: traversable and non-traversable. Traversable curbs are designed with a sloped profile to allow vehicles to safely travel over the curb. Non-traversable curbs are designed with a steep (i.e., vertical) face to prevent vehicles from going over the curb. Figure 4 shows examples of traversable and non-traversable curb configurations used for roundabouts. The typical height of these curbs is six inches.



(a) Traversable curb with lower rise. May be used at truck apron.

(b) Traversable curb with more rise than (a) example. May be used at splitter island or medium.



(c) Rolled, mountable curb. May be used at truck apron.

(d) Non-traversable curb with sloped face. May be used at splitter island or median.

Figure 4. Geometry of Curb Types (NAS 2023).

METHODOLOGY

Computer simulations were performed to evaluate various design aspects of raised crosswalks, vertical drop-offs, and roundabouts and their effect on motorcycle safety. Specifically, the computer simulations aimed to evaluate the potential for motorcycle loss of stability and/or rider ejection.

The computer simulation analysis was performed using BikeSim software. It is a high-fidelity physics-based simulation software that can analyze the dynamic behavior of two-wheeled vehicles such as motorcycles and scooters. The software provides a configurable simulation environment that allows for modeling components such as roadway geometrics and weather effects (i.e., dry/wet roadway surface). Motorcycle models are available in the software package and have realistic inputs for suspension systems, tire models, and braking systems. There are three primary motorcycle types included in BikeSim. These consist of sport/standard, cruiser, and touring (Figure 5). Motorcycle rider maneuvers (e.g., turning, lane crossing, etc.) can be incorporated into the BikeSim environment.

a. Sport/Standard b. Cruiser c. Touring

Figure 5. Motorcycle Types in BikeSim Environment.

The setup for the computer simulations performed in BikeSim to evaluate raised crosswalks, vertical drop-offs, and roundabouts are summarized below.

Raised Crosswalk

The roadway environment consisted of a 22 ft long raised crosswalk with an upward sloped ramp of 6 ft in length and 3 inches in height, followed by a 10 ft long horizontal surface, and ending with a 6 ft sloped down ramp. Figure 6 depicts the raised crosswalk in the BikeSim environment.

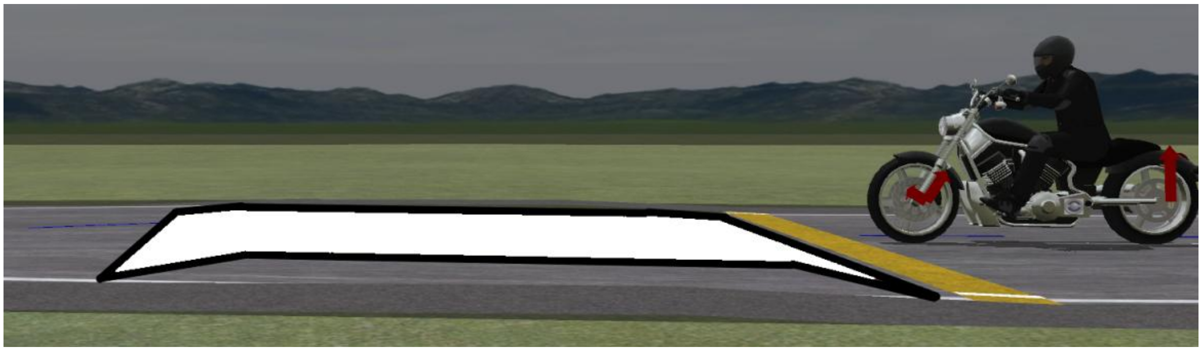


Figure 6. Visual Representation of a Raised Crosswalk in BikeSim.

The impact speeds considered for the raised crosswalk were 25 mph, 28 mph, and 31 mph. These speeds consider variations around the standard 30 mph design speed for raised crosswalks. Two impact scenarios were considered for the raised crosswalk. The first scenario consisted of the motorcycle traversing straight over the raised crosswalk (Figure 7a). The second scenario consisted of the motorcycle turning from the roadway and traversing over the raised crosswalk as the turn is being completed (Figure 7b).

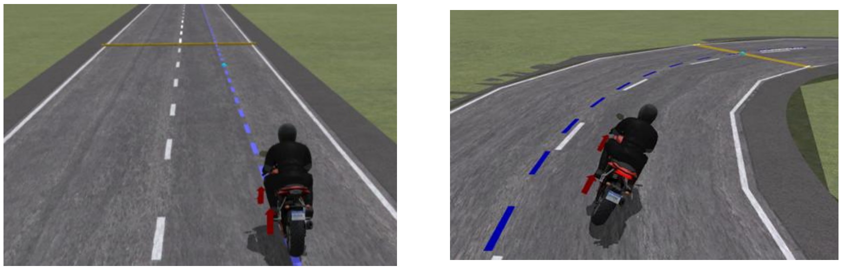

a. Straight Path b. Turn

Figure 7. Motorcycle Steering Paths for Raised Crosswalk.

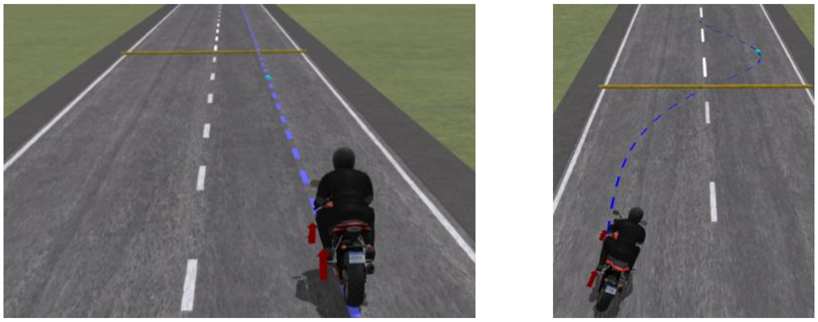
Another factor considered was roadway friction. Debris and accumulated water/snow around raised crosswalks can reduce the friction between the roadway and vehicle tires. This loss in friction can have a significant impact on motorcycle stability. Friction values ranging between 0.2 to 1.0 were considered in the simulations.

Speed Bump

The roadway environment for the speed bump consisted of a 4-inch-tall, rounded bump. Figure 8 depicts the speed bump in the BikeSim environment.

Figure 8. Visual Representation of a Speed Bump in BikeSim.

The impact speeds considered for the speed bump were 25 mph, 28 mph, and 31 mph. Two impact scenarios were considered for the speed bump. The first scenario consisted of the motorcycle traversing straight over the speed bump (Figure 9a). The second scenario consisted of the motorcycle traversing over the speed at an angle of 45 degrees (Figure 9b).



a. Straight b. Angle

Figure 9. Motorcycle Steering Paths for Speed Bump.

Another factor considered was roadway friction. Debris and accumulated water/snow around speed bumps can reduce the friction between the roadway and vehicle tires. This loss in friction can have a significant impact on motorcycle stability. Friction values ranging between 0.2 to 1.0 were considered in the simulations.

Vertical Drop-Off

The roadway environment for the vertical drop-off consisted of a two-lane roadway with a vertical drop-off between the two lanes. The vertical drop-off height was 3 inches. Figure 10 shows the roadway environment in BikeSim.

