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Commentary

A

Further discussion and elaboration are provided on certain sections in the text. Those sections for which commentary is given correspond to section numbers in the text preceded by the letter "A." For example, "A3.2.1" refers to Section 3.2.1 in the text.

CHAPTER ONE

A1.2 UNDERLYING PHILOSOPHY

Vehicle crash tests are complex experiments that are not easily replicated because of difficulties in controlling critical test conditions such as speed, angle, and condition of test vehicle and the sometimes random and unstable behavior of dynamic crush and fracture mechanisms. Testing guidelines are intended to enhance precision of these experiments while maintaining their costs within acceptable bounds. User agencies should recognize the limitations of these tests and exercise care in interpreting the results.

It is impractical to attempt to duplicate the innumerable site and safety feature layout conditions that exist along the nation's highways in a limited number of standardized tests. Accordingly, the aim of the guidelines is to normalize or idealize test conditions. Hence, straight longitudinal barriers are tested, although curved installations exist; a flat grade is recommended, even though installations are sometimes situated on sloped shoulders and behind curbs. These normalized factors have significant effect on the performance of many safety features and may obscure serious safety deficiencies that exist under more typical but less ideal conditions. However, these normalized factors are thought to be secondary in importance when the object of a test program is to compare the results of two or more systems. Moreover, the normalized conditions are more easily duplicated by testing agencies and help to assure consistency from one lab to the next. Nevertheless, when the highway engineer suspects that a system will be particularly sensitive to some specific site conditions such as a unique soil or roadside geometry, it is important that the feature be tested under these "more critical" conditions instead of, or in addition to, the idealized conditions recommended herein.

These guidelines are intended for use with highway safety features that will be permanently or temporarily installed along the highway. Temporary features are generally used in work or construction zones or other temporary locations, and their duration of use is normally relatively small. An important additional characteristic of a work zone is the exposure of construction personnel to errant traffic. Thus, a barrier in a work zone may be required to (1) redirect errant traffic away from a roadside hazard or other traffic and (2) to shield workers from errant vehicles. Depending on specific site conditions, the impact severity in construction zones may equal or even exceed conditions found at typical non-construction zone sites.

CHAPTER TWO

A2.1 GENERAL

The multiple service level (MSL) concept for highway safety features was first introduced for bridge railings in NCHRP Report 239 (22). NCHRP Report 230 (92) also incorporated the MSL concept to some degree. Table 3 in NCHRP Report 230, "Crash Test Conditions for Minimum Matrix," provided testing for an MSL of 2. Table 4 of Report 230, "Typical Supplementary Crash Test Conditions," provided test conditions for MSLs of 1 and 3. The supplementary matrix applied primarily to longitudinal barriers. Section 20 of AASHTO's *Standard Specifications for Highway Bridges* (5) also incorporated the MSL concept by including four different performance levels for bridge railings. The MSL concept was formally introduced for all safety features with the publication of NCHRP Report 350 (129), which included 6 levels of service or "Test Levels." This document also includes 6 test levels, largely modeled after the test conditions recommended by NCHRP Report 350.

Unfortunately, there are no widely accepted warrants or criteria that identify roadway classifications, traffic conditions, traffic volumes, etc., for which a safety feature meeting a given test or performance level should be used. Given the choice, it would be preferable to first establish conditions or warrants for which features having given capabilities would be cost-effective and thereby define appropriate test levels. Instead, it is necessary to first establish a set of test levels with the uncertainty as to where features developed to meet these levels have application. When warrants for multiple test level features are developed, it is possible that some of the levels will prove to have little application and other levels are needed.

Errant vehicles of all sizes and classes leave the travelway and strike highway safety features with a wide range of speeds, angles, and attitudes. It should be a goal of transportation officials to design safety features that will satisfactorily perform over as wide a range of impact conditions as can practically be accommodated. Combinations of vehicle speed, mass, and approach angle that occur are unlimited. However, impact conditions must be reduced to a very limited number to keep an evaluation test series within economic and practical bounds. The approach used in formulating the recommended test conditions is to evaluate the devices for cases that are believed to represent the worst practical condition. Accordingly, there is no assurance that a safety feature will perform acceptably with other vehicle types presently in service or those vehicle types that may come into use during the normal service life of the device. This "worst practical condition" has been defined as the combination of the 5th percentile lightest and heaviest passenger vehicles striking a safety feature at the 85th percentile highest speed and 85th percentile highest angle. This combination of nearly worst case weight, speed, and angle is believed to produce an extremely rare impact event. Nevertheless, these impacts do occur and have been designated as representative of the most severe impact conditions that can be practically accommodated. This definition of the worst practical impact condition was originally implemented for large passenger vehicles with the first set of evaluation guidelines presented in *Highway Research Board Circular 482* (153). The precedent established with the first set of guidelines for full-scale crash testing has been extended through *Transportation Research Circular 191* (154), and NCHRP Reports 230 (92) and 350 (129).

