CRASH TEST PERFORMANCE OF LARGE TRUCK REAR UNDERRIDE GUARDS

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ABSTRACT

Large truck crashes account for a substantial portion of the fatalities and serious injuries occurring in modern passenger vehicles designed for good frontal crash protection. Incompatibilities in mass, stiffness, and ground clearance present challenges in improving crash outcomes for passenger vehicle occupants. A recent Insurance Institute for Highway Safety study of cases from the Large Truck Crash Causation Study (LTCCS) found that rear underride guards meeting US federal requirements still can allow severe passenger vehicle underride, often resulting in serious or fatal injury. The study identified patterns of real-world guard failure, but the impact speeds necessary to produce these failures could not be determined. Also, due to the LTCCS case selection requirement that each crash produce an injury, differences among the large number of guard designs and resulting crash performance and injury risk could not be compared. The current study used a series of six crash tests to investigate these issues.

Crash tests were conducted in which the front of a midsize sedan impacted the rear of a semi-trailer equipped with an underride guard. Three trailer/guard designs were evaluated in various conditions. Each guard design was certified to the US Federal Motor Vehicle Safety Standard (FMVSS) 223 requirements, and two also met the more stringent Canadian Motor Vehicle Safety Standard (CMVSS) 223 regulation. Quasi-static tests were conducted to determine the compliance margins.

In a full-width test at 56 km/h, the guard design built only to the US requirements failed catastrophically at the points of attachment to the trailer, allowing severe underride and trailer contact with the dummy's head. The second guard failed in 50 percent overlap tests at 40 and 56 km/h, producing underride to the base of the sedan's windshield in the first test and to the dummy's head in the second. The third guard was able to prevent underride in full-width and 50 percent overlap tests at 56 km/h but failed when the overlap was reduced to 30 percent.

The minimum force requirements of FMVSS 223 are too low to prevent guard failure in full-width crashes. CMVSS 223 is an improvement over the US regulation, but its requirements also should be strengthened because underride still can occur in offset crashes. Both standards should require quasi-static tests to be conducted with guards attached to a trailer. The current standards allow tests using a rigid fixture, so even well-designed guards could be attached to a trailer such that they fail to prevent underride due to weakness of the trailer chassis or attachment mechanism.

INTRODUCTION

According to the Fatality Analysis Reporting System (FARS), about 10 percent of passenger vehicle occupant fatalities occur in crashes involving large trucks. Two recent studies limited to frontal crashes of vehicles designed to perform well in crash test programs found that large truck crashes are a common source of fatality or serious injury for belted front-seat occupants [1,2]. The only US regulations addressing the structural incompatibility between passenger vehicles and large trucks are Federal Motor Vehicle Safety Standards (FMVSS) 223 and 224, which require rear underride guards on some tractor-trailers [3]. Both standards became effective in 1998, with FMVSS 224 outlining the types of trailers required to have underride guards as well as dimensional requirements for the guards, and FMVSS 223 describing strength and energy absorption requirements in quasi-static tests at three locations on the guard. The National Highway Traffic Safety Administration (NHTSA) issued this rule to "reduce the number of deaths and serious injuries occurring when light duty vehicles impact the rear of trailers and semitrailers with a gross vehicle weight rating of 4,536 kg or more" [4].

In setting the requirements for underride guards, NHTSA was concerned that "overly rigid guards could result in passenger compartment forces that would increase the risk of occupant injuries even in the absence of underride" (61 FR 2005). At the same time, the agency recognized the need for adequate guard strength because "the more the guard yields, the farther the colliding vehicle travels and the greater the likelihood of passenger compartment intrusion" (61 FR 2009). In the end, NHTSA believed the standards would produce guard designs that could be struck by passenger vehicles at speeds of 40-56 km/h and deform enough to prevent excessive deceleration while not allowing the passenger compartment to strike the trailer.

