Evaluation of Crash Tests of the MDS-4 and MDS-5 Barriers According to Report 350

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Abstract
Two new all-steel bridge railings have been developed and tested in Europe according to the crash test requirements of EN1317 which be used in both permanent or temporary construction. The MDS barriers feature a unique sliding base design that minimizes deck forces while still providing good performance in heavy vehicle crash tests. The system is characterized by a steel safety shape style traffic face, a tubular pipe top rail and inter-locking 20-ft long steel panels. This paper presents the results of the crash tests and relates them to the Report 350 and AASHTO MASH test level four and five requirements. The results of the crash tests, when evaluated according to Report 350 and MASH, demonstrate that the two barriers satisfy both the Report 350 and MASH criteria at test levels four and five, respectively. The FHWA has accepted the MDS-4 and MDS-5 as Report 350 and MASH test level four and five bridge railings, respectively.

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Malcolm H. Ray, P.E., Ph.D. and Marta Mastova

INTRODUCTION

Two new barrier systems have been developed that incorporate both a crash-tested barrier safety system and an optional noise wall that can be used in both permanent and temporary construction. The new MDS barrier systems provide protection against the collision of vehicles as well as noise pollution. A photograph of the 62-5/8 inch (1.595-m) tall version is shown in Figure 1 and a simplified drawing of both systems in the AASHTO-ARTBA-AGC drawing format is shown in Figure 2.

The MDS Barriers are all-steel safety-shape barriers that are bolted directly to the bridge deck. Twenty ft (6 m) long, 38.5 in(980-mm) high safety-shape panels made of 5/32-in (4 mm) steel plate are attached to the bridge deck and a circular steel tube top rail is mounted to the top of the bridge panels. The safety-shape panels have dimensions that place it between the conventional dimensions of the New Jersey shape and the F shape and the traffic face has two corrugations. The barrier is available in two varieties: a 48.5-inch (1.240-m) high system suitable for Report 350/MASH test level four situations, called the MDS-4 in this report, and a 62.625-inch (1.595-m) high system suitable for Report 350/MASH test level five conditions, called the MDS-5 in this report (note: the nominal heights are measured to the center of the top rail). Both versions of the MDS barrier can be used with or without optional noise barriers that are attached to the rear face of the safety barrier. The noise barrier does not contribute to the safety performance of the railing so the drawings in Figure 2 are shown without the optional noise panel.

The integration of both the safety barrier and the noise-protection barrier within a single barrier system provides considerable savings in terms of occupied space, supporting sub-structures and overall cost. The special backward positioning of the noise-protection barrier requires less lateral space on the bridge deck and also makes the disposal of snow easier.

Figure 1. Photographs of the MDS-4 barrier with noise-wall installed (left) and a post-collision photograph of the MDS-5 barrier without the noise wall installed

The barriers take advantage of a unique sliding base attachment. For the MDS-4, two threaded rods are attached to the deck which are then bolted into an inverted hat section in the barrier panels. For the MDS-5, a skid-plate is mounted is bolted to the bridge deck using four deck anchor bolts that may either be drilled through the deck or epoxyed into the deck depending on the deck design requirements and the threaded rods are attached to the skid plate at the bottom and the inverted hat section in the barrier panels. The sliding action of the barrier dissipates considerable energy while isolating the deck from high impact forces. The bolt attachment to the deck used in the MDS-5 crash tests were 5/8-inch diameter bolts epoxied five inches (M16 bolt 130 mm into the deck) into the deck. The attachment causes very little disruption of the deck making it ideal for re-decking projects or temporary staged construction. The barrier can be placed in one location on the deck during re-decking and then un-bolted and moved to its final position without any major change to the deck. The 20-ft (6-m) panels are easily moved using a fork lift so repositioning the panels is easily accomplished during a re-decking project.

Both the MDS-4 and MDS-5 barriers were tested according to the European crash test standard EN 1317 at the BASt/TÜV test facility in Munich, Germany. The MDS-4 system passed all the required EN 1317 tests for containment level H2 and the MDS-5 barrier passed all the required EN 1317 tests for containment level H4b. The purpose of this paper is to assess the EN 1317 crash tests using the test and evaluation guidelines in Report 350 and MASH. As will be shown in the following sections, the MDS-4 barrier satisfies both the Report 350 and MASH criteria for test level four conditions and the MDS-5 barrier satisfies the requirements for test level five. MDS requested and obtained Federal Highway Administration (FHWA) acceptance of the MDS-4 barrier as a Report 350/MASH test level four barrier and the MDS-5 barrier as a Report 350/MASH test level five barrier.

