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TEST MATRICES FOR EVALUATING CABLE MEDIAN BARRIERS PLACED IN V-DITCHES

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Cable barrier systems designed to be used in median ditches have been traditionally full-scale crash tested placed either within 4 ft from the slope break point (SBP) of a 4H:1V front slope or near the bottom of the ditch. Recently, there has been some discussion about proposing specific standard test conditions for cable barrier systems which are designed to be placed in a median ditch.

The objective of this research was to propose a matrix of critical tests for cable barriers placed in median V-ditches. Critical tests were proposed based on the identification of those locations where the potential for override/underride is more likely, as indicated by an analysis of the simulated bumper trajectory of small cars, passenger sedans, and pickup trucks when trespassing a median V-ditch. The bumper trajectories as well as the vehicle kinematics were obtained using LS-DYNA computer simulations considering different ditch widths and slopes. Results from previous full-scale crash tests of cable systems placed in V-ditches were also considered in the assessment of the test matrices.

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1 INTRODUCTION

1.1 Background

Cable barrier systems, as well as any other safety hardware, need to pass federal testing standards in order to be placed on the National Highway System (NHS). Testing standards are set forth in the American Association of State Highway Officials (AASHTO) *Manual for Assessing Safety Hardware* (MASH) [1], which superseded the previous National Highway Cooperative Research Program (NCHRP) Report No. 350 [2]. In particular, for Test Level 3 (TL-3), two full-scale crash tests are required involving a small passenger car and a pickup truck. These tests are run with the barrier placed on level terrain. Neither NCHRP Report No. 350 nor MASH specifically addresses cable barrier systems placed on slopes or in depressed medians.

Previously, cable systems successfully tested on level terrain were generally accepted for 6H:1V or shallower slopes without any additional analysis or evaluation. However, cable barrier systems are commonly desired for use in various locations throughout ditches as steep as 4H:1V. These desires and the lack of evaluation criteria for sloped terrain outline the need for testing standards for barrier systems placed in median ditches. Recently, there has been significant discussion in the roadside safety community regarding the development of test matrices for evaluating cable barrier systems placed throughout a ditch as steep as 4H:1V [3]. In particular, three test matrices have been proposed for the safety evaluation of cable systems designed to be placed: (1) anywhere in a median ditch; (2) on one side of the ditch and within a 0 to 4 ft from the front slope break point (SBP); or (3) on both sides of the ditch and within 0 to 4 ft from the front SBP. The three proposed test matrices (Matrices A through C), shown in Tables 1 through 3, respectively, were based on some preliminary numerical simulations, results from available previous full-scale crash tests of systems placed in V-ditches, as well as engineering judgment.

1.2 Objectives

The objective of this research effort is to propose critical test matrices for evaluating cable barriers placed in 4H:1V and 6H:1V V-shaped median ditches. Test matrices for three different configurations will be proposed: (1) single median barrier placed anywhere through the ditch; (2) single median barrier placed at a 0-to-4 ft lateral offset; and (3) double median barrier placed at a 0-4 ft offset. Prior proposed test matrices for evaluating cable median barriers placed in 4H:1V ditches will be evaluated and updated. Further, the updated test matrices for 4H:1V V-ditches will be adapted into new test matrices for evaluating cable barriers in 6H:1V V-ditches.

1.3 Scope

Critical tests were proposed based on the identification of those locations which provide the greatest potential for override/underride, as indicated by an analysis of the bumper trajectories of small vehicles and pickup trucks when traversing median V-ditches. The bumper trajectories as well as the vehicle kinematics were obtained using LS-DYNA computer simulations with various ditch widths and side slopes scenarios. Also, results from previous full-scale crash tests on cable systems placed in V-ditches were considered for the assessment of the critical test scenarios.

Table 1. Previous Matrix A - Single Median Barrier Placed Anywhere in Ditch (4H:1V)

Test No.	**Test Designation No.**	**Vehicle Type**	**Impact Conditions**		**Ditch Width (ft)**	**Barrier Position**	**Barrier Location**	**Primary Evaluation Factors**
			Speed (mph)	**Angle (deg)**				
1a	3-11	2270P	62	25	46	Front Slope	12 ft from Front SBP	Vehicle containment, override prevention, & W.W.
1b	3-11	2270P	62	25	30	Front Slope	12 ft from Front SBP	
2	3-10	1100C	62	25	46 or 30	Front Slope	Note 1	Vehicle stability & A-pillar integrity
3	3-10	1100C	62	25	46	Back Slope	4 ft from Ditch Bottom (27 ft from Front SBP)	Vehicle containment, ORA/OIV, & underride prevention
4a	3-10	1100C	62	25	46	Back Slope	4 ft from Back SBP	Increased vehicle orientation at impact & override
4b	3-10	1100C	62	25	30	Back Slope	4 ft from Back SBP	
5	TBD	1500A	62	25	Note 2	Note 2	Note 2	Vehicle penetration & A-pillar integrity
6	3-11	2270P	62	25	NA	Level Terrain	NA	Vehicle containment & W.W.
7	3-10	1100C	62	25	NA	Level Terrain	NA	Vehicle stability & A-pillar integrity

SBP – Slope Break Point
W.W. – Working Width
NA – Not Applicable
Note 1 – Testing laboratory should determine critical barrier position on front slope of ditch in order to maximize propensity for vehicular instabilities with 1100C small car striking barrier while airborne, say with offset of 4 to 12 ft.
Note 2 – Testing laboratory should determine critical barrier position on front slope of ditch or on level terrain in order to maximize propensity for front end of 1500A vehicle to penetrate between adjacent vertical cables. Critical factors may include vertical cable spacing, location and type of cable release mechanisms, vehicle projectile motion, etc.

Table 2. Previous Matrix B - Single Median Barrier Placed at 0 to 4-ft Offset from SBP (4H:1V)

Test No.	**Test Designation No.**	**Vehicle Type**	**Impact Conditions**		**Ditch Width (ft)**	**Barrier Position**	**Barrier Location**	**Primary Evaluation Factors**
			Speed (mph)	**Angle (deg)**				
1	3-11	2270P	62	25	46 or 30	Front Slope	4 ft from Front SBP	Vehicle containment, override prevention, & W.W.
2	3-10	1100C	62	25	46 or 30	Front Slope	4 ft from Front SBP	Vehicle stability & A-pillar integrity
3	3-10	1100C	62	25	Narrow	Back Slope	4 ft from Back SBP	Vehicle containment, ORA/OIV, & underride prevention
4a 4b	3-10 3-10	1100C 1100C	62 62	25 25	46 30	Back Slope Back Slope	4 ft from Back SBP 4 ft from Back SBP	Increased vehicle orientation at impact & override
5	TBD	1500A	62	25	Note 1	Note 1	Note 1	Vehicle penetration & A-pillar integrity
6	3-11	2270P	62	25	NA	Level Terrain	NA	Vehicle containment & W.W.
7	3-10	1100C	62	25	NA	Level Terrain	NA	Vehicle stability & A-pillar integrity

SBP – Slope Break Point
NA – Not Applicable
Note 1 – Testing laboratory should determine critical barrier position from 0 to 4 ft on front slope of ditch or on level terrain in order to maximize propensity for front end of 1500A vehicle to penetrate between adjacent vertical cables. Critical factors may include vertical cable spacing, location and type of cable release mechanisms, vehicle projectile motion, etc.

Table 3. Previous Matrix C - Double Median Barrier Placed at 0 to 4-ft Offset from Both SBP (4H:1V)

Test No.	**Test Designation No.**	**Vehicle Type**	**Impact Conditions**		**Ditch Width (ft)**	**Barrier Position**	**Barrier Location**	**Primary Evaluation Factors**
			Speed (mph)	**Angle (deg)**				
1	3-11	2270P	62	25	46 or 30	Front Slope	4 ft from Front SBP	Vehicle containment, override prevention, & W.W.
2	3-10	1100C	62	25	46 or 30	Front Slope	4 ft from Front SBP	Vehicle stability & A-pillar integrity
3	TBD	1500A	62	25	Note 1	Note 1	Note 1	Vehicle penetration & A-pillar integrity
4	3-11	2270P	62	25	NA	Level Terrain	NA	Vehicle containment & W.W.
5	3-10	1100C	62	25	NA	Level Terrain	NA	Vehicle stability & A-pillar integrity

SBP – Slope Break Point
NA – Not Applicable
Note 1 – Testing laboratory should determine critical barrier position from 0 to 4 ft on front slope of ditch or on level terrain in order to maximize propensity for front end of 1500A vehicle to penetrate between adjacent vertical cables. Critical factors may include vertical cable spacing, location and type of cable release mechanisms, vehicle projectile motion, etc.

2 LITERATURE REVIEW

Although standardized impact conditions have yet to be created, most manufacturers have begun testing their proprietary high-tension cable barrier systems in 4H:1V ditches. As shown in Table 4, most proprietary cable systems designed for use in median ditches have been full-scale crash tested when placed 4 ft from the front and/or back SBP [4-8].

These tests were performed according to the standard TL-3 conditions prescribed by either NCHRP Report No. 350 or MASH, depending on which standard was available at the time of testing. One manufacturer also conducted a modified test no. 3-11 to assess the performance of the system placed 4 ft into a V-ditch with a sedan [8]. While the location relative to the front or back SBP was consistent for all of the systems full-scale crash tested in a V-ditch, the ditch width varied between 24 ft and 32 ft. The ditch width may affect the vehicle kinematics during the impact if the cable deflection is large enough to allow the vehicle to contact the back slope. Further, for barriers tested on the back slope, varying the ditch width may affect the vehicle-barrier interaction by causing the compression of the vehicle suspensions or the vehicle to bounce off the back slope and become airborne a second time. As such, it is necessary to consider these effects when assessing the worst-case testing conditions (placement and ditch width) for cable barrier systems in a depressed median ditch.

Recently, in the effort to develop a non-proprietary high tension cable system (Midwest Cable Median Barrier), the Midwest Roadside Safety Facility (MwRSF) has performed a series of full-scale crash tests with concept designs of cable barrier systems placed in various locations of a 46-foot wide V-ditch [9-10] and on level terrain [11]. Additionally, a full-scale crash test of the most recent concept design of the Midwest Cable Median Barrier placed in a 30-ft wide ditch was performed by the Texas Transportation Institute (TTI) under the project NCHRP 22-14(4) [12]. This extensive full-scale crash testing effort, which is summarized in Table 5, was conducted under three of the critical conditions listed in the originally proposed Matrix A (Table 1). The failure of 50 percent of these full-scale crash tests strengthens the case for the worst-case testing conditions identified by the prior proposed Matrix A.

A preliminary investigation of the dynamics of vehicles traversing V-ditches was recently performed by the National Crash Analysis Center (NCAC) using multibody simulations [13]. Vehicle models representing 820C, 1100C, 1500A, and 2270P vehicles were used to determine the trajectories of the lower and upper points of the front bumper corner while traversing depressed 4H:1V V-ditch slopes characterized by different widths. In the simulations, which were performed using a multi-body code, no potential interaction between the ditch surface and the vehicle bumper and/or undercarriage was considered. The simulated trajectories of the tracked points were plotted relative to the ditch surface, but no specific test matrix for testing cable systems in V-ditches was proposed.