The real-world performance of FMVSS-compliant underride guards had not been evaluated until a recent study by Brumbelow and Blanar [5]. The authors analyzed 115 cases from the Large Truck Crash Causation Study (LTCCS) in which a passenger vehicle struck the rear of a large truck. They identified that 30 of these trucks were equipped with guards that met one or both of the standards. In most of these cases, the guards failed to prevent severe passenger vehicle underride, defined as intrusion of the truck into the passenger compartment. An overall rate of guard failure could not be established because at least one injury was required for inclusion in LTCCS, but the authors were able to categorize the mode in which the guards failed. The most common failures were due to weakness in the attachment between the guard and trailer, deformation of the trailer chassis itself, or excessive bending of one outboard end of the guard in narrow overlap crashes.

Brumbelow and Blanar's [5] findings confirmed that the problems with FMVSS-compliant guards identified in a previous series of crash tests were indicative of field crash performance. The crash tests, conducted by NHTSA in support of the rulemaking, illustrated how an underride guard could meet all of the requirements of both standards yet still produce severe underride due to attachment failure or deformation of the trailer chassis [6]. The tested guard design was able to prevent severe underride of a 1992 Honda Civic in a 48 km/h full-width test only after the attachment hardware was upgraded and the trailer structure was reinforced. Elias and Monk [6] stated that compliance with FMVSS 223 was insufficient to ensure good crash performance if the "attachment hardware or the trailer sub-system to which the guard is attached is not of sufficient strength." However, the final rule that later was issued allowed guards to be tested independently of trailers and contained no provision for evaluating the strength of the trailer or attachment. NHTSA did state that adequate guard performance could not be assured at crash speeds above 45 km/h (61 FR 2010).

Transport Canada also conducted a series of full-width tests with guards meeting US requirements. A baseline guard design minimally compliant with FMVSS 223 was compared with a design equipped with "stoppers" to limit maximum guard deformation and with another guard that was strengthened to provide more resistance throughout the crash. Based on results of these tests, Transport Canada issued Canadian Motor Vehicle Safety Standard 223 [7]. Although this regulation contains substantially greater strength and energy absorption requirements than the US version for the main vertical supports of the guard, it does not require increased strength on the outboard ends of the guard nor does it directly address the potential for attachment or trailer weakness. In a follow-up test, a CMVSS 223-compliant guard mounted to a trailer prevented underride of a 1998 Honda Civic with an impact speed of 56 km/h, but damage to the trailer chassis allowed the guard to begin rotating upward.

The study of real-world guard performance raised some questions that previous crash tests did not address. Because delta Vs could not be calculated for the LTCCS cases, it was unknown what impact speeds would produce failure of production guards. The NHTSA and Transport Canada tests were conducted at speeds ranging from 48 to 64 km/h, but the guards were nonproduction designs developed specifically for research. Additionally, in 15 of the 18 previous tests, the guard was attached to a rigid test buck instead of a trailer, precluding the possibility of observing some of the failure modes present in the LTCCS sample and possibly exacerbating others. Brumbelow and Blanar [5] also identified several cases where the outboard end of the guard bent forward due to narrow overlap loading, but all of the previous crash tests were conducted with full overlap. Finally, due to the lack of cases without injury in LTCCS, it was unknown whether some production guard designs perform better than others. The current study evaluated these issues with a series of six crash tests conducted with production semi-trailers equipped with FMVSS-compliant underride guards.

METHODS

The 2007 Hyundai, 2007 Vanguard, and 2011 Wabash semi-trailers were selected for testing based on their availability through local dealers and the presence of major visible differences in the design of their underride guards. The most obvious differences pertained to the design of the guards' main vertical support members (Figure 1). The Hyundai's vertical supports were bolted directly to the lower rear cross-member of the trailer without any forward attachment points to the trailer's axle slide rails or other structure. The Vanguard and Wabash both had diagonal gussets to forward portions of the trailer chassis, but there also was a difference between the designs. The Vanguard relied on the shear strength of the attachment bolts as the only load path between the guard and trailer, whereas the Wabash was designed to transfer loads from the guard to the chassis through overlapping steel plates.