The MDS-4 barrier system has been approved for use both with and without the noise-wall in Ireland, Great Britain and Hungary and as a safety barrier with the noise wall in Germany and Austria.[1] [2] European approval of the MDS-5 barrier has been obtained in Germany, Austria, Ireland, Great Britain and Hungary.[3]

TEST CONDITIONS

The tests described in the following sections and more fully documented in the test reports were performed according to the DIN EN 1317 specifications used in Europe for evaluating roadside hardware.[4] There are, of course, differences between the testing guidelines used in Europe and those used in the US. Table 1 shows a comparison of the basic test conditions between Report 350, the Report 350 update and the EN 1317 tests.[5, 6]

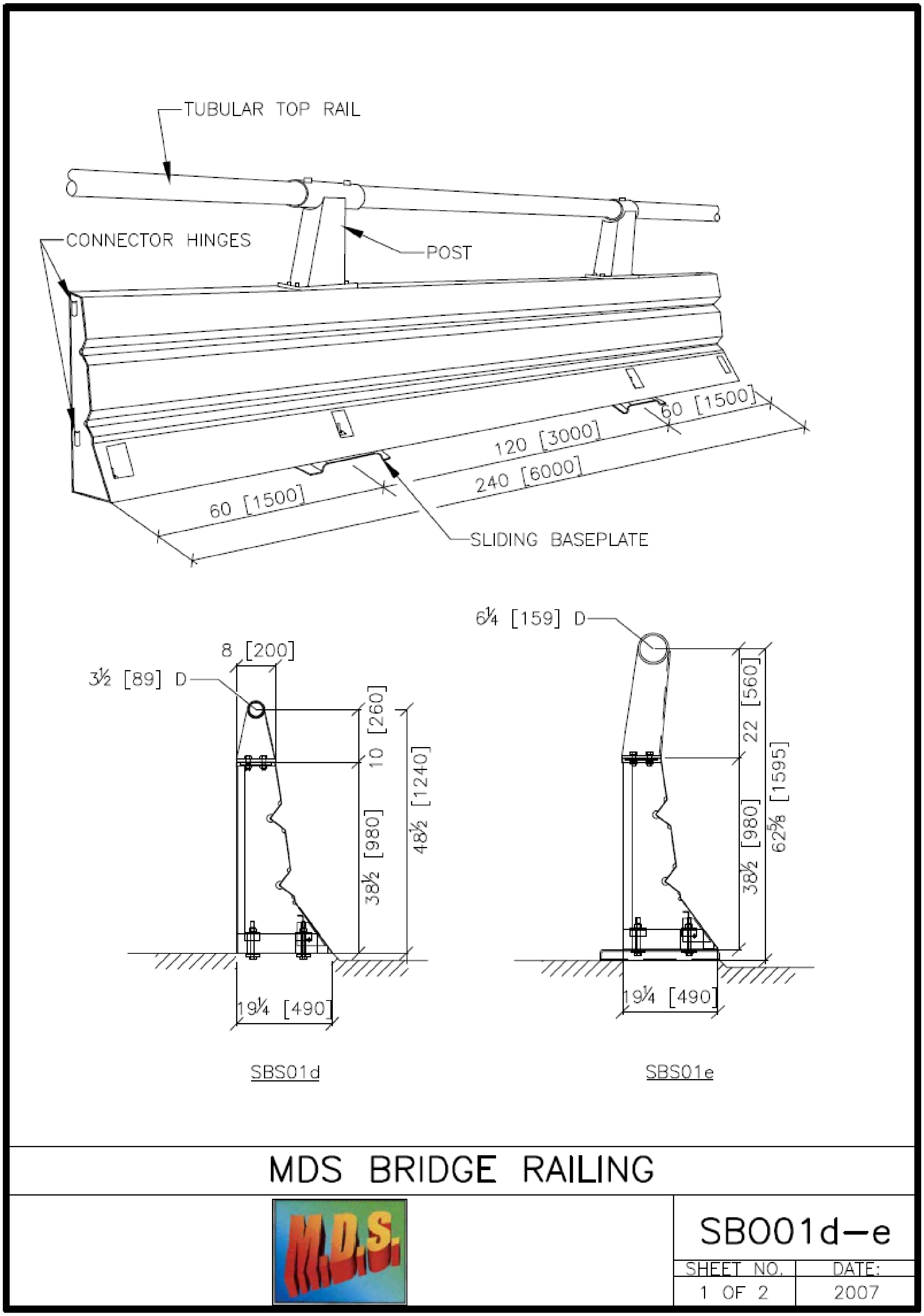

Figure 2. Schematic drawings of the MDS-4 and MDS-5 barriers.