Table 4. Summary of Testing Conditions for Cable Barrier Systems Tested in a 4H:1V V-Ditch

Barrier	**Vehicle Type**	**Ditch Width (ft)**	**Slope Location**	**Barrier Position (ft)**	**Standard**	**Speed (mph)**	**Angle (deg)**	**Test No.**	**Passed?**
Gibraltar [4]	820C	24	Back Slope	3 from Back SBP	NCHRP 350	65.1	25	P26133-01	Y
Gibraltar [4]	2000P	24	Front Slope	4 from Front SBP	NCHRP 350	61.3	25	P26133-02	N(1)
Gibraltar [4]	2270P	24	Front Slope	4 from Front SBP	MASH	60.3	25	P26133-03	Y
Gibraltar [4]	820C	24	Front Slope	4 from Front SBP	NCHRP 350	63.2	20	P26133-04	Y
Nucor 4-Cable Nu-Cable [5]	820C	30	Front Slope	4 from Front SBP	NCHRP 350	63.9	20	102350.01-3	Y
Nucor 4-Cable Nu-Cable [5]	820C	30	Back Slope	4 from Back SBP	NCHRP 350	61.8	21.4	400001-NSM11	Y
Nucor 4-Cable Nu-Cable [5]	2270P	30	Front Slope	4 from Front SBP	MASH	63.2	26.6	400001-NSM10	NA(2)
SAFENCE [6]	2270P	26	Front Slope	4 from Front SBP	MASH	63	25	NA	Y
SAFENCE [6]	1100C	26	Front Slope	4 from Front SBP	MASH	64	25	NA	Y
CASS [7]	2270P	30	Front Slope	4 from Front SBP	MASH	NA	NA	NA	NA(2)
CASS [7]	820C	30	Front Slope	4 from Front SBP	NCHRP 350	NA	NA	NA	Y
CASS [7]	820C	30	Back Slope	4 from Back SBP	NCHRP 350	NA	NA	NA	Y
CASS [7]	2270P	30	Front Slope	4 from Front SBP	MASH	NA	NA	NA	NA(2)
Brifen WRSF [8]	1500A	32	Back Slope	4 from Back SBP	NCHRP 350	59.4	26.5	BCR-2	Y
Brifen WRSF [8]	820C	32	Front Slope	4 from Front SBP	NCHRP 350	62.9	21.1	BCR-5	Y
Brifen WRSF [8]	2000P	32	Front Slope	4 from Front SBP	NCHRP 350	63	24.1	BCR-4	Y

(1) Vehicle instability after contact with backslope

(2) Tested installation shorter than 600 ft, otherwise successful test

Table 5. Summary of Testing Conditions for the Midwest Cable Median Barrier Design Concepts on 4H:1V Slope

Test No.	**Vehicle Type**	**Ditch Width (ft)**	**Slope Location**	**Barrier Position (ft)**	**Standard**	**Speed (mph)**	**Angle (deg)**	**Test Results**
4CMB-1 [9]	2270P	46	Front Slope	12 from Front SBP	MASH	61.8	27.9	Passed - Vehicle safely captured and redirected
4CMB-2 [9]	1100C	46	Back Slope	27 from Front SBP	MASH	62.7	26.8	Marginally acceptable
4CMB-3 [9]	1100C	46	Back Slope	27 from Front SBP	MASH	62.0	27.2	Failed - Excessive roof crush and penetration
4CMB-4 [10]	1100C	46	Back Slope	27 from Front SBP	MASH	61.1	25.8	Passed - Vehicle safely captured and redirected
4CMB-5 [10]	2270P	46	Front Slope	12 from Front SBP	MASH	61.9	26.5	Failed - Vehicle overrode barrier
4CMB-LT1 [11]	1500A	NA	NA	Level Terrain	MASH	62.2	25.3	Failed - Excessive roof crush and penetration
478730-2 [12]	1100C	30	Back Slope	4 from Back SBP	MASH	62.0	23.5	Failed - Vehicle roll over after being redirected

NA – Not Applicable

3 METHODOLOGY

Computer simulations were utilized to study the kinematics of a vehicle as it travels into and through a median ditch. These simulations were conducted using the non-linear finite element code LS-DYNA [14], which is capable of accurately simulating both the vehicle trajectory and the deformation of the vehicle front end and suspensions upon contact with the ditch surface. Five different vehicle models were utilized, a Geo Metro (820C), a Dodge Neon (1100C), a Ford Taurus (1500A), a Chevrolet C2500 (2000P), and a Chevrolet Silverado (2270P). The 1100C and 2270C vehicles are the standard MASH vehicles required for TL-3 testing of longitudinal barrier systems, while the 1500A passenger sedan is indicated as an optional vehicle. The 820C and 2000P vehicles were the standard vehicles described in NCHRP Report No. 350 and were included to cover a broader spectrum of vehicles in this investigation. Each of the vehicles were prescribed the TL-3 impact conditions set forth in MASH, or a speed of 62 mph and 25-degreee angle with respect to the front SBP as the vehicle entered the V-ditch.

During each simulation a critical point on the vehicle was tracked as it was traveling through the V-ditch. For each vehicle, this critical point was identified as the node of the front bumper protruding the furthest towards the ditch edge considering a vehicle orientation of 25 degrees. This point was considered to be the most critical for two main reasons: (1) it identified the part of the vehicle which would first contact the cable barrier and (2) due to bumper profiles, cables impacting below this point are likely to be pushed downwards, thus allowing the vehicle to override the cable. As such, the front bumper is likely to slide over the closest struck cable if the trajectory of this critical point overrides that cable. Figure 1 shows the location of the critical bumper point for each of the five different vehicles models. The initial height for the critical bumper node was 18.6 in., 19.1 in., 18.9 in., 23.1 in., and 25.6 in., for the 820C, 1100C,1500A, 2000P and 2270P vehicles, respectively.

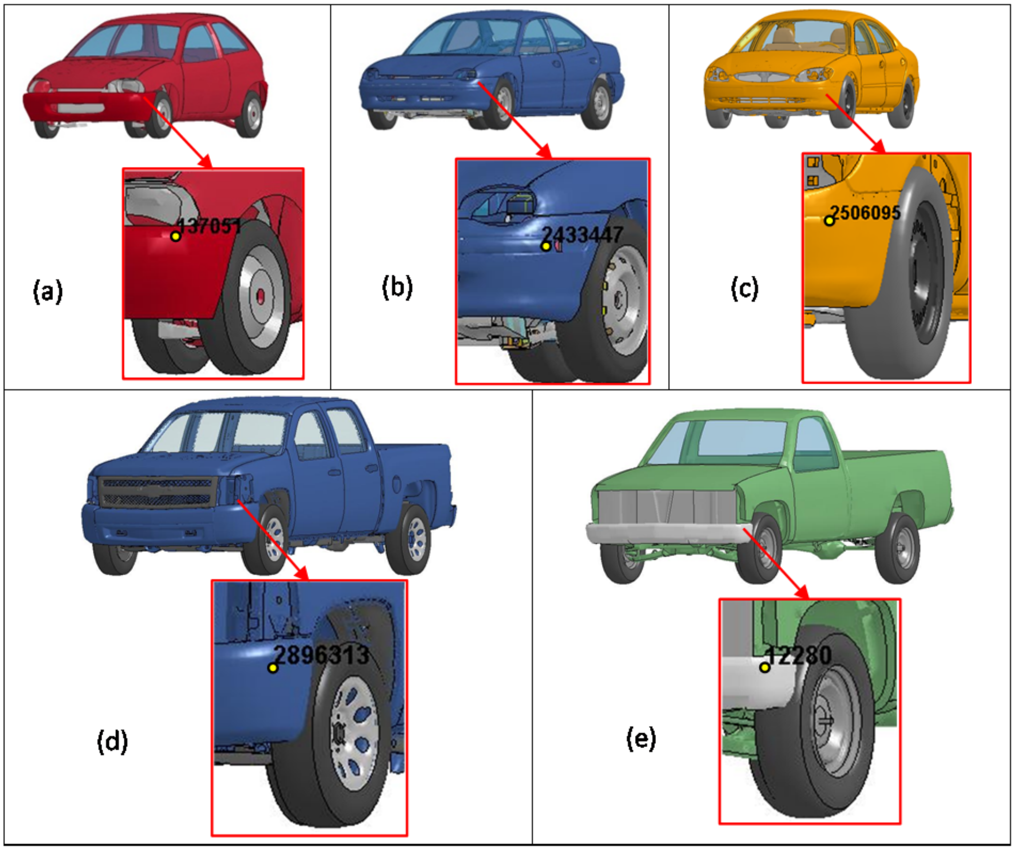


Figure 1. Critical node location for (a) 820C, (b) 1100C, (c) 1500A, (d) 2270P, and (e) 2000P

This simulation effort was limited to symmetrical V-ditch geometries and considered both 4H:1V and 6H:1V side slopes. For each slope steepness, four different ditch widths were investigated: 24, 30, 38, and 46 ft. The 24-ft and 46-ft wide ditches were considered to be representative of narrow and wide configurations commonly installed along the National Highway System (NHS), respectively, while the 30-ft and 38-ft wide ditches could provide useful information regarding the vehicle kinematics at intermediate widths.

For each combination of ditch width, slope steepness, and vehicle type, the trajectory of the critical bumper point was tracked as the vehicle traveled across the V-ditch. For each simulated bumper trajectory three critical barrier locations for vehicle capture were analyzed: (1) the location on the front slope where the trajectory reached its maximum height relative to the slope surface (override potential); (2) the location on the back slope in which the front suspension reached the maximum compression and the front bumper was at its minimum height (underride potential); and (3) the location on the back slope in which the bumper trajectory reached its maximum height after rebounding off the back slope (override/rollover potential). The lateral offset and the bumper height corresponding to each of these three critical situations were measured from the simulated trajectories and were eventually tabulated for each vehicle type and ditch width. An analysis of these tabulated data grouped by critical barrier location was then performed to identify the worst-case scenarios. Based upon this analysis, a review of the original test matrices A through C for 4H:1V V-ditches was made, and new test matrices were recommended also for the case of shallower 6H:1V ditches.

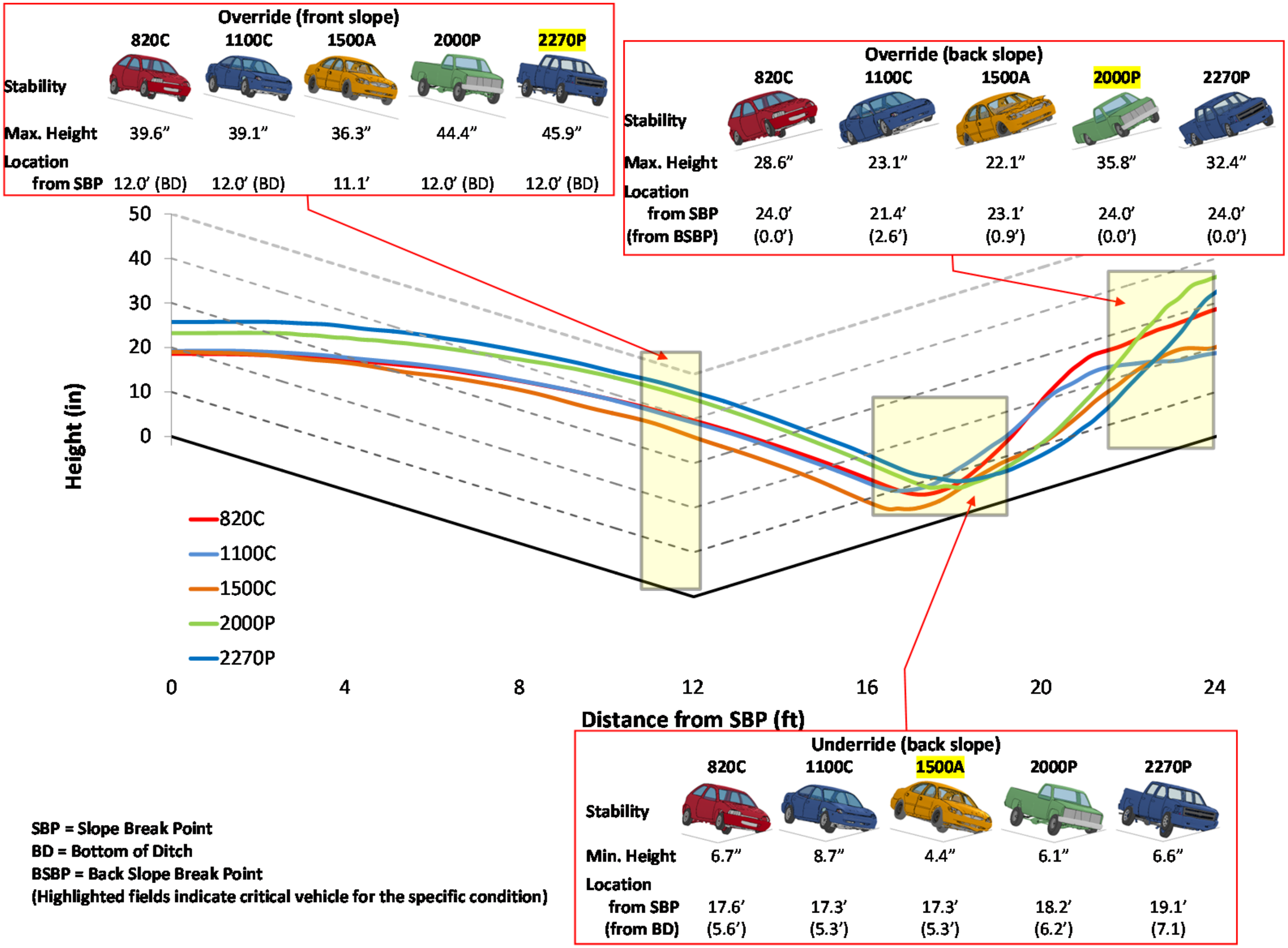
Due to unavailability of full-scale tests with vehicles traversing V-ditches, a validation of the vehicle models for the specific case of landing and rebounding was not possible. As such, the simulated trajectories have to be considered as indicative until further validation is possible.