The only significant revision to passenger vehicle testing philosophy incorporated with the current guidelines is application of the 85th percentile impact angle to the small passenger vehicle. All available accident data shows that impact angles for small cars are at least as high as those associated with large passenger vehicles and SUVs. Further, accident investigations appear to indicate that higher impact angles significantly increase accident severities for all sizes of passenger vehicles. Therefore, the recommended impact angle for tests involving small car redirection matches that for the light truck test vehicle.

A2.1.1 IMPACT CONDITIONS

A number of studies involving detailed accident investigations have been conducted since the 1970s (79, 85, 96, 97, 103). Data from "Critical Impact Point for Longitudinal Barriers" (125) was the primary basis for the selection of impact conditions incorporated in NCHRP Report 350 (129). Data from this study was collected in the late 1970s under the national speed limit law. When this law was eliminated during the 1990s, speed limits on rural freeways were raised all across the country. Based on increased speed limits, it was widely anticipated that crash speeds would increase significantly and that impact angles may be reduced. However, more recent data, collected after the increase in speed limits on rural freeways, did not show higher impact speeds or lower impact angles for run-off-the-road crashes. In fact, the best available data appears to indicate that the 85th percentile impact speed and angle remained essentially the same as in the earlier studies (97). In retrospect, this finding should have been anticipated because the 85th percentile impact speed and angle were not found to be significantly lower under the national speed limit law (85) than prior to the law's implementation (79, 103). Based upon these findings that impact speeds and angles were little changed, limiting passenger vehicle impact speeds and angles were not revised from NCHRP Report 350 recommendations.

Unfortunately, there is limited crash data available with which to quantify heavy truck crash severities. Heavy truck impact conditions recommended in NCHRP Report 350 were primarily based on Section 20 of AASHTO's *Standard Specifications for Highway Bridges* (5). However, the increased severity of the limiting TL-3 test now exceeds the severity of the limiting TL-4 test from NCHRP Report 350 by approximately 18 percent when measured in terms of Impact Severity, IS, which is defined as follows:

$$\text{IS} = \tfrac{1}{2} M \left(V \sin\theta \right)^2$$

Where:

IS	=	impact severity, kip-ft (kJ)
M	=	mass of impacting vehicle, kip-sec^2/ft (kg)
V	=	velocity of impacting vehicle, ft/sec (m/sec)
θ	=	impact angle (deg)

It is logical to expect that TL-4 barriers should be capable of withstanding higher impact severity levels than TL-3 barriers. Although there is insufficient data available to identify the full distribution of impact angles and speeds for heavy truck impacts on roadside barriers, the data that is available clearly indicates impact severities can be as high as or higher than what has been proposed for TL-4 and TL-5 in NCHRP Report 350 (129) (84). The TL-4 impact conditions incorporated into NCHRP Report 350 originated with Section 20 of AASHTO's *Standard Specifications for Highway Bridges* (5) and were selected as a replacement for several bus tests included in NCHRP Report 230 (92). These bus tests were replaced due to the inflammatory nature of some test videos showing surrogate bus occupants being ejected from the vehicle's windows, even though the vehicle was successfully contained and redirected. The four bus tests had IS values ranging from a low of 112 kip-ft (152 kJ) to a high of 323 kip-ft (438 kJ). Unfortunately, when the bus tests were replaced with single-unit trucks, the IS value for TL-4 was reduced to 98 kip-ft (132 kJ), well below even the least severe bus test included in NCHRP Report 230. These reduced impact conditions were originally selected because the single-unit truck was deemed to be less stable and would, therefore, place additional demand on barrier performance in order to prevent rollover. However, after the TL-4 impact conditions were selected and approved, the evaluation criteria for all heavy truck tests were revised to allow the impacting vehicle to roll over on the traffic side of the railing. In light of the increase in the severity of TL-3 testing and the history of the TL-4 impact conditions, this test was revised to significantly increase the impact severity so that there is some increase in capacity going from TL-3 to TL-4 barriers by raising the mass and impact speed for the TL-4 test to 22,046 lb (10,000 kg) and 55.9 mph (90 km/h), respectively.

