Development of a MASH TL-2 Crashworthy Pedestrian Railing System

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ABSTRACT

In 2010, the National Highway Traffic Safety Administration (NHTSA) estimated that approximately 4,300 pedestrian fatalities occurred in the United States, with the highest risk for pedestrian injury occurring when crossing the street. When pedestrians choose a more direct path to cross a street at non-designated areas, driver expectations are violated and perception-reaction times are delayed, thus increasing pedestrian risks. In urban environments, pedestrian rails could be utilized to prevent dangerous excursions into nearby roadways as well as protect pedestrians from hazardous drop offs, such as near water crossings. Numerous pedestrian rails have been designed and implemented across the U.S. However, their crashworthiness has never been evaluated. The Wisconsin Department of Transportation funded a study to develop, test, and evaluate a crashworthy pedestrian railing system using the Test Level 2 (TL-2) impact safety criteria for longitudinal channelizers, as published in AASHTO's *Manual for Assessing Safety Hardware* (MASH). Twenty-five preliminary railing concepts. Four concepts were advanced for final design and later subjected to dynamic bogie testing, evaluation, and re-design. The preferred railing was configured as a discrete panel system fabricated from aluminum rails, posts, base plates, and spindles, all welded together. The system consisted of 2-in. x 4-in. x ¼-in. x 43-in. tall posts with three 2-in. x 2-in. x ⅛-in. rail components at heights of 42 in., $24^{15}/_{16}$ in., and 7⅞ in. Two MASH TL-2 full-scale vehicle crash tests were conducted with small cars using test designation no. 2-90, but at impact angles of 25 and 0 degrees. Both tests successfully satisfied the MASH evaluation criteria for longitudinal channelizers. For the 0-degree impact condition, the maximum longitudinal occupant ride-down acceleration was near the acceptable limit. Thus, further modifications could be considered to reduce occupant ride-down accelerations for end-on impact events.

KEYWORDS

Highway Safety, Crash Test, Bogie Test, Roadside Safety, Roadside Hardware, MASH, AASHTO, ADA, LRFD, Longitudinal Channelizer, Pedestrian Rail, and TL-2.

INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) estimated that approximately 4,300 pedestrian fatalities occurred in the United States in 2010 *(1)*. Leaf and Preusser had estimated that only 5 percent of pedestrians would die when struck by a vehicle traveling at 20 mph or less, while fatality rates of 40, 80, and nearly 100 percent would occur for vehicles striking pedestrians at 30, 40, and 50 mph or more, respectively *(2)*. University of North Carolina researchers found that pedestrian fatalities may be related to transportation designs as well as human behaviors *(3)*. Further, many pedestrian crashes occurred as a result of motorists and pedestrians not obeying traffic laws, not understanding safe driving practices, and not following safe walking behaviors *(4)*.

Many intersections have marked crosswalks to provide increased pedestrian safely; since, the risk of pedestrian injury is highest when crossing the street. These marked areas also inform drivers to be mindful of nearby pedestrians. However, pedestrians may choose a more direct path to cross the street or even become distracted, thus entering the roadway at non-designation areas (i.e., locations without a marked crosswalk). Crossing at non-designated areas can increase the likelihood of a fatal or serious injury crash.

Rails are often placed adjacent to roadways to protect pedestrians from hazardous drop-offs, prevent dangerous excursions into the roadway, as well as provide access control. Several examples of pedestrian rail applications are shown in Figure 1 and include (1) busy streets where median fences deter pedestrians from crossing in non-designated locations, (2) median barrier retrofits to prevent pedestrians from crossing high-speed highways and freeways, and (3) sidewalks over culverts where rails separate pedestrians from hazardous drop-offs. In some cases, rails are installed to prevent pedestrians from entering areas beyond the right of way, as shown in Figure 2. Thus, the design and placement of pedestrian rails should carefully consider site-specific needs and requirements.

Although numerous pedestrian rails have been designed and implemented, their crashworthiness has never been evaluated using current impact safety standards. There are safety concerns for passengers of errant vehicles which strike non-crashworthy pedestrian rails. For example, vehicle-to-rail crashes could result in barrier elements penetrating the occupant compartment, excessive decelerations, and vehicle instabilities.

Serious failures, such as rails spearing through windshields, have been documented during real-world vehicle crashes into pedestrian rails *(5)*. Therefore, a need existed to develop a crashworthy pedestrian railing system to meet current impact safety standards as well comply with the appropriate structural and geometric requirements published in existing design guidelines and standards.

Figure 1. Examples of Pedestrian Rails

Figure 2. Pedestrian Rail with Limited Escape Routes from Errant Vehicles

RESEARCH OBJECTIVES AND PLAN

The research objective was to design a crashworthy pedestrian rail that would direct pedestrians away from various hazards (i.e., falling over drop-offs and crossing roads at non-designated areas) while not posing undue safety risk to motorists. The new pedestrian rail must meet the pedestrian rail standards contained in the American Association of State Highway and Transportation Officials (AASHTO*) Load and Resistance Factor Design (LRFD) Bridge Design Specifications (6)*. The new pedestrian rail should also be configured in a manner such that it potentially may be modified to meet the design standards associated with the Americans with Disabilities Act (ADA) *(7)*. Other pedestrian rail criteria from common codes should be reviewed and considered, such as the International Building Code (IBC) *(8)* and Occupational Safety and Health Administration (OSHA), Part 1910 *(9)*. In addition, the pedestrian rail should be tested and evaluated using the Test Level 2 (TL-2) safety performance criteria for longitudinal channelizers, as published in the AASHTO *Manual for Assessing Safety Hardware* (MASH) *(10)*.