4 CRITICAL PLACEMENT LOCATIONS FOR 4H:1V V-DITCHES

4.1 Simulated Bumper Trajectories

The simulated trajectories of the critical bumper points for all the five vehicles when traversing a 4H:1V V-ditch with a width of 24, 30, 38, and 46 ft are shown in Figures 2 through 5, respectively. For each plot, the three most critical placement locations (i.e., override on front slope, underride potential, override/rollover potential on back slope) are highlighted and the respective local minimum or maximum values for the bumper trajectories are indicated along with the vehicle attitude. Five dashed lines placed parallel to the ditch profile and equally spaced at increments of 10 in. facilitate the identification of the height reached by the tracked bumper node relative to the ditch surface for each of the trajectories plotted in the graphs. Due to unavailability of full-scale crash tests with vehicles traversing V-ditches, a validation of the vehicle models for the specific case of landing and rebounding was not possible. As such, the simulated trajectories have to be considered as indicative until further validation is possible.

Tables 6 through 8 provide a summary of the bumper heights obtained for the four ditch widths and involving the impact scenarios of override on the front slope, underride on the back slope, and override on the back slope. Tables 9 and 10 summarize the bumper heights as measured at 4 ft offset from the front SBP and in the 0 to 4 ft range from the back SBP of the ditches, respectively. A detailed discussion of the potential risks for each of the above-mentioned critical placement locations is provided in the following sections.



Override (front slope)

	820C	1100C	1500A	2000P	**2270P**
Stability					
Max. Height	39.6"	39.1"	36.3"	44.4"	45.9"
Location from SBP	12.0' (BD)	12.0' (BD)	11.1'	12.0' (BD)	12.0' (BD)

Override (back slope)

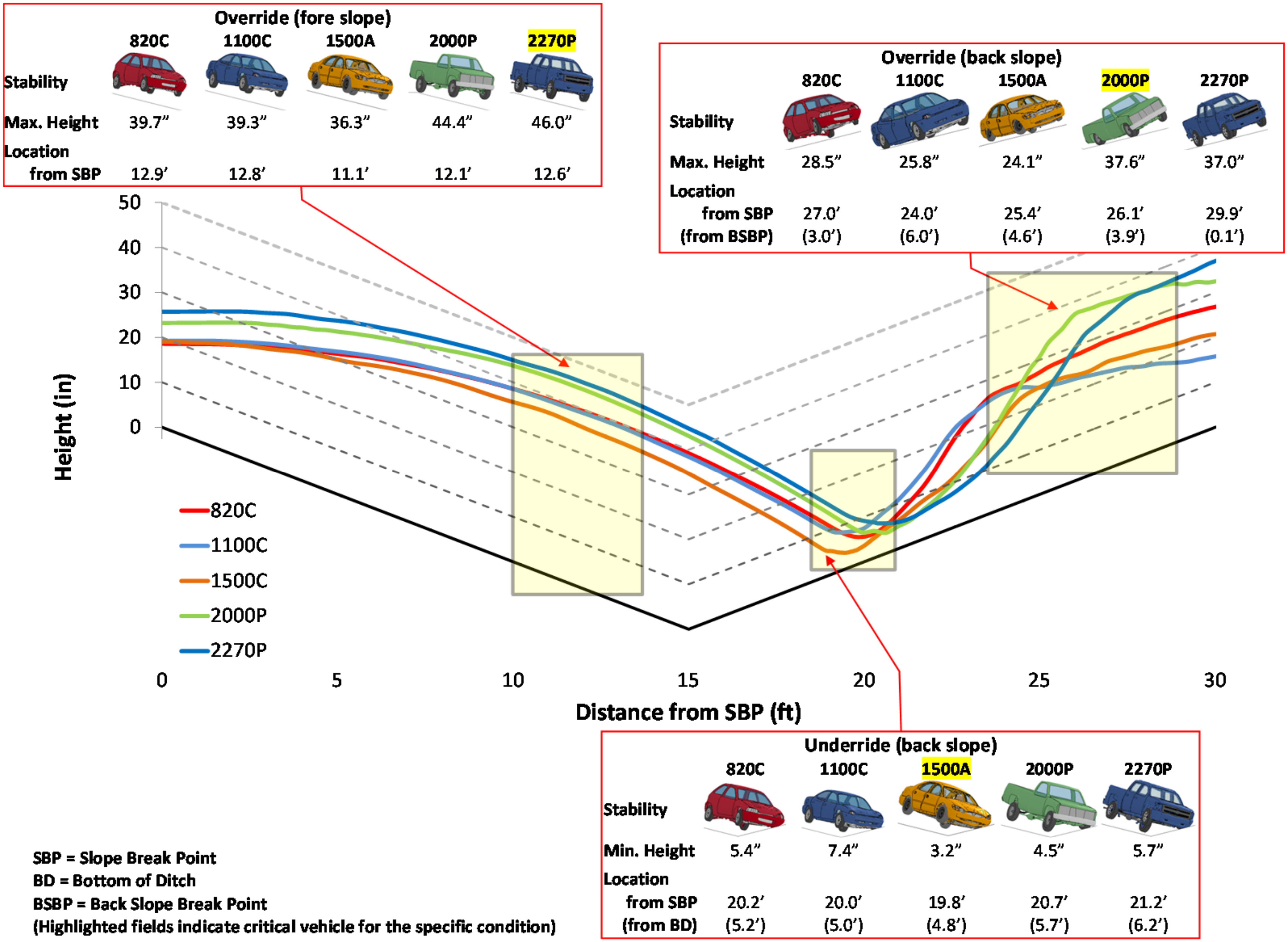
	820C	1100C	1500A	**2000P**	2270P
Stability					
Max. Height	28.6"	23.1"	22.1"	35.8"	32.4"
Location from SBP (from BSBP)	24.0' (0.0')	21.4' (2.6')	23.1' (0.9')	24.0' (0.0')	24.0' (0.0')

Underride (back slope)

	820C	1100C	**1500A**	2000P	2270P
Stability					
Min. Height	6.7"	8.7"	4.4"	6.1"	6.6"
Location from SBP (from BD)	17.6' (5.6')	17.3' (5.3')	17.3' (5.3')	18.2' (6.2')	19.1' (7.1)

SBP = Slope Break Point
BD = Bottom of Ditch
BSBP = Back Slope Break Point
(Highlighted fields indicate critical vehicle for the specific condition)

Figure 2. Trajectories of Critical Bumper Nodes of Five Passenger Vehicles – 4H:1V V-Ditch, 24 ft Wide



Override (fore slope)

	820C	1100C	1500A	2000P	2270P
Stability					
Max. Height	39.7"	39.3"	36.3"	44.4"	46.0"
Location from SBP	12.9'	12.8'	11.1'	12.1'	12.6'

Override (back slope)

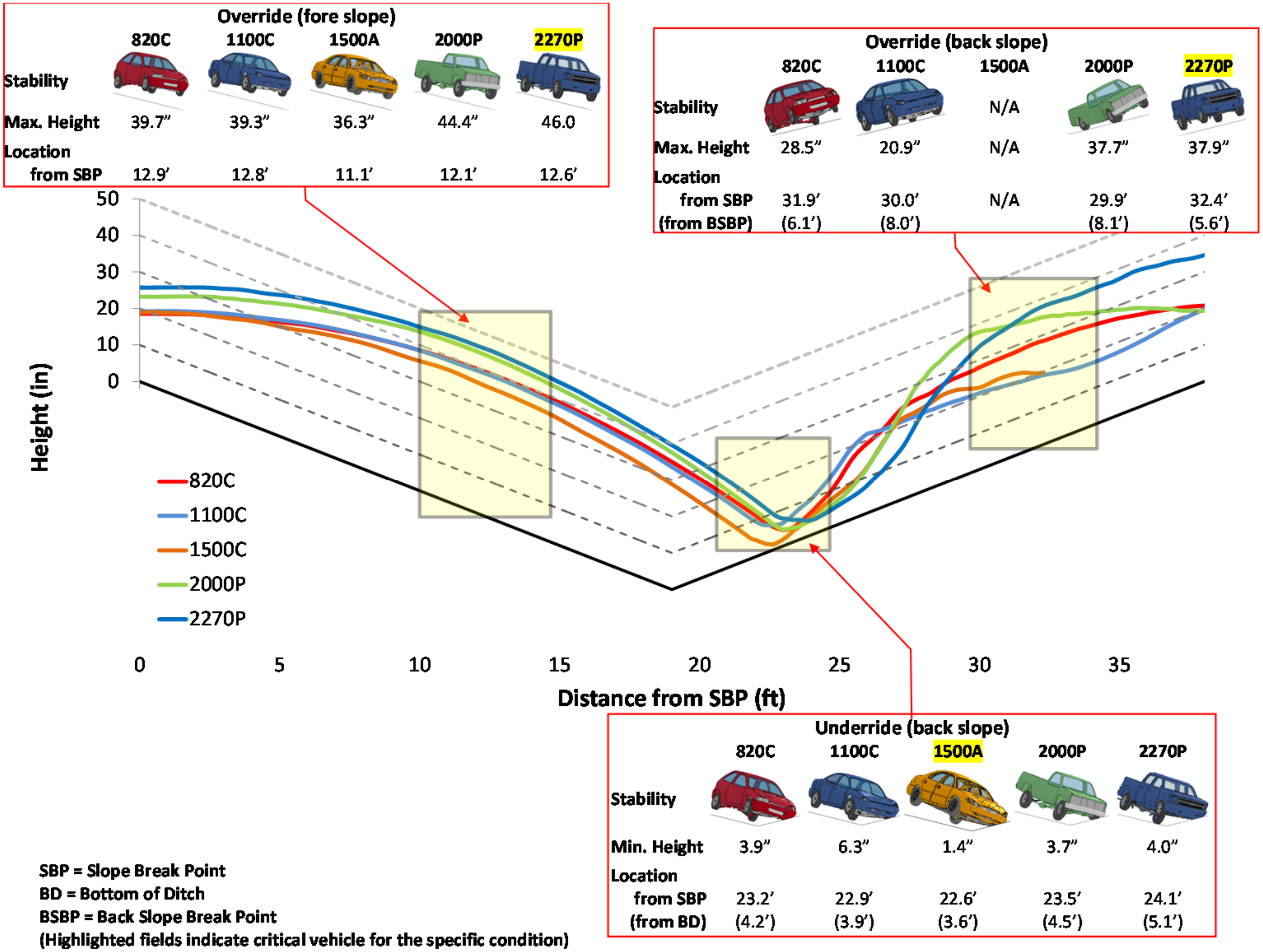
	820C	1100C	1500A	2000P	2270P
Stability					
Max. Height	28.5"	25.8"	24.1"	37.6"	37.0"
Location from SBP	27.0'	24.0'	25.4'	26.1'	29.9'
(from BSBP)	(3.0')	(6.0')	(4.6')	(3.9')	(0.1')

Underride (back slope)

	820C	1100C	1500A	2000P	2270P
Stability					
Min. Height	5.4"	7.4"	3.2"	4.5"	5.7"
Location from SBP	20.2'	20.0'	19.8'	20.7'	21.2'
(from BD)	(5.2')	(5.0')	(4.8')	(5.7')	(6.2')

SBP = Slope Break Point
BD = Bottom of Ditch
BSBP = Back Slope Break Point
(Highlighted fields indicate critical vehicle for the specific condition)

Figure 3. Trajectories of Critical Bumper Nodes of Five Passenger Vehicles – 4H:1V V-Ditch, 30 ft Wide



Override (fore slope)

	820C	1100C	1500A	2000P	2270P
Stability					
Max. Height	39.7"	39.3"	36.3"	44.4"	46.0
Location from SBP	12.9'	12.8'	11.1'	12.1'	12.6'

Override (back slope)

	820C	1100C	1500A	2000P	2270P
Stability			N/A		
Max. Height	28.5"	20.9"	N/A	37.7"	37.9"
Location from SBP	31.9'	30.0'	N/A	29.9'	32.4'
(from BSBP)	(6.1')	(8.0')		(8.1')	(5.6')

Underride (back slope)