Note that cable barriers have traditionally been tested without any cable splices in the impact region. However, cable splices must be used in long runs of cable barrier and to repair cables damaged during a crash. Hence, any splice that is expected to be used in the field must be incorporated into the critical impact region during crash testing.

A2.1.3 SAFETY FEATURE ORIENTATION

Impact angles listed in Chapter 2 are to be measured relative to the highway centerline. Most safety features are normally installed parallel to the highway centerline, and therefore, impact angles for these features can be measured relative to the system centerline. However, systems such as flared guardrail terminals and inertial crash cushion systems are normally installed at an angle relative to the highway centerline. For these features, effective impact angles will be different than the nominal angle reported in Section 2.2. Flared guardrail terminals are installed such that the effective impact angle will be increased relative to the values shown in Table 2-3 while inertial crash cushions are normally oriented toward the roadway in a manner that reduces the effective impact angle.

Note that guardrails and median barriers may occasionally be flared relative to the travelway such that the effective impact angle is increased. This document does not recommend that every barrier system be tested under the highest possible flare rate condition. However, decisions regarding appropriate barrier flare configurations must be based upon a careful evaluation of the consequences of increasing or decreasing the flare rate. Increasing a barrier flare rate is believed to increase the severity of barrier crashes. However, increasing flare rates also reduces the number of barrier collisions and total barrier costs by reducing the barrier length. Optimal barrier flare rates should be chosen based upon a cost-effectiveness analysis that provides the lowest total societal cost, including crash costs and barrier construction costs. Optimal flare rates chosen in this manner may produce barrier or terminal installations that cannot meet the full-scale crash testing requirements described herein under the conditions in which they are installed. The guidelines contained in Chapter 2 are intended to assure a minimum level of impact performance for barriers installed parallel to the travelway, not for every possible barrier flare configuration.

A2.2.1 LONGITUDINAL BARRIERS

Longitudinal barriers, including Test Levels 4 through 6, must be designed to safely accommodate passenger vehicles. In order to assure proper performance for passenger cars, it is necessary to conduct tests with both the 1100C and 2270P vehicles for all longitudinal barrier systems, including Test Levels 4 through 6.

Note that target IS values for Test Levels 1 through 4 have been increased significantly. The increased severity will produce higher barrier impact loadings. It is therefore recommended that barrier design loads presented in AASHTO's Standard Specifications for Highway Bridges (4) be adjusted upward to reflect the new impact conditions.

A transition between two longitudinal barriers with differing lateral stiffness, such as a rigid concrete bridge rail and a W-beam guardrail, can pose a difficult design problem. The most common method for constructing such a transition is to build an intermediate barrier section with stiffness somewhere between the approach guardrail and bridge rail. Testing has shown that vehicles impacting upstream of the intermediate stiffness section can pocket behind the stiffer barrier and either roll over or rupture the rail element (110). In this situation, it is important to conduct transition testing at both critical locations, i.e., the transition between the intermediate stiffness section and the bridge rail as well as the transition between the approach guardrail and the intermediate stiffness system. Note that small car testing has not indicated a significant problem for either impact location. Thus, when approach barriers have geometries very similar to previously tested systems, it may not be necessary to conduct small car tests at either impact location.

While it is preferable that the test vehicle remain upright after each test described herein, exceptions are made for all heavy vehicle tests. A one-quarter roll is permitted in the heavy vehicle tests because the primary goal in these tests is to demonstrate that the longitudinal barrier being evaluated can contain and redirect the vehicle. Further, analysis of truck accident data does not show the same strong link between vehicle rollover and injury and fatality that is found with passenger vehicle data. Note that even though overturn is permitted for all heavy vehicle tests, evaluation criterion D of Table 5-1B must be satisfied, i.e., the overturn must not result in deformations of the occupant compartment that could cause serious injuries.