The study objectives were met through the completion of several tasks. A review was conducted of existing pedestrian rails and fences that are used with State Departments of Transportation (DOTs) and available from various manufacturers. A survey was sent to and completed by several State DOTs to identify common locations and circumstances where crashworthy pedestrian rails may be warranted. A preliminary concept development effort was performed while investigating potential fabrication materials, such as aluminum, steel, wood, and polymers. Several design concepts were configured, and preferred concepts were selected for further refined and evaluation. Dynamic bogie tests were conducted on four design concepts to evaluate their dynamic performance. Design improvements were made, and two full-scale vehicle crash tests were performed on an aluminum railing system using MASH TL-2 impact conditions for longitudinal channelizers. The test results were analyzed and evaluated, while conclusions and recommendations were provided regarding the safety performance of a new pedestrian railing system. This paper provides a condensed summary of the research study, while additional details are provided by Lechtenberg et al *(5)*.

DESIGN STANDARDS AND GUIDELINES

AASHTO LRFD Bridge Design Specifications

The AASHTO *LRFD Bridge Design Specifications* provided requirements for use in the design of a pedestrian rail *(6)*. Pedestrian rail height should be a minimum of 42 in. above the walkway. A clear spacing shall apply to the lower 27 in. of the railing where a 6-in. diameter sphere cannot pass thought the rail elements. The clear spacing in the upper section of the railing above 27 in. shall not allow an 8-in. diameter sphere to pass through the rail elements. Chain link or metal fabric fence should not have openings larger than 2 in.

Longitudinal railing elements must withstand a uniform live load of 50 lb/ft simultaneously applied both transversely and vertically, along with a concentrated live load of 200 lb applied at any point and in any direction on the longitudinal element, as shown in Figure 3. The posts are subjected to a concentrated live load, P_{LL}, defined in Equation 1. The concentrated live load P_{LL} shall be applied transversely at the center of gravity of the upper horizontal element. For a railing mounted taller than 5 ft, P_{LL} shall be applied at a point 5 ft above the walkway. Chain link or metal fabric fence shall be designed for a distributed live wind load of 15 lb/ft^2 applied perpendicular to the entire mesh surface.

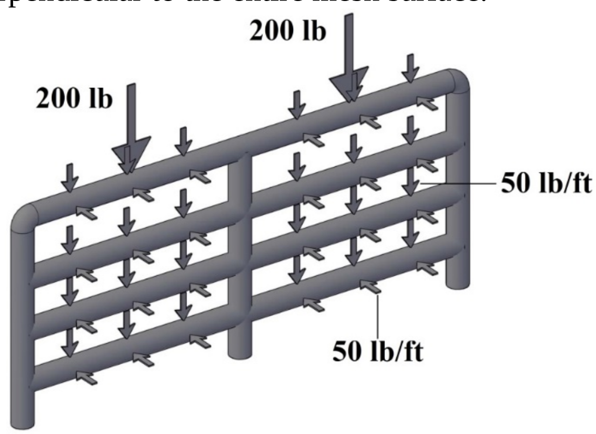


Figure 3. AASHTO Loading Criteria (Vertical 200-lb Point Load Shown)

$$P_{LL} = 200 + 50L \quad (1)$$

Where: P_{LL} = Post Point Live Load (lb)
L = Post Spacing (ft)

American with Disabilities Act Design Criteria

A pedestrian rail must be accessible to all people, including those with disabilities. The *2010 ADA Standards for Accessible Design* sets forth handrail criteria *(7)*. The handrail must be continuous along the full length of the walkway and not be obstructed on the top or sides. The handrail top gripping surface should be a minimum of 34 in. and a maximum of 38 in. vertically above the walking surface. There should be a minimum separation of 1½ in. between the back surface of the handrail and any adjacent surface. The handrail gripping surface for a circular cross section shall have minimum and maximum outside diameters of 1¼ in. and 2 in., respectively. Non-circular cross sections shall have minimum and maximum perimeters of 4 in. and 6¼ in., respectively, with the diagonal cross section length no greater than 2¼ in. If fittings are used, the handrail shall not rotate within them. When a vertical or horizontal force of 250 lb is applied on any point on the handrail, fasteners, mounting devices, or supporting structures, the allowable stresses shall not be exceeded.

International Building Code

The 2012 IBC *(8)* also contains handrail design criteria. Handrail criteria for continuity, height of gripping surfaces, separation distance between back of rail and adjacent surfaces, and sizes of circular cross sections, are identical those noted by the ADA. Non-circular cross sections shall have minimum and maximum surface perimeters of 4 in. and 6¼ in., respectively, with a cross-sectional dimension of at least 1 in. but no greater than 2¼ in. Edges shall have a minimum radius of 0.01 in. If fittings are used, the handrail shall not rotate within them. Handrails should be designed to resist a linear load of 50 lb/ft. Handrails should also be designed to resist a concentrated load of 200 lb applied in any direction at any point along the top. Intermediate rails, balusters, and panel fillers should be designed to resist a concentrated load of 50 lb.

Occupational Safety & Health Administration (OSHA)

Handrail design criteria is also contained in *Part 1910 – Occupational Safety & Health Administration Regulations (Standards – 29 CFR) (9)*. A standard railing shall consist of a top rail, intermediate rail, and posts, and it shall have a vertical height of 42 in., as measured between the upper surface of top rail to the ground. The top rail shall be smooth throughout the length of the railing. Pipe railings, posts, and top and intermediate railings shall have a nominal diameter of at least 1½ in. with posts spaced not more than 8 ft on center. The complete structure shall withstand a 200-lb load applied in any direction at any point on the top rail.

AASHTO MASH Longitudinal Channelizers

Longitudinal channelizers are intended to provide clear visual indication of the intended vehicle path through a construction or work zone. They are not intended to contain and redirect impacting vehicles, but rather a vehicle can traverse through and behind the system. Thus, the impact performance criterion for longitudinal channelizers is different from those used for longitudinal barriers. For MASH TL-2 longitudinal channelizers, two full-scale crash tests are recommended, test designation no. 2-90 with an 1100C vehicle and test designation no. 2-91 with a 2270P vehicle *(10)*. For each vehicle type, the impact conditions consist of a speed of 44 mph and a critical impact angle ranging between 0 and 25 degrees, selected to maximize the risk of vehicle rollover and excessive vehicle decelerations.