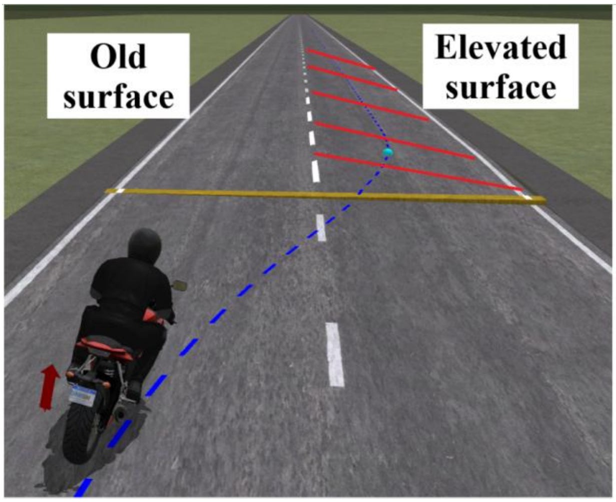


Figure 10. Visual Representation of Different Elevated Roadway Surfaces in BikeSim.

Low-speed traversals were considered for this roadway environment to replicate low-speed work zone conditions. The impact speeds consisted of 25 mph, 28 mph, and 31 mph.

The motorcycle maneuver considered for this roadway environment involved a transition from the original roadway surface to the elevated newly paved roadway surface. This involved traversal over the 3-inch drop-off height.

The friction value for the newly paved roadway surface was 0.85. The friction value for the original roadway surface ranged from 0.2 to 0.7 to represent varying pavement conditions.

Roundabout

It was not possible to configure a full roundabout roadway environment in BikeSim. A simplified version of the environment was used to represent the roadway conditions for two scenarios. The first scenario considered a motorcyclist that entered the roundabout but did not make the turn. This would result in contact/interaction with the central island curb. The simplified roadway environment for this scenario consisted of a 6-inch-tall non-traversable curb element with the motorcyclist impacting at various speeds and angles. Figure 11 shows the simplified environment in BikeSim. The second scenario consisted of a motorcyclist that does not enter the roundabout correctly and contacts the splitter island curb. The simplified roadway environment for this scenario consisted of a splitter island curb shape with the motorcyclist impacting at various speeds and angles. The curb was a 6-inch-tall non-traversable configuration. Figure 12 shows the simplified environment in Bikesim.

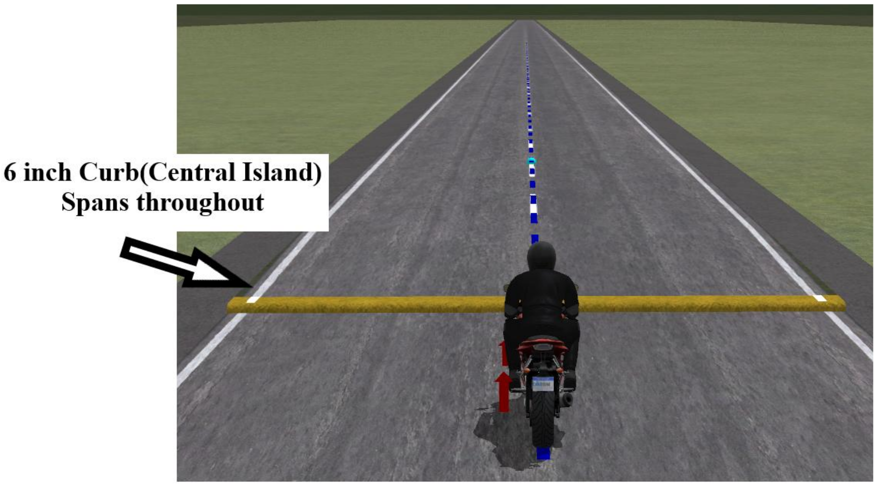


Figure 11. Simplified Central Island Curb Environment in BikeSim.

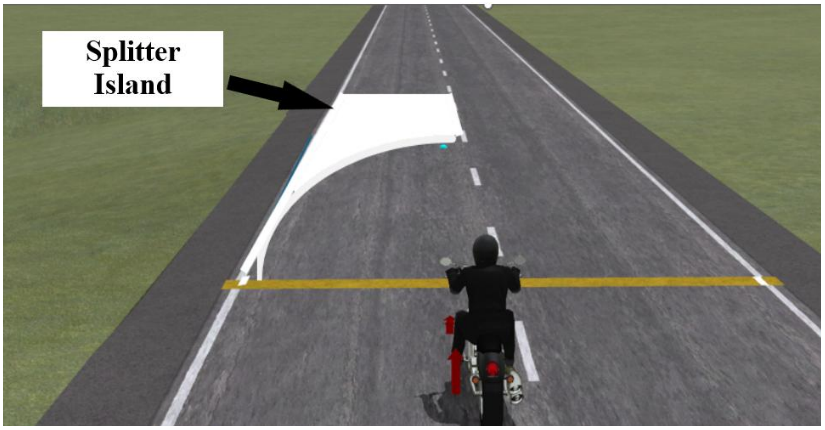


Figure 12. Simplified Splitter Island Curb Environment in BikeSim.

Impact speeds considered for these roundabout scenarios were 25 mph, 28 mph, and 31 mph. These speeds consider variations around the 30 mph entry speed for roundabouts.

For the central island and splitter island scenarios, two traversals were evaluated. One traversal consisted of the motorcyclist impacting the curb head-on, and the second traversal consisted of the motorcyclist impacting the curb at a 45-degree angle.

The friction value for the roadway environment was 0.7. This value was not changed during the simulations.

RESULTS

Computer simulations were performed in BikeSim based on the conditions described in the Methodology section. The primary evaluation factor for the simulations was loss of stability for the motorcycle vehicle. The results are presented based on the roadway environment.

Raised Crosswalk

Table 1 presents the simulation results for raised crosswalks. Loss of stability for the motorcycle vehicle was observed for most of the simulation events with the motorcycle turning and traversing over the raised crosswalk. For a friction coefficient of 1.0, a few of the simulation events indicated a stable motorcycle vehicle. For the straight path motorcycle vehicle traversal, all the simulations indicated stability throughout the event.

Table 1. BikeSim Results for Raised Crosswalks.

Vehicle Maneuver	Motorcycle Type	Impact Speed (mph)	Friction Coefficient	Loss of Stability?
Right Turn	Sport	25	0.2	Yes
		25	0.7	Yes
		25	1.0	No
		28	0.2	Yes
		28	0.7	Yes
		28	1.0	No
		31	0.2	Yes
		31	0.7	Yes
		31	1.0	Yes
	Cruiser	25	0.2	Yes
		25	0.7	Yes

Vehicle Maneuver	**Motorcycle Type**	**Impact Speed (mph)**	**Friction Coefficient**	**Loss of Stability?**
		25	1.0	No
		28	0.2	Yes
		28	0.7	Yes
		28	1.0	Yes
		31	0.2	Yes
		31	0.7	Yes
		31	1.0	Yes
	Touring	25	0.2	Yes
		25	0.7	Yes
		25	1.0	Yes
		28	0.2	Yes
		28	0.7	Yes
		28	1.0	Yes
		31	0.2	Yes
		31	0.7	Yes
		31	1.0	Yes
Straight	Sport	25	0.2	No
		25	0.7	No
		25	1.0	No
		28	0.2	No
		28	0.7	No
		28	1.0	No
		31	0.2	No
		31	0.7	No
		31	1.0	No
	Cruiser	25	0.2	No
		25	0.7	No
		25	1.0	No
		28	0.2	No

Vehicle Maneuver	Motorcycle Type	Impact Speed (mph)	Friction Coefficient	Loss of Stability?
		28	0.7	No
		28	1.0	No
		31	0.2	No
		31	0.7	No
		31	1.0	No
	Touring	25	0.2	No
		25	0.7	No
		25	1.0	No
		28	0.2	No
		28	0.7	No
		28	1.0	No
		31	0.2	No
		31	0.7	No
		31	1.0	No

Speed Bump

Table 2 presents the simulation results for speed bumps. Loss of motorcycle vehicle stability was observed for most of the angled traversals involving lower roadway friction coefficients. For higher friction coefficients, the observance of motorcycle vehicle instability decreased. Stability of the vehicle after traversing over the speed bump was observed for all simulation cases with the straight vehicle maneuver.