In 2012, researchers at the Midwest Roadside Safety Facility (MwRSF) proposed an updated series of crash tests for evaluating cable median barriers placed in symmetric V-ditches (150). Using LS-DYNA simulations, critical bumper trajectories were plotted for five different vehicle models encroaching across both 4H:1V and 6H:1V V-ditches with widths varying from 24 to 46 ft. The maximum and minimum simulated bumper height trajectories were used to determine critical locations for barrier override or underride as well as an increased risk for vehicle instability, bar-

rier penetration, or excessive deformation of the occupant compartment. For this effort, simulated trajectories of MASH vehicles (1100C, 1500A, and 2270P) and NCHRP 350 vehicles (820C and 2000P) were included to obtain a more complete understanding of the risks associated with cable barrier impacts involving passenger vehicles.

Although the ability to validate the vehicle models was limited, the simulated vehicle behaviors were believed to be generally representative of vehicles traversing V-ditches. It should be noted that the simulation results were based on the assumption that the ditch surface was uniform and rigid. In real-world applications, varying soil conditions and surface irregularities could affect vehicle kinematics and alter vehicle trajectories.

TESTS 10 and 11

Historically, Tests 10 and 11 have primarily been used to evaluate the impact performance of longitudinal barriers (e.g., W-beam guardrails and cable barriers), installed on flat, level terrain. However, cable barrier systems are typically installed in median ditches. For these applications on slopes, the cable barrier systems are typically taller than those systems that were historically crash tested and evaluated on level terrain but subsequently installed on slopes as steep as 6H:1V. Higher longitudinal cable elements may pose an increased risk to the integrity of the vehicle's occupant compartment (e.g., A-pillar, windshield, and roof). As such, Tests 10 and 11 are designed to investigate the safety performance of cable barrier systems that are configured for ditch applications but may also include use on mostly flat, level terrain. Further, Tests 10 and 11 would also be used to evaluate cable barrier systems intended for shielding roadside slopes steeper than 3H:1V when installed in front of or at the slope break point.

TEST 13

Test 13 may also provide a critical test for evaluating a cable barrier's working width due to: (1) the likelihood for vehicle contact higher on the barrier system; (2) the potential for the top cable to more easily release from posts; (3) the propensity for fewer cables to be active in capturing the airborne vehicle; and (4) an increased impact energy due to the elevation change at barrier contact.

Previously, both 30-ft and 46-ft wide V-ditches were considered for Test 13. From one perspective, a 46-ft wide ditch was believed to provide greater propensity for override and/or vehicle instability if the vehicle were allowed greater vertical drop as well as increased pitch and roll motion prior to redirecting or reaching the bottom of the backslope. Another perspective was that a 30-ft wide ditch provided greater propensity for vehicular instability when wheel and/or bumper contact with the backslope occurred more quickly and abruptly during the redirection process. It is noted that the identification of the critical ditch width would require comparisons between numerous cable barrier crash tests in both ditch configurations. In the absence of this extensive testing data, and in an effort to simplify the test matrices, a 46-ft wide V-ditch was recommended for Test 13 in 4H:1V median sections, while a 30-ft wide V-ditch was recommended for Test 13 in 6H:1V median sections.

TEST 15

For depressed medians, the greatest risk of barrier underride occurs when an airborne vehicle contacts the back slope and fully compresses the vehicle's front suspension, resulting in the lowest front-end height above the ditch surface immediately prior to barrier contact. Previously, both the 1100C small car and 1500A mid-size sedan were considered critical for evaluating the propensity to underride cable barriers installed in depressed medians. The 1500A vehicle is heavier than the 1100C vehicle and achieved a lower minimum bumper height in the simulated vehicle encroachments. Thus, it was argued that a 1500A crash test may provide a higher risk for barrier underride. However, the low-profile, front-end geometry of the 1100C vehicles may also lead to vehicle underride. Additionally, the 1100C passenger car is typically characterized as having a weaker A-pillar compared to the 1500A mid-size passenger sedan. Further, the lighter 1100C vehicle may likely have increased concerns for excessive occupant ridedown accelerations and/or occupant impact velocities compared to the 1500A vehicle. Consequently, due to its low-profile, front-end geometry, weaker A-pillar structure, and lower mass, the 1100C small passenger car was selected as the design vehicle for Test 15 to evaluate barrier underride within the ditch.