Test EN1317 test TB-11, the small car test, involves a vehicle that is about 80 kg heavier than the 820-kg small car used in Report 350 Test 6-10 (i.e., 820 kg versus 900 kg). Both Report 350 and EN 1317 test TB-11 use an impact velocity of 100 km/hr and an impact angle of 20 degrees. MASH recommends the use of an 1100-kg small car as a test vehicle with an impact velocity of 100 km/hr and an impact angle of 25 degrees. Since the vehicle used in the TB-11 crash test is between the Report 350 and MASH vehicles (i.e., the 900-kg test vehicle is slightly heavier than the 820-kg Report 350 vehicle and slightly lighter than the 1100-kg MASH vehicle) the performance in this test is believed to be functionally equivalent to both the Report 350 test 3-10 as well as MASH test 3-10. In addition, the basic shape of the steel barrier panels has geometry between the widely tested and used New Jersey safety shape and the F-shape barriers. Both the New Jersey and F shape have been shown to have good performance in the small car test under Report 350 test 3-10 conditions for a variety of barriers so it is reasonable to expect similar performance on this similar barrier face shape. The EN 1317 test TB-11, then, can be considered equivalent to both Report 350 and MASH-8 test 3-10 for purposes of evaluating this steel safety shape barrier. The FHWA has already issued acceptance letters on other barrier systems where the results of EN 1317 TB-11 tests were considered the equivalent of Report 350 test 3-10.[7]

The heavy vehicle test for Report 350 test level four involves an impact with a single unit truck. Report 350 specifies an 8,000-kg single unit truck striking the barrier at 80 km/hr and 20 degrees whereas MASH increases the mass to 10,000 kg and the impact angle to 25 degrees. There is no similar test in EN 1317 but test TB-51 involves a 13,000 kg intercity bus striking the barrier at 70 km/hr and 20 degrees. The trend in the U.S. has been toward increasing impact severity for test 4-12 as indicated by the increasing mass and impact angle specified in MASH. The impact severity (IS) has increased from 103 MJ to 209 MJ between Report 350 and MASH. The impact severity of the TB-51 test is 287 MJ, even higher than MASH test 4-12, so it is a more severe test. Often, the most important issue in test 4-12 is the stability and rollover potential of the single unit truck. The height of the center of gravity is 1,250 mm and 1,700 mm respectively for the Report 350 and MASH test 4-12 vehicles. This is similar to the 1,400 mm center of gravity height for the bus used in EN1317 test TB-51. The AASHTO LRFD Bridge Design Guide specifies a minimum effective rail height of 32 inches (810 mm) for a test level four railing whereas the MDS-4 barrier is 48.5 inches tall (1240 mm tall), 16.5 inches (430 mm) taller than required.[8] Since the impact severity is higher in the TB-51 test, the center of gravity height is similar, and in the case of the MDS-4 barrier the rail height is well above the minimum TL-4 AASHTO requirement, the TB-51 test is a more severe test than either version of test 4-12. A barrier that can contain and redirect the 13,000 kg bus without compromising the barrier or rolling over seems highly likely to perform well in the Report 350/MASH tests with the single unit truck. Since the TB-51 test is more severe, it seems reasonable to accept the results of an EN 1317 TB-51 test in lieu of either the Report 350 or MASH test 4-12.

Table 1. Test conditions for Report 350, the Report 350 update and EN 1317.

Parameter	Report 350	Report 350 Update	EN1371
Test	4-10/5-10	4-10/5-10	TB-11
Vehicle Type	Passenger Car	Passenger Car	Passenger Car
Vehicle Mass (kg)	820	1100	900
Vehicle c.g. height (mm)	550		490
Impact Velocity (km/hr)	100	100	100
Impact Angle (deg)	20	25	20
Impact Severity (kJ)	37,007	75,797	40,617
Test	4-12	4-12	TB-51
Vehicle Type	Single Unit Truck	Single Unit Truck	Bus
Vehicle Mass (kg)	8,000	10,000	13,000
Vehicle c.g. height (mm)	1,250	1,700	1400
Impact Velocity (km/hr)	80	90	70
Impact Angle (deg)	15	15	20
Impact Severity (kJ)	132,320	209,334	287,478
Test	5-12	5-12	TB-81
Vehicle Type	Tractor Trailer	Tractor Trailer	Tractor Trailer
Vehicle Mass (kg)	36,000	36,000	38,000
Vehicle c.g. height (mm)	Not specified	1,850	1,900
Impact Velocity (km/hr)	80	80	65
Impact Angle (deg)	15	15	20
Impact Severity (kJ)	595,438	595,438	724,562

The heavy vehicle test in both Report 350 and MASH are exactly the same featuring an 80 km/hr 15 degree impact with a 36,000-kg tractor trailer truck. Test TB-81, the articulated truck test, involves a slightly heavier vehicle (i.e., 38,000 kg rather than 36,000 kg) striking the barrier at a slightly lower velocity (65 km/hr rather than 80 km/hr) and a higher impact angle (20 degrees rather than 15 degrees). The TB-81 test conditions (i.e., the tractor trailer truck test) results in an impact severity of 724 MJ compared to 595 MJ in the Report 350 Test 5-12, (i.e., the tractor trailer truck test) so the European test is a much higher severity test. Since the vehicles are similar and the impact severity is higher in the EN 1317 test due to the higher impact angle and larger mass, the EN 1317 test presents a more critical situation. The minimum barrier height for a TL-5 railing according to the AASHTO LRFD Bridge Design Guide is 54 inches (1370 mm) and the MDS-5 is 62.625 inches (1,595 mm), 8.625 inches (225 mm) higher than the minimum required by AASHTO. Successful performance in the EN 1317 TB-81 test should be considered evidence of satisfactory performance in Report 350/MASH test 5-12. This approach has also recently been used by the FHWA in evaluating the acceptance of another barrier system tested in Europe according to EN 1317.[1]

Based on the discussion presented above, it seems a reasonable approach to accept the results of EN 1317 tests TB-11 and TB-51 as indicative of the performance for test level four in both Report 350 and the update. Likewise, it seems reasonable to accept the results of EN 1317 tests TB-11 and TB-81 as indicative of the performance of the barrier for Report 350/MASH test level five conditions.

