American Association of State Highway and Transportation Official| | 119

# Commentary A

urther 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.”

F

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 diffi culties in controlling critical test conditions such as speed, angle, and condition of test vehicle and the some- times 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 ac- ceptable 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 fl at grade is recommended, even though installations are sometimes situated on sloped shoulders and behind curbs. These normalized factors have signifi cant effect on the performance of many safety features and may obscure serious safety defi ciencies 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 specifi c site conditions such as a unique soil or road- side 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 construc- tion zones or other temporary locations, and their duration of use is normally relatively small. An

120 | Manual for Assessing Safety Hardware

important additional characteristic of a work zone is the exposure of construction personnel to er- rant traffi c. Thus, a barrier in a work zone may be required to (1) redirect errant traffi c away from a roadside hazard or other traffi c and (2) shield workers from errant vehicles. Depending on specifi c 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 fi rst introduced for bridge railings in NCHRP Report 239 (20). NCHRP Report 230 (83) 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 lon- gitudinal barriers. Section 20 of AASHTO’s *Standard Specifi cations for Highway Bridges* (4) 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 (119), 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 classifi cations, traffi c conditions, traffi c 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 fi rst establish conditions or warrants for which features having given capabilities would be cost-effective and thereby defi ne appropriate test levels. Instead, it is necessary to fi rst 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 fea- tures 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 offi cials to de- sign 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 oc- cur 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 ac- ceptably 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 defi ned 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 condi-

Appendix A—Commentary | 121

tions that can be practically accommodated. This defi nition of the worst practical impact condition was originally implemented for large passenger vehicles with the fi rst set of evaluation guidelines presented in *Highway Research Board Circular 482* (141). The precedent established with the fi rst set of guidelines for full-scale crash testing has been extended through *Transportation Research Circular 191* (142), and NCHRP Reports 230 (83) and 350 (119).

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 avail- able crash data shows that impact angles for small cars are at least as high as those associated with large passenger vehicles and SUVs. Further, crash investigations appear to indicate that higher impact angles signifi cantly increase crash severities for all sizes of passenger vehicles. Therefore, the recommended impact angle for tests involving small car redirection has been raised to match that previously incorporated for the light truck test vehicle.

A2.1.1 IMPACT CONDITIONS

A number of studies involving detailed crash investigations have been conducted over the last four decades (75, 81, 86, 87, 93). Data from “Critical Impact Point for Longitudinal Barriers” (115) was the primary basis for the selection of impact conditions incorporated in NCHRP Report 350 (119). 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 upon increased speed limits, it was widely anticipated that crash speeds would increase signifi - cantly 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 (87). In retrospect, this fi nding should have been anticipated because the 85th percentile impact speed and angle were not found to be signifi cantly lower during the national speed limit law (81) than prior to the law’s implementation (75, 93). Based upon these fi ndings 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 severi- ties. Heavy truck impact conditions recommended in NCHRP Report 350 were primarily based on Section 20 of AASHTO’s *Standard Specifi cations for Highway Bridges* (4). 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 defi ned as follows:

IS = 1 2

*M* (*V* sin θ)2

Where:

IS = impact severity, kip-ft (kJ)

*M* = mass of impacting vehicle, kip-sec2/ft (kg) *V* = velocity of impacting vehicle, ft/sec (m/sec) θ = impact angle (deg)

122 | Manual for Assessing Safety Hardware

It is logical to expect that TL-4 barriers should be capable of withstanding higher impact severity lev- els than TL-3 barriers. Although there is insuffi cient data available to identify the full distribution of impact angles and speeds for heavy truck impacts on roadside barriers, the data that is available clear- ly 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 (119) (80). The TL-4 impact conditions incorporated into NCHRP Report 350 originated with Section 20 of AASHTO’s *Standard Specifi cations for Highway Bridges* (4) and was selected as a replacement for several bus tests included in NCHRP Report 230 (83). These bus tests were replaced due to the infl ammatory nature of some test videos showing surrogate bus occu- pants 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 per- formance 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 traffi c 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 signifi cantly increase the impact se- verity 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 fi eld must be incorporated into the critical impact region during crash testing.

A2.1.2 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 fl ared 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 nor- mally oriented toward the roadway in a manner that reduces the effective impact angle.

Note that guardrails and median barriers may occasionally be fl ared 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 fl are rate condition. However, decisions regarding appropriate barrier fl are confi gurations must be based upon a careful evaluation of the consequences of increasing or decreasing the fl are rate. Increasing a barrier fl are rate is believed to increase the severity of barrier crashes. However, increasing fl are rates also reduces the number of barrier collisions and total barrier costs by reducing the barrier length. Optimal barrier fl are rates should be chosen based upon a cost- effectiveness analysis that provides the lowest total societal cost, including crash costs and barrier

Appendix A—Commentary | 123

construction costs. Optimal fl are rates chosen in this manner may produce barrier or terminal installa- tions 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 bar- rier fl are confi guration.

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 con- duct 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 Specifi cations for Highway Bridges* (4) be adjusted upward to refl ect 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 diffi cult 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. Recent 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 (100). 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 signifi cant problem for either impact location. Thus, when ap- proach 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 con- tain and redirect the vehicle. Further, analysis of truck crash 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 5-1 must be satisfi ed, 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, barrier 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 prior 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

124 | Manual for Assessing Safety Hardware

350 (119), 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 up to 25 degrees everywhere except at the beginning of length-of-need. In order to eliminate this inconsistency, impact angles for Tests 36 and 37 were increased to 25 degrees.

In recognition that terminals and redirective crash cushions perform the same function and for rigid barriers the terms have become interchangeable, these devices are subjected to the same set of full-scale crash tests. Non-redirective crash cushions are not designed to perform as a longitudinal barrier when struck downstream from the nose of the system and therefore are subjected to a reduced set of tests. Note that NCHRP Report 350 also identifi ed different test conditions for “gating” and “non-gating” ter- minals and crash cushions. Although the defi nition of “gating” and “non-gating” has been retained from the prior publication, the two types of systems are now subjected to the same set of full-scale crash tests, Tests 30 through 38. In order for a terminal or crash cushion to be classifi ed as non-gating, it must capture the impacting vehicle during Tests 32 and 33. Note that the impact angle is given as ranging from 5 to 15 degrees for these tests. Each device must be tested at the impact angle that will maximize the risk of test failure. Devices expected to qualify under the gating category should be tested near the lower end of this range and devices designed to function as non-gating should be tested near the upper end of the range. Note that if a non-gating device fails to capture the impacting vehicle during Tests

32 or 33, it must be retested at the lower impact angle in order to qualify as a gating system. Similarly, systems that capture impacting vehicles when tested near the lower end of this range must be retested at the higher impact angle before qualifying as a non-gating design.

Tests 38 and 45 have been added to ensure that staged attenuation systems perform adequately for all sizes of passenger vehicles. Note that the purpose of this test is to identify occupant ridedown accel- erations for mid-sized vehicles. Since this behavior is primarily related to the mass of the impacting vehicle and the critical vehicle weight may vary from system to system, the acceptable mass range was increased to ±220 lb (100 kg). Further, removal of up to 441 lb (200 kg) of test vehicle compo- nents to reduce mass and the addition of up to 441 lb (200 kg) of ballast to meet the mass guidelines is acceptable. This test can be waived if the analysis shown in Appendix G indicates that Test 38 or 45 will meet occupant risk criteria.

Note that the recommended test matrices cannot and should not be expected to be an all-inclusive set of standardized procedures. When appropriate, testing agencies and/or user agencies should devise other critical test conditions consistent with the range of expected fi eld impact conditions.

A2.2.3 TRUCK-MOUNTED ATTENUATORS (TMA)

There are three basic areas of concern in an impact with a TMA: (1) risks to occupants of the impacting vehicle, (2) risks to workers if the support truck is pushed or rolls forward into the construction zone, and (3) risks to occupants of the support truck to which the attenuator is attached. All other factors being equal, risks to the occupants of the impacting vehicle generally increase as the mass or the degree of braking of the support truck increases. However, risks to workers shielded by the support truck generally increase as the mass or the degree of braking decreases because of increased roll-ahead distances.

Appendix A—Commentary | 125

It is important to assess both the risk to occupants of impacting vehicles when a TMA is mounted to a heavy truck and the anticipated roll-ahead distance when mounted to a light truck. Therefore, Tests 50, 51, and 52 are to be conducted with the maximum allowable support truck weight while Test 53 is to be conducted with the minimum allowable support truck weight. Support truck roll-ahead distances should be carefully documented for all four tests. It is noted that roll-ahead distances can be accurate- ly estimated from the “conservation of momentum” principle of mechanics based upon an estimate

of the frictional resistance of the support truck to forward movement (67). Results of recommended full-scale crash tests can be used to assess effective friction values. Using these techniques, testing agencies should evaluate expected roll-ahead distances over the entire range of support truck weights ranging from the minimum to the maximum.

Risks to the support truck occupants increase as the truck weight is reduced. However, as long as the support truck weighs signifi cantly more than the impacting vehicle, truck accelerations will be sig- nificantly less than those measured on the test vehicle. For example, if the support truck weighs 20 percent more than a 2270P test vehicle and the attenuator mass is 992 lb (450 kg), the support truck would experience approximately 30 percent lower accelerations than the impacting 2270P test vehicle. Further, during an impact, the support truck is accelerated forward, pushing its occupants backward into their seat. Rearward occupant movement is generally less dangerous than forward movement, primarily because the body is well supported by the seat and head-rest system. Therefore, provided the support truck weighs signifi cantly more than the impacting vehicle and proper head rests and seat- belt systems are utilized, the risks to support truck drivers should be signifi cantly less than risks to the occupants of the impacting vehicle.

Test 54 is implemented to assess if TMAs with staged energy absorption would perform satisfactorily during impacts with mid-sized vehicles. Clearly all TMAs should be designed to accommodate the full range of passenger vehicles, including mid-sized cars. However, there is concern that the stag- ing of some TMAs may be too fi nely tuned to accommodate only the small passenger car and the heavy pickup truck that they may not perform satisfactorily for a mid-sized vehicle, particularly the ridedown acceleration. On the other hand, there is also concern over the possibility that many exist- ing TMAs might fail this test. This would require re-design of these TMAs that may lead to increased costs and operational and durability problems. Thus, this test is considered optional. Manufacturers and users are strongly encouraged to develop and implement TMA designs that can be both operation- ally effi cient and exhibit proper impact performance during mid-sized vehicle testing.

Tests 50 and 51 are recommended for use in evaluating the impact performance of variable message signs and arrow boards. These same tests are also recommended for evaluating the safety risks associ- ated with any other large work-zone devices that begin to be recognized as a potential safety hazard.

A2.2.4 SUPPORT STRUCTURES, WORK-ZONE TRAFFIC CONTROL DEVICES, BREAKAWAY UTILITY POLES, AND LONGITUDINAL CHANNELIZERS

Impact performance evaluation criteria for breakaway devices are based upon the “state-of-the-

practical” rather than the threshold at which the risk of serious injury or fatality reaches a critical level or begins to increase rapidly. Breakaway devices have been shown to provide very low velocity

126 | Manual for Assessing Safety Hardware

changes, even for impacts with large luminaire and sign supports. Hence, velocity change limits for breakaway supports have been set at very low levels.