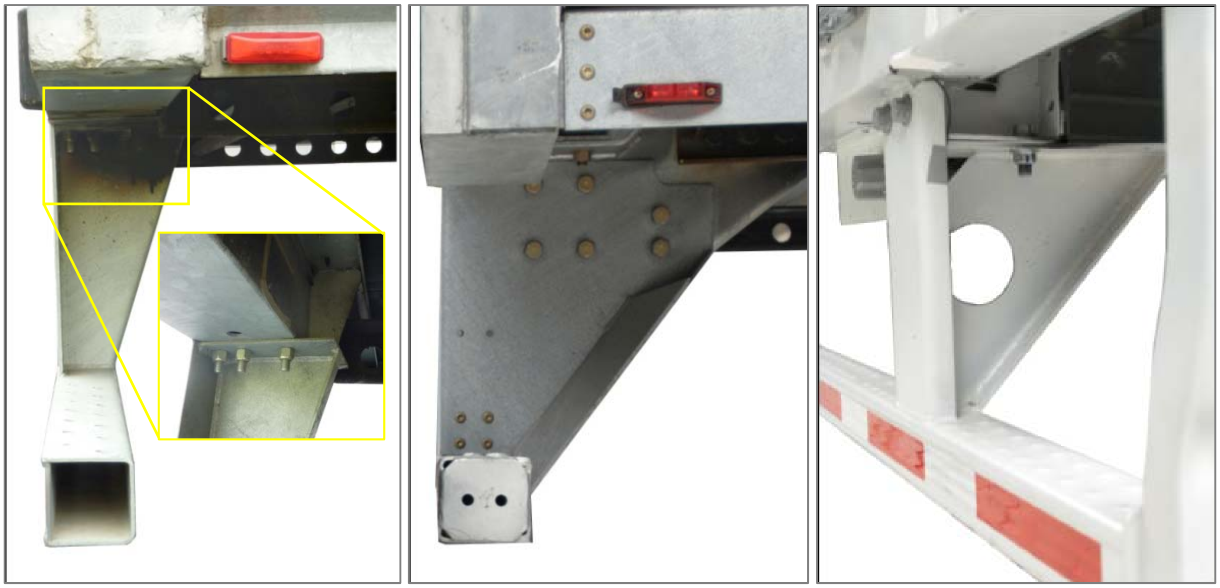

Figure 1. Vertical underride guard support members of 2007 Hyundai (left), 2007 Vanguard (middle), and 2011 Wabash (right) semi-trailers.

The certification labels on the Vanguard and Wabash trailers indicated they complied with CMVSS 223 as well as FMVSS 223. However, the Vanguard's production date corresponded with a time period when CMVSS compliance still could be achieved by testing to the US requirements. To verify compliance with both rules and enable comparison of crash test outcomes with the margin of compliance, quasi-static tests of all three guard designs were conducted. Both FMVSS 223 and CMVSS 223 specify three test locations on the underride guard, designated P1, P2, and P3 (Figure 2). Each location is loaded with a rigid force application device measuring 203 mm square. For the current study, the guards were tested at locations P1 and P3 but not P2. Each guard design was tested twice at P3 because CMVSS 223 requires cutting the guard in half to prevent any strength contribution from the nontested side of the guard. The tests were conducted according to NHTSA and Transport Canada test procedures [8,9] with a loading rate of 1.3 mm/sec. Tests were conducted with a rigid fixture, and a new guard was mounted for each test.

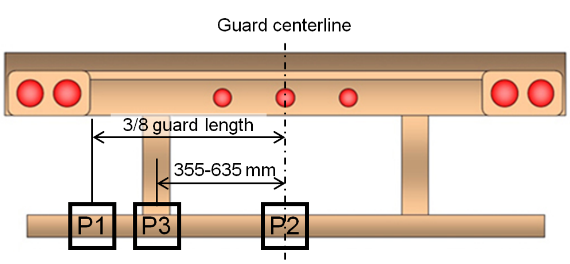

Figure 2. FMVSS 223 and CMVSS 223 test locations. The CMVSS P3 test is conducted with the guard cut in half.