REVIEW OF EXISTING SYSTEMS

At the onset of this study, researchers conducted a review of existing pedestrian rails that were used by State DOTs as well as commercially-available systems used by homeowners, businesses, and sporting venues. Several types of pedestrian rails were considered, including combination pedestrian rail and concrete parapet systems, plastic fences, wood fences, and metal rails. Combination concrete barriers are often used in combination with a metal rail or chain link fence to accommodate pedestrian safety in high-speed facilities, but those systems are associated with higher costs due to their ability to contain and redirect vehicles. Metal rails are typically fabricated with aluminum or steel materials for strength and ease of construction. Wood fences are often used for economic reasons. Numerous polymer fences are fabricated with polyvinyl chloride (PVC), high density polyethylene (HDPE), and fiber-reinforced polymers (FRP) to provide aesthetics and corrosion resistance. Most combination pedestrian rail and concrete parapet systems have been crash tested and have met safety performance guidelines. However, plastic, wood, and metal fences or railings have not been crash tested. A summary of existing pedestrian rails can be found in Lechtenberg et al *(5)*.

STATE DOT SURVEY – PEDESTRIAN RAIL NEEDS

A survey was conducted to identify the most common locations and circumstances where a crashworthy pedestrian rail would be warranted. The survey was sent to the Wisconsin DOT as well as members of the Midwest States Pooled Fund Program. Respondents were asked to evaluate pedestrian rail usefulness in various applications, including: (1) placement on top of culverts; (2) placement on top of retaining walls; (3) jaywalk prevention; (4) rail protection around private or public property; (5) bicycle or pedestrian path separation from roadway; (6) hazard protection for bicycle path traffic; (7) locations with raised sidewalks relative to surroundings; and (8) placement on bridges.

For the Pooled Fund member states, the first and second highest priority needs for a crashworthy pedestrian rail pertained to shielding hazardous drop-offs through its placement on top of culverts and on top of retaining walls. For the Wisconsin DOT, the highest-priority need for a crashworthy pedestrian rail pertained to its use in preventing urban/suburban pedestrian crossings at non-designated locations, such as jaywalking. Based on the survey results, the Wisconsin DOT prioritized the research study to focus on an application which prevents pedestrian crossings at non-designated locations.

INITIAL CONCEPT DEVELOPMENT

Preliminary Concepts

Following the system review and survey, researchers developed 25 concepts for a pedestrian rail *(5)*. These concepts met the geometric requirements noted previously and the structural loading criteria when possible. Various materials were initially considered, which included steel, aluminum, PVC, wood, HDPE, and FRP, which were based on aesthetics, strength, weight, cost, and workability. The handrail, infill, and connections were not designed during the initial development effort.

Refined Concepts

Following a review, several preliminary concepts and fabrication materials were eliminated from consideration. FRP rail systems were eliminated due to material cost concerns. HDPE rail systems were eliminated due to concerns for lower material stiffness and strength, especially at elevated temperatures. Numerous concepts were eliminated due to concerns for aesthetics as well as feasibility of fabrication. Segmented systems were preferred over continuous systems to reduce barrier damage during impact events as well as to improve constructability and repair. Thus, only seven preliminary concepts were further refined, including: two modular aluminum concepts; one welded aluminum concept; two PVC concepts; and two wood concepts. System details are provided in Lechtenberg et al *(5)*. Examples of the refined concepts are shown in Figure 4. Although some design guidance was provided with the concepts, final system details were not completed for each concept, such as the determination of welded or bolted connection details.

The refined concepts were submitted to the project sponsor for review and comment. Subsequently, the sponsor identified preferred concepts based on aesthetics, cost, installation, maintenance, and sight lines. Some concerns were raised with various concepts, including the possibility for a system to obstruct a driver's visual line of sight at critical locations, such as near intersections; the need to preservative treatment or routine maintenance of wood railing systems to prevent visual or structural degradation; additional fabrication costs associated with heat-treating welded aluminum components; and the potential for system components to fracture away from the railing panels and become projectile hazards to pedestrians or motorists. PVC-based concepts were eliminated due to lack of aesthetic appeal, difficulty with design and fabrication of post and rail connections, and instability of PVC rail segments. The wood-based concepts were eliminated due to the concerns for long-term durability, warping of the wood sections, and splinter hazards to pedestrians, vehicle occupants, and bystanders. After eliminating PVC-based and wood-based concepts, the modular and welded aluminum railing systems were recommended to be further pursued.

DESIGN LOADS – RAIL, POSTS, AND CONNECTIONS

For the initial concepts, simplified load cases were used to estimate longitudinal rails, vertical posts, and any infill components of a pedestrian rail. When a more complete analysis and design was required for the two types of aluminum systems, additional assumptions and load scenarios were used determine (1) rail members, (2) post members, (3) infill components, (4) post-to-rail connections, (5) post-to-base connections, (6) infill-to-rail connections, and (7) anchorage hardware. Details on the load scenarios can be found in Reference *(5)*.

For rail components, the analysis and design was based on 60-in. long rails. Using the AASHTO *LRFD Bridge Design Specifications*, a 200-lb concentrated point load was applied at the ends, midspan locations, or anywhere between supports. The maximum shear and bending moment due to point loading on simply-supported beam was 200 lb and 3,000 lb-in. for end and midspan locations, respectively. A 50-lb/ft uniform load was applied across the entire rail. The maximum shear and rail bending moment due to uniform loading on a simply-supported beam was 125 lb and 1,876.5 lb-in. for end and midspan locations, respectively. The AASHTO criteria specifies that the two uniform loads must be applied vertically and transversely, but the concentrated load may be applied to the rail at any point and in any direction. The maximum shear and bending moment was determined from uniform loads in both transverse and vertical directions as well as the concentrated load acting in either vertical or transverse directions. Since it could be applied in either direction, a doubly-symmetric section would be most efficient for longitudinal rails. The maximum resultant shear force at the end of the rail was 348.2 lb. The combined bending moment resulting from the three separate loads acting on the longitudinal member were combined to determine a maximum bending stress in the cross section. For a doubly-symmetric section, the maximum rail bending moment on a simply-supported beam was determined as the sum of the maximum bending moments from the loads applied both vertically and transversely (i.e., two distributed loads plus a concentrated load at midspan), or 6,750 lb-in.