The energy or force required to fracture a breakaway device or support structure, in general, may be sensitive to its orientation with respect to direction of impact or the impact angle. For example, tests have indicated a breakaway transformer base breaks more readily when struck on a corner than on a fl at side. Because errant vehicles may approach a support structure, work-zone traffi c control device,

or a breakaway utility pole at various angles, it is recommended that the device be tested assuming the most severe direction of vehicle approach consistent with expected traffi c conditions or at the critical impact angle (CIA) discussed in Section 2.2.4. For instance, the transformer base should be oriented so the vehicle strikes a flat side. Moreover, because the energy required to fracture a device can be increased due to buckling of the support at the point of contact with the vehicle, the handhole in the luminaire shaft should be positioned during a test so that the probability of local collapse of the shaft is maximized.

Energy-absorbing, yielding support structures have been developed as potential replacements for con- ventional breakaway systems. These devices are designed to decelerate the vehicle to a controlled and safe stop, similar to a crash cushion, rather than permitting the vehicle to break through and continue with minimal reduction in speed. Rigid, non-breakaway supports are often used in urban areas where encroachment of the vehicle beyond the pole could endanger pedestrians or other innocent bystand- ers. While this practice may offer protection for the innocent bystander, it also increases risks to errant motorists. The yielding pole may have application in these areas, and/or areas where trees or other hazards exist just beyond the pole line that could endanger occupants of the encroaching vehicle. However, since such a design would not pass occupant risk criteria recommended for breakaway support structures, it should be evaluated according to criteria recommended for a crash cushion. Although recommendation on the use of such features is beyond the purview of this document, the appropriate applications for this type of device should be identifi ed based upon a benefi t/cost analysis of the various alternatives.

Work-zone traffi c control devices are subjected to similar testing as structural supports. However, due to their light mass, most of these systems will meet all vehicle velocity change criteria. In these cases, the primary concerns are related to windshield damage and the potential for structural components

to intrude into the occupant compartment. In fact, instrumentation of test vehicles is not required for testing of work-zone devices, provided the system is free-standing and its total weight is less than 220 lb (100 kg). Note that many testing agencies impact two work-zone traffi c control devices in a single run. The devices are placed to impact opposite quarter points of the front of the vehicle. Device spacing is selected such that the fi rst device is usually completely disengaged from the test vehicle before it strikes the second device. In some cases, the fi rst device does not disengage or it produces suffi cient damage that it is impossible to determine the extent of windshield damage for the second device. In these situations, the second device should be retested.

Breakaway utility poles are tested and evaluated somewhat differently from other breakaway support structures. A higher occupant impact velocity is permitted in a utility pole test because the substantial mass of a typical utility pole produces a much higher velocity change than allowed for a conventional

Appendix A—Commentary | 127

breakaway device. Since a higher occupant impact velocity is permitted, the impact speed for the “low speed” test was set at 31 mph (50 km/h), or 47 ft/s (13.9 m/s). Note that for an impact speed of 19 mph (30.0 km/h) or 27 ft/sec (8.3 m/s), as used for other breakaway support structures, the vehicle could come to an abrupt stop and still pass the 39 ft/s (12.0 m/s) maximum occupant impact veloc- ity criterion. Recommended tests and assessment criteria notwithstanding, it should be a goal of the designer to develop breakaway utility pole systems that minimize vehicular velocity change and, when possible, limiting occupant impact velocities should equal those for other support structures. Replacement of solid timber poles with lighter structures, if feasible, could reduce or eliminate prob- lems associated with the relatively large mass of timber poles. Utility poles could then be expected to meet the same safety standards as other support structures.

Other objects that are placed near high-speed roadways, such as fi re hydrants, electrical transformers, etc., should be subjected to the same crash test matrix as a breakaway support structure. Most of these elements can be made to meet the criteria associated with breakaway supports. If a device is incapable of meeting these criteria simply due to its mass, evaluation criteria presented for breakaway utility poles should be utilized.

Longitudinal channelizers do not function as a longitudinal barrier, and testing agencies should clear- ly state this fact in all test reports. Because these systems are designed to allow an impacting vehicle to penetrate through the line of elements, the critical impact angle appropriate for each system is dif- fi cult to determine. It is anticipated that most longitudinal channelizers will function as a barrier when struck at extremely low approach angles. Further, these systems are expected to allow rapid gating during high-angle impacts. The impact angle most prone to cause a vehicle to roll over is generally believed to be somewhere in between, where the risk of a vehicle contacting and possibly overriding

the end of one of the system’s segments is maximized. Another potential failure mode for longitudinal channelizers involves an impacting vehicle rotating as it penetrates into the system and the side of

the vehicle contacting the end of one of the segments. In this situation, occupant compartment defor- mation can become excessive. Designers and testing agencies must attempt to identify the expected system behavior and the appropriate critical impact angle to maximize the risk of undesirable perfor- mance through computer simulation or evaluation of tests of similar systems.

### A2.3 IMPACT POINT FOR REDIRECTIVE DEVICES

Longitudinal barriers generally fail due to structural inadequacies that allow snagging or pocketing on stiff points in the barrier systems or rupture of one of the “weak points” in the barrier system, such as at a splice. Thus, most barrier systems have one or more critical locations where failure is likely to take place, whether through wheel snag or rupture of a barrier element. The potential for every failure is affected to some extent by the selected impact point.

NCHRP Report 350 (119) produced procedures for identifying these critical impact points on any type of longitudinal barrier. These procedures have been updated for the new test vehicles recom- mended herein and are presented in Chapter 2. Nevertheless, as recommended previously under NCHRP Report 350, Barrier VII or another simulation program should be used, whenever possible,

128 | Manual for Assessing Safety Hardware

to identify CIPs for longitudinal barrier tests. Techniques for utilizing simulation programs to identify critical impact points are summarized in References 78 and 110.

For flexible cable barriers intended for use in median ditches, four out of the eight full-scale crash tests in the test matrices utilize an 1100C small car passenger vehicle. In general, narrow post spacing is generally deemed more critical for small car tests than a wide post spacing. First, there is greater risk for excessive occupant compartment deformation to the roof, windshield, and A-pillar due to increased cable loading imparted to the vehicle. Second, there is an increased risk for vehicular instability due to contact with a greater number of support posts. Thus, the narrowest post spacing was selected for use in Tests 10, 14, and 16. If underride is a primary concern, then the widest post spacing would provide the greatest risk for small car passenger vehicles to penetrate under the bottom cable and push it upward. Thus, the widest post spacing was selected for use in Test 3-15.

Only one mid-size vehicle (1500A) is included in the test matrices for evaluating flexible cable barriers installed in median ditches. Test 17 is intended to investigate the potential for a heavier, sharp-nosed, passenger vehicle to penetrate between adjacent vertically-spaced cables as well as to evalaute the propensity for excessive occupant compartment damage. The widest post spacing was deemed most critical due to an increased propensity for adjacent cables to separate and allow vehicle penetration.

Finally, three out of the eight full-scale crash tests in the test matrices for evaluating flexible cable barriers installed in median ditches utilize a 2270P light-truck passenger vehicle. When a range of post spacing is desired, Test 11 is conducted on level terrain at both the widest and narrowest post spacings in order to define the system’s working width at the two limits of lateral barrier stiffness. For Test 13 on the front slope and Test 18 on the back slope, arguments can be made that both a narrow spacing or wide spacing could be more critical for evaluating the potential for vehicle override. The narrowest post spacing provides an increased propensity for vehicle instability due to vehicle interaction with additional support posts and/or higher lateral cable resistance imparted to the side of the vehicle that could result in tripping. On the other hand, the widest post spacing may provide increased opportunity for vehicle override due to the fact that the top cables could be more easily pushed down. Thus, the remaining two 2270P tests were used to evaluate override at both the widest and narrowest post spacing. Test 13 utilizes the narrowest post spacing as the vehicle would be airborne above the front slope when contacting the upper region of the cable barrier, thus creating a critical condition for evaluating stability, rollover, and override. For light-truck vehicles traversing up the back slope, a more severe impact condition may be achieved as a result of the vehicles interaction with the back slope prior to contacting the cable barrier, thus increasing concerns for override or penetration. Thus, Test 18 was selected to utilize the widest post spacing.

In general, most flexible, cable median barriers may be impacted on either side of the system. Consequently, guidance has been provided for evaluating cable median barriers in an orientation that places its primary capture cable in the most critical position for each test. Using this methodology, a cable median barrier system could be installed in the field at either 0 degrees or 180 degrees, either at 0 to 4 ft offset from the SBP or anywhere within the median ditch. However, it is possible that some cable median barriers may be prescribed to be installed using only one orientation (i.e., 0 degrees but not 180 degrees or vice versa) within 0 to 4 ft offset from the SBP. Under those circumstances, there may be justification for evaluating a cable median barrier with a vehicular impact only on the front side for Tests 13, 14, and 17 and only on the back side for Tests 15, 16, and 18. For Tests 10 and 11, the cable median system is evaluated on level terrain and may be struck on either side of the system. Thus, these tests should always be performed with the primary capture cable placed in its most critical position (i.e., back side of critical post).

###### A2.3.2.1 Tests with 1100C and 2270P Vehicles

The small mass and low crush stiffness of passenger vehicles increases the likelihood and severity of wheel snag or pocketing on stiff elements of longitudinal barriers. Therefore, testing of longitudinal barriers with the 1100C and 2270P vehicles must be planned to examine the potential for wheel snag- ging and pocketing as well as structural failure of the barrier elements. Wheel snagging and vehicular pocketing are the two barrier failure modes that exhibit the greatest sensitivity to impact point selection. When an impact point is too close to a post or other stiff point in a barrier system, the vehicle will not penetrate into the barrier prior to reaching the snag point. Conversely, when the selected impact point is too far from a snag point, the vehicle will redirect and begin to exit the barrier prior to snagging.

Connection loading is another important test parameter that is affected by impact location. Fortunately, impact locations that maximize wheel snagging or pocketing at one point in the barrier will also maximize connection loads near that same point in the barrier. Therefore, whenever rail splices or other critical connections fall at or near (within 5 ft (1.5 m)) a snag point such as a barrier post, the impact location can be chosen to maximize both the potential for snagging and connection loadings. Since barrier loadings are generally higher upstream of the snag point, critical connec- tions should be placed at or just upstream of the snag point, provided the connection locations are consistent with in-service locations. Rail tensile loads are maximized all along the length of the fi rst span upstream from the snag point. Thus, the potential for rail splice tensile failure can generally be

maximized by choosing the CIP for snagging if the connection is placed at the snag point or anywhere within the fi rst span upstream from the snag point.

However, when a barrier connection is not located within approximately 5 ft (1.5 m) of a snag point, bending moment and shear in the connection will not be maximized by an impact location chosen to maximize snagging. When barrier connections are not within 5 ft (1.5 m) of a snag point and when wheel snagging or pocketing as well as connection loading in bending and/or shear are signifi cant con- cerns, the designer may consider conducting two tests with different impact locations. Barrier VII or a similar simulation program is recommended to investigate the need for two tests and to select CIPs.

It has been found that the CIP with regard to snagging is sensitive primarily to dynamic yield force of barrier posts, plastic moment of rail elements, and post spacing (127). Post yield forces and spacing were then combined into a single parameter, F*p*, by dividing the dynamic post yield forces by the post spacing. CIP selection curves were then developed as a function of plastic moment of rail elements, *Mp*, and post yield force per unit length of barrier, *Fp*. Reference 78 contains a more detailed descrip- tion of the development of CIP selection curves shown in Figures 2-6 through 2-17.