One major difference between EN1317 and Report 350/MASH is that there is no pickup truck test specified so the performance of the MDS bridge rails has not yet been established by crash testing although based on the size and shape of the barriers good performance seems likely. The resolution of this issue will be discussed later in this paper. The following sections present a summary of the test level four and five testing on the MDS barriers. Complete details are shown in the test reports cited in the following sections.

MDS-4 Barrier

The MDS-4 Barrier is a 48.5 inch (1,240-mm) tall all-steel barrier with an 3.5-inch (89-mm) diameter steel tubular rail mounted 48.5-inches (1,240 mm) above the pavement on a 38.5-inch (980 mm) tall steel safety shape constructed of 5/32-inch (4-mm) thick steel plate. The steel plates used in the MDS-4 crash tests were actually thinner (i.e., 1/8-inch (2.5-mm)) than the steel plates approved by the FHWA. Since the effective rail height is well above that required for TL-4 by the AASHTO Bridge Specification, it is appropriate to evaluate this particular barrier as a TL-4 system. TL-4 involves two required tests: one with a small car and the other with a single unit truck. The results of the testing on the MDS-4 barrier are presented in the following sections.

Test 4-10

A test of a small car impacting the MDS-4 Barrier was performed at the BASt/TÜV test facility in Munich, Germany on 1 December 2004.[9] The test was performed using EN 1317 TB-11 test conditions; namely, a 900-kg passenger car striking the barrier at 100 km/h and 20 degrees. As discussed in the previous section, the TB-11 test is functionally equivalent to Report 350 test 4-10.

As documented in the test report, the small passenger vehicle struck the barrier at a 20 degree angle and a velocity of 102.9 km/hr. After the initial impact, the vehicle was redirected parallel to the barrier. During its interaction with the barrier, the vehicle rode up the barrier as is typical in small car tests of safety shaped barriers and experienced a maximum clockwise roll angle of about 49 degrees. The un-instrumented dummy in the driver seat struck and shattered the driver-side window but the head-form did not contact the barrier itself. The hood-latch released letting the hood open and strike the windshield. Three of the vehicle wheels lifted off the ground for a short time during redirection. The vehicle lost contact with the barrier and all four tires were lifted off the ground for a short period. The passenger-front tire quickly re-contacted the ground with the remaining tires re-contacting the ground shortly thereafter. The vehicle continued downstream where it came to rest near the end of the test installation as shown in the photographs in Annex 3 of the test report.

The 20-ft (6-m) long barrier segment that was the initial point of contact was bent and otherwise deformed but all the damage was limited to this one panel (see Annex 3 of the test report). The anchor bolts under the impacted panel were deformed but the base performed as designed, sliding laterally backwards during the impact. The maximum dynamic deflection of the barrier was 10.25 inches (260 mm) and the maximum permanent lateral deflection was 4.3 inches (110 mm). The damage to the barrier was not extensive and all the damage was contained in the single panel where the initial impact occurred. The barrier successfully contained and redirected the vehicle as designed.

Table 2. Safety Evaluation Summary – Test Bast/2004 7D 33/HB (Report 350 4-10) of the MDS-4 Barrier.

Evaluation Factors		Evaluation Criteria	Result
Structural Adequacy	A.	Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
	B.	The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.	NA
	C.	Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.	NA
Occupant Risk	D.	Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.	Pass
	E.	Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.	NA
	F.	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.	Pass
	G.	It is preferable, although not essential, that the vehicle remain upright during and after collision.	NA
	H.	Occupant impact velocities should satisfy the following: Occupant Impact Velocity Limits (m/s) Component / Preferred / Maximum	
		Longitudinal and Lateral / 9 / 12	6.7 Pass 5.7 Pass
		Longitudinal / 3 / 5	NA
	I.	Occupant ridedown accelerations should satisfy the following: Occupant Ridedown Acceleration Limits (g's) Component / Preferred / Maximum	
		Longitudinal and Lateral / 15 / 20	7.2 Pass 6.2 Pass
	J.	(Optional) Hybrid III dummy responses.	NA
Vehicle Trajectory	K.	After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	Pass
	L.	The occupant impact velocity in the longitudinal direction should not exceed 12 m/sec and the occupant rideown acceleration in the longitudinal direction should not exceed 20 G's.	NA
	M.	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.	$11^{\circ}<0.6\cdot 20^{\circ}$ Pass
	N.	Vehicle trajectory behind the test article is acceptable.	NA

NA = Criterion not applicable to this test condition.