(a)

(b)

(c)

(d)

Figure 4. Sample Refined Pedestrian Rail Concepts: (a) PVC; (b) Wood; (c) Modular Aluminum; and (d)Welded Aluminum.

For rail components, the analysis and design was based on 60-in. long rails. Using the AASHTO *LRFD Bridge Design Specifications*, a 200-lb concentrated point load could be applied at the ends, midspan locations, or anywhere between supports. The maximum shear and bending moment due to point loading on simply-supported beam was 200 lb and 3,000 lb-in. for end and midspan locations, respectively. A 50-lb/ft uniform load was applied across the entire rail. The maximum shear and rail bending moment due to uniform loading on a simply-supported beam was 125 lb and 1,876.5 lb-in. for end and midspan locations, respectively. The AASHTO criteria specifies that the two uniform loads must be applied vertically and transversely, but the concentrated load may be applied at any point and in any direction on the rail element. The maximum shear and bending moment was determined from uniform loads in both transverse and vertical directions as well as the concentrated load acting in either vertical or transverse directions. Since it could be applied in either direction, a doubly-symmetric section would be most efficient for longitudinal rails. The maximum resultant shear force at the end of the rail was 348.2 lb. The combined bending moment resulting from the three separate loads acting on the longitudinal member were combined to determine a maximum bending stress in the cross section. For a doubly-symmetric section, the maximum rail bending moment on a simply-supported beam was determined as the sum of the maximum bending moments from the loads applied both vertically and transversely (i.e., two distributed loads plus a concentrated load at midspan), or 6,750 lb-in.

For post components, the analysis and design was based on 60-in. long rails and 41-in. load height on posts. Using the AASHTO loads noted above, the maximum shear and bending moment in the cantilevered posts was 450 lb and 18,450 lb-in., respectively.

Other loading conditions were examined for use in designing infill regions, post-to-rail connections, post-to-base connections, and infill-to-rail connections, and base plate anchorages. The maximum shear and bending moments for designing these other components are contained in Reference *(5)*.

SYSTEM DESIGN

The mechanical properties of aluminum can vary depending on alloy, shape, thickness, and existence of weld-affected zones. The process of welding aluminum at connections significantly reduces the material strength surrounding weld locations. While heat treatment can be used to regain most of the material strength in weld-affected zones, heat treatment was not desired. Thus, pedestrian rail concepts were to be designed using the lower weld-affected material strengths. A common aluminum alloy, 6061-T6, was selected for the pedestrian rail designs. The mechanical properties of non-welded 6061-T6 aluminum were provided in Table A.3.4 in the Aluminum Design Manual (ADM) *(11)*. The mechanical properties of weld-affected 6061-T6 aluminum were provided in Table A.3.5 in the ADM.

As obtained from the ADM *(11)*, LRFD design equations were used to configure most components used in the aluminum railing systems. The modular and welded aluminum concepts were further refined into four prototypes - one modular aluminum system and three welded aluminum systems, as shown in Figure 5. It should be noted that the modular system used commercially-available hardware from Hollaender's standard Speed-Rail® system *(12)*. Complete design calculations and system drawings are not provided herein but can be found in Reference *(5)*.

DYNAMIC BOGIE TESTING

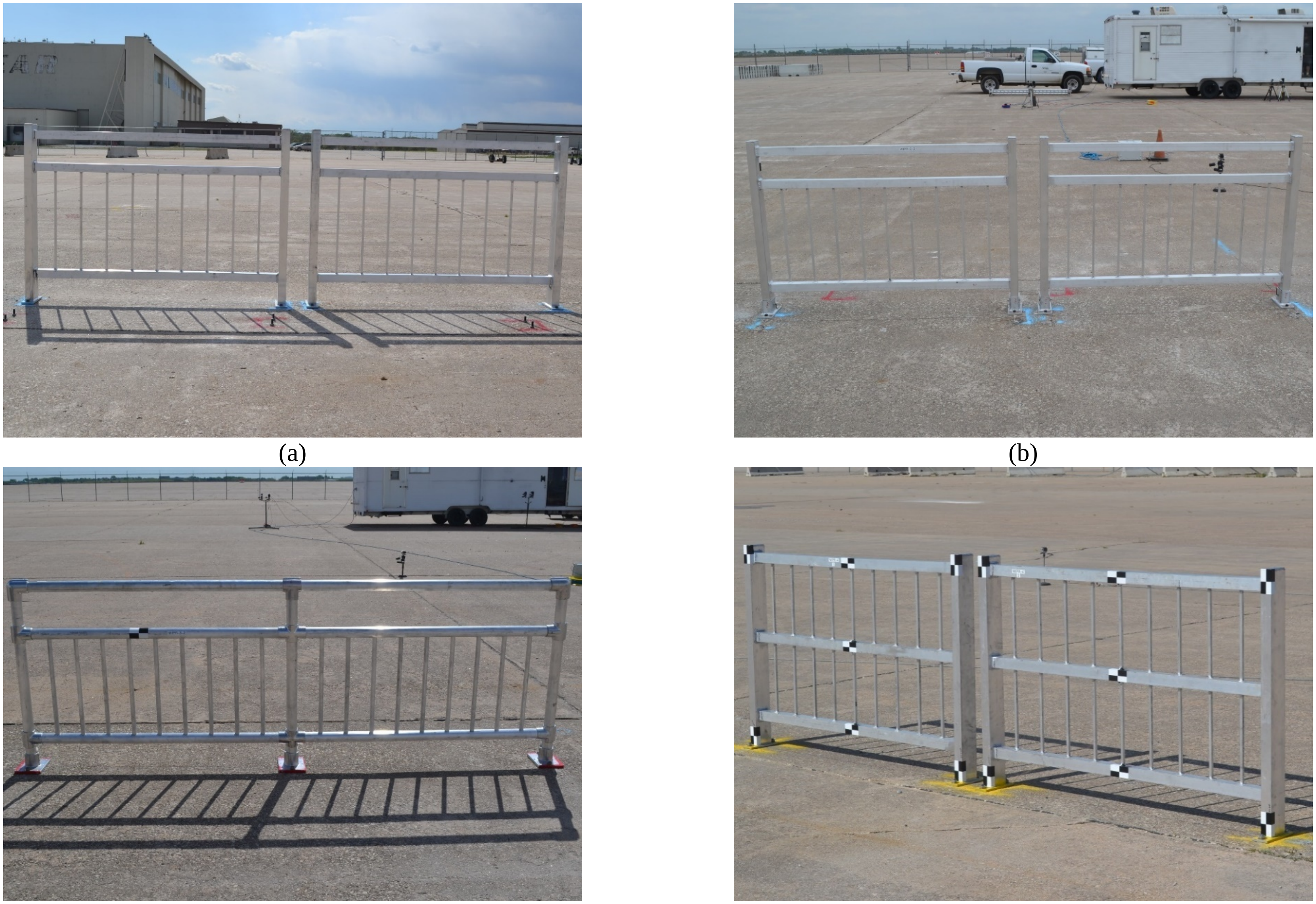
Dynamic bogie testing was utilized to evaluate the impact performance and system fracture for all four pedestrian rail prototypes. The rigid-frame bogie was configured with a front bumper positioned approximately 13⅝ in. above the ground line. The bogie was not configured with a windshield, floorpan, or body panels. System evaluation considered trajectory of debris as well as potential for fractured components to deform and/or penetrate a hypothetical occupant compartment or windshield. Preferred system behaviors included: clean and consistent component fracture; no anchor damage; component trajectory away from windshield and undercarriage; limited to no vehicle instability; and no concerns for occupant risk.