The plastic moment of a barrier rail element is merely the product of the beam’s plastic section modu- lus and the material yield stress. Procedures for calculating plastic section modulus are presented in many textbooks on plastic design of steel structures (124). The plastic section modulus can be estimat- ed with a reasonable degree of accuracy by multiplying the elastic section modulus by a form factor. Form factors for common beam shapes vary from a low of about 1.1 to a maximum of 2.0. As the

Appendix A—Commentary | 129

fraction of a beam’s cross section located near the neutral surface increases, the form factor of the cross section increases. Wide fl ange beams have very little material near the neutral surface and, as a result, generally have form factors less than 1.18 with an average near 1.14. Form factors for square box beams range from a low of 1.13 for a very thin-walled tube to a high of 1.5 for a solid rectangular rod. Form factors and plastic moments for some common barrier rail elements are shown in Table A-1.

TABLE A-1. Properties of Common Barrier Rail Elements

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Raila** | **Elastic Sec- tion Modu- lus, in.3 (cm3)** | **Form Factor** | **Plastic Sec- tion Modulus, in.3 (cm3)** | **Yield Strength, ksi (MPa)** | **Plastic Mo- ment, kip\*ft (kN\*m)** |
| 12-gauge W-beam | 1.37 (22.45) | 1.41 | 1.93 (35.63) | 50 (345) | 8.0 (10.9) |
| 10-gauge W-beam | 1.76 (28.84) | 1.41 | 2.48 (40.64) | 50 (345) | 10.3 (14.0) |
| 12-gauge Thrie-Beam | 2.19 (35.89) | 1.4 | 3.07 (50.31) | 50 (345) | 12.8 (17.3) |
| 10-gauge Thrie-Beam | 2.80 (45.88) | 1.4 | 3.92 (64.24) | 50 (345) | 16.3 (22.1) |
| TS 6 by 6 by 3/16Box Beam | 7.93 (129.9) | 1.17 | 9.24 (151.4) | 46 (317) | 35.4 (48.0) |
| TS 6 by 6 by 3/8Box Beam | 13.90 (227.8) | 1.21 | 16.80 (275.3) | 46 (317) | 64.4 (87.3) |
| TS 8 by 6 by 1/4Box Beam | 15.00 (245.8) | 1.2 | 18.00 (295.0) | 46 (317) | 69.0 (93.5) |

a Rail sizes are in English units.

Barriers with multiple rail elements complicate the selection of an appropriate plastic moment for the barrier. When this type of barrier defl ects during an impact, the upper rail defl ection is much higher than that of lower rail elements. A simple energy analysis indicates that the total energy absorbed by each rail element is roughly proportional to the mounting height of the element. Equation 2-4 was then developed to estimate an equivalent plastic moment for multiple rail systems. A limited sensitivity study using Barrier VII revealed that the CIP determined by use of Equation 2-4 accurately estimates the CIP for most multiple rail barrier systems. This study indicated that the procedure was somewhat less accurate for barriers that have relatively stiff rail elements well above the impacting vehicle. For this situation, barrier posts will yield above the impacting vehicle and the upper rails will not defl ect as much as the lower rails. Although the CIP selection procedures do give reasonable estimates of critical

impact locations for most of these barriers, a simulation program should be used when possible to verify the fi ndings.

Prior to determining *Fp*, it is necessary to determine the dynamic yield force of the post. The post yield force will be governed by the smaller of two values—that necessary to yield the post itself assuming it is rigidly anchored at its base, or that necessary to yield the soil in which the post is embedded.

130 | Manual for Assessing Safety Hardware

When barrier posts are rigidly anchored, yield forces are controlled by the material properties of the post. A dynamic magnifi cation factor is normally applied to the plastic section modulus of metal posts to estimate the dynamic yield force for a post as given in Eq. A3-1.

⎛ σ*y Z p* ⎞

*Fy* = *D* ⎜ ⎟

(Eq. A3-1)

⎝ *Hr* ⎠

Where:

*Fy* = dynamic post yield force for a rigid anchor;

*D* = dynamic magnifi cation factor;

σ*y* = post yield stress;

*Zp* = post plastic section modulus; and

*Hr* = height of highest rail above base of post.

The accuracy of Eq. A3-1 can be demonstrated by comparing a measured value of *Fy* for a rigidly anchored W6 by 9 (W152 by 13.4) steel post with the calculated value. A dynamic magnifi cation fac- tor of 1.5 is typically used for steel posts and a W6 by 9 (W152 by 13.4) beam has a plastic section modulus of 6.3 in.3 (103 cm3) and a yield stress of 36 ksi (248 MPa). For a 1.7-ft (0.53-m) mounting height, Eq. A3-1 gives an *Fy* of 16.2 kip-force (71.9 kN) compared to a measured value of 16.8 kip- force (74.7 kN) from *Development of a Cost-Effectivness Model for Guardrail Selection* (27).

Wood materials exhibit a brittle failure mechanism, and therefore, the plastic section modulus in

Eq. A3-1 is replaced by the modulus of rupture. Reference 27 reported that pendulum tests of 6- by 8-in. (15.2- by 20.3-cm) Douglas Fir posts have an average failure force of 16.2 kip-force (72.1 kN) when mounted in a rigid support. Southern Douglas Fir has an average modulus of rupture of 6800 psi (46.8 MPa) (80). Using a dynamic magnifi cation factor of 1.0, Eq. A3-1 predicts failure forces of

20.7 kip-force (91.9 kN) and 16.6 kip-force (74.0 kN) for rough cut and fi nished posts with a nominal 6- by 8-in. (15.2- by 20.3-cm) size. Although it is unclear whether posts used in the pendulum tests were rough cut or fi nished size, the test results do indicate that the dynamic magnifi cation factor from Eq. A3-1 should be no more than 1.0 for wood materials. Table A-2 shows the modulus of rupture for some common wood post materials.

TABLE A-2. Wood Post Properties

|  |  |  |
| --- | --- | --- |
| **Wood** | **Modulus of Rupture, psi (MPa)** | **Shear Strength, psi (MPa)** |
| Douglas Fir | 6800 (46.8) | 960 (6.6) |
| Southern Yellow Pine | 7300 (50.4) | 860 (5.9) |
| Redwood | 5900 (40.8) | 900 (6.2) |

Dynamic yield forces for posts embedded in soil are generally more diffi cult to estimate. Soil yield forces are usually measured through pendulum or instrumented cart testing at speeds near 20 mph

Appendix A—Commentary | 131

(32 km/h). A number of guardrail posts have been tested for various soil embedment conditions (22, 27, 40, 42, 137, 138). Dynamic yield forces for common guardrail posts embedded in strong soils are shown in Table A-3. The testing programs referenced above have shown that post yield forces can be approximated as a function of the square of the embedment depth. Thus, yield forces from Table A-3 can be extrapolated for other embedment depths by multiplying the forces shown by the square of the ratio of the two embedment depths as given in Eq. A3-2.

2

⎛ *D*′ ⎞

*F* ′ = *F* × *e*

(Eq. A3-2)

*s s*

Where:

⎜ ⎟

⎝ *D e* ⎠

′

*FS*′ = soil dynamic yield force at alternate embedment depth, *De* ;

*Fs* = soil dynamic yield force shown in Table A-3;

′

*De* = alternate embedment depth; and

*De* = post embedment depth shown in Table A-3.

Some pendulum tests have been conducted in soft soils and are reported in *Development of a Cost- Effectivness Model for Guardrail Selection* (27). Analytical procedures for estimating the yield forces of other post sizes and soil conditions are discussed in *A Study of the Soil-Structure Interaction Behavior of Highway Guardrail Posts* (40).

TABLE A-3. Dynamic Yield Forces of Posts Embedded in Strong Soil

|  |  |  |  |
| --- | --- | --- | --- |
| **Post Typea** | **Embedment Depth, ft (m)** | **Maximum Soil Limit, kips (kN)** | **Maximum Post Limit, kips (kN)** |
| 6 in. by 8 in. Wood Post | 3.0 (0.91) | 11.3 (50.2) | 16.2 (72.1) |
| 8 in. by 8 in. Wood Post | 3.0 (0.91) | 12.4 (55.2) | 22.7 (101)b |
| 10 in. by 10 in. Wood Post | 3.0 (0.91) | 16.3 (72.5) | 46.1 (205)b |
| W6 by 9 Steel Post | 3.7 (1.12) | 12.4 (55.2) | 14.6 (65.0) |
| W6 by 15 Steel Post | 3.7 (1.12) | 18.3 (81.4) | 23.7 (105) |

a Post sizes are in English units. b Estimated for Douglas Fir.

###### A2.3.2.2 Tests with 10000S, 36000V, and 36000T Vehicles

Connection loading is the test parameter of primary importance for selecting impact points for heavy vehicle crash tests. Impact point selection guidelines presented in Section 2.3.2.2 are based on the distance from initial contact to the location of maximum lateral force. When possible, the impact point should be selected to generate maximum lateral loading at all important connection points including rail splices, rail-to-post connections, and post-to-base or post-to-deck connections. If the primary concern is for the truck to roll over the top of the barrier, the impact point should be selected to maximize lateral loading at mid-span where the top barrier rail would be expected to defl ect down-

132 | Manual for Assessing Safety Hardware

ward and increase rollover potential. Note that since heavy trucks spread impact loads over a larger area, a single test can usually be devised to apply near maximum loadings on all critical connections and adequately investigate the potential for post failure as well as rollover. Table 2-7 presents fi ndings from full-scale testing of rigid barriers and instrumented walls (12, 25, 65).

### CHAPTER THREE A3.2 TESTING SITE

The attitude of the vehicle at the point of impact can have a signifi cant effect on the performance of the feature being tested. For example, a nose-diving vehicle can result in underride of the barrier while an upwardly bouncing vehicle can promote override of the barrier. Thus, it is critical to have a relatively fl at surface in the approach area so that the vehicle attitude is stabilized at impact. The

runout area for the post-impact vehicle should be long and wide enough for the vehicle trajectory to be properly assessed.

### A3.3 SOIL

The impact performance of many longitudinal barriers and breakaway or yielding support structures depends on the strength and fi xity of the soil foundation. Thus, soil foundation is an integral part

of such systems. For example, displacement and/or rotation of a breakaway device footing during collision can adversely affect the fracture mechanism. Insuffi cient soil support can lead to exces- sive guardrail post movements and guardrail lateral defl ection during vehicle collision and result in a lower system capacity to contain and redirect errant vehicles. Insuffi cient soil strength can also be a critical and limiting factor for the anchoring function of a longitudinal barrier terminal. On the other hand, an unusually fi rm soil can increase the lateral stiffness of a longitudinal barrier and subject oc- cupants of a colliding vehicle to undue risk.

Soil conditions along the highway are variable and may be affected by many factors. Soil type could range from soft sand materials to hard rock materials; moreover, the soil type may vary considerably within a locale as well as from region to region. In addition to soil type, soil strength may also be a function of the season as it can be signifi cantly affected by moisture content and whether the soil is frozen. Other signifi cant factors may include compaction, density, and consolidation of the soil. The testing agency should be aware of the importance of soil strength and select the most appropriate soil type consistent with potential application of the feature.

Recommended soils are well-graded materials that should be readily available to most testing agen- cies. The standard soil of Section 3.3.1 is a selected AASHTO material that compacts to form a relatively strong foundation. The weak soil of Section 3.3.2 is a typical AASHTO fi ne aggregate. These soils are essentially the same as the “strong” and “weak” soils of NCHRP Reports 350 (119).