	820C	1100C	1500A	2000P	2270P
Stability					
Min. Height	3.9"	6.3"	1.4"	3.7"	4.0"
Location from SBP	23.2'	22.9'	22.6'	23.5'	24.1'
(from BD)	(4.2')	(3.9')	(3.6')	(4.5')	(5.1')

SBP = Slope Break Point
BD = Bottom of Ditch
BSBP = Back Slope Break Point
(Highlighted fields indicate critical vehicle for the specific condition)

Figure 4. Trajectories of Critical Bumper Nodes of Five Passenger Vehicles – 4H:1V V-Ditch, 38 ft Wide

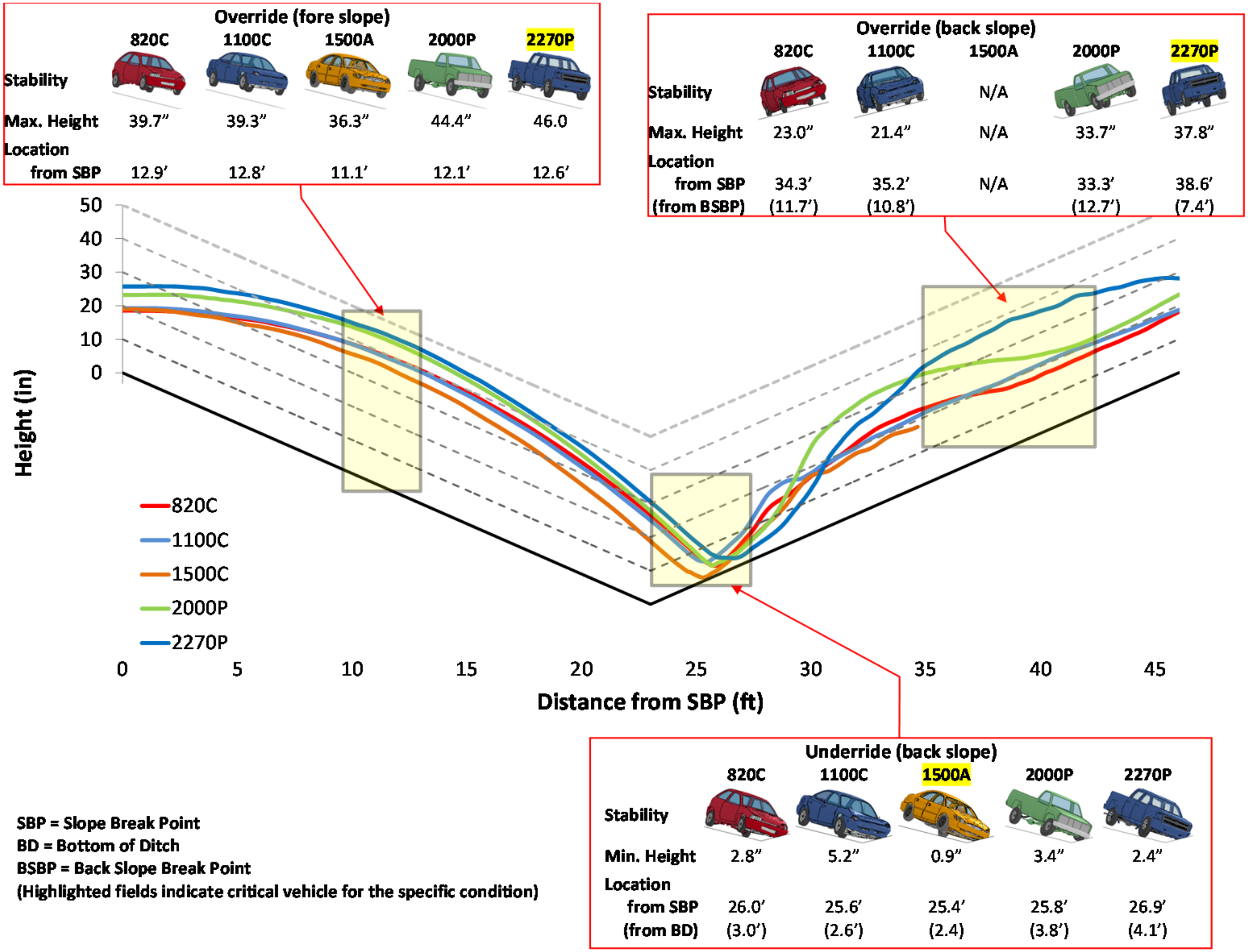


Figure 5. Trajectories of Critical Bumper Nodes of Five Passenger Vehicles – 4H:1V V-Ditch, 46 ft Wide

Table 6. Maximum Height of Critical Bumper Node on Front Slope (4H:1V)

Vehicle Type	Max. Height (in.) [Location from Front SBP (ft)]	
	24 ft wide	≥30 ft wide
820C	39.6 [12.0]	39.7 [12.9]
1100C	39.1 [12.0]	39.3 [12.8]
1500A	36.3 [11.1]	36.3 [11.1]
2000P	44.4 [12.0]	44.4 [12.1]
2270P	45.9 [12.0]	46.0 [12.6]

Highlighted fields indicate the critical condition for each vehicle

Table 7. Minimum Height of Critical Bumper Node on Back Slope (4H:1V)

Vehicle Type	Min. Height (in.) [Location from Bottom of Ditch (ft)]			
	24 ft wide	30 ft wide	38 ft wide	46 ft wide
820C	6.7 [5.6]	5.4 [5.2]	3.9 [4.2]	2.8 [3.0]
1100C	8.7 [5.3]	7.4 [5.0]	6.3 [3.9]	5.2 [2.6]
1500A	4.4 [5.3]	3.2 [4.8]	1.4 [3.6]	0.9 [2.4]
2000P	6.1 [6.2]	4.5 [5.7]	3.7 [4.5]	3.4 [3.8]
2270P	6.6 [7.1]	5.7 [6.2]	4.0 [5.1]	2.4 [4.1]

Highlighted fields indicate the critical condition for each vehicle

Table 8. Maximum Height of Critical Bumper Node on Back Slope (4H:1V)

Vehicle Type	Max. Height (in.) [Location from Back SBP (ft)]			
	24 ft wide	30 ft wide	38 ft wide	46 ft wide
820C	28.6 [0.0]	28.5 [3.0]	28.5 [6.1]	23.0 [11.7]
1100C	23.1 [2.6]	25.8 [6.0]	20.9 [8.0]	21.4 [10.8]
1500A	22.1 [0.9]	24.1 [4.6]	NA	NA
2000P	35.8 [0.0]	37.6 [3.9]	37.7 [8.1]	33.7 [12.7]
2270P	32.4 [0.0]	37.0 [0.1]	37.9 [5.6]	37.8 [7.4]

Highlighted fields indicate the critical condition for each vehicle
NA – Not Available

Table 9. Height of Critical Bumper Node at 4 ft from Front SBP (4H:1V)

Vehicle Type	Height (in.) @ 4 ft from Front SBP ≥24 ft wide
820C	29.2
1100C	29.7
1500A	28.6
2000P	34.2
2270P	36.7

Table 10. Maximum Height of Critical Bumper Node at 0-4 ft range from Back Slope (4H:1V)

Vehicle	Max. Height (in.) [Location from Back SBP (ft)]			
Type	24 ft wide	30 ft wide	38 ft wide	46 ft wide
820C	28.6 [0.0]	28.5 [3.0]	27.4 [4.0]	18.1 [0.0]
1100C	23.1 [2.6]	22.8 [4.0]	19.8 [0.0]	20.1 [4.0]
1500A	22.1 [0.9]	23.8 [3.1]	NA	NA
2000P	35.8 [0.0]	37.3 [3.9]	30.7 [4.0]	23.2 [0.0]
2270P	32.4 [0.0]	37.0 [0.1]	37.6 [2.5]	35.4 [4.0]

Highlighted fields indicate the critical condition for each vehicle
NA – Not Available

4.2 Override Potential (Front Slope)

The maximum height of the critical bumper node relative to the ditch surface was tracked for each vehicle to determine the placement location where the risk of override is most likely to occur. For all widths except for the narrowest ditch (24-ft wide), the maximum trajectory height above the front slope remained constant and occurred at the same lateral offset from the front SBP, at a distance between 11.1 ft and 12.9 ft, depending of the vehicle type. In the case of a 24-ft wide ditch, lower critical bumper heights were measured and occurred at the bottom of the ditch due to the narrower width (except for the 1500A vehicle).

The bumper trajectories for pickup trucks reached higher critical heights than those observed for the three passenger cars (due to the higher initial bumper locations relative to the ground), as indicated in Figures 2 through 5 and Table 6. More specifically, the 2270P and the

2000P vehicles resulted in maximum critical bumper heights of 46.0 in. and 44.4 in. at lateral offsets of 12.6 ft and 12.1 ft from the front SBP, respectively. Considering these critical bumper heights as well as the increased inertia and higher centers of mass, pickup trucks represent the most critical category of passenger vehicles for use in evaluating the potential for barrier override on the front slope.

The location of the maximum of the simulated bumper node trajectory was measured based on an ideally sharp SBP. However, in actual conditions a rounded edge is likely and would reduce this distance by a few inches. Since the critical heights of the bumper trajectories for the 2000P and 2270P vehicles were reached at 12.1 ft and 12.6 ft from the front SBP, respectively, the critical override condition would consider a barrier placed approximately 12 ft from the front SBP.

The largest maximum bumper height amongst the three small to midsize passenger cars was 39.7 in. at 12.9 ft from the front SBP for the 820C vehicle, as shown in Table 6. This height is significantly lower than the maximum height reached by the pickup truck, thus if a cable barrier system located 12 ft from the front SBP safely captured a 2270P vehicle under MASH conditions, then it is unlikely that barrier override would occur with small to midsize passenger cars. Hence, no crash testing conditions with small to midsize passenger cars would be deemed necessary for evaluating barrier override.

4.3 Underride Potential (Back Slope)

The minimum height of the critical bumper node relative to the ditch surface was tracked for each vehicle as it landed in the ditch and the front suspensions and tires reached maximum compression. This condition represents the most critical scenario for a vehicle to underride a cable barrier system.

For the simulated conditions, all five vehicle types landed in a stable manner with moderate pitch and limited roll angles. For all four investigated widths, the vehicles landed onto the back slope of the ditch. The worst-case underride condition was represented by the 46-ft wide ditch, as indicated in Table 7. In this case, the kinetic energy of the free-falling vehicles reached the highest values due to the increased vertical drop. For the 46-ft wide ditch, the lateral locations where minimum bumper trajectories were reached ranged between 2.4 and 4.1 ft from the ditch bottom and with critical heights from 0.9 in. to 5.2 in. In particular, the minimum critical bumper height reached by the 820C, 1100C, and 1500A were 2.8 in., 5.2 in., and 0.9 in., respectively; while the 2000P and the 2270P pickup trucks reached a minimum height of 3.4 in. and 2.4 in., respectively. Despite their relatively low bumper heights, the 2000P and 2270P pickup trucks were not deemed as critical as small passenger vehicle for underride due to the taller front-end profile.

The 1500A passenger sedan represents the most critical vehicle for underride since it demonstrated (a) the minimum critical bumper height (0.9 in.) and (b) it is characterized by the largest inertia amongst all passenger car models considered in this study. Although the 1100C vehicle reached a higher critical bumper height compared to the 1500A, it may be considered a critical vehicle as well because of a potentially weaker A-pillar and more penetrating front-end geometry. Thus, the 1100C occupant compartment may be subjected to excessive crush or penetration.

For the sake of simplicity, computer simulations were performed assuming a rigid ditch surface. This assumption does not always represent the real situation of the ground, especially in proximity of the ditch bottom where softer soil is likely to occur due to the accumulation of water run-off and/or high water table. In this condition, there is a potential for the impacting wheel to gouge into and drag through the soil when the vehicle lands in the ditch, thus increasing the potential for the vehicle to underride the cable barrier system when positioned only a short distance from the actual landing point. For this reason, the critical barrier placement should be moved about 1 ft beyond the point where the minimum bumper height occurred in the simulations with rigid soil condition. Thus, the recommended critical location is 4 ft from the ditch bottom.

4.4 Override Potential (Bouncing Effect on Back Slope)

When a vehicle lands on the ground surface after free falling, the springs of the suspension system are compressed. Subsequently, the suspension system unloads and the vehicle bounces above the ditch back slope. During this rebound phase, the airborne vehicle may pose some risks for overriding a cable barrier system placed on the back slope. The critical override condition on the back slope would likely correspond to the location where the maximum bumper height is observed for a given vehicle type, impact condition, and ditch configuration.