Figure 3. 900-kg 100 km/hr 20 degree small car test of the MDS-4 barrier showing (top) barrier damage, (bottom left and middle) vehicle-barrier interaction and (bottom right) vehicle damage.

The vehicle was smoothly redirected and the test satisfied all the evaluation criteria of both EN 1317 for TB-11 as certified by the test engineer. The test report and test data were used to re-evaluate the crash test according to Report 350 for test level 4-10 conditions. A summary of the Report 350 evaluation parameters are shown in Table 2 and photographs of the vehicle-barrier interaction, vehicle damage and barrier damage are shown in Figure 3. As demonstrated by the data in Table 2, the small passenger car crash test satisfied all the requirements of Report 350 and the testing conditions, as described earlier, are essentially the same for the European test TB-11 and Report 350 test 4-10. The MASH evaluation criteria are essentially the same as the Report 350 criteria for test 4-10. The exceptions are that more detail is provided for measuring occupant compartment intrusion (i.e., criterion D), the allowable roll and pitch are limited to 75 degrees in MASH (i.e., criterion F) and Report 350 criteria K and M are eliminated. As detailed in the test report, there was some minor damage to the floor pan but it was not extensive so the revised criterion D is not affected. The maximum roll and pitch angles were approximately 40 and 36 degrees respectively so the new criterion F was likewise not affected. The evaluation of this small car test indicates, therefore, that the MDS-4 barrier satisfies the requirements for test 4-10 for both Report 350 and MASH.

Test 4-12

A second full-scale crash test was performed on the MDS-4 barrier with a noise-wall installed using a 13,000-kg intercity bus at the TÜV test-field in Munich, Germany using the EN 1317 test TB-51 specifications. [10] A bus test is not required by Report 350 or MASH but the TB-51 test is more severe than the usual test 4-12 involving the single unit truck as described in the previous section. Test TB-51 is also very similar to the old Report 230 supplemental test S19. The test demonstrated that the barrier can contain and safely redirect a heavy vehicle since all the evaluation parameters specified in the European EN 1317 specification were satisfied. In particular, the colliding vehicle was contained by the barrier, the area involved in the impact was limited and the vehicle remained upright.

The front-left side of the 13,000-kg bus struck the barrier at 71.6 km/hr and 20 degrees. Upon impact, the vehicle began to push the steel-plate section rearward and the bus began to be redirected, rolling slightly clockwise away from the barrier as it rode up onto the safety-shaped face of the steel panel. The windshield detached during the initial impact and was propelled forward of the vehicle. After the front of the bus pitched upward, the bus was redirected parallel to the barrier. Upon contact with the rear axle the rear pitched upwards as the bus was redirected away from the barrier at a seven degree angle. The pitching of the vehicle caused the front bumper to contact the ground and subsequently regain its stability. The bus then steered back toward the barrier, re-contacting it approximately 132 ft (40 m) downstream of its initial impact point. The vehicle again is redirected parallel to the barrier and along the barrier where it comes to rest.

Most of the damage to the barrier was contained in the panel that was initially contacted. The steel safety shape section was deformed and pushed back but retained its structural integrity and functioned as intended by the designers. The safety shape panel where the second impact occurred was also slightly bowed and deformed but to a lesser extent than the initial impact location. The maximum lateral dynamic deflection was 32.5 inches (800 mm) and the maximum lateral permanent deflection was 25.5 inches (650 mm).

A unique feature of the BASt/TÜV impact test facility is that the forces on the bridge deck can be directly measured during the experiment as discussed by Kübler.[11] The forces transmitted by the impact of the bus to the bridge deck were determined using the instrumented bridge deck at the TÜV test facility in Munich. The maximum lateral force on the deck was always less than 3.04 kips/ft (15.2 kN/m) of deck and the bending moment was less than 1.42 ft-lbs/ft (6.3 kN-m/m) of bridge deck.

The vehicle was smoothly redirected and the test satisfied all the evaluation criteria of both EN 1317 for TB-51 as certified by the test engineer. Photographs of the impact event, barrier damage and vehicle damage are shown in Figure 4. The test report and test data were used to re-evaluate the crash test according to Report 350 for test 4-12 conditions. As demonstrated by the data in Table 3, the bus crash test satisfied all the requirements of Report 350 and the testing conditions, as described earlier, are more severe than the usual Report 350 test 4-12 involving the single-unit truck. The windshield did become detached and was propelled forward but it is believed this does not constitute an undue hazard under Report 350 criterion D. In any case, the wind shield detachment is more a feature of this particular vehicle design than the barrier. The MDS-4 barrier, therefore, meets all the requirements for Report 350 and MASH test 4-12.