Conditions for each of the six crash tests are listed in Table 1. Despite model year differences, all trailers were new, and none had corrosion or other damage that could have affected the test results. The 2010 Chevrolet Malibu midsize sedan was selected as the test passenger vehicle based on its Top Safety Pick designation by IIHS and five-star frontal scores for both the driver and front passenger in NHTSA's New Car Assessment Program (1990-2010 test format).

Table 1.
2010 Chevrolet Malibu front into trailer rear crash tests

Trailer	Speed (km/h)	Malibu overlap with guard	Guard ground clearance (cm)
2007 Hyundai	56	Full-width	47.6
2007 Vanguard	40	50%	42.2
2007 Vanguard	56	50%	42.7
2011 Wabash	56	Full-width	44.5
2011 Wabash	56	50%	44.3
2011 Wabash	56	30%	45.3

The trailers were loaded with 11 concrete blocks totaling 18,700 kg for the 53-foot (16.2-m) Vanguard and Wabash trailers, and 9 blocks totaling 15,300 kg for the 48-foot (14.6-m) Hyundai trailer. The ground clearances listed in Table 1 were measured with the trailers loaded and the air suspensions pressurized. All of the guards were closer to the ground than the 56-cm maximum allowed by FMVSS 224. The trailers' sliding rear axles were placed in a position that resulted in a setback of about 200 cm from the rear surface of the rear tires to the rear of the trailer. When tested, each trailer was attached to a 2001 Kenworth tractor, and the trailer's brakes were pressurized to 40 psi to simulate being stopped in traffic. Injury measures were recorded from Hybrid III 50th percentile male dummies positioned in the driver seat of each Malibu and in the right front passenger seat for the two full-width tests. High-speed film and digital cameras were used to document the dynamic performance of the underride guards. Precrash and postcrash measures were taken of the Malibu A-pillars and roof header.

RESULTS

When tested quasi-statically on a rigid fixture, all three guard designs met FMVSS 223 requirements at the P1 and P3 test locations by large margins. The Vanguard and Wabash trailers also met the CMVSS 223 requirements. Performance of the Wabash was especially notable, as it sustained a higher force level throughout the test and absorbed much more energy than the Vanguard. Table 2 lists results of the quasi-static testing. Two of the tests had to be stopped early due to yielding of the test fixture.

Deformation patterns of the underride guards varied substantially in the quasi-static tests. For example, in the FMVSS 223 P3 test, the vertical support member of the Hyundai guard was pulled slowly from some of the bolts attaching it to the fixture, whereas the vertical member itself deformed only minimally. In the same test, the Vanguard's vertical member flexed for the first 50 mm of loading and then the attachment bolts began to shear, causing the measured force to drop below that measured for the Hyundai later in the test. The Wabash guard reached its peak force earliest, and then the vertical member began buckling near its attachment to the horizontal member. As the buckling continued, the rear surface of the guard eventually bottomed out against the diagonal gusset, causing the load to increase again late in the test. Figure 3 shows the force-displacement curves for all three guards in the FMVSS 223 P3 test.

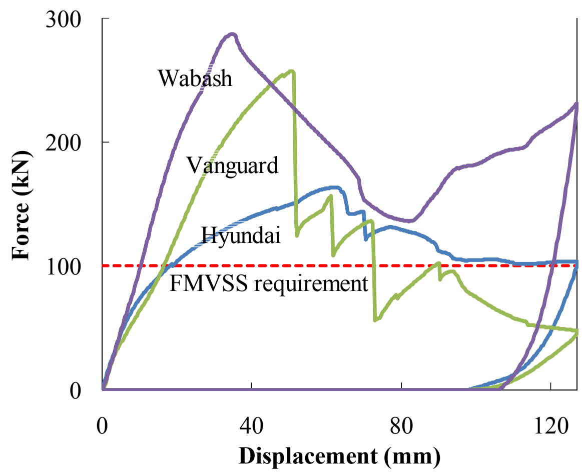

Figure 3. FMVSS 223 P3 test results.