The simulated vehicle kinematics clearly indicated that the bumper trajectories for the two pickup trucks were higher than those observed for the small cars and midsize sedan. From an analysis of the bumper trajectories, the 2000P and the 2270P vehicles reached a maximum rebound height in a 38-ft wide ditch, as summarized in Table 8. As the maximum bumper heights for the 2270P vehicle in ditches with a width of 30, 38, and 46 ft varied by less than 1 in., any of the three widths may arguably provide a critical override test scenario for evaluating barrier systems installed on the back slope. Lower bumper trajectories were obtained with a 24-ft wide ditch for both the 2000P and 2270P, as shown in Table 8. This indicates that widths equal to or greater than 30 ft can be selected as critical for evaluating override with pickup trucks. Further, the simulated bumper trajectory indicated that, for the cases of 30-, 38-, and 46-ft wide ditches, the 2270P vehicle reached a height relative to the ditch surface close to the maximum value at a distance from the bottom of the ditch ranging between 12 ft and 14 ft. After reaching that point, the height of the bumper trajectory basically remained constant with only the exception of the 46-ft wide ditch, for which the high of the trajectory started to decrease. As such, the critical location for testing the potential for the 2270P vehicle to override the cable system placed on the back slope can be reasonably defined to be at 13 ft from the bottom of a 30-, 38-, or 46-ft wide ditch.

As previously discussed, the simulated vehicle rebound trajectories indicated lower critical bumper heights for small cars as compared to pickup trucks. However, a recent full-scale crash test performed by the TTI involving a 1100C vehicle with a cable system placed 4 ft from the back SBP of a 30-ft wide ditch resulted in a vehicle rollover [12]. For this test, the small car encountered significant rebound above the back slope, much more than what predicted by the numerical simulations shown herein. A refinement of the suspensions in the 1100C vehicle model would be necessary to more accurately predict vehicle rebound on the back slope. During the full-scale crash test, after the vehicle was captured by a top cable positioned at 45 in. above the ground and was redirected, it rolled over. Although the vehicle rollover may have been a consequence of the cables becoming entangled with the guidance system attached to the right-front wheel, a crash test with the 1100C vehicle on a cable barrier placed 4 ft from the back SBP is still recommended in combination with a 30-ft wide ditch.

Due to unavailability of full-scale tests with vehicles traversing V-ditches, a validation of the vehicle models for the specific case of landing and rebounding was not possible. As such, the simulated trajectories have to be considered as indicative until further validation is possible.

4.5 Proposed Critical Tests Identified from Bumper Trajectories in a 4H:1V V-Ditch

A summary of the critical testing scenarios for evaluating 4H:1V V-ditches (i.e., combinations of vehicle type, barrier location, and ditch width) is provided in Table 11. Note that these critical locations are based purely on considerations for underride/override, and do not take into account potential vehicular instabilities or penetrations. A more comprehensive test matrix is provided in Chapter 5 of this report.

Table 11. Override/Underride Testing Scenarios for Cable Barriers Placed in a 4H:1V V-Ditch

Vehicle Type	**Critical Ditch & Location**			**Expected Potential Risk**
	Ditch Width (ft)	**Barrier Position**	**Barrier Location (ft)**	
2270P	≥ 30	Front Slope	12 from Front SBP	Override/Rollover
1100C	46	Back Slope	27 from Front SBP (4 from Ditch Bottom)	Underride
1500A	46	Back Slope	27 from Front SBP (4 from Ditch Bottom)	Underride
2270P	≥ 30	Back Slope	(13 from Ditch Bottom)	Override/Rollover
1100C	30	Back Slope	26 from Front SBP (4 from Back SBP)	Override/Rollover

5 MODIFIED TEST MATRICES FOR A 4H:1V V-DITCH

5.1 Background

MwRSF and TTI have recently proposed three potential test matrices (Matrices A through C) for evaluating cable median barriers placed in 4H:1V V-ditches. In particular, Matrices A and B included a series of tests for evaluating the scenarios of a single cable barrier system placed anywhere in the ditch or within a range of 0 to 4 ft beyond the front or back ditch SBP, respectively. While Matrix C included a series of tests for evaluating the scenario of two cable barrier systems placed in the ditch, each 0 to 4 ft from a SBP. The three test matrices were shown previously in Tables 1 through 3.

The three updated proposed test matrices, including modifications (indicated in red) based on the simulation results provided herein are shown in Tables 12 through 14.

5.2 Test Descriptions

5.2.1 Test No. 1

The primary evaluation factors for test no. 1 are to assess the capability of the system to contain the vehicle and prevent override. The 2270P vehicle was considered to be the most critical vehicle because of its large inertia, the high center of mass, and the highest peak reached by the bumper trajectory above the ditch surface. The critical barrier placement was determined to be 12 ft from the front SBP, where the tracked critical bumper node reached its maximum height with respect to the ditch surface.

Currently two ditch widths are listed for Test no. 1, a 30 ft (test no. 1a) and a 46 ft (test no. 1b). The dual listing is due to conflicting views on the identification of the critical width. On one side, override and containment risks are maximized if the 2270P is allowed to continue down the foreslope of a wide ditch. On the other side, vehicle contact with the backslope surface while being contained and redirected by the system may cause some instability. As such, in order to

Table 12. Matrix A - Single Median Barrier Placed Anywhere in Ditch (4H:1V)

Test No.	**Test Designation No.**	**Vehicle Type**	**Impact Conditions**		**Ditch Width (ft)**	**Barrier Position**	**Barrier Location**	**Primary Evaluation Factors**
			Speed (mph)	**Angle (deg)**				
1a	3-11$^{(+)}$	2270P	62	25	46	Front Slope	12 ft from Front SBP	Vehicle containment, override prevention, & W.W.
1b	3-11$^{(+)}$	2270P	62	25	30	Front Slope	12 ft from Front SBP	
2	3-10$^{(+)}$	1100C	62	25	≥30	Front Slope	12 ft from Front SBP	Vehicle stability & A-pillar integrity
3	3-10$^{(+)}$	1100C	62	25	46	Back Slope	4 ft from Ditch Bottom (27 ft from Front SBP)	Vehicle containment, ORA/OIV, & underride prevention
4a	3-10$^{(+)}$	1100C	62	25	46	Back Slope	4 ft from Back SBP	Increased vehicle orientation at impact & override
4b	3-10$^{(+)}$	1100C	62	25	30	Back Slope	4 ft from Back SBP	
5	TBD	1500A	62	25	Note 1	Note 1	Note 1	Vehicle penetration & A-pillar integrity
6	3-11	2270P	62	25	NA	Level Terrain	NA	Vehicle containment & W.W.
7	3-10	1100C	62	25	NA	Level Terrain	NA	Vehicle stability & A-pillar integrity
8	3-11$^{(+)}$	2270P	62	25	≥30	Back Slope	13 ft from Ditch Bottom	Override & increased vehicle orientation at impact
9	TBD	1500A	62	25	46	Back Slope	4 ft from Ditch Bottom	Vehicle containment, ORA/OIV, & underride prevention

SBP – Slope Break Point
W.W. – Working Width
ORA – Occupant Ridedown Acceleration
OIV – Occupant Impact Velocity
NA – Not Applicable
Note 1 – Testing laboratory should determine critical barrier position on front slope of ditch or on level terrain in order to maximize propensity for front end of 1500A vehicle to penetrate between adjacent vertical cables. Critical factors may include vertical cable spacing, location and type of cable release mechanisms, vehicle projectile motion, etc.
$^{(+)}$ Specific test designation to be assigned

Table 13. Matrix B - Single Median Barrier Placed at 0 to 4-ft Offset from SBP (4H:1V)

Test No.	**Test Designation No.**	**Vehicle Type**	**Impact Conditions**		**Ditch Width (ft)**	**Barrier Position**	**Barrier Location**	**Primary Evaluation Factors**
			Speed (mph)	**Angle (deg)**				
1	3-11(+)	2270P	62	25	≥30	Front Slope	4 ft from Front SBP	Vehicle containment, override prevention, & W.W.
2	3-10(+)	1100C	62	25	≥30	Front Slope	4 ft from Front SBP	Vehicle stability & A-pillar integrity
3(*)	3-10(+)	1100C	62	25	Narrow (22 ft wide)	Back Slope	4 ft from Back SBP	Vehicle containment, ORA/OIV, & underride prevention
4a	3-10(+)	1100C	62	25	46	Back Slope	4 ft from Back SBP	Increased vehicle orientation at impact & override
4b	3-10(+)	1100C	62	25	30	Back Slope	4 ft from Back SBP	
5	TBD	1500A	62	25	Note 1	Note 1	Note 1	Vehicle penetration & A-pillar integrity
6	3-11	2270P	62	25	NA	Level Terrain	NA	Vehicle containment & W.W.
7	3-10	1100C	62	25	NA	Level Terrain	NA	Vehicle stability & A-pillar integrity
8(*)	3-11(+)	2270P	62	25	30	Back Slope	2 ft from Back SBP	Override & increased vehicle orientation at impact
9(*)	TBD	1500A	62	25	Narrow (22 ft wide)	Back Slope	4 ft from Back SBP	Vehicle containment, ORA/OIV, & underride prevention

SBP – Slope Break Point
W.W. – Working Width
ORA – Occupant Ridedown Acceleration
OIV – Occupant Impact Velocity
NA – Not Applicable
Note 1 – Testing laboratory should determine critical barrier position from 0 to 4 ft on front slope of ditch or on level terrain in order to maximize propensity for front end of 1500A vehicle to penetrate between adjacent vertical cables. Critical factors may include vertical cable spacing, location and type of cable release mechanisms, vehicle projectile motion, etc.
(*) Corresponding test from Matrix A (4H:1V) can be considered an equivalent substitute
(+) Specific test designation to be assigned

Table 14. Matrix C - Double Median Barrier Placed at 0 to 4-ft Offset from Both SBP (4H:1V)*

Test No. (*)	**Test Designation No.**	**Vehicle Type**	**Impact Conditions**		**Ditch Width (ft)**	**Barrier Position**	**Barrier Location**	**Primary Evaluation Factors**
			Speed (mph)	**Angle (deg)**				
1	3-11$^{(+)}$	2270P	62	25	≥ 30	Front Slope	4 ft from Front SBP	Vehicle containment, override prevention, & W.W.
2	3-10$^{(+)}$	1100C	62	25	≥ 30	Front Slope	4 ft from Front SBP	Vehicle stability & A-pillar integrity
5	TBD	1500A	62	25	Note 1	Note 1	Note 1	Vehicle penetration & A-pillar integrity
6	3-11	2270P	62	25	NA	Level Terrain	NA	Vehicle containment & W.W.
7	3-10	1100C	62	25	NA	Level Terrain	NA	Vehicle stability & A-pillar integrity

SBP – Slope Break Point
W.W. – Working Width
NA – Not Applicable
Note 1 – Testing laboratory should determine critical barrier position from 0 to 4 ft on front slope of ditch or on level terrain in order to maximize propensity for front end of 1500A vehicle to penetrate between adjacent vertical cables. Critical factors may include vertical cable spacing, location and type of cable release mechanisms, vehicle projectile motion, etc.

[*] Tests 3, 4, 8, 9 defined in Matrices A and B not necessary for a double system
(+) Specific test designation to be assigned

identify the critical ditch width, it will be necessary to initially run test no. 1 on the same cable system in both 30-ft and 46-ft wide ditches. The feedback provided by testing experience will create the basis for identifying which width is worse. Eventually, one selected width will be recommended for future testing under test no. 1.

For Matrices B and C, the critical location is limited to the maximum placement offset for these matrices, i.e., 4 ft from the front SBP.

5.2.2 Test No. 2

The primary evaluation for test no. 2 is to assess the system capability to prevent vehicle instability and rollover while capturing and redirecting a small car (1100C) which is traveling into the ditch. The risk of vehicle rollover for the small car is the result of the combination of three different factors: (1) the relatively small rotational inertia, (2) the roll and pitch rotations obtained by the vehicle while traveling into the ditch before it contacts the barrier; and (3) the potential instability caused by the redirecting forces acting on the vehicle while it is still airborne. To maximize the airborne interaction time, the critical barrier location was set where the 1100C vehicle reaches the maximum height above the ditch surface, at 12 ft from the front SBP. Test no. 2 should be performed in a ditch width equal or greater than 30 ft.

For Matrices B and C, the critical location is limited to the maximum placement offset for these matrices, i.e., 4 ft from the front SBP.