Table 3. Safety Evaluation Summary – Test Bast/2004 7D 34/HB (Report 350 4-12) of the MDS-4 Barrier.

<table>
<tr><th>Evaluation Factors</th><th colspan="3">Evaluation Criteria</th><th>Result</th></tr>
<tr><td rowspan="3">Structural Adequacy</td><td colspan="3">A. Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>Pass</td></tr>
<tr><td colspan="3">B. The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.</td><td>NA</td></tr>
<tr><td colspan="3">C. Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.</td><td>NA</td></tr>
<tr><td rowspan="14">Occupant Risk</td><td colspan="3">D. Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</td><td>Pass</td></tr>
<tr><td colspan="3">E. Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.</td><td>NA</td></tr>
<tr><td colspan="3">F. The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.</td><td>NA</td></tr>
<tr><td colspan="3">G. It is preferable, although not essential, that the vehicle remain upright during and after collision.</td><td>Pass</td></tr>
<tr><td colspan="3">H. Occupant impact velocities should satisfy the following:</td><td></td></tr>
<tr><td colspan="3">Occupant Impact Velocity Limits (m/s)</td><td></td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td><td></td></tr>
<tr><td>Longitudinal and Lateral</td><td>9</td><td>12</td><td>NA</td></tr>
<tr><td>Longitudinal</td><td>3</td><td>5</td><td>NA</td></tr>
<tr><td colspan="3">I. Occupant ridedown accelerations should satisfy the following:</td><td></td></tr>
<tr><td colspan="3">Occupant Ridedown Acceleration Limits (g's)</td><td></td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td><td></td></tr>
<tr><td>Longitudinal and Lateral</td><td>15</td><td>20</td><td>NA</td></tr>
<tr><td colspan="3">J. (Optional) Hybrid III dummy responses.</td><td>NA</td></tr>
<tr><td rowspan="4">Vehicle Trajectory</td><td colspan="3">K. After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.</td><td>Pass</td></tr>
<tr><td colspan="3">L. The occupant impact velocity in the longitudinal direction should not exceed 12 m/sec and the occupant rideown acceleration in the longitudinal direction should not exceed 20 G's.</td><td>NA</td></tr>
<tr><td colspan="3">M. The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.</td><td>$7.1^{\circ}<0.6\cdot20^{\circ}$ Pass</td></tr>
<tr><td colspan="3">N. Vehicle trajectory behind the test article is acceptable.</td><td>NA</td></tr>
</table>

NA = Criterion not applicable to this test condition.

Figure 4. 13,000-kg 70 km/hr 20 degree intercity bus test of the MDS-4 barrier showing (top) barrier damage and (bottom) the vehicle-barrier interaction.

Summary

Based on the tests described in the previous sections, the MDS-4 barrier satisfies the requirements for both Report 350 and MASH for test level four. While the crash test conditions are not identical to those specified in Report 350 and MASH, the EN 1317 tests are more severe and therefore present a more demanding test than the usual test level four conditions.

MDS-5 Barrier

The MDS-5 barrier is very similar to the MDS-4 in that it uses the same 38.5-inch (980-mm) tall all-steel 5/32-inch (4-mm) thick safety shape panels. The steel plates used in the MDS-5 crash test were actually thinner (i.e., 1/8-inch (3-mm)) than the steel plates approved by the FHWA. The primary difference is a 6.25-inch (159-mm) diameter top rail is fitted to the top of the safety-shape panel resulting in an effective rail height of 62.625 inches (1,595-mm) (i.e., the distance from the top of the pavement to the middle of the tubular railing). Also, a skid plate is used where four bolts attached the skid plate to the bridge deck and two rods pass up from the skid plate and attach to the inverted hat section to provide the sliding mechanism. The AASHTO LRFD Bridge Design Specifications require TL-5 bridge railings to be at least 52 inches (1,370 mm) tall so it is appropriate to treat this 62.625-inch (1,595 mm) tall railing as a TL-5 design. TL-5 involves crash tests with a small car and a tractor trailer truck. The results of the EN 1317 testing are presented below.

Test 5-10

A test of a small car impacting the MDS-5 barrier was performed at the BASt/TÜV test facility in Munich, Germany on 26 April 2006.[12] The test was performed using EN 1317 TB-11 test conditions; namely, a 900-kg passenger car striking the barrier at 100 km/h and 20 degrees. As discussed earlier, the TB-11 test is functionally equivalent test 5-10 in the Report 350 and MASH.

The small passenger vehicle struck the barrier at 102.4 km/hr at an angle of 20 degrees. After the initial impact, the vehicle was redirected parallel with the barrier. During its interaction with the barrier, the vehicle rode up the barrier and rolled in a clockwise direction as is typical in small car tests of safety shaped barriers. The maximum roll during the interaction with the barrier was approximately 45 degrees and the maximum pitch was approximately 17 degrees. The un-instrumented dummy in the driver seat shattered the driver-side window but the head-form did not contact the barrier itself. The vehicle was lifted off the ground for a short time during redirection loosing contact with the barrier and landing first with the right front wheel followed by the left front wheel and rear wheels. The vehicle continued downstream where it experienced a secondary minor impact with another barrier before coming to rest. Not surprisingly, the performance of the vehicle in this test was nearly identical to the results of the small car test with the MDS-4 barrier.