For cable barriers installed 0 to 4 ft away from the SBP of a 4H:1V V-ditch, simulation results for a narrow, 24-ft wide ditch indicated that the location with the maximum potential for underride with an 1100C vehicle occurred approximately 6 ft away from the back SBP. Hence, the critical underride test condition would likely correspond with barrier placement approximately 4 ft away from the back SBP of a slightly narrower, 22-ft wide ditch. When deemed necessary and for barrier placement 0 to 4 ft away from the SBP, Test 15 could be conducted in a 4H:1V V-ditch with a barrier placed: (1) 4 ft away from the back SBP of a 22-ft wide V-ditch; (2) 6 ft away from the back SBP of a 24-ft wide V-ditch; or (3) conservatively 4 ft away from the ditch bottom and up the back slope of 46-ft wide ditch. In order to simplify the test matrices, a 46-ft wide V-ditch was recommended for Test 15 when evaluating cable barrier placed in 4H:1V median sections.

For cable barriers installed 0 to 4 ft away from the SBP of a 6H:1V V-ditch, simulation results for a narrow, 24-ft wide ditch indicated that the location with the maximum potential for underride with a 1100C vehicle occurred approximately 8 ft away from the back SBP. Hence, the critical underride test condition would likely correspond with barrier placement approximately 4 ft away from the back SBP of a narrower, 20-ft wide ditch. When deemed necessary and for barrier placement 0 to 4 ft away from the SBP, Test 15 could be conducted in a 6H:1V V-ditch with a barrier placed: (1) 4 ft away from the back SBP of a 20-ft wide V-ditch; (2) 8 ft away from the back SBP of a 24-ft wide V-ditch; or (3) conservatively 4 ft away from the ditch bottom and up the back slope of 30-ft wide ditch. In order to simplify the test matrices, a 30-ft wide V-ditch was recommended for Test 15 when evaluating cable barriers placed in 6H:1V median sections.

TEST 16

Prior crash testing has demonstrated that two critical conditions can arise when a small passenger car lands in the ditch bottom and traverses up the back slope prior to barrier contact. After vehicle contact with the slope, the front tires may potentially steer up the back slope and increase the heading angle and/or induce a yaw velocity counter to the desired redirection. This phenomenon, which has been observed in previous 820C crash testing under NCHRP Report No. 350, can result in an increased impact severity and greater propensity for occupant compartment deformation and vehicular instability.

Alternatively, small passenger vehicles may encounter significant rebound and become airborne after landing on the ditch back slope prior to contact with the barrier system, thus resulting in greater propensity for barrier override and vehicular instability. Barrier override may occur after the airborne vehicle contacts the ditch surface and rebounds up the back slope, once again becoming airborne. Results from a full-scale crash test demonstrated that an 1100C small passenger vehicle can rebound off of the back slope and launch into a cable barrier that is placed 4 ft away from the back SBP of a 30-ft wide 4H:1V V ditch (157). In this test, the vehicle was captured by the top cable positioned at a height of 45 in. above grade. From the simulation effort (150), the 1100C bumper trajectory was lower than observed in the noted crash test (157). However, the simulation results indicated that the greatest rebound off the back slope for the 1100C vehicle occurred in a 30-ft wide 4H:1V V-ditch. Conversely, the simulations indicated that the greatest rebound off of the back slope for the 1100C vehicle occurred in a 46-ft wide 6H:1V V-ditch.

In order to simplify the test matrices and consider all critical behaviors, a 46-ft wide V-ditch was recommended for Test 16 in 4H:1V median sections, while a 30-ft wide V-ditch was recommended for Test 16 in 6H:1V median sections.

TEST 17

For Test 17, a 1500A mid-size sedan was selected instead of an 1100C small car due to its larger inertia combined with a relatively-narrow front profile. Additionally, a recent cable barrier accident study had shown that mid-size sedans were the most common vehicles involved in cable barrier penetrations (158, 159).