Four test runs, or seven bogie tests, were conducted at 45 mph on four prototypes. Each prototype consisted of a two-panel system, which anchored to an existing concrete tarmac. Three prototypes were evaluated using two impact orientations in one test run, as shown in Figure 5(a) through 5(c). For the first device, the bogie impacted the spindle region on the first panel at 25 degrees. For second device, the bogie impacted the first panel at 0 degrees or end-on. For fourth test run, the prototype was only evaluated in the end-on orientation due to its similarity to two of the first three prototypes, as shown in Figure 5(d).

For the three square-tube, welded-aluminum prototypes, posts seemed to fracture or release from bases more consistently when directly welded to bases versus inserted into sockets that were welded to bases. For all four prototypes, minor deformations were observed in each base plate. Permanent deformations in base plates could likely be eliminated with increased plate thickness. Prototypes anchored with ⅜-in. diameter threaded rods exhibited slight permanent deformations in the fasteners, while prototypes anchored with ½-in. diameter threaded rods exhibited no visual permanent deformations in the fasteners.

For the systems depicted in Figure 5(a) through 5(c), the observed impact performance raised safety concerns when struck end-on. Specifically, the upper and middle horizontal rails had fractured or disengaged away from the posts, rode over the top of the bogie, and posed increased risk for windshield penetration and excessive deformation. The six bogie tests on these three prototypes had also indicated that end-on impact event were more critical than oblique impacts at 25 degrees. These three prototypes fractured away from the bases when impacted at 25 degrees and did not present concerns for penetration or excessive deformation to an impacting vehicle.

As shown in Figure 5(d), the middle rail was lowered to more closely align with the bumper heights of both pickup trucks and small cars and improve dynamic impact behavior. The change in position for the middle horizontal rail, along with (1) extending spindles from top rail to bottom rail, (2) passing spindles through the middle rail, (3) inserting rails into posts, and (4) increasing anchor size to ½ in. diameter, greatly improved system behavior. Therefore, the welded aluminum prototype with posts welded to base plates and full spindles was recommended for further testing and evaluation.



(a) (b)

(c) (d)

Figure 5. Four Aluminum Prototypes: (a) Welded Base; (b) Socketed Post; (c) Modular System with Round Sections; and (d) Welded Base with Full Spindles.

TEST REQUIREMENTS AND EVALUATION CRITERIA

Longitudinal channelizing systems, or pedestrian rails, should be subjected to two full-scale vehicle crash tests using the MASH TL-2 guidelines. Test Designation No. 2-90 consists of a 2,425-lb passenger car (designated 1100C) impacting at 44 mph and a critical angle ranging between 0 and 25 degrees. Test Designation No. 2-91 consists of a 5,000-lb pickup truck (designated 2270P) impacting at 44 mph and a critical angle ranging between 0 and 25 degrees. The critical angle should be selected to maximize risks for rollover or excessive decelerations. During discussions with FHWA, the 0-degree impact angle was deemed to likely provide greater risk for excessive decelerations, cause instabilities, as well as potentially result in excessive deformation and/or penetration to occupant compartment, including windshield. The 25-degree angle could cause instabilities as well as result in unacceptable damage to occupant compartment, including windshield. Thus, 0- and 25-degree angles were deemed critical, while other angles were deemed less critical.

Test no. 2-90 with a 1100C small car was also deemed critical due to concerns for excessive decelerations based on a smaller mass and instabilities while overriding components. The small car has lower hood, windshield, and floor pan heights. Thus, a small car versus a pickup truck is likely more susceptible to occupant compartment and windshield penetration and deformation under impacts with a pedestrian rail. Following discussions with FHWA, only 1100C small car tests were initially planned using test no. 2-90 at 0 and 25 degrees. If the results from either test indicated concerns for 2270P vehicles, then additional pickup truck testing would be considered.