Table 2. BikeSim Results for Speed Bumps.

Vehicle Maneuver	Motorcycle Type	Impact Speed (mph)	Friction Coefficient	Loss of Stability?
Angle	Sport	25	0.2	Yes
		28	0.2	Yes
		31	0.2	Yes
		25	0.3	Yes
		28	0.3	Yes

Vehicle Maneuver	**Motorcycle Type**	**Impact Speed (mph)**	**Friction Coefficient**	**Loss of Stability?**
		31	0.3	Yes
		25	0.4	Yes
		28	0.4	Yes
		31	0.4	No
		25	0.5	Yes
		28	0.5	No
		31	0.5	No
		25	0.7	Yes
		28	0.7	No
		31	0.7	No
		25	1	Yes
		28	1	No
		31	1	No
	Cruiser	25	0.2	Yes
		28	0.2	Yes
		31	0.2	Yes
		25	0.3	Yes
		28	0.3	Yes
		31	0.3	Yes
		25	0.4	Yes
		28	0.4	Yes
		31	0.4	Yes
		25	0.5	Yes
		28	0.5	Yes
		31	0.5	No
		25	0.7	No
		28	0.7	No
		31	0.7	No
		25	1	No

Vehicle Maneuver	Motorcycle Type	Impact Speed (mph)	Friction Coefficient	Loss of Stability?
		28	1	No
		31	1	No
	Touring	25	0.2	Yes
		28	0.2	Yes
		31	0.2	Yes
		25	0.3	Yes
		28	0.3	Yes
		31	0.3	Yes
		25	0.4	Yes
		28	0.4	No
		31	0.4	No
		25	0.5	No
		28	0.5	No
		31	0.5	No
		25	0.7	No
		28	0.7	No
		31	0.7	No
		25	1	No
		28	1	No
		31	1	No
Straight	Sport	25	0.2-1	No
		28	0.2-1	No
		31	0.2-1	No
	Cruiser	25	0.2-1	No
		28	0.2-1	No
		31	0.2-1	No
	Touring	25	0.2-1	No
		28	0.2-1	No
		31	0.2-1	No

Vertical Drop-Off

Table 3 presents the simulation results for vertical drop-offs. Loss of stability was primarily observed for the lower speeds of 25 and 28 mph, with a low friction coefficient of 0.2 for the original roadway. This finding was consistent for the three motorcycle vehicle types. The other speed and friction combinations did not indicate any loss of stability for motorcycle riders.

Table 3. BikeSim Results for Vertical Drop-Off.

Motorcycle Type	Speed (mph)	Original Roadway Friction Coefficient	Newly Paved Roadway Friction Coefficient	Loss of Stability?
Sport	25	0.2	0.85	Yes
	28	0.2	0.85	Yes
	31	0.2	0.85	No
	25	0.3	0.85	No
	28	0.3	0.85	No
	31	0.3	0.85	No
	25	0.7	0.85	No
	28	0.7	0.85	No
	31	0.7	0.85	No
Cruiser	25	0.2	0.85	Yes
	28	0.2	0.85	Yes
	31	0.2	0.85	No
	25	0.3	0.85	No
	28	0.3	0.85	No
	31	0.3	0.85	No
	25	0.7	0.85	No
	28	0.7	0.85	No
	31	0.7	0.85	No
Touring	25	0.2	0.85	No
	28	0.2	0.85	Yes
	31	0.2	0.85	Yes
	25	0.3	0.85	No

	28	0.3	0.85	No
	31	0.3	0.85	No
	25	0.7	0.85	No
	28	0.7	0.85	No
	31	0.7	0.85	No

Roundabout

Table 4 presents the simulation results for the roundabout central island curb scenario. Only one simulation event indicated loss of stability for the motorcycle vehicle. This event consisted of the touring motorcycle impacting the central island curb at an angle and speed of 31 mph. All other simulation events indicated stable motorcycle traversal over the curb.

Table 4. BikeSim Results for Roundabout Central Island.

Vehicle Maneuver	Motorcycle Type	Impact Speed (mph)	Friction Coefficient	Loss of Stability?
Straight Path	Sport	25	0.7	No
		28	0.7	No
		31	0.7	No
	Cruiser	25	0.7	No
		28	0.7	No
		31	0.7	No
	Touring	25	0.7	No
		28	0.7	No
		31	0.7	No
45-Degree Angle	Sport	25	0.7	No
		22	0.7	No
	Cruiser	25	0.7	No
		28	0.7	No
		31	0.7	No
	Touring	25	0.7	No
		22	0.7	No
		31	0.7	Yes

Table 5 presents the simulation results for the roundabout splitter island curb scenario. None of the simulation impacts indicated loss of stability for the motorcycle vehicle.

Table 5. BikeSim Results for Roundabout Splitter Island.

Vehicle Maneuver	Motorcycle Type	Impact Speed (mph)	Friction Coefficient	Loss of Stability?
Straight Path	Sport	25	0.7	No
		12.5	0.7	No
		31	0.7	No
	Cruiser	25	0.7	No
		12.5	0.7	No
		31	0.7	No
	Touring	25	0.7	No
		12.5	0.7	No
		31	0.7	No

SUMMARY

Computer simulations were performed in the BikeSim environment to evaluate four roadway design elements. The simulation outcome was evaluated for loss of motorcycle vehicle stability.

A standard raised crosswalk design was evaluated with three different motorcycle vehicle types, three impact speeds, two vehicle maneuvers, and three roadway friction coefficients. There was no loss of stability observed for any of the simulation cases that involved the motorcycle traversing straight over the raised crosswalk. For the scenario where the motorcycle vehicle turned and traversed over the raised crosswalk, a majority of the simulation cases indicated loss of stability for the motorcycle vehicle. A few cases with a friction coefficient of 1.0 did indicate a stable motorcycle vehicle throughout the event.

A standard speed bump design was evaluated with three different motorcycle vehicle types, three impact speeds, two vehicle maneuvers, and seven roadway friction coefficients. Similar to the raised crosswalk, there was no loss of stability observed when the motorcycle vehicle traversed straight over the speed bump. Loss of motorcycle vehicle stability was observed for several of the simulation cases involving the vehicle traversing over the speed bump at an angle. This finding was primarily observed when the roadway friction coefficient was below 0.5. Stable motorcycle vehicle traversal over the speed bump was observed when the friction coefficient was higher than 0.5.

A vertical drop-off was evaluated with three different motorcycle vehicle types, three impact speeds, a single vehicle maneuver, and three roadway friction coefficients. The primary configuration that resulted in loss of vehicle stability was a low friction coefficient for the original roadway surface. All other simulation cases indicated stable motorcycle vehicle interaction with the vertical drop-off.