The following general guidance in soil selection is offered to the user agency and the testing agency:

Appendix A—Commentary | 133

A3.3.1 STANDARD SOIL

Unless the test article is limited to areas of weak soils, the standard soil should be used with any feature whose impact performance is sensitive to soil-foundation or soil-structure interaction. A large percentage of previous testing has been performed in similar soil and a historical tie is needed. Although it is probably stronger than the average condition found along the roadside, it is still repre- sentative of a considerable amount of existing installations.

A3.3.2 SOIL STRENGTH

The soil specifi cations in NCHRP Report 350 (119) are intended to provide consistency to soil strength and test results of soil-based installations among the testing agencies. However, even though the soil types available to the various testing agencies locally all meet the material specifi cations, they vary widely in their characteristics, including soil strength. The installation procedures specify the width and depth of the fi ll material for embedment of posts to ensure that the test results are not affected by the characteristics of the native soil. However, these recommendations were seldom followed since they required an inordinate amount of fi ll materials for a typical test installation. There are also other fac- tors affecting soil strength that are not clearly covered by the specifi cations, such as moisture content. These factors led to concerns over the repeatability of test results among the test agencies.

To overcome these concerns, a performance-based specifi cation is added to the material-based specifi cations contained in Appendix B of NCHRP Report 350. A minimum level of soil strength as

measured by an in-situ test procedure is specifi ed to ensure that the soil strength is comparable among the various testing agencies. Details of the in-situ test procedure are presented in Appendix B and will not be repeated herein.

Each testing agency is asked to conduct an initial set of calibration tests to establish the baseline val- ues for the in-situ soil strength testing. The purposes of these calibration tests are to defi ne the range of soil strength among the testing agencies and to establish the minimum acceptable value. However, it is recommended that the individual testing agencies also use this opportunity to establish the rela- tionships between soil strength and the various infl uencing factors, such as native and fi ll material soil type, width and depth of fi ll material, gradation, compaction, soil density, and moisture content. The information would allow the testing agencies to judge if suffi cient soil strength is available for testing without actual conduct of the in-situ tests.

The in-situ test should be conducted immediately prior to each crash test to verify that the soil strength exceeds the minimum acceptable value. If the test results indicate insuffi cient soil strength, the crash test should be postponed until the soil conditions improve. For each test installation, a minimum of two posts should be installed for in-situ testing in case the fi rst in-situ test results are not acceptable. Unless more than two posts are installed, there will only be two opportunities for the in-situ soil strength tests. Thus, it is important for the testing agencies to understand the relationships between soil strength and the various infl uencing factors so that the in-situ test is conducted only when the soil conditions are favorable.

134 | Manual for Assessing Safety Hardware

A3.3.3 SPECIAL SOILS

The weak soil should be used, in addition to the standard soil, for any feature whose impact perfor- mance is sensitive to soil-foundation or soil-structure interaction if: (1) identifi able areas of the state or local jurisdiction in which the feature will be installed contain soil with similar properties, and

1. there is a reasonable uncertainty regarding performance of the feature in the weak soil. Tests have shown that some base-bending or yielding small sign supports readily pull out of the weak soil upon impact. For features of this type, the strong soil is generally more critical, and tests in the weak soil may not be necessary.

In addition to soil selection, the footing or foundation used in a test of a breakaway support structure should be designed for the minimum wind conditions permitted, thus yielding a minimum footing mass and size; a larger footing will yield a greater fi xity for a breakaway device and is, hence, less critical.

The standard soil of Section 2.2.1.1 is especially sensitive to moisture content. The testing agency should sample and test the soil to ensure moisture content is within recommended limits given in the specifi cation at the time of the test.

A3.3.4 EMBEDMENT OF TEST ARTICLE

As mentioned previously, the requirement on the width and depth of fi ll materials has been revised in this document. Each testing agency may establish its own installation procedures, including the

width of the fi ll material and method of compaction. However, these installation procedures should be followed in the calibration tests and all future constructions. The minimum width of the fi ll material should be that used in the calibration tests, but greater widths are acceptable. Also, the depth of the fi ll materials should always extend below the installed appurtenances.

### A3.4 TEST ARTICLE

Failure or adverse performance of a highway safety feature during crash testing can often be attribut- ed to seemingly insignifi cant design or construction details, something as innocuous as a substandard washer. For this reason, it is most important to assure that the test article has been properly assembled and erected and that critical materials have the specifi ed design properties. Details of most con-

cern are those that are highly stressed (such as welded and bolted connections, anchor cables, cable connections, and concrete footings) or those that must fracture or tear away during impact (such as breakaway sign bases or weakened barrier posts). Compressive tests of concrete cylinders, proof tests of cable assemblies, and physical and chemical properties of materials, in general, should be per- formed on a random sample of the test article elements or obtained from the supplier of the material. Even though well-defi ned material specifi cations and appropriate fracture modes may not be fully de- veloped, the properties of all components and materials used in the test article should be documented in detail in the test report or at least be traceable should any questions arise.

Appendix A—Commentary | 135

###### A3.4.2.1 Longitudinal Barriers

Proper judgment must be exercised in establishing test installation length. In specifying minimum length of a longitudinal barrier installation, the intent is to minimize infl uence of terminals and thereby simulate a long barrier. Recommendations in the minimum installation lengths are provided in the document and should be followed unless there are extenuating circumstances. Barrier lengths may also need to be extended to ensure that heavy trucks are fully contained prior to reaching the end of the barrier. Also to be considered is the possible need to extend the barrier installation to observe a second collision between vehicle and barrier.

###### A3.4.2.4 Truck-Mounted Attenuators (TMA)

See commentary in Section A2.2.3.

A3.4.3 TEST INSTALLATION DOCUMENTATION

More emphasis is placed on the documentation of test installations, from CAD drawings to compo- nents and materials. The objective of the improved documentation requirement is to provide user agencies with suffi cient information on the crash tests to properly evaluate the test articles and test results. The test installation should be described with suffi cient detail to allow complete reconstruc- tion of the test article.

### CHAPTER FOUR

### A4.2 TEST VEHICLE DESCRIPTIONS

Two test vehicles have traditionally been used to represent the entire fl eet of passenger vehicles op- erating on the roadside. The philosophy behind this approach has been that, if a roadside feature can safely accommodate both ends of the vehicle size spectrum, it should provide good performance for almost all vehicle sizes in between. For most classes of safety features, the same approach has been maintained in this document. Over the last decade, vehicle masses have increased dramatically as the popularity of large sport utility vehicles (SUVs) has grown. If history is any indication, the size and nature of the vehicle fl eet will change signifi cantly over the next 10 to 15 years as vehicle weights decline to more closely match historical averages. In such a circumstance, it would be desirable to revise test vehicle specifi cations to more accurately refl ect the new vehicle fl eet. A brief summary of this process is presented below.

A mid-sized test vehicle, designated 1500A, has been added to the test matrix in order to evaluate staging of energy-absorbing terminals, crash cushions, and truck-mounted attenuators. This vehicle will be used to determine if staging in an attenuation system is designed properly to safely accommo- date high-speed, head-on impacts with mid-sized vehicles. In this situation, the mass of the mid-sized vehicle will carry it beyond the point where the 1100C vehicle is brought to a stop and likely enter into the high-energy dissipation ranges of an attenuator where deceleration forces may become exces- sive for mid-sized cars. Hence, the primary concern is that this test will cause excessive ridedown accelerations. Because activation of attenuation systems is primarily related to vehicle mass and the

136 | Manual for Assessing Safety Hardware

test is a head-on impact, where spin-out and rollover are not a factor, total mass is the only important vehicle parameter for the 1500A. The 3,314-lb (1500-kg) vehicle mass was chosen after evaluating the potential for excessive occupant ridedown acceleration in recently tested energy-absorbing termi- nals and crash cushions. This analysis showed that test vehicles weighing between 2,872 and 3,755 lb (1300 and 1700 kg) would be most likely to cause excessive ride-down accelerations.

Note that safety hardware designers are expected to consider the full range of vehicle sizes when de- signing attenuation devices. The mid-sized vehicle test is merely added as a minimal check to verify that designers are achieving this goal. The new test does not indicate that designers do not need to consider other vehicle weights between the small car and light truck test vehicles. Attenuation sys- tems should be designed to accommodate all vehicle masses between 2,425 lb and 5,004 lb (1100 kg and 2270 kg).

A4.2.1 PRODUCTION VEHICLES

In keeping with the approach used in prior impact performance evaluation guidelines, no specifi c make and model of test vehicle is recommended for use in tests requiring 1100C and 2270P vehicles. Nevertheless, it is expected that a single model will be used predominantly for each of the two vehicle categories. Under NCHRP Report 350 (119), the Geo Metro and Chevrolet C2500 became the “unof- fi cial” test vehicles used by most agencies. After careful evaluation of availability and the geometric and structural characteristics of various vehicles in the two categories, it is recommended the Kia

Rio and the two-wheel drive Dodge Ram 1500 Quadcab be utilized under the new guidelines as the “unoffi cial test vehicle models”.

NCHRP Report 350 included an exception that permitted the 820C and 2000P vehicles to be more than six model years old at the time of the test. The exception was predicated upon the testing agency being able to demonstrate that:

“…key properties of the test vehicle are essentially the same as those of a vehicle meeting all of the recommended requirements. Key properties include those given in Table 2-1 plus unspecifi ed properties that may change with succeeding model years such as dynamic force-

deformation properties of the bumper and frontal structure of the vehicle and vehicular profi le as defi ned by bumper height, hood height, hood sweep, windshield sweep, and height of the windshield.”

Based upon this exception, many testing agencies have utilized older test vehicles. Unfortunately, there has been little effort to verify that the force-deformation characteristics are similar to vehicles within the six model year limit. A detailed analysis, including full-scale validation testing, would be required to properly ascertain similarity in vehicle force-deformation characteristics. Further, the

“unspecifi ed properties” that are listed above do not encompass all of the important vehicle character- istics that can affect the outcome of a test. For example, suspension characteristics and failure modes have been shown to be important to many barrier and transition tests. With the increased frequency

of design changes in the light truck market, it is impractical to even attempt to ascertain that an older vehicle is structurally similar to one within the recommended age limit.

Appendix A—Commentary | 137

Therefore, the exception for using older light trucks and automobiles in full-scale crash testing has been revised. The new exception now allows test vehicles to be within 6 model years of the date that the research and development project was undertaken. This revised exception was adopted in recog- nition that some research and development efforts experience delays that would potentially require

a testing agency to sell a test vehicle and repurchase a newer one. Under the revised guidelines, a testing agency can purchase six-year-old test vehicles without fear that the project may extend into the next calendar year.

The high cost of heavy trucks precludes implementing the six-year limit for these vehicles. Nevertheless, heavy truck test vehicles should be structurally sound and representative of widely used designs. Whenever possible, it is recommended that heavy trucks not be more than 12 model-years old.

Test vehicle design and overall condition at the time of testing can have a major infl uence on the impact performance of a feature. Among the more important parameters are vehicle bumper height, confi guration, and stiffness; vehicle mass distribution; suspension system; and vehicle structure. In order to assure proper safety feature performance and consistency in test results from one test to the next, test vehicles should correspond closely to the recommended vehicle properties. Test vehicles should be in sound structural condition without major sheet metal damage. Further, tires used during full-scale crash tests should be in good condition and match manufacturer specifi cations shown on the vehicle identifi cation plate.

Use of a vehicle for more than one crash test without repairs should be avoided because vehicle dam- age may affect performance in a subsequent test. This is particularly important in evaluating safety features such as a breakaway support where vehicle crush can signifi cantly affect fracture mechanisms.