Table 3 summarizes results of the six crash tests, and Figures 4-6 show the 2010 Chevrolet Malibus at the times of maximum forward excursion. In the first 56 km/h full-width test, the 2007 Hyundai guard was ripped from the trailer's rear crossmember early in the crash, allowing the Malibu to underride the trailer almost to the B-pillar. The heads of both dummies were struck by the hood of the Malibu as it deformed against the rear surface of the trailer. Under the same test conditions, the main horizontal member of the 2011 Wabash guard bent forward in the center but remained attached to the vertical support members, which showed no signs of separating from the trailer chassis. The Malibu rebounded rearward from the trailer without underride.

Table 2.
Quasi-static test results

Requirement	FMVSS/CMVSS P1 peak force (kN)	FMVSS P3 peak force (kN)	FMVSS P3 energy absorbed (kJ)	CMVSS P3 peak force (kN)	CMVSS P3 energy absorbed (kJ)
Requirement	**50**	**100**	**5.6**	**175**	**10**
2007 Hyundai	109	163	13.9	135	11.8
2007 Vanguard	143*	257	14.0	209	11.8
2011 Wabash	162	287	22.1	297*	21.5*

*Test was stopped prior to 125 mm (49 mm for Vanguard, 116 mm for Wabash).

Table 3.
2010 Chevrolet Malibu front into trailer rear crash test results

Conditions	Trailer	Guard performance	Underride	Max. longitudinal A-pillar deformation (cm)
56 km/h, full-width	2007 Hyundai	Attachments failed	Catastrophic	80
	2011 Wabash	Good	None	0
40 km/h, 50% overlap	2007 Vanguard	Attachments failed	Moderate	0
56 km/h, 50% overlap	2007 Vanguard	Attachments failed	Severe	27
	2011 Wabash	End bent forward	None	6
56 km/h, 30% overlap	2011 Wabash	End bent forward	Catastrophic	87

Figure 4. 56 km/h, full-width tests with 2007 Hyundai trailer (left) and 2011 Wabash trailer (right).

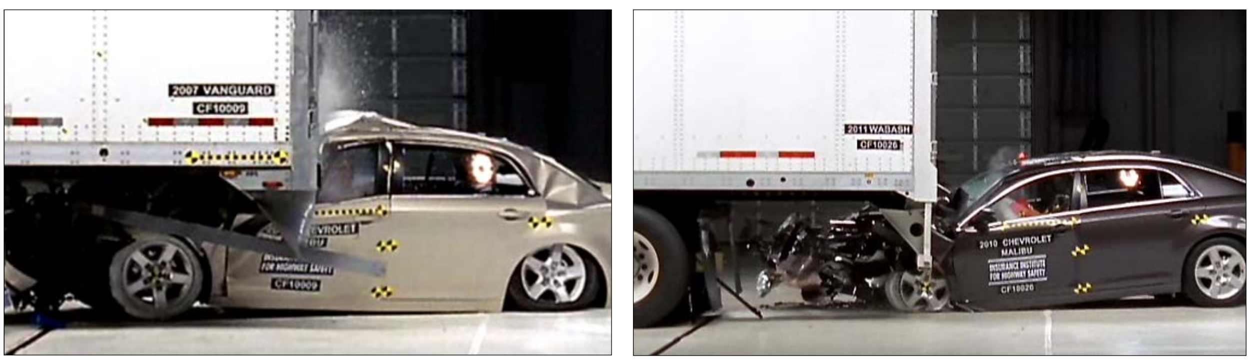

Figure 5. 56 km/h, 50 percent overlap tests with 2007 Vanguard trailer (left) and 2011 Wabash trailer (right).