Two roundabout design elements were evaluated with three different motorcycle vehicle types, three impact speeds, two vehicle maneuvers, and one roadway friction coefficient. The first roundabout design element was the central island with a 6-inch-tall non-traversable curb. Only one simulation case indicated loss of vehicle stability during the impact event. This case consisted of a touring motorcycle impacting the curb at an angle and at a speed of 31 mph. All other cases indicated stable motorcycle vehicle performance during the impact event. The second roundabout design element was the splitter island with a 6-inch-tall non-traversable curb. All simulation events indicated stable motorcycle vehicle performance during the impact event.

Overall, the computer simulation analysis indicated a minimal effect on motorcycle vehicle safety for the four roadway design elements. Low roadway friction coefficients did have a negative effect on motorcycle safety in some situations. Thus, practitioners should consider appropriate practices to maintain friction coefficient levels in the range of 0.4 to 0.6.

CHAPTER 3. EVALUATION OF MOTORCYCLE RUBRAIL TERMINATION

BACKGROUND AND NEED

A motorcycle-friendly guardrail system was previously designed and evaluated according to the Manual for Assessing Safety Hardware (MASH) Test Level 3 (TL-3) (Schulz et al. 2023). The system indicated satisfactory crashworthy performance for TL-3. This system was also evaluated for motorcyclist impacts in an upright and sliding configuration (Schulz et al. 2024). The system performed satisfactorily for the non-standard motorcycle test criteria. The main components of this motorcycle-friendly guardrail system are a cap rail that covers the top of the w-beam rail and top of the guardrail posts, and a rubrail that provides continuous protection along the bottom of the guardrail system.

In most field installations, this motorcycle-friendly guardrail system will be implemented at locations with high risk for motorcycle crashes (e.g., sharp horizontal curves). Thus, only a portion of the entire guardrail system may incorporate the cap rail and rubrail elements in the motorcycle-friendly guardrail system. The other sections would consist of standard guardrail components. It was necessary to consider how to transition between these two sections and develop termination details for the cap rail and rubrail.

The cap rail nests behind the w-beam rail and would not be exposed to vehicle impacts. Thus, no specific design was required to shield the end of the cap rail. However, the rubrail would present an exposed end to vehicle impacts that may negatively impact the crashworthiness of the guardrail system. Thus, a specific termination design may be required to shield the end of the rubrail from potential vehicle impacts.

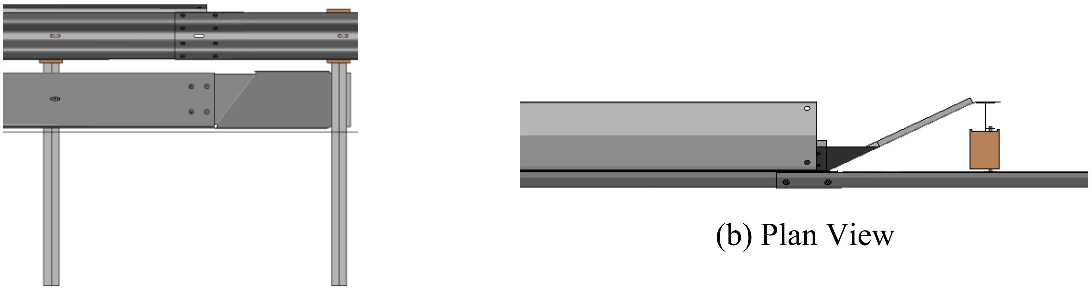
This chapter presents an evaluation of two rubrail termination design concepts according to MASH TL-3. Finite element computer simulations were used as the primary tool for evaluating the crashworthiness of the two designs. Computer simulations were performed using LS-DYNA.

METHODOLOGY

Finite element (FE) analysis was used to evaluate the crashworthy performance of two design concepts for termination on the rubrail. This section provides details for the design concepts, FE models, and evaluation criteria.

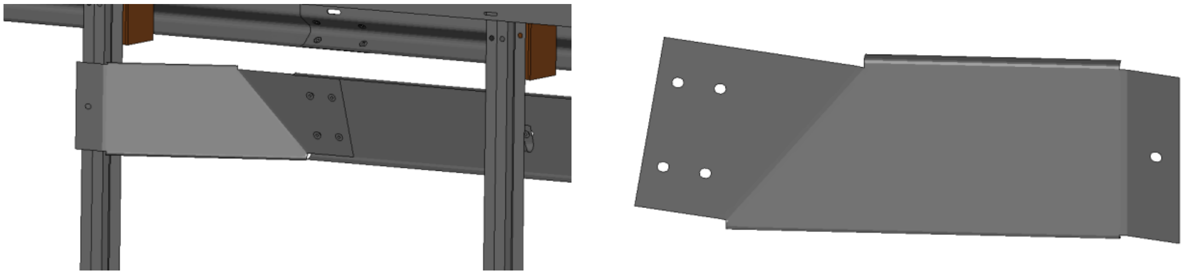
Design Concepts

Two design concepts were developed that consisted of terminating the rubrail behind a guardrail post to shield the blunt end from vehicle impacts. The first design concept consisted of a single bent rail piece that attaches to the main rubrail and connects on the back side of the nearby guardrail post. Figure 13 shows different views for the first design concept. The second design concept consisted of multiple shortened rubrail pieces that taper back and are terminated behind a guardrail post. Bent plates are used to connect the shortened rubrail pieces together and taper the system. Figure 14 shows different views for the second design concept.



(a) Elevation View

(b) Plan View



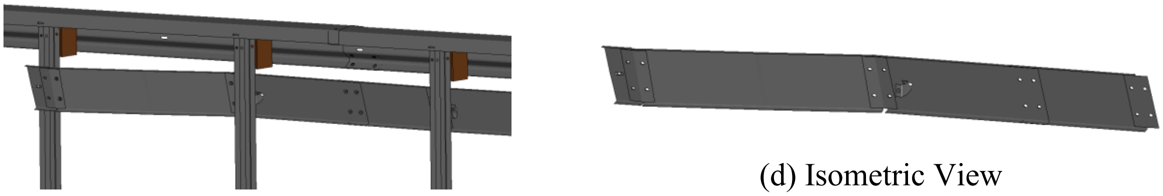
(c) Close-Up View

(d) Isometric View

Figure 13. Bent Rail Rubrail Termination Design Concept.

(a) Elevation View

(b) Plan View



(c) Close-Up View

(d) Isometric View

Figure 14. Multiple Tapered Rail Rubrail Termination Design Concept.

Model

A finite model of each design concept was developed for evaluation through computer simulations. Each model generally included the following components: steel posts, w-beam steel rail, steel rubrail, steel cap rail, timber blockouts, guardrail bolts, and the rubrail termination components. The timber blockouts were modeled using MAT_WOOD. The steel posts, w-beam rail, cap rail, rubrail, and rubrail termination components were modeled using

MAT_PIECEWISE_LINEAR_PLASTICITY. Figure 15 through Figure 17 show different views of the FE model. This model represents the second design concept. The first design concept was similar except for the differences in the termination of the rubrail.

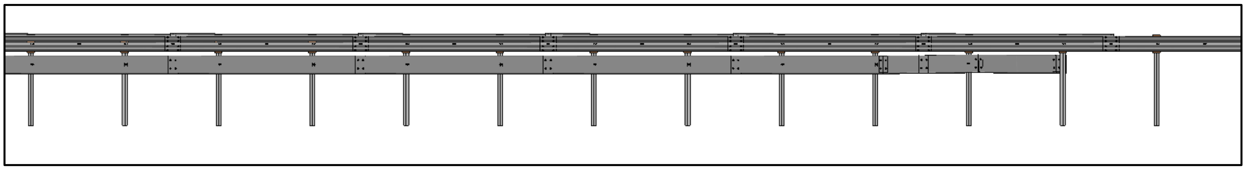


Figure 15. Elevation View of FE Model.