As cable barrier systems are configured for use in depressed medians, a greater number of cables may be necessary for containing and redirecting the range of passenger vehicles. Compared to configurations designed for use on flat, level ground, cable barriers designed for use in median ditches typically require cable elements placed higher than normal on support posts to prevent override, and lower than normal on posts to prevent underride. As the top and bottom cables are raised and lowered to mitigate concerns for override and underride, respectively, the vertical spacing between cables will increase if the number of cables is held constant. An increased vertical spacing between cables may increase the propensity for vehicle penetration between the cables. Thus, it is necessary to evaluate the risk for vehicle penetration between vertically adjacent cables. For this test, the critical impact point is midspan between adjacent posts rather than 12 in. upstream from a barrier post.

The risk for vehicle penetration is dependent on the specific design details of a particular cable barrier system, including the position of adjacent cables relative to the front bumper of the 1500A vehicle, vertical cable position and width of the largest vertical opening between adjacent cables, cable-to-post attachment release mechanisms, and the vehicle's projectile motion beyond the slope break point. The testing agency should identify the critical barrier placement that maximizes the propensity for the vehicle's front end to penetrate between adjacent cables. Depending on the barrier configuration, a cable barrier installed on level terrain but at the front SBP may provide a critical test condition for evaluating the risk of penetration. However, if the largest vertical cable gap occurs higher on the posts or a cable is aligned closer to the center of the bumper, it may be

necessary to laterally shift the barrier down the foreslope to obtain the critical impact condition. A vehicle's projectile motion for a critical bumper point beyond the front SBP may aid in selecting a lateral barrier offset that results in a critical impact height.

Similar to Tests 10 and 11, Test 17 would also be used to evaluate cable barrier systems intended for shielding roadside slopes steeper than 3H:1V when installed in front of or at the slope break point.

TEST 18

As previously noted, two critical vehicle behaviors were found to occur as small passenger vehicles contact the ditch surface and traverse up the back slope prior to barrier contact. Likewise, it is reasonable to expect similar behaviors for other vehicle types, such as pickup trucks and mid-size passenger sedans. Computer simulations and limited crash testing involving pickup trucks impacting median ditches revealed similar tendencies to rebound and become airborne after landing on the back slope prior to contact with the cable barrier, thus resulting in greater propensity for barrier override and vehicular instability (150, 151, 156, 160). Simulated bumper trajectories demonstrated that a 2270P vehicle would reach greater heights above the ditch surface than an 1100C vehicle after rebounding off of the back slope. The difference in the maximum height of the 2270P bumper trajectories for 30-ft, 38-ft, and 46-ft wide 4H:1V V-ditches was negligible. However, these simulations indicated that the greatest rebound of the 2270P vehicle off of the back slope occurred in a 46-ft wide 4H:1V V-ditch and at a location 8 ft away from the back SBP. For a 30-ft wide 4H:1V V-ditch, the greatest rebound off of the back slope for a 2270P vehicle occurred approximately at the back SBP. For 6H:1V V-ditches, the maximum bumper height was very close for both 30 and 46 ft wide sections, although the greatest rebound off of the back slope for a 2270P vehicle occurred in a 46-ft wide section and 6 ft away from the back SBP. For a 30-ft wide 6H:1V V-ditch, the greatest rebound of the 2270P vehicle off of the back slope occurred approximately at the back SBP.

Light trucks and SUVs may also acquire an increased heading angle due to interaction with the back slope prior to contact with the barrier, thus leading to a greater propensity for vehicular instability or cables passing over the engine hood and contacting the windshield. In order to simplify the test matrices and consider all critical behaviors, a 46-ft wide V-ditch was recommended for test 18 in 4H:1V median sections, while a 30-ft wide V-ditch was recommended for Test 18 in 6H:1V median sections.

A2.2.2 TERMINALS AND CRASH CUSHIONS

Longitudinal barriers have traditionally been designed to accommodate impacts at angles up to 25 degrees and impact angles are believed to increase with the lateral offset distance from the travelway. Terminals are placed on the ends of longitudinal barriers where lateral offsets are often greater than the main section of the barrier. Crash cushions are often used as terminals for rigid barriers and are often placed long distances from the travelway. Further, prior to the publication of NCHRP Report 350 (129), barrier terminals, impacted downstream of the beginning of length-of-need, were also required to contain vehicles impacting at angles up to 25 degrees. NCHRP Report 350 reduced this impact angle to 20 degrees and created an inconsistency whereby a longitudinal barrier was designed to contain impacts of