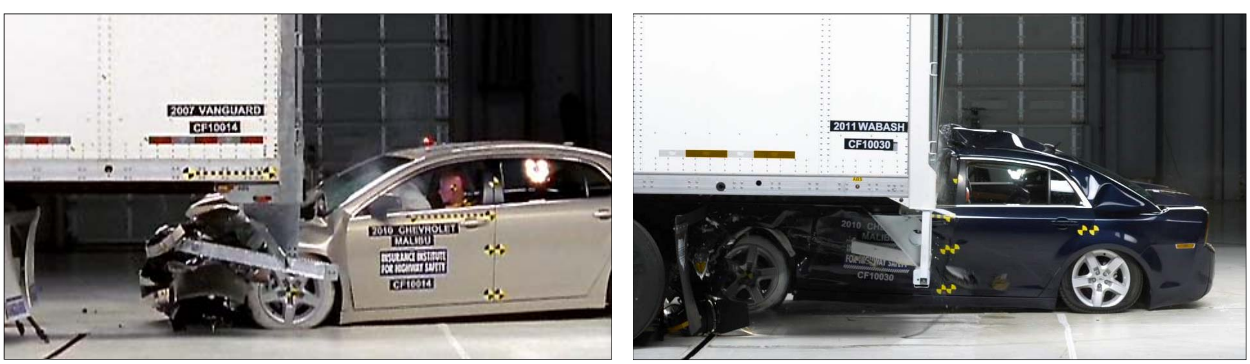

Figure 6. 40 km/h, 50 percent overlap with 2007 Vanguard trailer (left); 56 km/h, 30 percent overlap test with 2011 Wabash trailer (right).

In the 50 percent overlap tests at 40 and 56 km/h, several of the bolts attaching the Vanguard guard to the trailer failed in shear, allowing the Malibu to underride the trailer. At the lower test speed, the Malibu's hood was pushed into the base of the windshield, but the trailer itself did not cross the plane of the windshield into the passenger compartment. When struck at 56 km/h, the trailer loaded the driver-side A-pillar and roof, and the driver dummy's head struck the trailer's rear crossmember. In contrast, the Wabash guard was able to prevent underride in the 56 km/h, 50 percent overlap test. The outboard end of the guard's horizontal member bent forward early in the test, but the right vertical support remained engaged with the Malibu's left wheel and shock tower, and stopped the car without any indication of separating from the trailer.

In the 30 percent overlap test, the Malibu's left wheel was aligned just outboard of the Wabash guard's right vertical support. When struck at 56 km/h, the outboard end of the guard bent forward early in the test, and the Malibu underrode the trailer until the front of the car struck the trailer's right rear tires, with the longitudinal extent of the underride damage stopping just short of the B-pillar. The driver dummy's head struck the rear of the trailer.

Peak injury measures recorded by the dummies during the tests are listed in Table 4. Resultant head accelerations ranged from 107 to 130 g for the four dummies that struck the rear of the trailer or the hood of the Malibu as it was pushed through the windshield by the trailer. Loading durations for these impacts were very short; maximum head injury criterion (HIC) values were calculated during 4-7 ms intervals, with values ranging from 254 to 880.

DISCUSSION

The current study supports the analysis of real-world cases from LTCCS that found underride guards compliant with FMVSS 223 and 224 could fail catastrophically and allow severe underride of the passenger compartments of striking vehicles [5]. Although the impact speeds at which these failures occurred could not be determined from the previous study, the lack of cases with serious injuries due to overly stiff guards suggested that the benefits of strengthening the requirements would outweigh any potential increased risk of deceleration-based injuries in lower-speed crashes. The current study confirms this by showing that production guard designs fail at speeds used in consumer information tests where low injury risk is an industry-accepted target. The underride resulting from these guard failures essentially nullifies the frontal crashworthiness built into modern passenger vehicles. As shown in Table 4, head injury measures recorded by the dummies in the tests with severe underride were much higher than those reported for the Malibu's NCAP rigid wall test at the same speed. Although measures of chest acceleration and deflection were greater in tests without underride than in those with guard failure, they still were comparable with or lower than the peak levels recorded in the NCAP test.