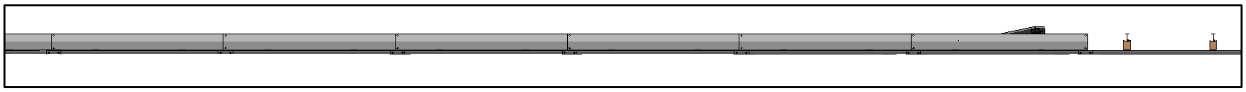


Figure 16. Plan View of FE Model.

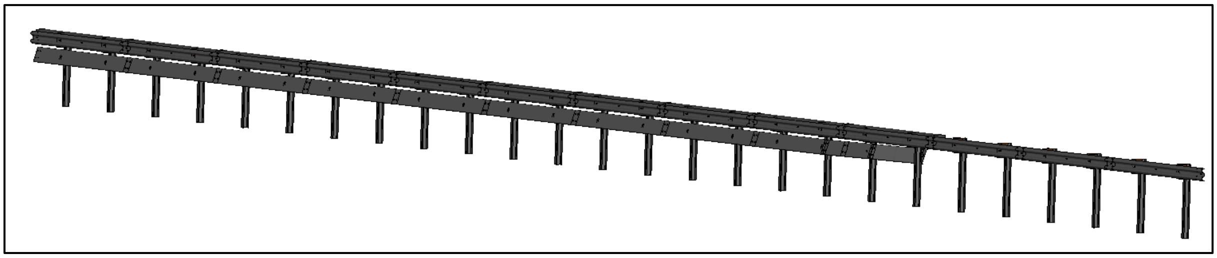


Figure 17. Overall View of FE Model.

Simulation Setup

Computer simulations were performed using the FE method to evaluate each design concept according to MASH TL-3. This involved performing simulations for MASH Tests 3-10 and 3-11. LS-DYNA, which is a commercially available general purpose FE software, was used for all the finite element analyses. A 2,425-lb Toyota Yaris small car vehicle model was used for the MASH Test 3-10 computer simulations (Figure 18). A 5,000-lb Dodge Ram pickup truck vehicle model was used for the MASH Test 3-11 computer simulations (Figure 19).

The MASH Test 3-10 and 3-11 computer simulations were performed with an impact speed and angle of 62 mph and 25 degrees. The critical impact location (CIP) for MASH Test 3-10 was 5.5 ft upstream of the end of the rubrail. The CIP for MASH Test 3-11 was 7.5 ft upstream of the end of the rubrail. The selection of the CIP was made to maximize the potential interaction of the vehicle with the end of the rubrail. In addition to these CIPs, two additional locations were considered for each test. This included one CIP 2 ft upstream of the original and one CIP 2 ft downstream of the original location. Thus, three simulations were conducted for MASH Test 3-10 with a CIP of 3.5 ft, 5.5 ft, and 7.5 ft upstream of the end of the rubrail. Three simulations were conducted for MASH Test 3-11 with a CIP of 5.5 ft, 7.5 ft, and 9.5 ft upstream of the end of the rubrail.

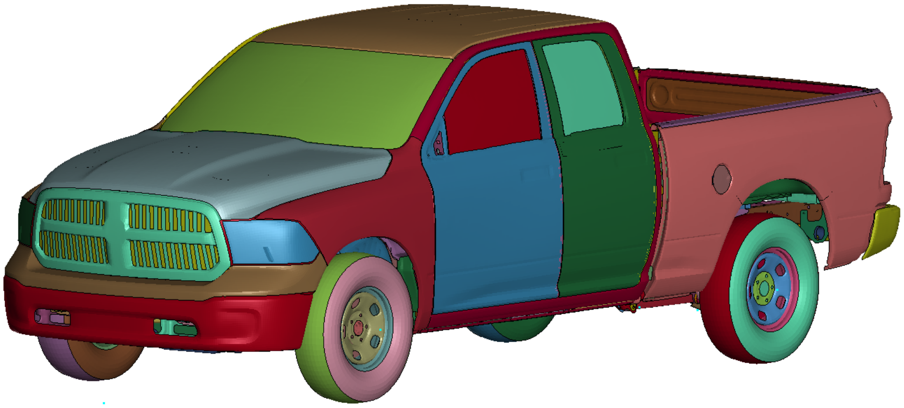


Figure 18. 2270P FE Vehicle Model.

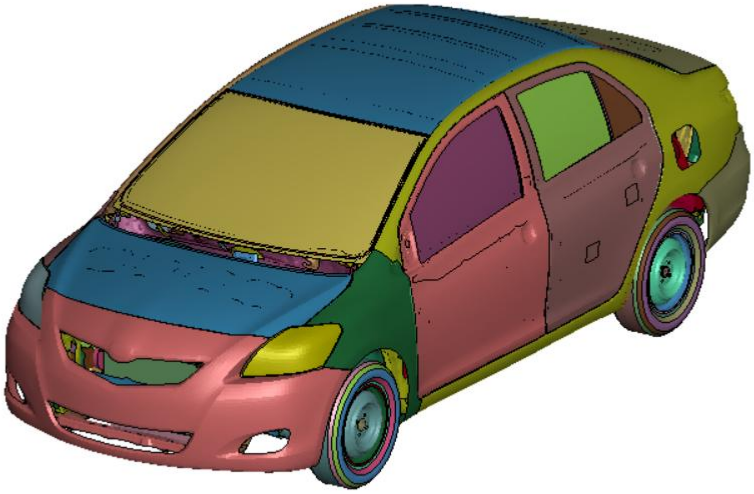


Figure 19. 1100C FE Vehicle Model.

RESULTS

Bent Rail Rubrail Termination

MASH Test 3-10 computer simulations were performed for the design concept involving a bent rail rubrail termination piece. Three simulations were performed to evaluate the system at different impact locations. Figure 20 shows sequential images for the simulation run with the impact location at 5.5 ft upstream of the end of the rubrail. The small car vehicle model was successfully contained and redirected and remained stable throughout the impact event. Similar satisfactory behavior was observed for the two other computer simulations with impacts at 3.5 ft and 7.5 ft upstream of the end of the rubrail. Table 6 shows the occupant risk values for the simulation runs. All occupant risk values were within the MASH limits. All computer simulations indicated satisfactory crashworthy performance for MASH Test 3-10 evaluation criteria.