MASH is unclear regarding centerline or quarter-point impacts on channelizers in end-on scenarios. Thus, centerline impact scenarios were selected to promote greater contact with panels, increasing risk for excessive decelerations. Although quarter-point impacts are often used to evaluate risks for rollover, it was deemed less critical for a channelizer system.

FINAL DETAILS – PEDESTRIAN RAIL

A 150-ft long pedestrian rail system was constructed using 26 aluminum panel sections. Complete system details are provided in Reference *(5)*, while a simple schematic is shown in Figure 6.

Each panel utilized 2-in. x 4-in. x ¼-in. by 43-in. tall aluminum posts with three 2-in. x 2-in. x ⅛-in. aluminum rail sections at heights of 42 in., $24^{15}/_{16}$ in., and 7⅞ in. (2 in. plus 5⅞ in. from ground to bottom of lower tube). Each rail end was inserted into a cutout in the posts and secured with a ⅛-in. fillet weld. Nine ½-in. x ½-in. x 32⅛-in. square spindles spanned between the top and bottom rails and passed through the middle rail. The aluminum spindles were attached with ⅛-in. fillet welds at each rail location. Each post was attached to a 3-in. x 7¾-in. x ⅜-in. aluminum base plate with a ¼-in. fillet weld. Each base plate had two ⅝-in. diameter holes spaced at 6¼ in. to accommodate two ½-in. diameter ASTM A193 Grade B7 threaded anchor rods with appropriate nuts and washers. Each rod was embedded 5 in. into the concrete using a chemical epoxy adhesive with a 1,450-psi minimum bond strength. All tubes, plates, and spindles conformed to 6061-T6 aluminum. The concrete foundation should have a minimum compressive strength of 2,500 psi and a minimum thickness of 7 in. The clear spacing between adjacent panel posts was 5½ in.

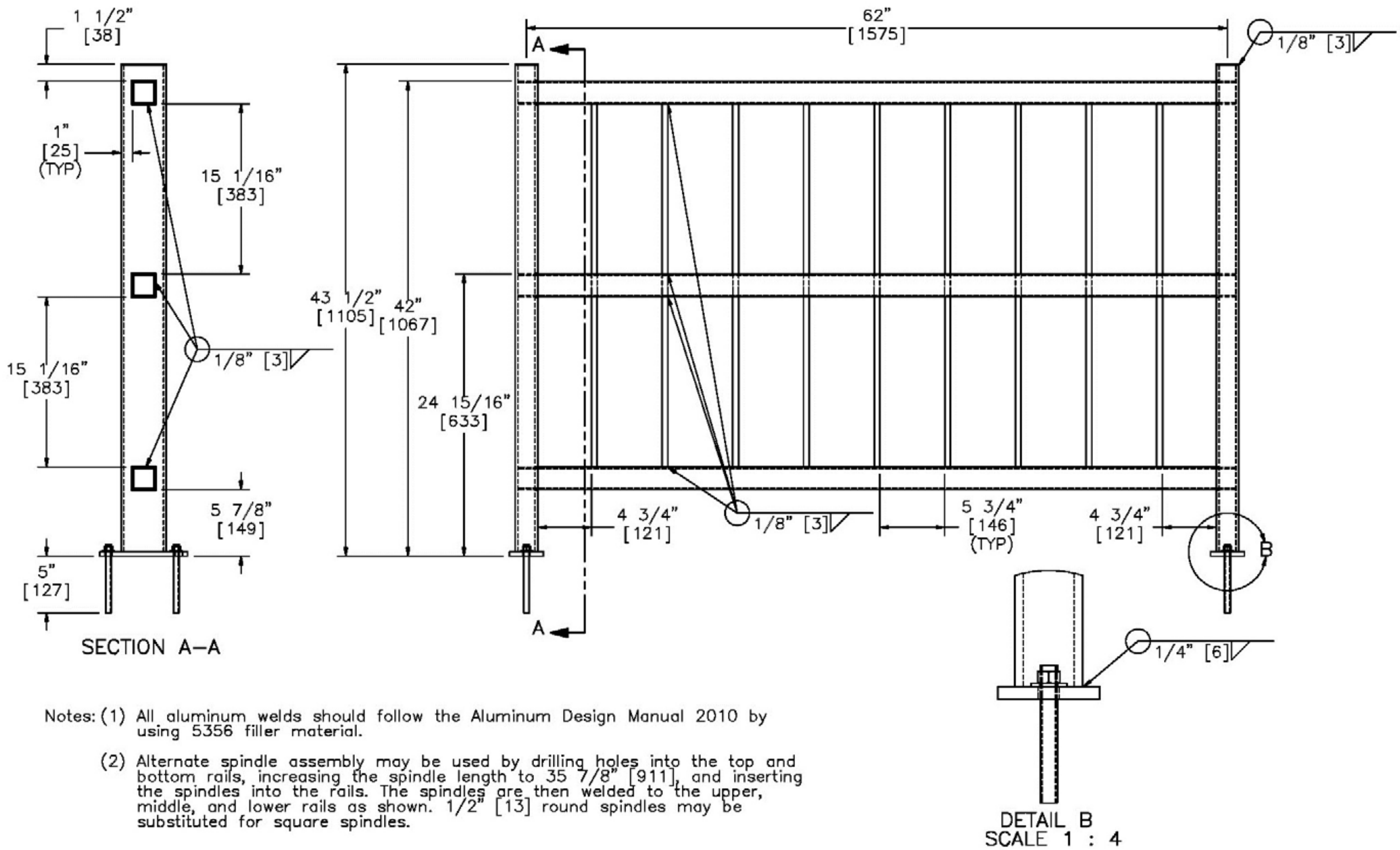


Figure 6. Schematic of Aluminum Pedestrian Rail - Final Design.