The vehicle was smoothly redirected and the test satisfied all the evaluation criteria of both EN 1317 for TB-11 as certified by the test engineer. The test report and test data were used to re-evaluate the crash test according to Report 350 for test 5-10 conditions. A summary of the Report 350 evaluation parameters are shown in Table 4 and photographs of the impact event, barrier damage and vehicle damage are shown in Figure 5. As demonstrated by the data in Table 4, the small passenger car crash test satisfied all the requirements of Report 350 and the testing conditions, as described earlier, are essentially the same for the European test TB-11 and Report 350 test 5-10. The MASH evaluation criteria are essentially the same as the original Report 350 criteria for test 5-10. The exceptions are that more detail is provided for measuring occupant compartment intrusion (i.e., criterion D), the allowable roll and pitch are limited to 75 degrees in the update (i.e., criterion F) and Report 350 criteria K and M are eliminated. As detailed in the test report, there was no occupant compartment intrusion so the so the revised criterion D is not affected. The maximum roll and pitch angles were approximately 45 and 17 degrees respectively so the new criterion F was likewise not affected. The evaluation of this small car test indicates, therefore, that the MDS-5 barrier satisfies the requirements for test 5-10 for both Report 350 and MASH.

Table 4. Safety Evaluation Summary – Test BASt/2006 7D 03/HK (Report 350 5-10) of the MDS-5 Barrier.

<table>
<tr><th>Evaluation Factors</th><th colspan="2">Evaluation Criteria</th><th>Result</th></tr>
<tr><td rowspan="3">Structural Adequacy</td><td>A.</td><td>Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>Pass</td></tr>
<tr><td>B.</td><td>The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.</td><td>NA</td></tr>
<tr><td>C.</td><td>Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.</td><td>NA</td></tr>
<tr><td rowspan="7">Occupant Risk</td><td>D.</td><td>Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</td><td>Pass</td></tr>
<tr><td>E.</td><td>Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.</td><td>NA</td></tr>
<tr><td>F.</td><td>The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.</td><td>Pass</td></tr>
<tr><td>G.</td><td>It is preferable, although not essential, that the vehicle remain upright during and after collision.</td><td>NA</td></tr>
<tr><td>H.</td><td>Occupant impact velocities should satisfy the following:<table><tr><td colspan="3">Occupant Impact Velocity Limits (m/s)</td></tr><tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr><tr><td>Longitudinal and Lateral</td><td>9</td><td>12</td></tr><tr><td>Longitudinal</td><td>3</td><td>5</td></tr></table></td><td>5.7 Pass
6.5 Pass
NA</td></tr>
<tr><td>I.</td><td>Occupant ridedown accelerations should satisfy the following:<table><tr><td colspan="3">Occupant Ridedown Acceleration Limits (g's)</td></tr><tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr><tr><td>Longitudinal and Lateral</td><td>15</td><td>20</td></tr></table></td><td>6.2 Pass
9.3 Pass</td></tr>
<tr><td>J.</td><td>(Optional) Hybrid III dummy responses.</td><td>NA</td></tr>
<tr><td rowspan="4">Vehicle Trajectory</td><td>K.</td><td>After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.</td><td>Pass</td></tr>
<tr><td>L.</td><td>The occupant impact velocity in the longitudinal direction should not exceed 12 m/sec and the occupant rideown acceleration in the longitudinal direction should not exceed 20 G's.</td><td>NA</td></tr>
<tr><td>M.</td><td>The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.</td><td>$5^{\circ}<0.6\cdot20^{\circ}$
Pass</td></tr>
<tr><td>N.</td><td>Vehicle trajectory behind the test article is acceptable.</td><td>NA</td></tr>
</table>

NA = Criterion not applicable to this test condition.

Figure 5. 900-kg 100 km/hr 20 degree small car test of the MDS-5 barrier showing (top) barrier damage and (bottom) the vehicle-barrier interaction.

Test 5-12

A second test was performed on the same MDS-5 barrier installation on the same day as the previous test using the same installation after the damaged panels from the first test were replaced. The test was performed using EN 1317 TB-81 test conditions; namely, a 38,000-kg articulated truck striking the barrier at 65 km/hr and 20 degrees.[13] As discussed earlier, this test is functionally equivalent to Report 350 test 5-12.