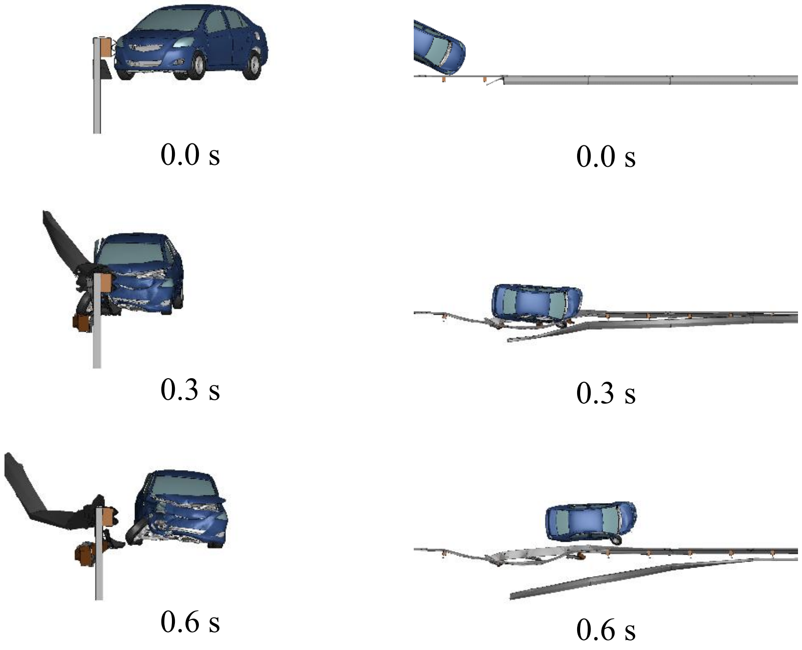


Figure 20. Sequential Images for MASH Test 3-10—Bent Rail.

Table 6. Occupant Risk Values for MASH Test 3-10—Bent Rail.

Occupant Risk	CIP1—5.5 ft Upstream of Rail End	CIP2—3.5 ft Upstream of Rail End	CIP3—7.5 ft Upstream of Rail End
Occupant Impact Velocity (OIV), Longitudinal (ft/s)	34.4	33.0	23.4
OIV, Lateral (ft/s)	15.9	18.2	16.2
Ridedown Acceleration (RDA), Longitudinal (g)	15.3	11.0	19.7
RDA, Lateral (g)	8.3	8.1	8.5
Roll (deg)	10.3	13.6	13.5
Pitch (deg)	5.2	4.8	4.2
Yaw (deg)	27.2	44.5	62.0

MASH Test 3-11 computer simulations were performed for the design concept involving a bent rail rubrail termination piece. Three simulations were performed to evaluate the system at different impact locations. Figure 21 shows sequential images for the simulation run with the impact location at 7.5 ft upstream of the end of the rubrail. The pickup truck vehicle model was successfully contained and redirected and remained stable throughout the impact event. Similar satisfactory behavior was observed for the two other computer simulations with impacts at 5.5 ft and 9.5 ft upstream of the end of the rubrail. Table 7 shows the occupant risk values for the simulation runs. All occupant risk values were within the MASH limits. All computer simulations indicated satisfactory crashworthy performance for MASH Test 3-11 evaluation criteria.

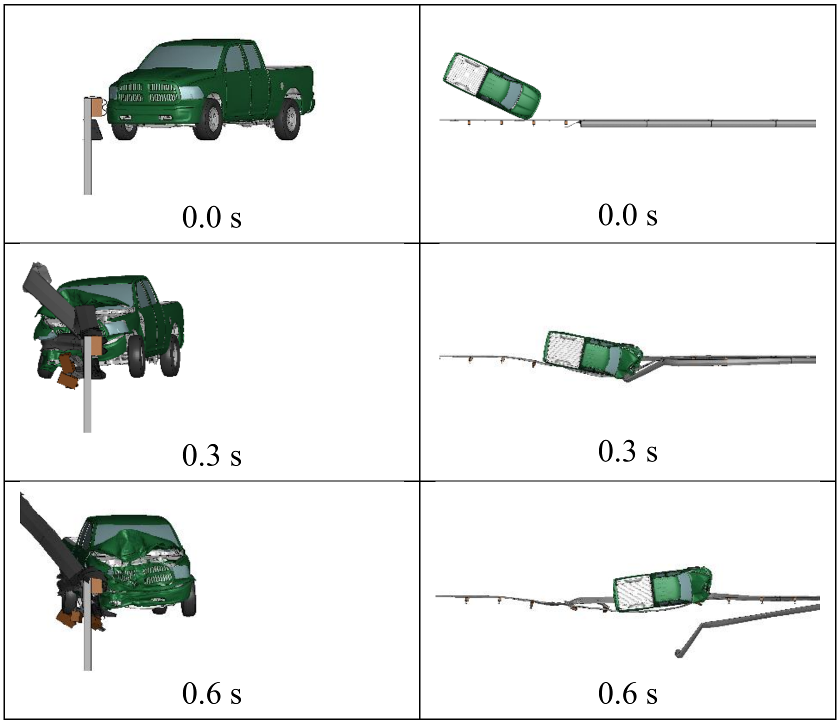


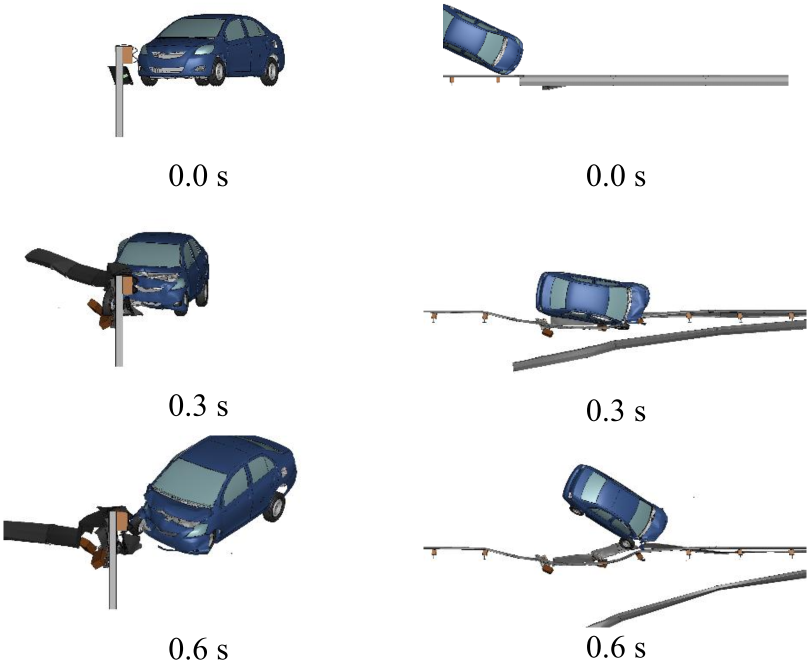
Figure 21. Sequential Images for MASH Test 3-11—Bent Rail.

Table 7. Occupant Risk Values for MASH Test 3-11—Bent Rail.

Occupant Risk	CIP1—7.5 ft Upstream of Rail End	CIP2—5.5 ft Upstream of Rail End	CIP3—9.5 ft Upstream of Rail End
OIV, Longitudinal (ft/s)	25.3	22.8	20.3
OIV, Lateral (ft/s)	13.3	13.3	12.9
RDA, Longitudinal (g)	7.5	5.9	7.9
RDA, Lateral (g)	7.5	7.0	6.8
Roll (deg)	4.5	10.4	11.9
Pitch (deg)	2.9	4.9	4.0
Yaw (deg)	32.4	48.4	47.1

Multiple Tapered Rail Rubrail Termination

MASH Test 3-10 computer simulations were performed for the design concept involving multiple tapered rails for the rubrail termination section. Three simulations were performed to evaluate the system at different impact locations. Figure 22 shows sequential images for the simulation run, with the impact location at 5.5 ft upstream of the end of the rubrail. The small car vehicle model was successfully contained and redirected, and remained stable throughout the impact event. Similar satisfactory behavior was observed for the two other computer simulations, with impacts at 3.5 ft and 7.5 ft upstream of the end of the rubrail. Table 8 shows the occupant risk values for the simulation runs. All occupant risk values were within the MASH limits. All computer simulations indicated satisfactory crashworthy performance for MASH Test 3-10 evaluation criteria.