The three heavy test vehicles, 10000S, 36000V, and 36000T, were selected for evaluation of the capacity of longitudinal barriers where higher levels of containment are necessary, such as on high- volume bridges, overpasses, and in medians of high-volume freeways. In these situations, penetration or overriding of the barrier would produce a high risk of driver fatality and could pose a risk to other traffi c below. Full-scale crash testing indicates that heights of approximately 36 in. (81 cm), 42 in. (107 cm), and 80 in. (203 cm) will be required for rigid barriers for the 10000S, 36000V, and 36000T vehicles, respectively, when ballasted as recommended.

Testing and user agencies should be aware of potential problems that may occur with a test using the 36000V test vehicle. In particular, the undercarriage attachment of the trailer tandems to the trailer frame may not be of suffi cient strength to provide necessary restraint during the specifi ed test. This problem is believed to be peculiar to sliding undercarriage or sliding axle designs. In at least one test, the attachment (which was the sliding undercarriage type) failed due to an inability to transfer lateral impact loads, and the trailer went over the barrier. In a similar test with a fi xed undercarriage attachment, no such failure occurred and the trailer did not go over the barrier. A sliding attachment is recommended for the test trailer since it is widely used in the industry. While it is desirable to test with widely used vehicles and equipment, the primary purpose of the test is to demonstrate structural

adequacy of the barrier, not the trailer. A barrier capable of containing a trailer with a sliding axle may

138 | Manual for Assessing Safety Hardware

have to be considerably taller than one capable of containing a trailer with a fi xed axle. Nevertheless, public safety requires effective containment of vehicles on the road. If testing reveals this type of trailer design will cause signifi cant increases in the cost of effective barrier systems, support should be sought from appropriate offi cials and agencies to develop improved trailer designs to eliminate this problem.

###### A4.2.1.1 Test Vehicle Mass

The test inertial mass of the 1500A vehicle was selected based upon analyses of impacts with ve- hicles ranging from 2,209 to 4,418 lb (1100 to 2200 kg). The highest ridedown accelerations were found to occur when the impacting vehicle mass was between 2,872 to 3,755 lb (1300 and 1700 kg). The mid-sized vehicle mass was set to 3,314 lb (1500 kg) because it fell near the center of what was believed to be the critical range and it provided some consistency with European safety hardware evaluation procedures. In recognition of the wide range of vehicle masses that produce near-critical occupant ridedown accelerations, a larger variation in vehicle mass, ±221 lb (100 kg) was deemed to be appropriate.

###### A4.2.1.2 Ballast

Ballast for test vehicles that is free to shift or break loose during impact may be totally ineffective or only partially effective in loading of the feature because it tends to move independently of the vehicle. Unless specifi cally designed to evaluate effects of cargo shifting, tests with the 10000S and 36000V vehicles are to be conducted with fi rmly secured ballast. The tie-down system should be capable of resisting a lateral load equal to approximately ten times the weight of the ballast.

It must be noted, however, that test experience has shown that it is quite diffi cult to design a ballast tie-down system for a van truck or trailer with suffi cient strength to resist typical impact loads for two reasons: (1) the absence of lateral stiffness in the walls of the van and (2) the height the ballast must be placed above the fl oor of the van to achieve the recommended center of mass of the ballast. For reasons of economy and convenience, sandbags on pallets are commonly used as ballast in tests of van trucks or van trailers. While this achieves the required mass and center-of-mass height, it is diffi cult to secure this type of ballast and it creates a concentrated lateral load at some height above the fl oor of the van during impact. It would be preferable to use a ballast material with a density

as low as possible so that the ballast would be uniformly distributed along the length, width, and height of the van, thus minimizing the need and structural requirements of the tie-down system. Bales of hay have been used as a relatively low-density ballast.

###### A4.2.1.3 Vehicle Damage

Vehicle damage has often been used as an indirect link between crash tests and real-world crashes. Most studies based on comparisons of vehicle damage have focused on the link between surrogate measures of occupant risk, such as occupant impact velocity and ridedown accelerations and the probability of injury. Identifying the appropriateness of existing occupant risk measures and their limits is critical to the future refi nement of impact performance evaluation guidelines. Therefore, it is recommended that testing agencies document vehicle damage using the historical damage index procedures, Vehicle Damage Scale (VDS) (119) and Collision Damage Classifi cation (CDC) (81) as well as the direct measurement technique described in the NASS Vehicle Measurement Techniques

Appendix A—Commentary | 139

(86). Incorporating the NASS vehicle measurement procedures will provide a link between full-scale crash test results and real-world crashes.

Occupant compartment deformation is used as an indicator of the potential for occupant injury. The risk of injury is believed to be related to the extent of deformation and thus special care must be taken to accurately measure occupant compartment deformations. This measurement is complicated by the fact that severe crashes can distort the entire occupant compartment. As described in Appendix E, pre- test measurements should be made using two different reference axes in order to minimize the errors associated with refl ected damage to the vehicle interior.

###### A4.2.1.4 Surrogate Occupants

Automobile manufacturers and the National Highway Traffi c Safety Administration (NHTSA) have devoted considerable effort to upgrading responsiveness and measurement techniques for dummies. New and highly advanced dummies such as Hybrid III, Eurosid, and THOR have been developed with up to 134 channels of data. However, it was concluded that the greatly increased cost of acquir- ing, maintaining, and applying dummies of this type and the added complexity of and demands on data acquisition and data reduction systems would more than offset the added benefi ts that may be realized in roadside safety design. Use of these dummies is therefore optional. Predecessors to the Hybrid III dummy have not been found to accurately measure the risks of occupant injury and, there- fore, these devices are not recommended except for use in studying the gross motion of an occupant and/or in studying the added mass effects of an occupant.

Sophisticated collision victim simulation (CVS) models are also gaining expanded applications. CVS models incorporate three-dimensional simulations of an occupant’s motions during a crash. Evaluation of occupant risk during a crash test involves using vehicle trajectory and acceleration data from the test as input for the CVS program. The program then computes the dynamic response of an occupant positioned anywhere in the passenger compartment in either a restrained or an unrestrained condition. However, the amount and complexity of input data required for CVS programs, the cost of running the program and, more importantly, the absence of any past record of performance and demonstrated ef-

fi cacy of these programs to predict occupant risk essentially precludes their application at this time.

A4.2.2 SURROGATE TEST VEHICLES

Surrogate test devices such as bogie vehicles or pendulums have been used to evaluate the impact performance of selected features for many years. Although these devices have primarily been used for compliance testing of breakaway sign and luminaire supports, bogie vehicles have also been used to evaluate work-zone traffi c control devices and some barrier components, such as blockouts and

posts for strong-post W-beam guardrails. Unfortunately, bogie vehicle and pendulum designs have not been updated in over 20 years. As a result, none of the existing bogie vehicle or pendulum systems accurately represent the test vehicles described in Chapter 4. Over the past 20 years, the stiffness and geometry of most passenger cars has changed signifi cantly. These changes in geometry and frontal stiffness can have a signifi cant impact on the performance of some roadside safety features. Issues to be addressed when utilizing surrogate vehicles for compliance testing are summarized below for each class of safety feature where their application is appropriate.

140 | Manual for Assessing Safety Hardware

**Breakaway Signs and Luminaire Supports**—The energy dissipated during an impact with a breakaway system is infl uenced by the stiffness of the front structure of the striking vehicle. In general, a softer nose structure will produce greater energy dissipation prior to activation of the breakaway mechanism. Fortunately, crushable nose systems used on today’s surrogate vehicles are believed to be much softer than vehicle structures found on small cars today. As a result, safety fea- tures tested with the older crushable nose systems are still believed to be acceptable. However, with the mass increase associated with the new test vehicles presented herein and the greatly improved crashworthiness of modern passenger cars, it is no longer appropriate to continue to test with outdated surrogate vehicles. In order for surrogate vehicles to be utilized in place of a production vehicle for testing of large breakaway structures, the frontal crush stiffness must be re-calibrated

to match a vehicle meeting the requirements of Section 4.2.1. Vehicle mass characteristics, such as weight distribution and yaw moments of inertia, have also changed signifi cantly over the past 20 years. Hence, surrogate vehicle mass characteristics must also be adjusted to match an appropriate production vehicle.

**Work-Zone Traffi c Control Devices**—Work-zone traffi c control devices include a wide range of free-standing features that are used to channelize traffi c and to warn or instruct motorists. The small mass of these free-standing systems greatly limits the maximum deceleration that could be pro- duced during a vehicular impact. Instead, the primary concern during an impact with these features is that a component of the device will penetrate into the occupant compartment or cause damage

to the vehicle’s windshield that obstructs a driver’s ability to see other objects in the work zone. Hence, the trajectory of the traffi c control device during an impact with a surrogate vehicle is used to evaluate the potential for test failure. It is necessary to mount a windshield and vehicle roof area on top of the bogie vehicle in order to determine the potential for a work-zone device penetrating into a vehicle. If the device is shown to clear the top of the vehicle structure without contacting the windshield region of the surrogate vehicle, the test is considered a success. Before a bogie vehicle is used in place of a production vehicle to evaluate the performance of work-zone traffi c control devices, it must be calibrated against full-scale crash tests of similar systems.

It is recommended that any surrogate test device be confi gured to model a specifi c production vehicle, as opposed to a generic vehicle, with the stipulation that the vehicle being modeled meet specifi cations for production model test vehicles, i.e., specifi cations that defi ne tolerances on age, weight, etc. This is by far the lesser expensive of the two options since properties of only one vehicle have to be measured and the validation process involves crash testing with only one

vehicle model. It is desirable for FHWA or NCHRP to establish a project in which all bogie proper- ties would be updated and validated periodically to keep current bogies within specifi cations. This would be the most effi cient approach since each testing agency would not have to do it indepen- dently, and it would also ensure uniformity and consistency among the testing agencies.

**Guardrail Posts and Blockouts**—Bogie vehicle tests are often used to assess post and blockout strength when considering alternative materials for use in established barrier systems. Dynamic testing of posts and blockouts must assure that the proposed replacement components are struc- turally equivalent to the original materials and shapes. Similarities in the results of bogie vehicle and/or pendulum tests of the proposed replacement and original components are often used as the

Appendix A—Commentary | 141

basis for asserting structural equivalency. Impact forces are normally calculated from measured bogie or pendulum accelerations. Unfortunately, post inertia has been shown to contribute signifi cantly to measured bogie accelerations. Utilizing a crushable nose system on the front of the impacting vehicle has been shown to virtually eliminate the inertial contributions to the measured accelerations. Note that the crushable nose system does not need to be the same as that used for breakaway support test- ing. Instead, the soft nose system merely needs to have a crush initiation stress that corresponds to an impact force that is below the expected post strength and a divergence stress that corresponds to an impact force that is signifi cantly above the estimated strength (60).

In order for two post and/or blockout systems to be structurally similar, the force-defl ection charac- teristics must at least be comparable. A proposed replacement post that can sustain the same ultimate load as a wood post, but only after defl ecting twice as far, cannot be considered to be structurally similar. Similarly, a blockout that exhibits 25 percent compression during bogie or pendulum testing cannot be considered structurally similar to a wood block that exhibits only 5 percent compression under the same test conditions. Therefore, it is important to measure both impact force and hardware defl ection during component testing. Note that when a soft or crushable nose system is utilized, the defl ection of the structural component must be measured directly, utilizing a string potentiometer or some other equivalent device.