The tractor-trailer truck struck the barrier at 67.6 km/hr at a 20 degree impact angle. The tractor climbed the safety-shaped face of the barrier pushing the impacted panels rearward as designed. During its climb, the tractor began to be redirected rolling away from the barrier with the tractor wheels leaving the pavement. The trailer subsequently struck the barrier and was redirected with the right trailer wheels leaving the ground for a short time. The tractor and trailer both remained upright throughout the entire collision event, loosing contact with the barrier and regaining a stable position. The vehicle lost contact with the barrier at essentially a zero degree angle, traveling parallel with the barrier after loosing contact. The tractor and trailer steered back into the barrier at a very shallow angle and scraped along parallel to the barrier until the end of the installation was reached.

The vehicle was smoothly redirected the barrier completely contained the tractor and the trailer. The test satisfied all the evaluation criteria of both EN 1317 Test TB-81. The test report and data were used to re-evaluate the crash according to Report 350 for test 5-12 condition. A summary of the test evaluation is shown in Table 5.

The damage to the barrier was contained in four of the 20-ft long (6-m) panels from the initial impact point downstream. The first panel was most seriously damaged with decreasing damage to downstream panels. The panels were bent and the sliding bases were moved back as designed and the system maintained its structural integrity throughout the impact event. A panel 130-ft (40-m) downstream of the initial impact was also somewhat damaged as a result of the second collision with the truck. The maximum lateral dynamic deflection of the barrier was 25 inches (640 mm) and the maximum lateral permanent deflection was 19 inches (480 mm).

A described earlier, the forces transmitted by the impact of the tractor trailer truck to the bridge deck were determined using the instrumented bridge deck at the TÜV test facility in Munich. The maximum lateral force on the deck was always less than 4.2 kips/ft (61 kN/m) of deck and the bending moment was less than 15.3 ft-kips/ft (68 kN-m/m) of bridge deck. These results represent relatively modest forces and moment considering the severity of the impact. The forces and moments transmitted to the deck are minimized through the use of the sliding base plate.

Based on the tests described in the previous sections, the MDS-5 barrier satisfies the requirements for both Report 350 and the update for test level five. While the crash test conditions are not identical to those specified in Report 350 and the update, the EN 1317 tests are either very similar (i.e., the TB-11 and 5-10 test conditions) or even more severe (i.e., the TB-81 and 5-12 test conditions) and therefore present a more demanding test than the usual test level five conditions.

Summary

As shown in the previous sections, the MDS-5 barrier satisfies all the evaluation parameters for EN 1317 test TB-81 and Report 350/MASH test 5-12. There are no substantial differences between the Report 350 and MASH impact conditions and evaluation parameters for the tractor trailer truck test 5-12 so satisfying one should satisfy the other.

Figure 6. 38,000-kg 65-km/hr 20-degree tractor trailer truck test of the MDS-5 barrier showing (top) barrier damage and (bottom) the vehicle-barrier interaction.

Table 5. Safety Evaluation Summary – Test BASt/2006 7D 04/HK (Report 350 5-12) of the MDS-5 Barrier.

Evaluation Factors	**Evaluation Criteria**	**Result**
Structural Adequacy	A. Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
	B. The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.	NA
	C. Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.	NA
Occupant Risk	D. Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.	Pass
	E. Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.	NA
	F. The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.	NA
	G. It is preferable, although not essential, that the vehicle remain upright during and after collision.	Pass
	H. Occupant impact velocities should satisfy the following: Occupant Impact Velocity Limits (m/s) Component; Preferred; Maximum	
	Longitudinal and Lateral; 9; 12	NA
	Longitudinal; 3; 5	NA
	I. Occupant ridedown accelerations should satisfy the following: Occupant Ridedown Acceleration Limits (g's) Component; Preferred; Maximum	
	Longitudinal and Lateral; 15; 20	NA
	J. (Optional) Hybrid III dummy responses.	NA
Vehicle Trajectory	K. After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	Pass
	L. The occupant impact velocity in the longitudinal direction should not exceed 12 m/sec and the occupant rideown acceleration in the longitudinal direction should not exceed 20 G's.	NA
	M. The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.	$0^{\circ}<0.6\cdot 20^{\circ}$ Pass
	N. Vehicle trajectory behind the test article is acceptable.	NA

NA = Criterion not applicable to this test condition.

CONCLUSSIONS

As described in the previous sections, the MDS-4 and MDS-5 barrier systems have been shown to satisfy the requirements of Report 350 and MASH for test levels four and five conditions, respectively. The information summarized in this paper was submitted to the FHWA which issued an acceptance letter on 3 June 2008. [14]The MDS barriers have several advantages over conventional barriers including:

- Performance for Report 350 and MASH test levels four and five,
- An optional noise wall that does not require more deck space or hinder snow removal,
- A sliding base attachment to the deck resulting in deck forces less than 4.2 kips/ft (61 kN/m) of lateral load and 15.3 ft-kips/ft (68 kN-m/m) of bending moment in the tractor-trailer truck test.
- Light weight (i.e., approximately 62.5 lbs/ft (78 kg/m) for the MDS-4 and 97 lbs/ft (121 kg/m) for the MDS-5 barrier).
- Easy attachment to the bridge deck that facilitates use in temporary or permanent construction.

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