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0.3 s 0.3 s

0.6 s 0.6 s

Figure 22. Sequential Images for MASH Test 3-10—Multiple Tapered Rail.

Table 8. Occupant Risk Values for MASH Test 3-10—Multiple Tapered Rail.

Occupant Risk	CIP1—5.5 ft Upstream of Rail End	CIP2—3.5 ft Upstream of Rail End	CIP3—7.5 ft Upstream of Rail End
OIV, Longitudinal (ft/s)	31.3	31.2	22.2
OIV, Lateral (ft/s)	16.0	15.6	14.4
RDA, Longitudinal (g)	16.3	8.9	17.5
RDA, Lateral (g)	9.0	7.9	12.2
Roll (deg)	18.5	20.3	25.0
Pitch (deg)	17.7	6.8	9.5
Yaw (deg)	36.6	52.7	39.3

MASH Test 3-11 computer simulations were performed for the design concept involving multiple tapered rails for the rubrail termination section. Three simulations were performed to evaluate the system at different impact locations. Figure 23 shows sequential images for the simulation run, with the impact location at 7.5 ft upstream of the end of the rubrail. The pickup truck vehicle model was successfully contained and redirected, and remained stable throughout the impact event. Similar satisfactory behavior was observed for the two other computer simulations, with impacts at 5.5 ft and 9.5 ft upstream of the end of the rubrail. Table 9 shows the occupant risk values for the simulation runs. All occupant risk values were within the MASH limits. All computer simulations indicated satisfactory crashworthy performance for MASH Test 3-11 evaluation criteria.

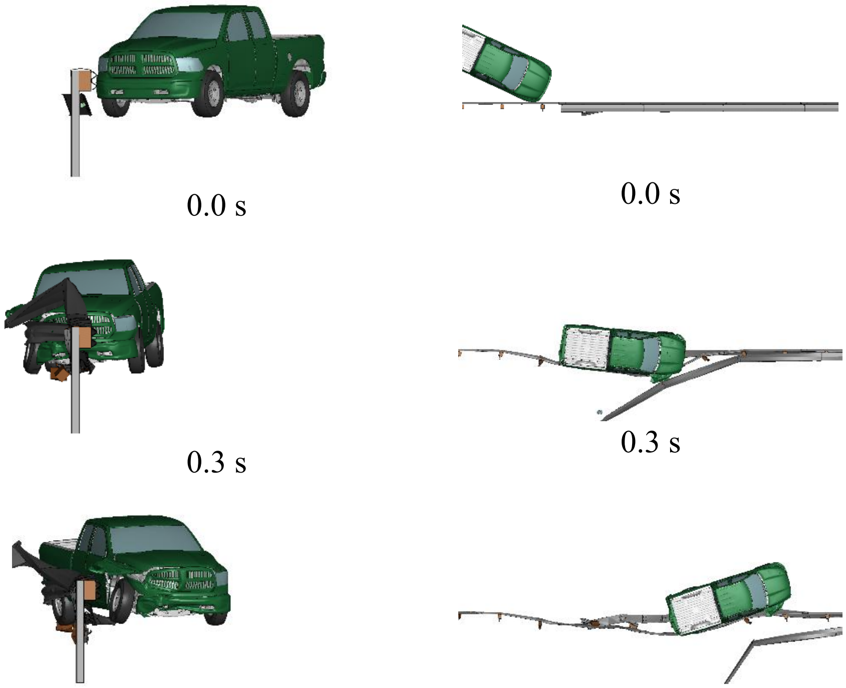
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Figure 23. Sequential Images for MASH Test 3-11—Multiple Tapered Rail.

Table 9. Occupant Risk Values for MASH Test 3-11—Multiple Tapered Rail.

Occupant Risk	**CIP1—7.5 ft Upstream of Rail End**	**CIP2—5.5 ft Upstream of Rail End**	**CIP3—9.5 ft Upstream of Rail End**
OIV, Longitudinal (ft/s)	20.2	18.6	19.7
OIV, Lateral (ft/s)	13.5	14.2	12.5
RDA, Longitudinal (g)	7.7	5.7	6.4
RDA, Lateral (g)	7.2	7.7	8.1
Roll (deg)	4.9	19.7	8.3
Pitch (deg)	3.5	3.3	2.1
Yaw (deg)	42.1	49.1	47.2

SUMMARY

A motorcycle-friendly guardrail system was developed and evaluated according to MASH TL-3. The system was found to perform satisfactorily according to the evaluation criteria. Crash tests were also conducted to evaluate the performance of the system for motorcyclist impacts. The motorcycle-friendly guardrail system incorporated two key elements: a cap rail and a rubrail.

These were intended to protect motorcyclists from interacting with blunt objects and sharp edges of the guardrail system.

The motorcycle-friendly guardrail system was designed for use in high-risk regions for roadway departure motorcycle crashes. This could include curved, mountainous roadways or other roadway types that tend to result in motorcyclists losing control and exiting the roadway. Thus, this system with the two added elements may not be used across the complete span of guardrail on the roadway. It was desired to design and evaluate concepts for terminating the rubrail as the system transitions to a standard span of guardrail section. Leaving the rubrail exposed with no termination component may present a risk to vehicles that impact near the end of the rubrail. Vehicle wheels and other parts could snag on the end of the rubrail causing high vehicle accelerations and/or vehicle instability.

Two design concepts were developed to terminate the rubrail and reduce the risk of vehicles impacting the blunt end of the rubrail. The first design concept consisted of a bent rail piece that attached to the main rubrail and connected on the back side of the nearby guardrail post. The second design concept consisted of multiple shortened rubrail pieces that tapered back and terminated behind a guardrail post.

Computer simulations were used to evaluate both design concepts according to MASH TL-3. This evaluation process involved developing FE models of the two design concepts and impacting them with a small car and pickup truck vehicle model at 62 mph and 25 degrees. For each system, multiple impact locations were evaluated. Overall, both rubrail termination concepts indicated satisfactory performance for MASH TL-3 in the computer simulations. Thus, both designs should be considered suitable for use in situations where it is desired to terminate the rubrail and protect impacting vehicles from the blunt end.

CHAPTER 4. SUMMARY AND RECOMMENDATIONS

Two research tasks were conducted under the fiscal year 2025 Motorcycle Safety Pooled Fund effort. The objective and results for each research task were discussed in the chapters contained within this report. A summary is provided below for each research task.

FEASIBILITY STUDY TO INVESTIGATE ROADWAY ELEMENT DESIGN CHARACTERISTICS AND THEIR EFFECTS ON MOTORCYCLE SAFETY THROUGH BIKESIM COMPUTER SIMULATIONS

An exploratory analysis of different roadway design elements and their effect on motorcycle safety was performed. Motorcyclists are often neglected when designing roadway elements despite their continued rise in fatalities over the past decade. This analysis considered four different roadway elements: raised crosswalks, speed bumps, vertical drop-offs, and roundabouts. BikeSim was used to evaluate these roadway elements and their effect on motorcycle safety. Specifically, the loss of motorcycle vehicle control was the primary safety evaluation factor.