5.2.3 Test Nos. 3 and 9

Test nos. 3 and 9 assess the potential risk for passenger vehicles to underride the cable system. The 1100C and 1500A vehicles have been proposed in test nos. 3 and 9, respectively. The 1500A vehicle is heavier than the 1100C vehicle and reached a lower minimum bumper height in the numerical simulations, so it may have a higher risk to underride the system. However, the front-end geometry of the 1100C may also lead to vehicle underride. Additionally, the 1100C passenger car is typically characterized as having a weaker A-pillar compared to the 1500A passenger sedan. Thus, a test with the 1100C vehicle is deemed necessary to evaluate crushing of the A-pillar or penetration into the occupant compartment as the vehicle tries to underride the cables.

With a steepness of 4H:1V, all simulated vehicles landed on the back slope, including on the 46-ft wide ditch. For wider ditches, vehicles will remain airborne for a longer period of time, thus maximizing the vertical velocity as well as the roll and pitch angles. The combination of these factors leads to the greatest amount of suspension compression and the lowest height of the vehicle front end. Thus, a 46-ft wide ditch was recommended for test nos. 3 and 9 in Matrix A. Simulation results indicated that the critical barrier location for this ditch width is about 4 ft laterally from the bottom and up the back slope for both the 1100C (test no. 3) and 1500A (test no. 9) vehicles.

For Matrix B, simulation results for a narrow ditch (24 ft wide) indicated that the location with the maximum potential for underride with the 1100C vehicle occurred at about 6 ft from the back SBP. Hence, with a slightly narrower ditch width, say 22 ft, the critical underride potential would likely occur approximately 3 to 4 ft from the back SBP. Therefore, test nos. 3 and 9 of Matrix B are to be conducted with the barrier placed 4 ft from the back SBP of a 22-ft wide V-ditch. The height of the critical bumper node reached by the 1100C and 1500A vehicles computed at a 4-ft offset from the back SBP of a 22-ft wide 4H:1V V-ditch as shown in Table 15. In case a 22-foot wide ditch is not available for testing, test nos. 3 and 9 in Matrix B can be substituted by the corresponding (and more severe) tests in Matrix A which require a 46-ft wide ditch.

Since the main evaluation criteria are vehicle containment and underride prevention, the impact point for test no. 9 with the 1500A vehicle should be at the midspan instead of 12 in. upstream of the barrier post as suggested by MASH for the this type of vehicle.

Test nos. 3 and 9 are not required for Matrix C as there would be a barrier on both sides of the ditch, thus preventing vehicle contact with the back slope.

Table 15. Height of Critical Bumper Node 4 ft from Back SBP of a 22-ft Wide Ditch (4H:1V)

Vehicle Type	**Height (in.)**
1100C	13.5
1500A	8.2

5.2.4 Test Nos. 4 and 8

Both test nos. 4 and 8 aim to evaluate potential risks associated with impacts after the vehicle travels across the center of the ditch and up the back slope. In particular, two different circumstances can arise that may lead to a critical system test: (1) increased vehicle orientation and (2) override of the system.

The possibility of the front tires steering up the back slope increases the vehicle heading and/or impact angles. This phenomenon, which has been seen in previous full-scale crash testing, may result in a significant increase in impact severity and may cause instability during the redirection of the vehicle as well. To maximize the possibility for increased vehicle orientation, test no. 4a involves an 1100C vehicle with a 46-ft wide ditch. The relatively low rotational inertia of the small car and the longer airborne time while the vehicle traverses a wider ditch will maximize the potential for an increased vehicle orientation. The critical location for test no. 4a is defined at 4 ft from the back SBP.

The potential for overriding the system is a result of the vehicle bouncing after impacting the back slope and becoming airborne again. Results from a recent full-scale crash test clearly indicated the risk for the 1100C vehicle to override the barrier when placed 4 ft from the back SBP of a 30-ft wide ditch as the vehicle was captured only by the top cable of a 45-in. tall system [12]. Although the simulated vehicle kinematics indicated bumper heights lower than that observed in the actual crash testing, simulations agreed that the 30-ft wide ditch would result in the greatest rebound off the backslope for the 1100C vehicle. Thus, test no. 4b involves an 1100C vehicle and a 30-ft wide ditch. Refinement of the suspension systems for all simulated passenger vehicles would be necessary if more accurate results are desired.

Although there are currently two combinations of ditch width and critical location listed for test no. 4, it is envisioned that one of these will prove to be more critical. Future full-scale testing results from both test nos. 4a and 4b on similar systems shall be used to determine which of these two ditch widths is more critical, thus resulting in the selection of a single test.

Simulated trajectories for the critical bumper node indicated that the 2270P bounced off the back slope and reached greater heights than the 1100C. Although the suspension rebound/bounce effect cannot be verified due to lack of testing, the general trend of the simulated trajectories shown in Figures 3 through 5 were assumed to be representative of the actual suspension rebound/bounce effect. Thus, there is a risk for the 2270P to override the barrier due to bouncing off the backslope. Test no. 8 was added to matrices A and B to evaluate this potential risk. The difference in the maximum height of the trajectories for 30-ft, 38-ft, and 46-ft wide ditches was negligible, as summarized in Table 8. Additionally, the maximum rebound height for the 2270P occurred in a range of 12 ft to 14 ft from the bottom of the ditch for these three widths. Therefore, the critical barrier location for test no. 8 was placed at 13 ft from the bottom of a V-ditch which is at least 30-ft wide.

For evaluations under Matrix B, the same barrier location would apply for test no. 8 but limited to only a 30-ft wide V-ditch. As for wider ditches, the barrier would be otherwise located outside the 0 to 4 ft offset if placed 13 ft from the bottom of the ditch. In case only ditches wider than 30 ft were available for testing, test no. 8 from Matrix A can be considered as an alternative due to the higher severity.

Test nos. 4 and 8 do not apply to matrix C as the barrier on the foreslope would prevent the impacting vehicle from traveling up the backslope.

5.2.5 Test No. 5

Test no. 5 is meant to evaluate the risk of vehicle penetration through a cable barrier. As cable heights are raised to prevent the potential for override of installations on slopes, the increased vertical spacing between cables may induce the vehicle penetration through the cables. The 1500A sedan was selected to evaluate penetration due to its larger inertia over the 1100C, while maintaining a small front-end profile. Additionally, a recent study has shown that sedans are the most common vehicles in cable barrier penetrations [15]. Since the main evaluation criteria are vehicle penetration and A-pillar integrity, the impact point should be at the midspan instead of 12 in. upstream of a barrier post as suggested by MASH for the this type of vehicle.

Although full vehicle penetration is the main concern for test no. 5, a partial penetration may also pose potential risks such as a crushing of the A-pillar by a cable sliding over the vehicle hood or instability caused by a cable going under the bumper and tripping the vehicle. Either of these events would result in a test failure.

The critical placement will be dependent on the specific barrier design, including factors such as cable spacing, vertical location of largest cable gap, cable-to-post connection, and height relative to the 1500A vehicle bumper. As such, the testing agency should determine the critical barrier placement as the location which maximizes the probability of front end penetration between adjacent cables. Either placement on level terrain or on a ditch foreslope such that the vehicle projectile motion off the front SBP results in an impact at the critical height can be considered.

5.2.6 Test Nos. 6 and 7

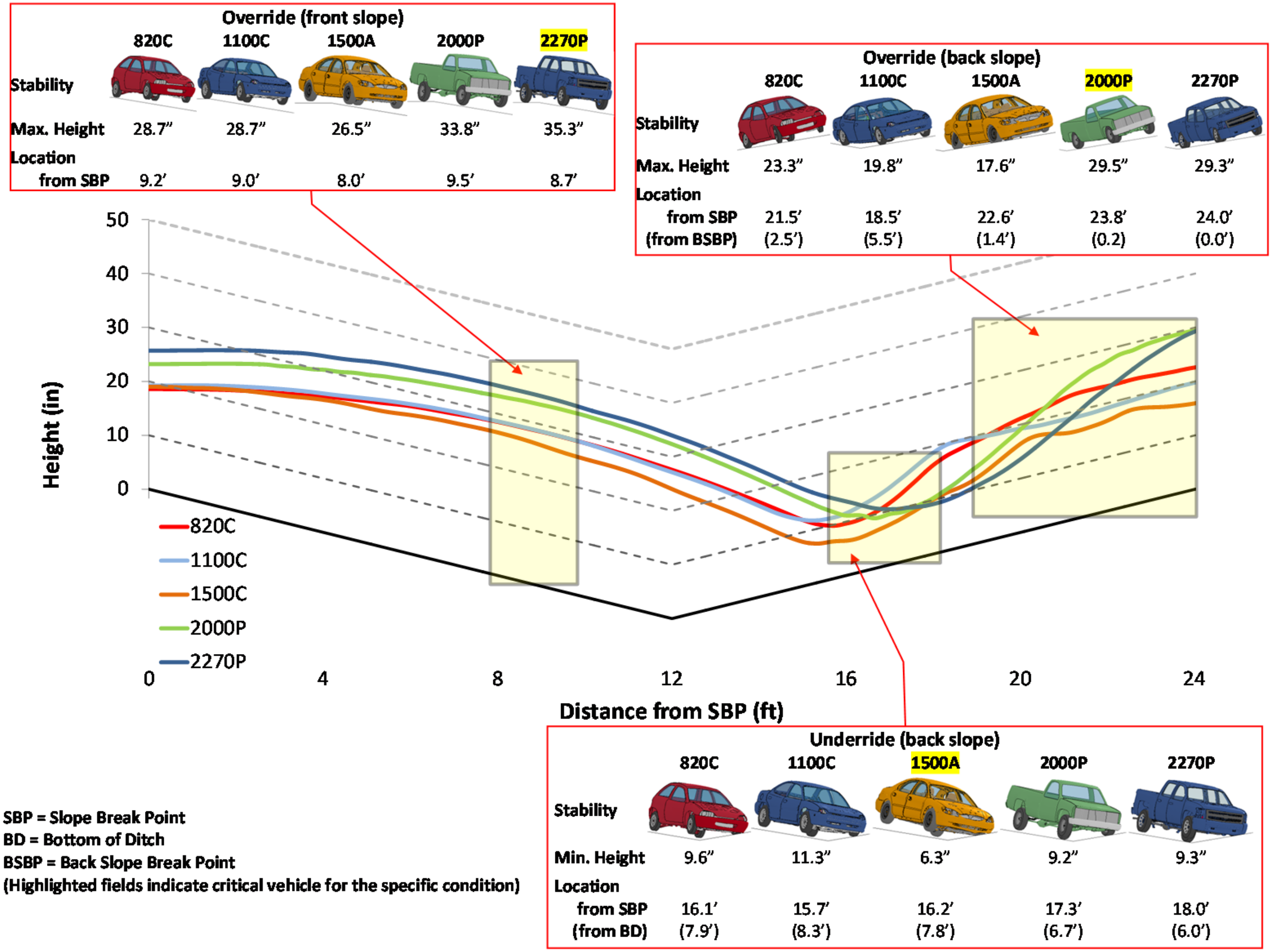
Test nos. 6 and 7 represent the present MASH test designation nos. 3-10 and 3-11, respectively, for testing longitudinal barrier systems on level terrain, including cable barriers. As cable systems placed on slopes will likely be taller than previous level terrain systems, the top cable(s) may pose an increased risk to the integrity of the occupant compartment (e.g. the vehicle A-pillar). Thus, test no. 6 with the 1100C may prove to be critical. Additionally, test no. 7 with the 2270P addresses containment and working width issues.

6 CRITICAL PLACEMENT LOCATIONS FOR 6H:1V V-DITCHES

6.1 Simulated Bumper Trajectories

Similarly to the case with a 4H:1V V-ditch, three critical locations for override/underride were investigated for shallower 6H:1V V-ditches width widths of 24, 30, 38, and 46 ft. The graphical results from these computer simulations are provided in Figures 6 through 9. A summary of the bumper heights obtained for the four ditch widths and involving the case of override on the front slope, underride on the back slope, and override on the back slope are shown in Tables 16 through 18, respectively. The bumper heights as measured at 4 ft offset from the front SBP and in the 0 to 4 ft range from the back SBP of the ditches are shown in Tables 19 and 20, respectively.

A detailed discussion of the potential risks for each of the above-mentioned locations is provided in the following sections.