Table 4.
Peak dummy injury measures

		Head resultant acceleration (g)	Head injury criterion (36 ms)	Chest resultant acceleration (3 ms clip, g)	Chest displacement (mm)	Left femur force (kN)	Right femur force (kN)
Hyundai							
Full overlap, 56 km/h	Driver	128	754	21	-19	-0.3	-0.3
	Passenger	107	557	14	-20	-0.1	-0.1
Vanguard							
50% overlap, 40 km/h	Driver	15	24	16	-25	-0.1	-0.1
50% overlap, 56 km/h	Driver	109	254	14	-20	-2.2	0.0
Wabash							
Full overlap, 56 km/h	Driver	54	328	36	-38	-2.2	-1.2
	Passenger	50	319	36	-37	-2.3	-1.8
50% overlap, 56 km/h	Driver	36	160	25	-33	-3.7	-0.9
30% overlap, 56 km/h	Driver	130	880	37	-16	-0.6	-0.1
NCAP							
Rigid wall, full	Driver	49	330	43	-40	-2.0	-1.2
overlap, 56 km/h	Passenger	55	389	42	-32	-0.5	-0.8

The requirements of both FMVSS 223 and CMVSS 223 are insufficient to produce underride guards with adequate crash performance. The current study indicates several changes are needed. Force requirements should be increased for the P1 and P3 test locations, the P1 test should be moved farther outboard, and all tests should be conducted with the guard attached to a trailer. These changes also would address all the failure modes observed in the study of LTCCS cases.

Both the Hyundai and Vanguard guards met the US requirements, with the Vanguard also passing the more stringent CMVSS P3 test. Yet both guards exhibited at least partial failure of their attachments in the quasi-static tests that were similar to those observed in the crash tests with disastrous results. Figure 7 shows how the rearmost edge of the top of the Hyundai's vertical guard support ripped away from two attachment bolts in the FMVSS 223 test and in the crash test. In the crash test, the forward bolts remained attached to the guard but were ripped from the trailer's rear crossmember. The force requirements of both standards at the P3 location are not high enough to guarantee robust attachment designs that can hold the underride guard in place during a crash. In the FMVSS P3 test, the Vanguard achieved a force 157 percent greater than the requirement before its attachment bolts began to fail. Yet some of the bolts fractured in the 50 percent overlap crash at 40 km/h, and when the test speed was increased to 56 km/h, the right half of the guard completely detached from the trailer.

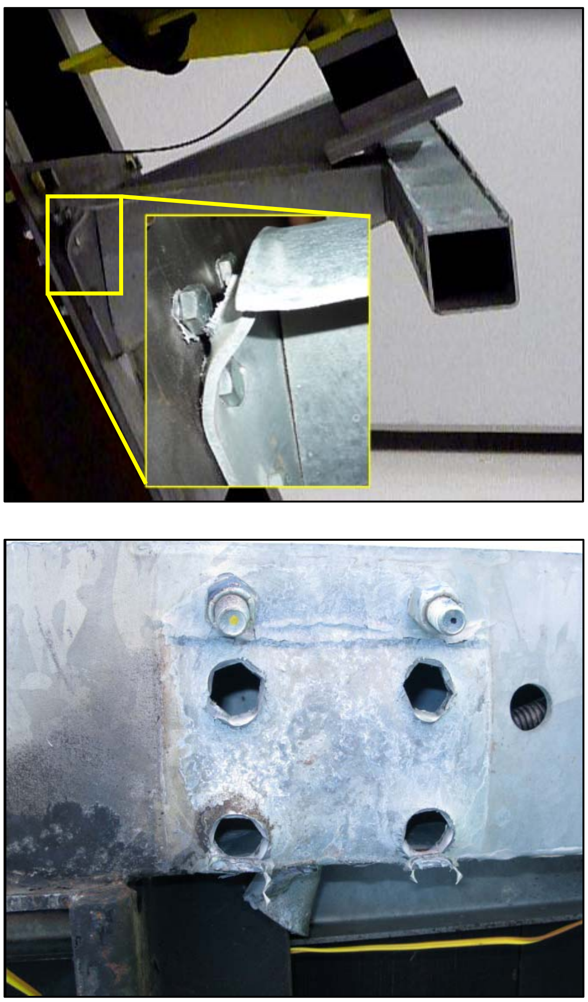

Figure 7. Hyundai underride guard after FMVSS P3 test (left) and Hyundai trailer rear crossmember after crash test, from below (right).