FULL-SCALE CRASH TESTING

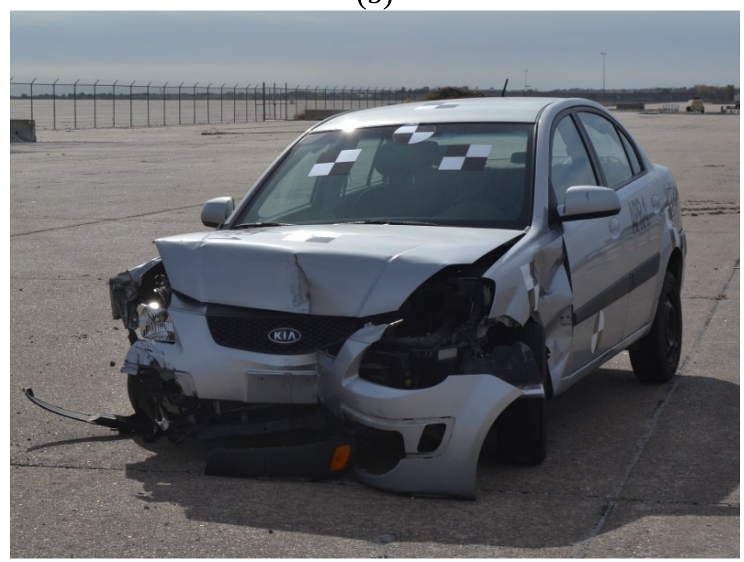
Test No. APR-1 (Test Designation No. 2-90 @ 25 Degrees)

The 2,428-lb small car impacted the aluminum pedestrian rail at a speed of 45.2 mph and an angle of 25.1 degrees. The target impact location utilized the vehicle centerline aligned with the centerline of the downstream post of panel no. 12, which was selected to evaluate windshield damage from panels sliding up the hood and debris field. Actual vehicle contact occurred at the second spindle upstream from the downstream post in panel no. 11. The vehicle came to rest upright and 45.5 ft behind the centerline of panel no. 26. The pre-impact barrier system, impact location, system damage, and barrier damage are shown in Figure 7. Six panels were damaged, largely consisting of fractured welds between posts and base plates, fractured welds between posts and rails, and spindle disengagement from rails. No damage was observed in the vertical anchors. Vehicle damage was moderate, consisting of deformations in engine hood, front bumper, front quarter panels, and wheels, as well as fractured/disengaged headlights. The windshield was not damaged. The maximum occupant compartment deformation was ½ in. at the side front panel in front of A-pillar and side door above the seat. The occupant impact velocities (OIVs) were -19.08 fps and 3.89 fps in the longitudinal and lateral directions, respectively. The maximum 0.010-sec occupant ridedown accelerations (ORAs) were -1.85 g's and -3.33 g's in the longitudinal and lateral directions, respectively. The maximum roll angle was 10.61 degrees. The pedestrian rail allowed controlled penetration of the 1100C vehicle. Neither detached elements nor fragments showed potential for penetrating the occupant compartment or for presenting undue hazard to other traffic. Note, none of the pedestrian rail panels went over the hood, near the windshield, or underneath the vehicle. Deformations of, or intrusions into, the occupant compartment that could have caused serious injury did not occur. The OIVs and ORAs were within the suggested limits provided in MASH. The test vehicle remained upright during and after the collision. Vehicle roll, pitch, and yaw angular displacements were deemed acceptable. Test no. APR-1 was deemed acceptable under the MASH TL-2 safety performance criteria.

(a)

(b)

(c)