Override (front slope)

	820C	1100C	1500A	2000P	2270P
Stability					
Max. Height	28.7”	28.7”	26.5”	33.8”	35.3”
Location from SBP	9.2’	9.0’	8.0’	9.5’	8.7’

Override (back slope)

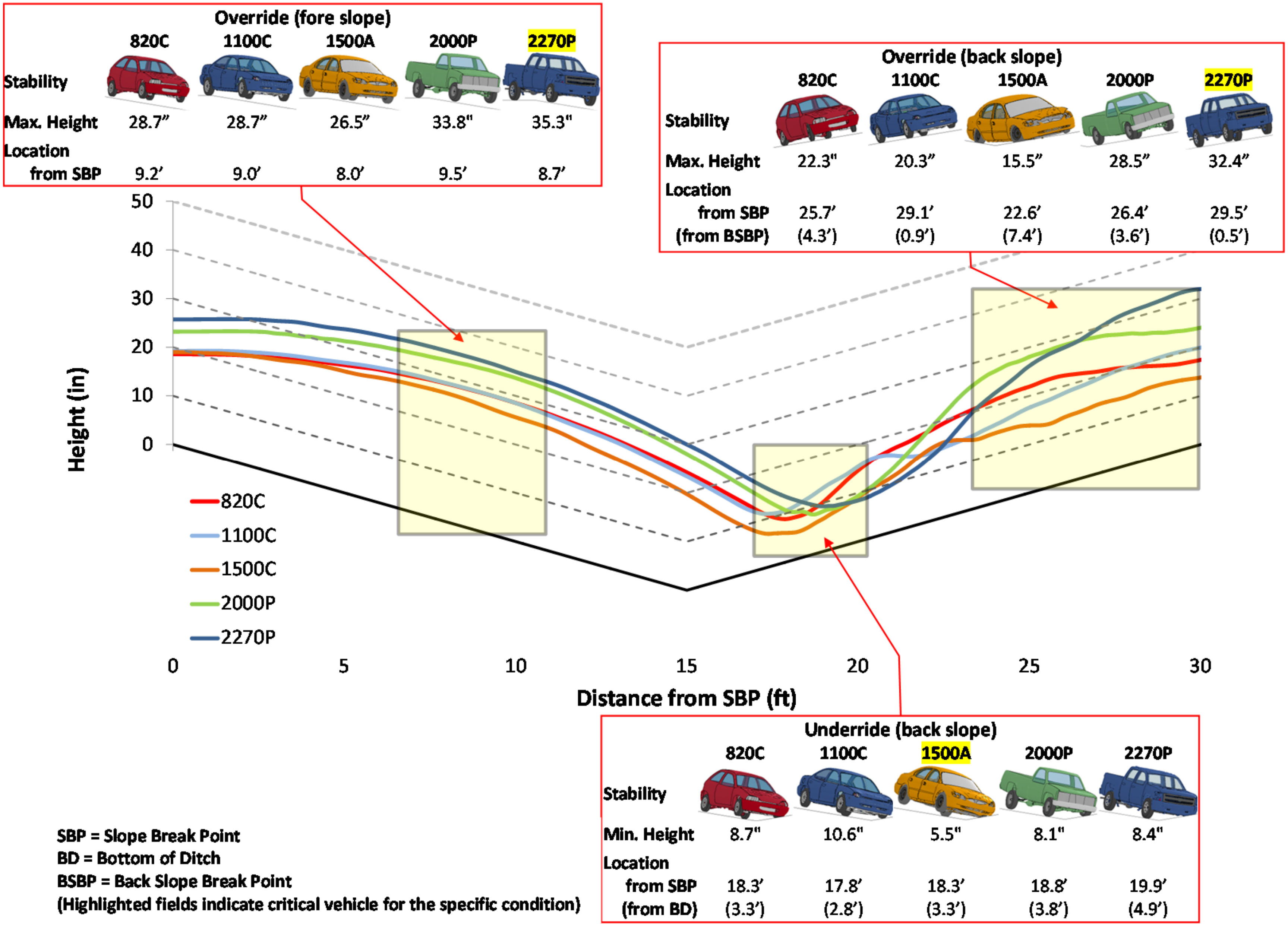
	820C	1100C	1500A	2000P	2270P
Stability					
Max. Height	23.3”	19.8”	17.6”	29.5”	29.3”
Location from SBP (from BSBP)	21.5’ (2.5’)	18.5’ (5.5’)	22.6’ (1.4’)	23.8’ (0.2)	24.0’ (0.0’)

Underride (back slope)

	820C	1100C	1500A	2000P	2270P
Stability					
Min. Height	9.6”	11.3”	6.3”	9.2”	9.3”
Location from SBP (from BD)	16.1’ (7.9’)	15.7’ (8.3’)	16.2’ (7.8’)	17.3’ (6.7’)	18.0’ (6.0’)

SBP = Slope Break Point
BD = Bottom of Ditch
BSBP = Back Slope Break Point
(Highlighted fields indicate critical vehicle for the specific condition)

Figure 6. Trajectories of Critical Bumper Nodes of Five Passenger Vehicles – 6H:1V V-Ditch, 24 ft Wide



Override (fore slope)

	820C	1100C	1500A	2000P	2270P
Stability					
Max. Height	28.7”	28.7”	26.5”	33.8"	35.3"
Location from SBP	9.2’	9.0’	8.0’	9.5’	8.7’

Override (back slope)

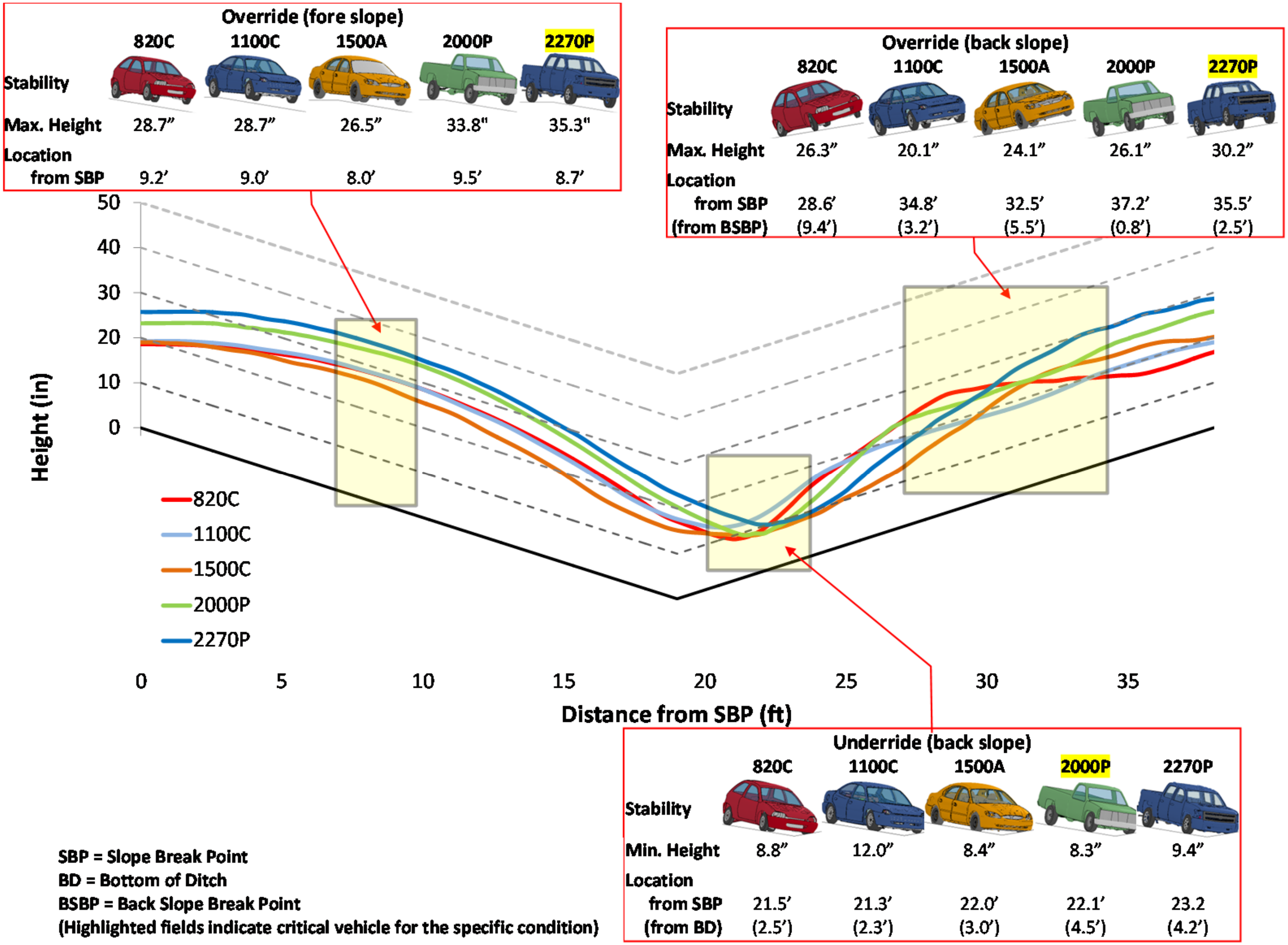
	820C	1100C	1500A	2000P	2270P
Stability					
Max. Height	22.3"	20.3”	15.5”	28.5”	32.4”
Location from SBP (from BSBP)	25.7’ (4.3’)	29.1’ (0.9’)	22.6’ (7.4’)	26.4’ (3.6’)	29.5’ (0.5’)

Underride (back slope)

	820C	1100C	1500A	2000P	2270P
Stability					
Min. Height	8.7"	10.6"	5.5"	8.1"	8.4"
Location from SBP (from BD)	18.3’ (3.3’)	17.8’ (2.8’)	18.3’ (3.3’)	18.8’ (3.8’)	19.9’ (4.9’)

SBP = Slope Break Point
BD = Bottom of Ditch
BSBP = Back Slope Break Point
(Highlighted fields indicate critical vehicle for the specific condition)

Figure 7. Trajectories of Critical Bumper Nodes of Five Passenger Vehicles – 6H:1V V-Ditch, 30 ft Wide



Override (fore slope)

	820C	1100C	1500A	2000P	2270P
Stability					
Max. Height	28.7”	28.7”	26.5”	33.8"	35.3"
Location from SBP	9.2’	9.0’	8.0’	9.5’	8.7’

Override (back slope)

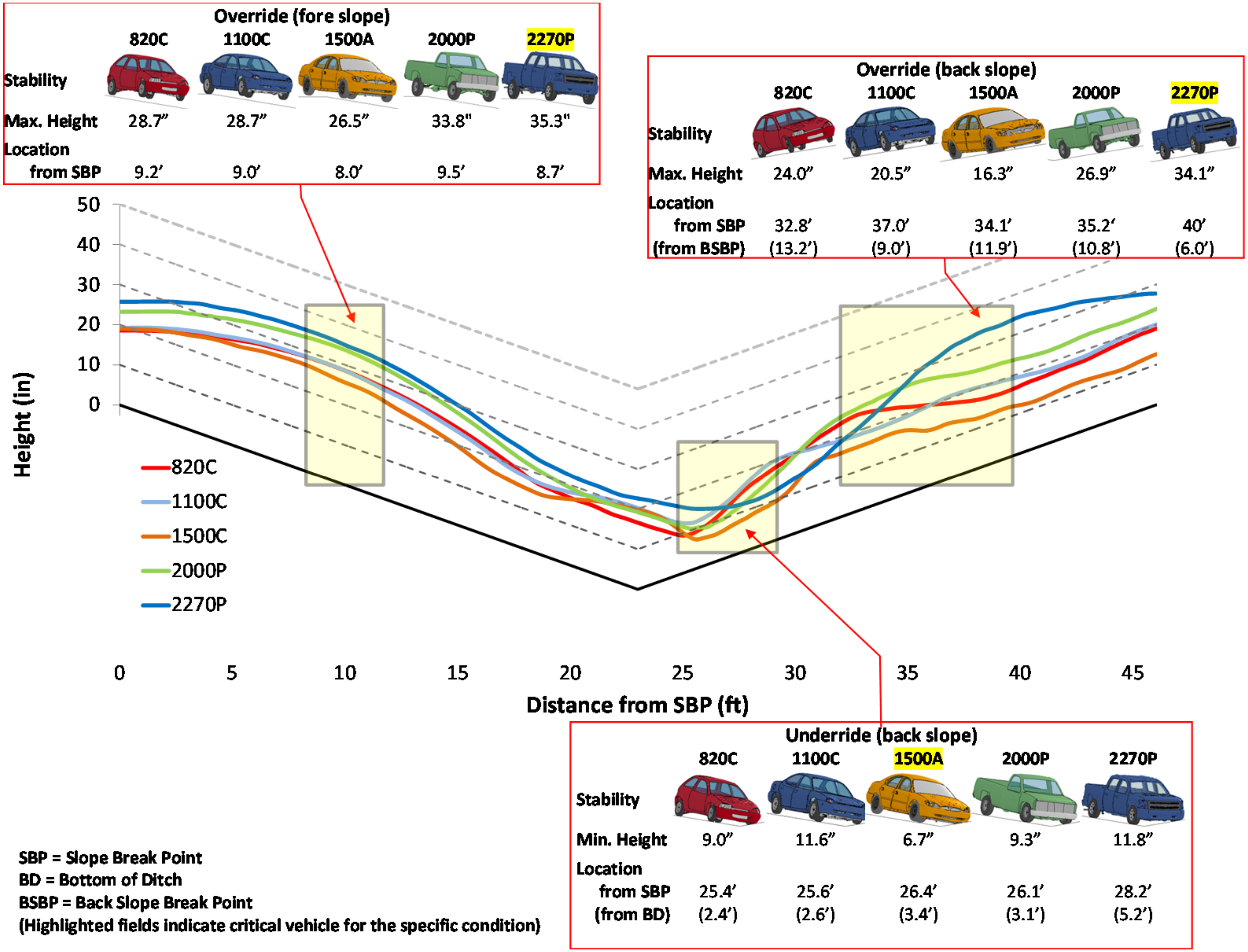
	820C	1100C	1500A	2000P	2270P
Stability					
Max. Height	26.3”	20.1”	24.1”	26.1”	30.2”
Location from SBP (from BSBP)	28.6’ (9.4’)	34.8’ (3.2’)	32.5’ (5.5’)	37.2’ (0.8’)	35.5’ (2.5’)