Guardrail posts and blockouts are often loaded in a torsional manner and fail due to a combination of bending and twisting during full-scale impact testing. It is important that surrogate vehicle testing procedures attempt to assess structural similarity for this loading condition as well as for perpen- dicular loading. Torsional loading characteristics can be evaluated by attaching a torsion bar to the post-and-block system and allowing the surrogate vehicle to strike the torsion bar instead of directly contacting the post or blockout. Alternatively, when evaluating components for a relatively fl exible rail element, such as W-beam, the surrogate vehicle can be confi gured to strike a rail element con- nected between two post-and-block systems. In both cases, the force defl ection and total deformation before failure should be similar for both the proposed replacement and the conventional barrier components.

A4.2.3 TMA SUPPORT TRUCK

Under previous evaluation guidelines, support vehicles for TMA tests were recommended to be bal- lasted to a mass of 19,881 lb (9000 kg). The advantage of using a standardized support truck mass is that all TMAs are tested under similar conditions. Unfortunately, in practice, TMAs are often

mounted on support trucks weighing much more than 19,881 lb (9000 kg). Users cannot be assured of adequate impact performance when a TMA is mounted to a support truck heavier than that used in the full-scale crash testing. Users have also questioned the performance of TMAs when mounted on very light support trucks. In this case, a high-energy impact can propel the support vehicle a long distance forward and potentially endanger workers. In order to alleviate these problems, the guidelines were revised to allow designers to defi ne both a maximum and a minimum support truck weight that can be safely used with a TMA. Tests 50, 51, and 52 are to be conducted with the TMA mounted to a support truck with the defi ned maximum weight, and Test 53 is to be conducted with the lightest allow-

able support truck weight. Note that no upper limit has been designated for support truck roll-ahead

142 | Manual for Assessing Safety Hardware

distance during Test 53. The measured roll-ahead trajectory is to be reported for this test in order for potential users to be able to place the support truck in a safe location relative to work crews.

Historical TMA testing has shown that ballast placed in the middle of a dump truck bed will shift signifi cantly during impact. This shifting ballast reduces the effective weight of the TMA support vehicle. In order to assure that a TMA will perform adequately for vehicles weighing up to the as- signed maximum, ballast shifting must be controlled. This can be accomplished by utilizing rigid ballast elements that are either secured to the truck bed or braced against the rear of a dump truck bed. If loose ballast is utilized, it must be placed in the bed of the dump truck in a manner that will prevent any signifi cant shifting.

The recommended braking of the support vehicle is believed to be representative of typical in-ser- vice conditions. Test 52 is designed to assess both occupant risks and the roll-ahead distance of the support truck. It is noted that roll-ahead distances for heavier support trucks can be estimated from the “conservation of momentum” principle of mechanics and simple friction calculations. Results from Test 52 can be used as a baseline for estimating roll-ahead distances for heavier support trucks.

A4.3.1 INSTRUMENTATION SPECIFICATIONS

Although not required at this time, the testing agency is encouraged to develop the capability to determine the six components of accelerations for the sprung mass (assumed to be a rigid body)— translational accelerations in the *x*, *y*, and *z* vehicular axes and angular accelerations about these axes. These data, as well as corresponding velocities and displacements, should be shown in the report in plots or tables as a function of time.

High-speed cine is essential for the study of crash dynamics to determine behavior of the test ve- hicle and the test article. In addition, high-speed cine has been used by some agencies as a backup system for determining vehicular accelerations and kinematics. Guidance for this secondary sys- tem consists of (1) minimum fi lm speed (see Table 4-1), (2) internal or external timing device, and

1. stationary references located in the fi eld of view of at least two cameras positioned 90 degrees apart. Layout and coordinates of references, camera positions, and impact point should be reported.

Reference targets should be located on the side and the top of the test vehicle and should be of suffi cient size and distance apart to allow accurate interpretation of the fi lm. The instant of impact

should be denoted by a fl ash unit placed in view of data cameras and should also be recorded on the electronic recording device(s).

A4.3.2 ACCELERATION AND RATE GYRO PLACEMENT AND DATA REDUCTION

The instrumentation block used to measure the vehicle motions should be securely attached to the vehicle structure. Ideally, the attachment mechanism should be capable of transmitting a 250-G ac- celeration to the instrumentation block without sustaining any plastic deformation in the mounting or attachment hardware.

Vehicular accelerations are used in the assessment of test results through the occupant fl ail space model. Accelerations may also be used to estimate impact forces between the vehicle and the test

Appendix A—Commentary | 143

article. Although it is recommended that accelerometers should be placed at the vehicle c. g., experi- ence has shown that this cannot always be done due to physical constraints within the vehicle. As

a result, actual placement of the set of accelerometers may be offset a signifi cant distance from the center of mass. Depending on the offset, major differences can occur between measured accelerations and those at the center of mass for redirection impacts (such as impacts with a longitudinal barrier) or impacts which cause angular vehicular motions.

The following procedure is recommended if accelerometers cannot be placed within 2 in. (5 cm) of the center of mass as measured in the *x*–*y* plane. Although roll motions (rotations about the vehicle’s *x*-axis) of the vehicle are not accounted for, the method has been shown to give acceptable levels of accuracy even for moderate roll motions.

**Procedure**:

1. A tri-axial set of accelerometers, set 1 in Figure A-1, is mounted on a common block and placed as close to the vehicle’s center of mass as practical with the positive directions corresponding

to the positive sign convention given in Figure 4-6. Measurement of the vertical (*z* direction) acceleration is optional, but preferred. The set must be mounted along the fore-aft centerline (along *x* axis) of the vehicle. Theoretically, it is not necessary that set 1 be placed near the cen- ter of mass; however, this is recommended in the event accelerometer set 2 malfunctions. It is preferable that distance *h*1 be within ±1.2 in. (3 cm) of distance *H*.

1. A tri-axial set of accelerometers, set 2 in Figure A-1, is mounted as far as practical from set 1, preferably 23.6 in. (60 cm) or greater, either in front of or behind set 1. Note that both sets must be mounted forward of the cab/bed interface for the 2270P vehicle. The separation distance of the two sets should be as large as practical to reduce computational errors provided the acceler- ometers are not placed in an area that would be expected to undergo signifi cant local dynamic deformations. Set 2 must also be mounted along the fore-aft centerline of the vehicle. It is pref- erable that distance *h*2 be within ±0.8 in. (2 cm) of distance *h*1.
2. Using output from the above two accelerometer sets and distances *d*1 and *d*2, lateral, longitudi- nal, and vertical accelerations at the center of mass are computed by Equations A4-3, developed below. Note that *d*1 and *d*2 and their signs are measured with respect to the origin of the *x*–*y*–*z* axes located at the center of mass. For positions shown in Figure A-1, both *d*1 and *d*2 are posi- tive. However, it is not necessary that either be positive.
3. Values of *d*1, *d*2, *h*1, *h*2, and *H* should be recorded and reported as shown in Figure A-1.

144 | Manual for Assessing Safety Hardware

Accelerometer Set 1

Accelerometer Set 2

Test Inertial C.M.

*Y*

*X* CL Vehicle

*d*1 *d*2

Accelerometer Set 1

Accelerometer Set 2

*X*

*h*2 *h*1 *H*

*Z*

Dimensions, in. (mm)

Note: *h* and *h* should

1 2

*d*1

*d*2

*h*1 *H*

*h*2

preferably equal *H*.

Figure A-1. Accelerometer Placement

##### Derivations of Equations:

Accelerations in the longitudinal direction *ax*, lateral direction *ay*, and vertical direction *az* are measured by:

*a* = *a*

− *d* (ω2 + ω2 )

*x xg y z*

*ay* = *ayg* + *d*ω& *z*

*az* = *azg* − *d*ω& *y*

(Eq. A4-1)

Where:

Appendix A—Commentary | 145

*axg*, *ayg*, *azg* = longitudinal, lateral, and vertical accelerations at the center of mass;

ω*y* , ω*z* , ω& *y* , ω& *z*

= pitch and yaw rates, and pitch and yaw accelerations.

### Thus, the accelerations at points 1 and 2, as shown in Figure A-1, are given by:

*a* = *a*

− *d* (ω2 + ω2 )

*x*1 *xg*

1 *y z*

*ay* = *ayg* + *d*1ω& *z*

1

*az* = *azg* − *d*1ω& *y*

1

*ax*2

= *axg*

− *d*2

(ω2 + ω2 )

(Eq. A4-2)

*ay* = *ayg* + *d*2ω& *z*

*y z*

2

*az* = *azg* − *d*2ω& *y*

2

Equations A4-2 can be solved to obtain the desired accelerations at the center of mass, *axg*, *ayg*, and

*azg*, as follows:

*axg*

*d*2 *ax*1 − *d*1*a x*2

*d*2 − *d*1

=

*d*2 *ay*

− *d*1*a y*

*ayg* =

 1 2

*d*2 − *d*1

(Eq. A4-3)

*azg*

*d*2 *a*

= 1

*z*

* *d*1*a z* 2

*d*2 − *d*1

Note that the second and fi fth equations and the third and sixth equations of set A4-2 can be solved to yield an explicit solution for pitch and yaw accelerations as follows:

ω& *y*

= *a* 1 − *a z* 2

*d*1 − *d*2

*z*

*ay* − *a y*

(Eq. A4-4)

ω& *z* =

 1 2

*d*1 − *d*2

Pitch rate, ω*y*, at any time, *T*, after impact can be obtained by adding the pitch rate at impact to the integral of the fi rst equation of set A4-4 with respect to time from impact to time *T*. Yaw rate, ω*z*, can be similarly computed using the second equation of set A4-4.

Measuring and recording both the vehicle damage scale (VDS) (formerly the traffi c accident data scale (TAD)), and the collision damage classifi cation (CDC), are recommended for the following rea- sons. First, VDS has been in use for a number of years by various crash investigation agencies, and a considerable bank of data exists relating VDS to occupant injuries. Hence, by not reporting VDS,

146 | Manual for Assessing Safety Hardware

the tie of future tests with these historical data would be lost. And second, the National Highway Traffi c Safety Administration (NHTSA) has standardized on the CDC for its multidisciplinary crash investigations. Therefore, CDC is needed to tie test vehicle damage (in which vehicle ac- celerations are measured) to real crashes in which occupant injury is documented.

### CHAPTER FIVE A5.1 GENERAL

Recommended evaluation criteria are limited to appraising impact performance of highway features for idealized vehicle crash test conditions. The basic purpose of crash tests is to screen out those candidate systems with functional defi ciencies and to compare the relative merits of two or more promising candidate safety features. The test results are insuffi cient to project the overall perfor- mance of a safety feature for in-service use or in an actual collision situation. Final evaluation of a safety feature should be based on carefully documented in-service use.

Criteria for evaluating a vehicular crash test of a safety feature are patterned after those in NCHRP Report 350 (119) and consist of three interrelated factors: structural adequacy, occupant risk, and post-impact vehicle trajectory. In comparison to NCHRP Report 350, the present criteria presented in Table 5-1 incorporate the following changes and/or modifi cations (further discussions of these items are given in following sections):

1. Criterion A—Additional language was incorporated to clarify acceptable vehicle action.
2. Criterion D—Limits were specifi ed for deformation or intrusion of occupant compartment.
3. Criterion F—Limits were specifi ed for maximum acceptable roll and pitch angles.
4. Criteria H and I—Precision was specifi ed for maximum acceptable occupant impact veloc- ity (OIV) and ridedown acceleration (RA).
5. Criterion J on the use of the Hybrid III dummy as an optional measure of occupant risk for frontal impacts was deleted.
6. Criteria K, L, and M were deleted.