The Wabash guard was the only design that showed no sign of attachment failure in the quasi-static and dynamic conditions. It exceeded the FMVSS 223 and CMVSS 223 P3 force requirements by 187 and 70 percent, respectively. Crucially, its design did not rely on the attachment hardware itself to transfer loads from the guard to the trailer chassis. To encourage such designs, the regulations could be further improved with a stipulation that all attachment hardware must remain intact for the duration of the test or until an even higher force threshold is reached.

To extend protection to the full width of the trailer, the P1 test also needs to be upgraded. The Wabash guard was able to prevent underride in the 50 percent overlap condition, but this almost entirely was due to the vertical support member's interaction with the Malibu's wheel and other outboard structure. When the overlap with the guard was reduced to 30 percent (36 percent overlap with the trailer), the strength of the guard's horizontal member was insufficient to prevent catastrophic underride despite exceeding the FMVSS 223 and CMVSS 223 P1 force requirement by 224 percent. This means that even the strongest guard tested was able to prevent underride only when the Malibu overlapped some portion of the center 49 percent of the trailer's width. Protecting the full width of the trailer from underride does not seem unrealistic because the main longitudinal structures of many semi-trailers are the side rails on the lateral ends of the trailer. Strong vertical support members attached to the side rails would be beneficial in narrow and some wider overlap crashes by allowing the main horizontal portion of the guard to distribute the load across more of the passenger vehicle's structure. Flatbeds and other trailers with their main structures farther inboard may require different design strategies, but this should not preclude extending protection where already possible. Brumbelow and Blanar [5] found that van trailers were the most common type of truck unit involved in fatal rear-end crashes (36 vs. 13 percent for flatbeds).

Even large increases in the FMVSS 223 and CMVSS 223 minimum force levels will not guarantee real-world improvements unless they are accompanied by a requirement that the certification tests be conducted with underride guards attached to the trailer design for which they are intended. Some of the crash tests produced deformation to various portions of the trailer, suggesting the total resistance of the guard-attachment-trailer system was lower than that of the guard alone when tested on a rigid fixture. As shown in the inset of Figure 1, the Hyundai's rear cross-member did not fully overlap the top mounting plate of the guard. A narrow metal tab was welded to the front surface of the crossmember to engage with the portion of the guard that was otherwise unsupported. During the crash test, however, the tabs on both sides were crushed as the guard rotated upward. Certifying such designs on a rigid fixture does not assess the guard's true ability to prevent underride.

NHTSA's compliance test reports show the agency has used a range of fixtures [10]. The standard states the guard should be attached to either "a rigid test fixture" or "a complete trailer," but most guards appear to have been tested on partial sections of the rear of a trailer. Although some of these configurations may be more realistic than the rigid fixture specified in the standard, the sections are fixed at locations that would be free to deform in real-world crashes. Ideally, the regulation would require guards to be certified while attached to complete trailers. At a minimum, they should be attached to sections of the trailer rear that include all the major structural components and that are constrained far enough forward that the load paths near the guard are not changed.

CONCLUSIONS

Tests of semi-trailers equipped with FMVSS 223 compliant underride guards demonstrate that guard failure and severe passenger vehicle underride can result from impact speeds and overlap conditions that passenger vehicles are designed to manage in crashes with stiffer objects. CMVSS 223 requirements are an improvement over US regulations but still are insufficient to produce good performance in offset crashes. Both standards should be upgraded to promote trailer and guard designs that are strong enough across their full widths to remain engaged with the frontal structures of striking passenger vehicles.

ACKNOWLEDGMENT

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