Loss of vehicle motorcycle control was routinely encountered in the simulation analysis of the four roadway elements in situations where the roadway friction was low. This low friction was intended to represent reduced roadway friction due to drainage issues, roadway degradation, and other factors. Thus, designers should aim to implement design practices and strategies to maintain appropriate roadway friction to improve motorcycle safety.

Further analysis of the roadway design elements and their effect on motorcycle safety should be considered. Detailed FE computer simulations could be performed to further evaluate the roadway design elements. Crash data studies could be considered to identify aspects of the four roadway design elements that may be contributing to motorcycle crashes.

FURTHER DEVELOPMENT AND REFINEMENT OF THE ANCHOR CAP FOR THE MOTORCYCLE RUBRAIL SYSTEM

Two design concepts were developed and evaluated to terminate and shield the rubrail element in a motorcycle-friendly guardrail system. The design concepts considered additional fabricated rails and plates to taper the rail away from traffic and connect behind a guardrail post. Each design concept was evaluated according to MASH TL-3 using FE computer simulations. Both systems indicated satisfactory crashworthy performance in the FE analysis. Thus, both design options should be considered suitable for use in situations where it is desired to shield the end of the rubrail element in the motorcycle-friendly guardrail system.

VALUE OF RESEARCH ASSESSMENT

The research team completed a Value of Research (VoR) assessment as part of the project. The VoR assessment was based on the benefit areas selected at the beginning of the project (shown in Table 10).

Table 10. Selected Benefit Areas for VoR Assessment.

Selected	Benefit Area	Qualitative	Economic	Both	TxDOT	State	Both	Definition in Context to the Project Statement
X	Safety		X			X		Reduce crash severity or crash frequency for motorcycle roadway departure crashes

The VoR assessment is based on the assumption that a total of 21 fatal crashes per year would be prevented through the implantation of motorcycle-friendly guardrail systems and concrete barrier systems developed under this research program. A crash data analysis found that MassDOT and TxDOT had approximately 200 crashes over a five-year span involving motorcycle impacts with guardrail or concrete barrier systems. Approximately 15 percent of the crashes were fatalities. This results in three fatal crashes per year per state. Applying this average to the seven state partners participating in this research program would result in approximately 21 fatal crashes per year with guardrail systems or concrete barrier systems. According to NHTSA, each fatality results in an average discounted lifetime economic cost of $1.4 million and an average comprehensive cost of $9.1 million (Blincoe et al., 2010). For a conservative estimate, the research team used the discounted economic cost of $1.4 million to arrive at the annual expected value of this research. Applying the discounted economic cost to the approximated fatal crashes resulted in a conservative annual expected value of research of $29,400,000.

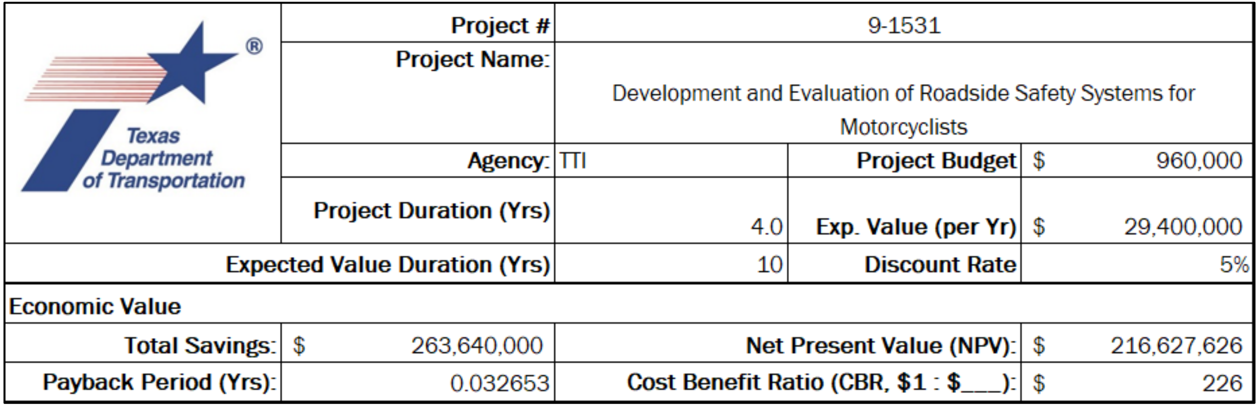
Table 11 shows the assignment of those variables to the appropriate economic benefit area for the VoR assessment.

Table 11. Value of Variables for VoR Assessment.

Economic Benefit Area	Variable 1	Variable 2	Variable 3	Variable 4	Variable 5	Total
Safety	$29,400,000	--	--	--	--	$29,400,000
					Total	$29,400,000

The research team entered the values shown in Table 11 into the TxDOT VoR Assessment spreadsheet to calculate the formal VoR measures. Those results are shown in Table 12. The results show that, based on the assumptions provided previously, the research project is estimated to have a benefit-cost ratio of approximately 226:1 over a 10-year expected value duration, with over $263.6 billion in savings.

Table 12. Results of VoR Assessment for Project 9-1531



Texas Department of Transportation	Project #	9-1531		
	Project Name:	Development and Evaluation of Roadside Safety Systems for Motorcyclists		
	Agency:	TTI	Project Budget	$ 960,000
	Project Duration (Yrs)	4.0	Exp. Value (per Yr)	$ 29,400,000
Expected Value Duration (Yrs)		10	Discount Rate	5%
Economic Value				
Total Savings:	$ 263,640,000		Net Present Value (NPV):	$ 216,627,626
Payback Period (Yrs):	0.032653		Cost Benefit Ratio (CBR, $1 : $___):	$ 226

REFERENCES

Blincoe, L. J., Miller, T. R., Zaloshnja, E., & Lawrence, B. A. *The Economic and Societal Impact of Motor Vehicle Crashes*. Report No. DOT HS 812 013. National Highway Traffic Safety Administration. 2010 [Revised]. https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812013.pdf

Federal Highway Administration. *Safe Transportation for Every Pedestrian: Countermeasure Tech Sheet.* 2018. https://highways.dot.gov/sites/fhwa.dot.gov/files/2022-06/techSheet_RaisedCW2018.pdf

Hermanus, S., Griffin, A., and Rodegerdts, L. *Accelerating Roundabouts in the United States: Volume IV of VIII—A Review of Fatal and Severe Injury Crashes at Roundabouts.* Report No. FHWA-SA-15-072. Kittelson & Associates, Portland, OR. 2015.

Massachusetts Department of Transportation. *Traffic Calming Design Guide: Chapter 16.* 2006. https://newburyportlivablestreets.org/wp-content/uploads/2020/03/massdot-2006-design-guide-traffic-calming.pdf

National Cooperative Highway Research Program. *Guide for Roundabouts.* Report 1043. The National Academies Press, Washington, DC. 2023.

National Highway Traffic Safety Administration. *Traffic Safety Facts—2023 Data.* U.S. Department of Transportation, Washington, DC. 2023.

Schulz, N., Bligh, R., and Bastin, B. *Evaluation of Lower and Upper Rail Elements with Midwest Guardrail System to Address Motorcycle Safety.* Report No. 9-1531-R2B. Texas A&M Transportation Institute. College Station, TX. 2023.

Schulz, N., Bligh, R., Dadashova, B., Silvestri Dobrovolny, C., and Schroeder, W. *Develop a Retrofit Design for Guard Fence System to Enhance Motorcycle Safety.* Report No. 0-6994-R1. Texas A&M Transportation Institute. College Station, TX. 2024.