### A5.2 STRUCTUAL ADEQUACY

The “structural adequacy” factor essentially assesses the feature from a structural and mechanical aspect. Depending on the feature, conditions to be examined include:

1. **Strength**—For longitudinal barriers, this requires containment and redirection of the test vehicle. The condition of controlled stopping while the vehicle remains in contact with the

Appendix A—Commentary | 147

rail is also considered satisfactory and added to Criterion A. Terminals and redirective crash cushions should develop necessary anchoring forces for anticipated site conditions.

1. **Geometry**—Longitudinal barrier rail members should engage the impacting vehicle at proper height to prevent the vehicle from underriding or overriding the installation. As a general rule, the vehicle-barrier contact surface should facilitate a smooth redirection. Rail discon- tinuities such as splices and transitions and other elements such as support posts should not cause snagging to the extent that occupant risk criteria would not be met, or another failure mode would occur. Shaped rigid barriers, such as the New Jersey concrete barrier, should be designed to consider the stability of test vehicles.
2. **Mechanisms**—Stiffness, deformation, yielding, fracture, energy absorption and/or dissipa- tion, etc., are characteristics of a feature that should be verifi ed over the range of test vehicles.

In general, a safety feature should perform its function of redirecting, containing, stopping, or per- mitting controlled penetration of the test vehicles in a predictable and safe manner. Violent roll or rollover, pitching, and spinout of the vehicle are unacceptable behavior, indicative of unstable and unpredictable dynamic interactions.

### A5.3 OCCUPANT RISK

Relationships between occupant risk and vehicle dynamics during interaction with a roadside safety feature are extremely diffi cult to quantify because they involve such important, but widely varying, factors such as occupant physiology, size, seating position, attitude and restraint, and vehicle interior geometry and safety features. There are sophisticated analytical and experimental tools available that can better defi ne these relationships, such as the crash victim simulator (CVS) computer program (52) and use of instrumented anthropometric dummies. However, the use of these tools was considered unfeasible for the present document because of: (a) costs associated with their purchase and/or use,

(b) level of instrumentation and expertise needed, and (c) the absence of experience by testing agen- cies involved in evaluating highway safety features. Studies are needed to better defi ne feasibility and effectiveness of tools of this type in improving occupant risk assessment in crash tests.

##### Occupant Compartment Deformation and Intrusion

Criterion D in NCHRP Report 350 (119) states that, “Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.” However, no guidance was provided in the document on what extent of deformation or intrusion would cause serious injuries. The Federal Highway Administration (FHWA) provided some interim guidelines on the maximum acceptable limits. A detailed assessment was conducted on this topic and a set of more objective evaluation criteria were established.

First, a clear distinction was made between: (a) penetration, in which a component of the test article actually penetrates into the occupant compartment; and (b) intrusion or deformation, in which the oc-

148 | Manual for Assessing Safety Hardware

cupant compartment is deformed and reduced in size. No penetration by any element of the test article into the occupant compartment is allowed.

Second, for deformation or intrusion, it was recognized that the potential for serious injury varies by the area of the vehicle damaged. For example, deformation in the roof area may potentially be more serious than the wheel/foot well area due to the proximity of the head to the roof. Thus, the limiting extents of deformation should also vary accordingly.

Third, the limiting extents for deformation were based on the recommended guidelines developed by the Insurance Institute for Highway Safety (IIHS) for evaluating structural performance of ve- hicles in offset frontal crash tests. The recommended guidelines were based on results from selected full-scale offset frontal crashes, which are as follows:

##### Rating Extent of Intrusion

Good < 6 in. (150 mm)

Acceptable 6 in. – 9 in. (150 – 225 mm)

Marginal 9 in. – 12 in. (225 – 300 mm)

Poor > 12 in. (300 mm)

Comments on the individual limiting extents are presented as follows:

* + **Roof ≤ 4 in. (102 mm)** —A much lower limiting extent of deformation was selected for the roof area since the headroom inside the vehicle is limited and impacts to the head are more likely to result in serious or fatal injuries.
	+ **Windshield** —No tear of plastic liner and maximum deformation of 3 in. (76 mm). A much lower limiting extent of deformation was selected for the windshield area; since, an occupant, particularly an unbelted occupant, would move forward toward the windshield. Thus, deforma- tion of the windshield would increase the potential of the occupant impacting the windshield and could lead to more severe injuries. Also, tearing of the plastic liner could lead to penetration of the occupant compartment and thus is not permitted. Note that a tear in the windshield’s plastic liner is only precluded when there is a potential for a test article component to penetrate into

the vehicle. Tearing of the plastic liner produced when a continuous test article contacts the windshield support structuremay be acceptable. For example, a continuous, flexible cable element may contact and plastically deform the A-pillar of an impacting vehicle within acceptable limits and result in minor tearing of the windshield’s plastic liner. Although tearing may occur, there may be no concern for a continuous cable element to penetrate into the occupant compartment. Under this scenario, minor tearing of plastic liner is considered acceptable.

* + **Window** —No shattering of a side window resulting from direct contact with a structural mem- ber of the test article, except for special situations discussed below. In cases where the windows are laminated, the guidelines for windshields will apply. It was observed that the occupants’ head would typically strike the side window in redirectional impacts with semi-rigid and rigid barriers. Thus, if the side window was shattered from direct contact with a structural member of the test article, it is logical to assume that the occupant’s head could also strike the structural member and result in serious injuries. However, longitudinal barriers can vary significantly in terms of lateral stiffness and strength, thus altering the safety risks posed to vehicle occupants. Passenger vehicle impacts into flexible cable barriers may allow a continuous cable element to contact a side window and cause it to fracture. Flexible cable elements may also contact and plastically deform a vehicle’s A-pillar and/or B-pillar within acceptable limits. Because of the low vehicle decelerations associated with impacts into flexible barriers, lateral movement of the occupant is limited and contact with the occupant’s head is unlikely. In such instances, it is reasonable to allow side window fracture to occur as long as several conditions are met: (1) the A- or B-pillars should not be completely severed, (2) the maximum resultant deformation to any support member does not exceed 5 in. (127 mm), and (3) the maximum lateral deformation to any support member does not exceed 3 in. (76 mm).
	+ **Wheel/foot well and toe pan areas ≤ 9 in. (229 mm)** —The limiting extent for deformation in these areas corresponds to the acceptable range as recommended by the IIHS. Due to the prox-

Appendix A—Commentary | 149

imity of the occupant’s lower extremities in these areas, any deformation would likely result in injuries to the lower extremities. While such injuries are typically not life-threatening, they could be severe, resulting in long-term disabilities.

* + **Side front panel (forward of A-pillar) ≤ 12 in. (305 mm)** —The limiting extent for deformation in this area corresponds to the marginal range as recommended by the IIHS. While deformation in the side front panel still could result in injuries to the lower extremities, the likelihood is lower

since the occupant’s lower extremities are typically located further away from the side front panel.

* + **Front side door area (above seat) ≤ 9 in. (229 mm)** —The limiting extent for deformation in these areas corresponds to the acceptable range as recommended by the IIHS. Due to the proximity of the occupant’s torso to this area, any deformation would likely result in serious injuries to the occupant.
	+ **Front side door area (below seat) ≤ 12 in. (305 mm)** —The limiting extent for deformation in this area corresponds to the marginal range as recommended by the IIHS. It is reasonable to as- sume that the seat assembly would shield the occupant from some of the deformation and a larger limiting extent is thus appropriate.
	+ **Floor pan and transmission tunnel areas ≤ 12 in. (305 mm)** —The limiting extent for deforma- tion in this area corresponds to the marginal range as recommended by the IIHS. Deformation in these areas is typically the result of induced damages, which has a much lower potential for serious injuries than deformation from direct contacts.

It should be emphasized that any occupant compartment damage should be carefully documented in the form of photographs and measurements, particularly for pentrations and area(s) where the maximum extent(s) are exceeded. The same applies for any damage to, or rupture of, the interior and exterior floorboard and rear trunk, the fuel tank, oil pan, or other features that might serve as a surrogate of a fuel tank.

##### Flail-Space Model

NCHRP Report 350 (119) continued to use the simplifi ed point mass, fl ail-space model fi rst devel- oped under NCHRP Report 230 (83) for assessing risks to occupants due to vehicular accelerations. Two measures of risk are used: (1) occupant impact velocity (OIV)—the velocity at which a hypo- thetical occupant impacts a hypothetical interior surface; and (2) ridedown acceleration—acceleration experienced by the occupant subsequent to contact with the interior surface. The fl ail space model has served its intended purpose well, and there are no indications that features designed and assessed thereby have performed adversely in service. Thus, it was decided to retain the fl ail space model for the present document.

All testing agencies are now using a standardized computer program for determination of the occu- pant risk factors. This should promote consistency among testing agencies and assure accuracy of the calculations.

150 | Manual for Assessing Safety Hardware

One source of potential error is inconsistencies in positioning accelerometers and rate gyros used in measuring accelerations and rotational rates, i.e., they are not being placed at the vehicle’s center of mass. Recommendations contained in Section 4.3.2 should greatly reduce or eliminate this problem.

In the fl ail-space approach, lateral and longitudinal, but not vertical, vehicular accelerations mea- sured at the vehicle’s center-of-mass are used. By requiring that the vehicle in the occupant risk test remain upright throughout the collision, it is believed that the vertical component of vehicle accelera- tion becomes of secondary importance with regard to occupant kinematics for the level terrain tests described in this document and for most roadside features. Consequently, the vertical acceleration is considered an optional factor at present and has been neglected in the fl ail-space calculations.

The performance design strategy for a feature should be to: (1) keep the occupant-vehicle interior impact velocity low by minimizing average vehicle accelerations or vehicle velocity change during the time the occupant is traveling through the occupant space; and (2) limit peak vehicle accelerations during occupant ridedown.

##### Limiting Values for Impact Velocity and Ridedown Acceleration

Two sets of limiting values are given in Table 5-1 of NCHRP Report 350 (119): “preferred” and “maximum.” The “maximum” limiting values should be treated as threshold limits. Test results should fall below these limits and desirably should not exceed the “preferred” values to promote safer performing features. In developing appropriate acceptance values, consideration should be given

to the state-of-the-possible (i.e., can a device be made, regardless of cost, to perform to the require- ments?) and cost-effectiveness (i.e., can the increase in impact performance level justify the added cost?). Establishment of acceptance values is a policy decision and, therefore, beyond the purview of this report.

Some questions were raised about the rounding of limiting values due to conversions from the English units in NCHRP Report 230 (83) to the SI system in NCHRP Report 350. To avoid such argu- ments, the maximum limiting values are set to the following: 40 ft/s (12.20 m/s) for the longitudinal and lateral occupant impact velocity; 16 ft/s (4.9 m/s) for the longitudinal occupant impact velocity of breakaway support structures; and 20.49 G for the ridedown acceleration.