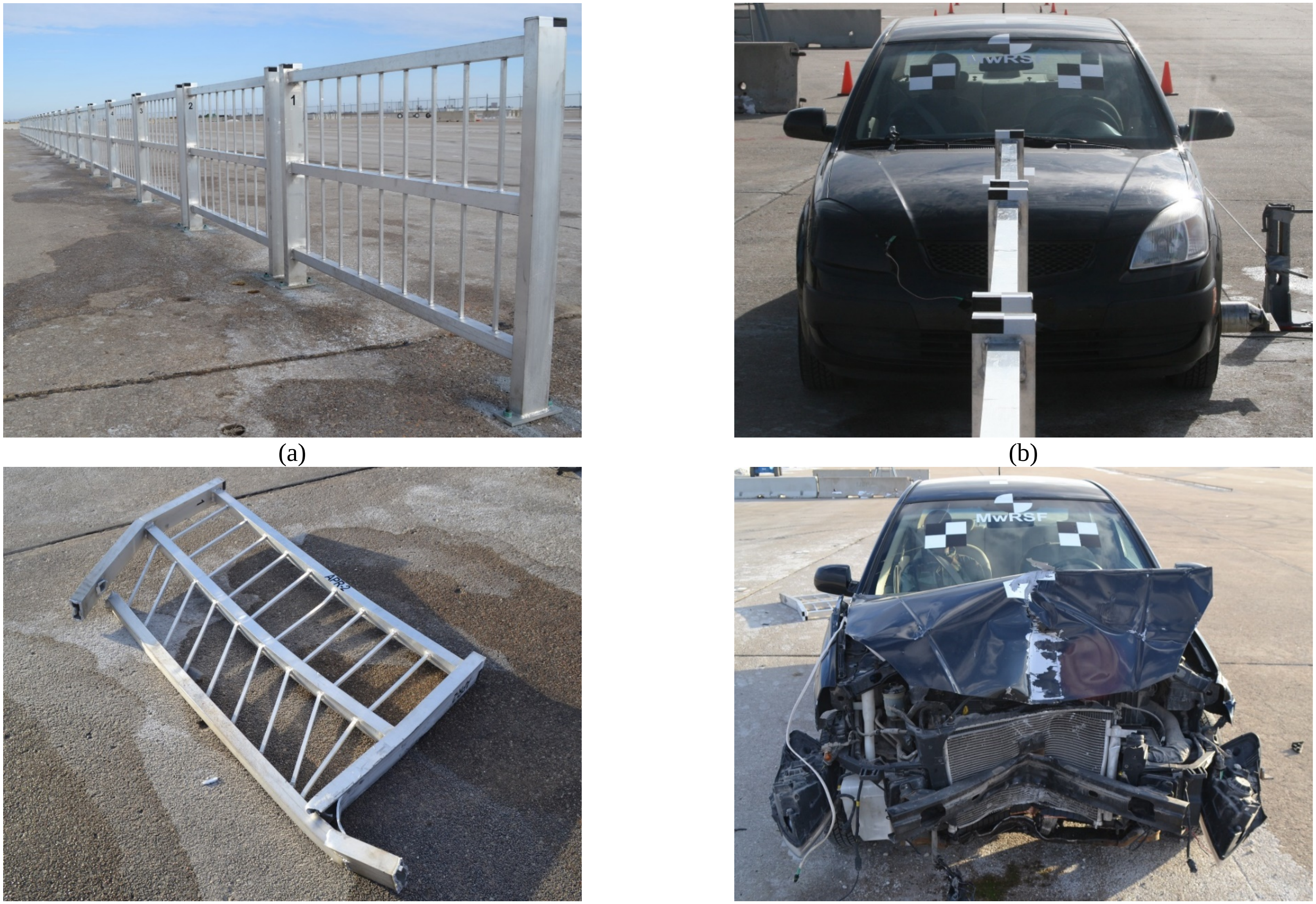


(d)

Figure 7. Test No. APR-1: (a) Pre-Impact Barrier System; (b) Impact Location; (c) System Damage; and (d) Barrier Damage.

Test No. APR-2 (Test Designation No. 2-90 @ 0 Degrees)

The 2,437-lb small car impacted the aluminum pedestrian rail at a speed of 44.5 mph and an angle of 0 degrees. The target impact location utilized the vehicle centerline aligned with the centerline of the upstream post of panel no. 1, which was selected to evaluate the potential for windshield and roof damage, vehicle instability, occupant risk, and debris field. Actual vehicle contact occurred at the centerline of the upstream post of panel no. 1. The vehicle came to rest 15 ft – 11 in. upstream from the upstream post of panel no. 10 and parallel to the centerline of the system. The pre-impact barrier system, impact location, system damage, and barrier damage are shown in Figure 8. Ten panels were damaged, largely consisting of fractured welds between posts and base plates, fractured welds between posts and rails, and deformed spindles. No damage was observed in the vertical anchors. Vehicle damage was moderate, consisting of deformations in engine hood, front bumper, front quarter panels, and wheels, as well as fractured/disengaged headlights. The lower-right corner of the windshield was cracked. The maximum occupant compartment deformation was ⅜ in. at the wheel well and toe pan. The occupant impact velocities (OIVs) were -21.69 fps and -1.19 fps in the longitudinal and lateral directions, respectively. The maximum 0.010-sec occupant ridedown accelerations (ORAs) were -19.41 g’s and -3.87 g’s in the longitudinal and lateral directions, respectively. The maximum roll angle was 8.63 degrees. The pedestrian rail allowed controlled penetration of the 1100C vehicle. Neither detached elements nor fragments showed potential for penetrating the occupant compartment or for presenting undue hazard to other traffic. Deformations of, or intrusions into, the occupant compartment that could have caused serious injury did not occur. The OIVs and ORAs were within the suggested limits provided in MASH. The test vehicle remained upright during and after the collision. Vehicle roll, pitch, and yaw angular displacements were deemed acceptable. Test no. APR-2 was deemed acceptable under the MASH TL-2 safety performance criteria.



(a) (b) (c) (d)

Figure 8. Test APR-2: (a) Pre-Impact Barrier System; (b) Impact Location; (c) System Damage; and (d) Barrier Damage.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The primary objective was to develop a crashworthy pedestrian rail to protect pedestrians from roadside and median hazards while not posing undue safety risk to motorists. The new pedestrian rail met the AASHTO *LRFD Bridge Design Specifications* and the AASHTO MASH TL-2 safety performance evaluation criteria for longitudinal channelizers. Other design guidance was considered, including that provided by the ADA. A review was completed on existing pedestrian rail systems and commercially-available railings. A survey was performed to identify common locations and circumstances where crashworthy pedestrian rails may be warranted, which focused on prevention of road crossings at non-designated locations. Twenty-five pedestrian rail concepts were brainstormed, which included numerous materials. After multiple rounds of sponsor review, several concepts and material were eliminated. Four aluminum prototypes were further developed, including complete design details, fabricated, and subjected to dynamic bogie testing. From this evaluation, the preferred configuration was an aluminum prototype with posts welded to base plates, which included full spindles, repositioned middle rails, rails inserted into post cutouts, and ½ in. diameter anchor rods.

Two full-scale vehicle crash tests with 1100C vehicles (test designation no. 2-90) were conducted on the preferred pedestrian rail system using the MASH TL-2 safety performance criteria longitudinal channelizers. Test no. APR-1 occurred at 45.2 mph and 25.1 degrees, while test no. APR-2 occurred at 44.5 mph and 0 degrees. Both tests met the MASH TL-2 safety performance criteria for longitudinal channelizers. Following a review of the test results, test designation no. 2-91 was deemed not critical and not performed. Further discussions of the tests are provided by Lechtenberg et al *(5)*.

The as-tested, prototype system did not include ADA-compliant handrails, which may be required for some roadside applications. As such, further design and crash testing may be required to investigate the use of ADA-compliant handrails. Initially, it was believed that the pedestrian rail system could be configured with segmented panels with gaps or as a continuous system. The researchers configured and tested a segmented panel system as it was believed to be easier to install. However, a continuous variation of this system is not recommended due to concerns for higher longitudinal ORAs when impacted end-on from loading simultaneously multiple posts. Although the pedestrian rail system met MASH requirements, further research on system modifications should be considered to improve safety performance, lower occupant risk measures, increase knowledge on crashworthiness of pedestrian rails, minimize debris, and incorporate ADA-compliant handrails.

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Wisconsin DOT nor the Federal Highway Administration, U.S. Department of Transportation. This paper does not constitute a standard, specification, regulation, product endorsement, or an endorsement of manufacturers.

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