The limiting value for the longitudinal occupant impact velocity was originally set at 40 ft/s

(12.2 m/s) in NCHRP Report 230, which was then hard converted to 39.4 ft/s (12.0 m/s) in NCHRP Report 350. Since a number of safety devices were approved with the maximum limiting values at 40 ft/s (12.2 m/s), this limit is used to allow for continuity among the guidelines. The limiting value for the longitudinal occupant impact velocity of breakaway support structures was originally set at 15 ft/s (4.6 m/s) with an impact speed of 20 mph (32.2 km/h). These values were hard converted to 16 ft/s (4.9 m/s) with an impact speed of 21.8 mph (35.0 km/h). Thus, the maximum limiting value of 16 ft/s (4.9 m/s) already represents a signifi cant easing of the requirement and should be consid- ered as the maximum limiting value. NCHRP Report 230 specifi ed 20 G as the maximum limiting value, which was retained for NCHRP Report 350. It was argued by some hardware developers that, since the limit is set as an integer, the actual maximum limiting values should be 20.49 G to account

Appendix A—Commentary | 151

for rounding and some devices were accepted with this limiting value. Again, to maintain continuity among guidelines, a maximum limiting value of 20.49 G is recommended.

##### Calculation Procedures

The expression for occupant impact velocity is

*V* = ∫

*t*\*

*a dt*

(Eq. A5-1)

*I x*, *y*

*x*, *y*

0

Where *VI x*, is occupant-car interior impact velocity in the *x* or *y* directions, *ax,y* is vehicular accelera- tion in *x* or *y* direction, and *t*\* is time when the occupant has traveled either 2 ft (0.6 m) forward or 1 ft

*y*

(0.3 m) lateral, whichever is smaller. Time *t*\* is determined by incremental integration as follows:

*t*\*

*X* ,*Y* = ∫ ∫

*t*\*

*ax*, *y dt*2

(Eq. A5-2)

0 0

where, *x* = 2 ft (0.6 m) and *y* = 1 ft (0.3 m). Acceleration in the *x* direction is integrated twice with respect to time to fi nd the value of time, *t* \*, at which the double integration equals 2 ft (0.6 m).

*x*

Acceleration in the *y* direction is integrated twice with respect to time to fi nd the value of time, *t* \*, at

*y*

*y*

which the double integration equals 1 ft (0.3 m). Time *t*\* is the smaller of *t* \*

*x*

and *t* \*.

In tests of breakaway features, the impulse on the vehicle may be relatively small and of short duration. It is not unusual in such tests for *x* and *y* to be less than 2 ft and 1 ft (0.6 m and 0.3 m), re- spectively, during the period in which accelerations are recorded or up to the time brakes are applied to the test vehicle. In such cases it is recommended that the occupant impact velocity be set equal

to the vehicle’s change in velocity that occurs during contact with the test article, or parts thereof. If parts of the test article remain with the vehicle after impact, the vehicle’s change in velocity should be computed at the time the vehicle clears the footing or foundation of the test article.

For the ridedown acceleration to produce occupant injury, it should have at least a minimum dura- tion ranging from 0.007 to 0.04 s, depending on body component (146). Thus, vehicular acceleration “spikes” of duration less than 0.007 s are not critical and should be averaged from the pulse. An arbi- trary duration of 0.010 s has been selected as a convenient and somewhat conservative time base for averaging accelerations for occupant risk assessment. This is accomplished by taking a moving 10-ms average of vehicular “instantaneous” accelerations in the *x* and *y* directions, subsequent to *t*\*.

The occupant impact velocity and the highest 10-ms average acceleration values are then compared to recommended limits; it is desirable that both values are below the “preferable” limits; values in excess of the “maximum” limits are considered to be unacceptable.

Recommendations relative to the measurement of accelerations are given in Section 4.3.2 and in Appendix C. Further, for purposes of standardization of occupant risk calculation procedures, the following are recommended:

152 | Manual for Assessing Safety Hardware

1. Prior to integration using above formulas, accelerometer analog data should be digitized at 1,500 samples per second. This is consistent with recommendations of Appendix C, Section

8.2. It is recommended therein that the sample rate be, at a minimum, eight times *Fh* , where *Fh* = 180 for measurement of vehicular response. Note that *Fh* × 8 = 1,440, which is round- ed to 1,500 for convenience and ease of integration.

1. It is recommended the “linear acceleration” assumption or the equivalent “trapezoidal rule” be used to integrate the digitized accelerometer data. As such, accelerations are assumed to vary linearly over each time step *ti* to *ti* + 1. Description of the trapezoidal rule can be found in most numerical methods textbooks.

### A5.4 POST-IMPACT VEHICULAR TRAJECTORY

In general, the ideal after-collision vehicular trajectory performance goal for all features should be that the vehicle trajectory and fi nal stopping position should not intrude into the adjacent or op- posing traffi c stream. For breakaway or yielding supports, the trajectory of a vehicle after it has collided with a test article that satisfi es structural adequacy and occupant risk requirements is gener- ally away from the traffi c stream and is, hence, less critical. For end-on impacts into crash cushions and barrier terminals that function as crash cushions, preferably the fi nal position of the vehicle should be next to the test device.

For redirectional performance tests of length of need, transitions, terminals and redirective crash cushions, the after-collision trajectory is more diffi cult to assess. The after-collision trajectory may be one of the least repeatable performance factors because of variation in method and timing of brake application. Further, variables that are in part related to the specifi c model of vehicle selected for tests, such as damage to vehicle suspension, tires, etc., may alter the vehicle’s stability and path. Moreover, because driver response in avoiding secondary collisions is not simulated in the crash tests, it seems inappropriate to predict in-service performance based on the complete test trajectory.

Under NCHRP Report 350 (119), there are four evaluation criteria under post-impact vehicular trajectory:

1. After collision it is preferable that the vehicle’s trajectory not intrude into adjacent traffi c lanes.
2. The occupant impact velocity in the longitudinal direction should not exceed 12 m/s and the occupant ridedown acceleration in the longitudinal direction.
3. The exit angle from the test article preferably should be less than 60 percent of test impact angle, measured at time of vehicle loss of contact with test device.
4. Vehicle trajectory behind the test article is acceptable.

Appendix A—Commentary | 153

Only Criterion N, which lists the tests for which vehicle trajectory behind the test article is accept- able, is retained in this document. Criteria K and M were excluded from this document since they are considered preferable, but not mandatory. An effort was made in this document to include only mandatory evaluation criteria that can be assessed in an objective manner. All safety feature crash

tests previously subject to criterion L are now required to meet criteria H and I. Thus, Criterion L was also eliminated from this document.

User agencies should assess the post-impact vehicle trajectory of a roadside safety feature in light of the actual fi eld conditions. For many tests, a scaled diagram showing the post-impact trajectory of the vehicle, including the point of fi nal rest, should provide suffi cient information for the user agencies to make their assessment. Additional information is provided for some features, such as the “exit box” criterion assessment for redirective devices and the “rebound” velocity for reusable crash cushions and attenuation systems.

For redirective devices, it is preferable that the vehicle be smoothly redirected. Under NCHRP Report 350, the assessment is based on the requirement that the exit angle should not exceed 60 percent of the impact angle. In the current document, the “exit box” criterion was adopted from the CEN stan- dards. As shown in Figure 5-1, the exit box is defi ned by the initial traffi c face of the barrier and a line parallel to the initial traffi c face of the barrier, at a distance A plus the width of the vehicle plus 16 percent of the length of the vehicle, starting at the fi nal intersection (break) of the wheel track with

the initial traffi c face of the barrier for a distance of B. It is preferable for the vehicle to exit within the “exit box,” i.e., all wheel tracks of the vehicle should not cross the parallel line within the distance B. As a point of reference, the “exit box” is equivalent to a maximum exit angle of 12.4 degrees.

Vehicle rebound has been noted for some reusable crash cushions and attenuation systems, which could potentially lead to secondary collisions. In order to provide user agencies with the necessary information regarding the use and placement of such crash cushions, testing agencies are required to document and report the rebound velocity and point of fi nal rest, as outlined in Section 5.4. While these reporting requirements are intended mainly for reusable crash cushions and attenuation systems, they would also apply to any feature resulting in rebound of the test vehicle.

### A5.5 GEOMETRIC FEATURES

Specifi c test and evaluation guidelines for geometric features are not provided due to the largely non- standard and variable nature of such features. However, it should be a goal of transportation agencies to design and implement geometric features that meet the spirit, if not the specifi cs, of safety recom- mendations for the more well-defi ned roadside safety features.

Evaluation guidelines given in this section were derived from a review of past practices and the col- lective expertise of those involved in preparing the document. They are, of necessity, general and may be amended as necessary to accommodate special designs or test conditions.

154 | Manual for Assessing Safety Hardware

### CHAPTER SIX

### A6.1 GENERAL REPORTING RECOMMENDATIONS

It should be borne in mind that the reporting guidelines presented herein are intended as minimum requirements. The underlying philosophy is that the test(s) should be documented in suffi cient detail such that the test(s) could be repeated by another testing laboratory without further inquiry. It is not possible to include all of the details necessary to achieve this goal. The actual level of detail needed will vary depending on test objectives, test article, and test levels involved. If there is any question about whether some details need to be included in the report, it is recommended that the additional information be included to assure that the testing is adequately documented.

### CHAPTER SEVEN A7.1 PURPOSE

In-service performance evaluation guidelines are intended to encourage a more consistent, system- atic, and thorough implementation of new devices and to monitor the fi eld performance of safety features on a continuing basis. With careful monitoring of a new device, unanticipated problems and design defi ciencies can be identifi ed before the feature has been installed in an excessive number of sites. Moreover, all the affected departments will have an opportunity to observe the performance of the device with respect to their operations. For instance, there may be minor design changes recom- mended by the maintenance groups that may reduce normal maintenance or damage repair costs. However, care should be taken not to make changes in design details that could adversely affect impact performance without verifi cation of adequate performance through full-scale crash testing or other acceptable means.

Continuous monitoring of installed safety features assures that changes in vehicle and traffi c char- acteristics do not adversely affect the fi eld performance of the devices. This aspect of in-service performance evaluation was not included in the guidelines set forth in NCHRP Report 350 (119), but added to this document in recognition of the need to monitor fi eld performance in light of changes in the vehicle population and other safety developments.

FHWA continues to serve as the key arbiter in establishing acceptability of new safety features, especially those used on federal-aid highways. The acceptability of a new safety feature is based on design details, specifi cations, and crash test results, but there is no assessment of the in-service performance of the features. Thus, the responsibility of in-service performance evaluation of new and existing safety features would fall on the state transportation agencies. For proprietary safety devices, it may be appropriate for the developer or manufacturer to sponsor or contribute to the in- service performance evaluation.

The need for in-service performance evaluation is well recognized, but there has only been lim- ited implementation of in-service performance evaluation programs due to lack of resources, both in terms of funding and manpower. State transportation agencies are faced with the problem of

Appendix A—Commentary | 155

ever increasing work load and shrinking budget, and it may be diffi cult to divert the resources from other more pressing needs. Nevertheless, the establishment of an in-service performance evalua- tion program, even if it is on a limited scale, would be highly benefi cial and strongly recommended.

Alternatives, such as pooling of resources from multiple states and cooperation with developers and manufacturers on proprietary devices, should be explored. Results from in-service performance evalu- ation studies should be made available to other state transportation agencies and disseminated through such channels as National Technical Information Services (NTIS), FHWA regional resource centers, and pooled fund consortiums.

The establishment of a new national center on in-service performance evaluation is also recommend- ed. This center will serve to:

* + Compile and disseminate results of studies on in-service performance evaluation.
	+ Coordinate efforts to pool resources from multiple states for conduct of specifi c in-service

performance evaluation studies.

* + Conduct in-service performance evaluation studies.

In summary, the need for in-service performance evaluation of existing and new roadside safety features cannot be overly emphasized. More in-service performance evaluation studies are needed to assess and monitor fi eld performance, and the results of the studies should be disseminated to the user agencies.

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