Underride (back slope)

	820C	1100C	1500A	2000P	2270P
Stability					
Min. Height	8.8”	12.0”	8.4”	8.3”	9.4”
Location from SBP (from BD)	21.5’ (2.5’)	21.3’ (2.3’)	22.0’ (3.0’)	22.1’ (4.5’)	23.2 (4.2’)

SBP = Slope Break Point
BD = Bottom of Ditch
BSBP = Back Slope Break Point
(Highlighted fields indicate critical vehicle for the specific condition)

Figure 8. Trajectories of Critical Bumper Nodes of Five Passenger Vehicles – 6H:1V V-Ditch, 38 ft Wide



Override (fore slope)

	820C	1100C	1500A	2000P	**2270P**
Stability					
Max. Height	28.7”	28.7”	26.5”	33.8"	35.3"
Location from SBP	9.2’	9.0’	8.0’	9.5’	8.7’

Override (back slope)

	820C	1100C	1500A	2000P	**2270P**
Stability					
Max. Height	24.0”	20.5”	16.3”	26.9”	34.1”
Location from SBP (from BSBP)	32.8’ (13.2’)	37.0’ (9.0’)	34.1’ (11.9’)	35.2’ (10.8’)	40’ (6.0’)

Underride (back slope)

	820C	1100C	**1500A**	2000P	2270P
Stability					
Min. Height	9.0”	11.6”	6.7”	9.3”	11.8”
Location from SBP (from BD)	25.4’ (2.4’)	25.6’ (2.6’)	26.4’ (3.4’)	26.1’ (3.1’)	28.2’ (5.2’)

SBP = Slope Break Point
BD = Bottom of Ditch
BSBP = Back Slope Break Point
(Highlighted fields indicate critical vehicle for the specific condition)

Figure 9. Trajectories of Critical Bumper Nodes of Five Passenger Vehicles – 6H:1V V-Ditch, 46 ft Wide

Table 16. Maximum Height of Critical Bumper Node on Front Slope (6H:1V)

Vehicle Type	Max. Height (in.) [Location from Front SBP (ft)]
	≥24 ft wide
820C	28.7 [9.2]
1100C	28.7 [9.0]
1500A	26.5 [8.0]
2000P	33.7 [9.4]
2270P	35.3 [8.8]

Table 17. Minimum Height of Critical Bumper Node on Back Slope (6H:1V)

Vehicle Type	Min. Height (in.) [Location from Bottom of Ditch (ft)]			
	24 ft wide	30 ft wide	38 ft wide	46 ft wide
820C	9.6 [4.1]	8.7 [3.3]	8.8 [2.5]	9.0 [2.4]
1100C	11.3 [0.7]	10.6 [2.8]	12.0 [2.3]	11.6 [2.6]
1500A	6.3 [5.7]	5.5 [3.3]	8.4 [3.0]	6.7 [3.4]
2000P	9.2 [2.8]	8.1 [3.8]	8.3 [4.5]	9.3 [3.1]
2270P	9.3 [2.7]	8.4 [4.9]	9.4 [4.2]	11.8 [5.2]

Highlighted fields indicate the critical width for each vehicle

Table 18. Maximum Height of Critical Bumper Node on Back Slope (6H:1V)

Vehicle Type	Max. Height (in.) [Location from Back SBP (ft)]			
	24 ft wide	30 ft wide	38 ft wide	46 ft wide
820C	23.3 [2.5]	22.3 [4.3]	26.3 [9.4]	24.0 [13.2]
1100C	19.8 [5.5]	20.3 [0.9]	20.1 [3.2]	20.5 [9.0]
1500A	17.6 [1.4]	15.5 [7.4]	24.1 [5.5]	16.3 [11.9]
2000P	29.5 [0.2]	28.5 [3.6]	26.1 [0.8]	26.9 [10.8]
2270P	29.3 [0.0]	32.4 [0.5]	30.2 [2.5]	34.1 [6.0]

Highlighted fields indicate the critical width for each vehicle

Table 19. Height of Critical Bumper Node at 4 ft from Front SBP (6H:1V)

Vehicle Type	Height (in.) @ 4 ft from Front SBP
	≥24 ft wide
820C	25.2
1100C	25.8
1500A	24.6
2000P	30.2
2270P	32.7

Table 20. Maximum Height of Critical Bumper Node at 0-4 ft range from Back Slope (6H:1V)

Vehicle Type	Max. Height (in.) [Location from Back SBP (ft)]			
	24 ft wide	30 ft wide	38 ft wide	46 ft wide
820C	23.3 [2.5]	22.2 [4.0]	19.2 [4.0]	19.0 [0.0]
1100C	19.8 [0.0]	20.3 [0.9]	20.1 [3.2]	20.0 [0.4]
1500A	17.6 [1.4]	14.7 [1.4]	23.3 [4.0]	12.6 [0.0]
2000P	29.5 [0.2]	28.5 [3.6]	26.1 [0.8]	23.9 [0.0]
2270P	23.9 [0.0]	32.4 [0.5]	30.2 [2.5]	32.8 [4.0]

Highlighted fields indicate the critical condition for each vehicle
NA – Not Available

6.2 Override Potential (Front Slope)

With shallower 6H:1V slopes, the maximum height of the critical bumper trajectory above the front slope occurred at the same lateral offset from the front SBP for all ditch widths considered. In particular, the peak of the bumper trajectories for the various vehicle types occurred at a distance of about 9 ft from the front SBP.

An analysis of the bumper trajectories identified that a maximum height of 35.3 in. was reached by the 2270P vehicle at a distance of 8.8 ft from the front SBP, as shown in Figures 6 through 9 and Table 16. The 2270P vehicle reached a peak higher than the other vehicles mainly due to the higher initial location of the critical bumper node, but it will likely result in greater deflection of the cables due to larger inertia with respect to the other vehicles and an increased potential to roll over the system due the higher location of the center of gravity. Since the maximum height of the bumper trajectories for the 2270P vehicle was reached at 8.8 ft from the front SBP, the critical override condition would consider a barrier placed approximately 9 ft from the front SBP.

The 820C, 1100C, and 1500A vehicles reached maximum bumper trajectories equal to 28.7 in., 28.7 in., and 26.5 in., respectively. As previously mentioned in section 4.2, if a cable system located at 9 ft from the front SBP is capable of safely containing a pickup truck, it will likely safely contain small to midsize passenger cars. As such, no crash testing conditions with small to midsize passenger cars were deemed necessary for evaluating barrier override.

6.3 Underride Potential (Back Slope)

The minimum height of the critical bumper node relative to the ditch surface was tracked for each vehicle as it landed in the ditch and the front suspensions and tires reached the maximum compression as shown in Figures 6 through 9 and Table 17. Two factors maximize the minimum height reached by vehicle when landing into a ditch: (i) the drop height and (ii) the impact on the back slope. A higher drop height increases the momentum reached by the vehicle resulting in greater compression of the front suspensions and tires, while landing on the back slope causes a reduction of the initial relative height between the vehicle front end and the ditch surface. Combining these two factors, the minimum trajectory height is reached for the largest ditch width for which the vehicle still lands in the back slope. For 6H:1V steep slopes, simulations indicated that all the vehicles landed on the back slope only for the 24-ft and 30-ft wide ditches, while for wider ditches (i.e., 38 ft and 46 ft) they landed on the front slope. In addition, the simulations confirmed that with the 30-ft wide V-ditch the minimum trajectory height was reached for each vehicle type, as summarized in Table 16. Hence, the 30-ft wide ditch was considered to be the most critical of the four width values investigated.

An analysis of the bumper trajectories for the 30-ft wide ditch indicates that the 1500A vehicle could have a higher potential of penetration than the 1100C, with a minimum bumper height of 5.5 in. for the 1500A against 10.6 in. for the 1100C. Additionaly, the larger inertia of the 1500A suggests that this type of vehicle would be more critical for underride due to a higher momentum at impact, which could consequently cause a larger deflection of the cables and a deeper penetration compared to the lighter 1100C vehicle. Nonetheless, as previously mentioned for the 4H:1V slopes, the 1100C remains a critical vehicle because of a lower front-end profile and an expected weaker A-pillar which could lead to potential crushing of the occupant compartment. For these reasons, both the 1100C and the 1500A vehicles should be considered for underride testing.

The simulated bumper trajectories for the 1100C and the 1500A indicated that the most critical location for both vehicles should be on the back slope of a 30-ft wide V-ditch at about 3 ft from the bottom of the ditch, as shown in Figure 7 and Table 17. As previously suggested for the case with the 4H:1V ditch, one additional foot should be considered to allow for the vehicle wheels to dig into the soil. Hence, the proposed critical placement should be about 4 ft from the bottom of the ditch.

6.4 Override Potential (Bouncing Effect on Back Slope)

The simulated bumper trajectories indicated that the maximum rebound height of the critical node was reached by the 2270P vehicle in a 46-ft wide ditch. Under this impact scenario, the maximum height above the ditch surface was 34 in. at a lateral offset of 6 ft away from the back SBP. Subsequently, the next largest rebound height (32.4 in.) was also reached by the 2270P vehicle, but in a 30-ft wide ditch and at 0.5 ft from the back SBP.

As with the 4H:1V ditches, the maximum heights relative to the back slope ditch surface reached by the 2270P vehicle for a 30-ft and 46-ft wide ditch were similar as well the offset of the corresponding locations from the bottom of the ditch. For these reasons, either a 30-ft or a 46-ft wide ditch can be used to assess the risk for the 2270P vehicle to override the cable system after bouncing on the back slope. The critical barrier placement was determined to be 15 ft from the bottom of the ditch.

Due to the severe bouncing and eventual rollover witnessed from previous testing of a cable system in a 4H:1V V-ditch [12], the 1100C passenger vehicle is recommended as well for evaluating potential override and vehicle instabilities after rebounding above the back slope. Both 30-ft and 46-ft wide ditches are suggested as critical to evaluate potential override of the cable system and instability issues for the 1100C vehicle after bouncing on the back slope. With a 30-ft wide ditch, the 1100C vehicle lands directly on the back slope and a greater rebound is likely to occur. However, for a 46-ft wide ditch, the vehicle lands on the front slope and is expected to maintain greater momentum to climb on the back slope. A greater rebound may pose a potential for override of the barrier, while a greater momentum and a wider ditch may increase the vehicle orientation at impact and lead to vehicle instabilities.

The magnitude of the simulated trajectories indicated similar maximum heights of 20.3 in. and 20.5 in. for the 30-ft and 46-ft wide ditches, respectively. Although it was not possible to validate the models due lack of previous experimental testing on vehicle traversing ditches, the general trends for rebounding were assumed to be correct. Thus, the critical barrier placement for evaluating the potential for override and critical instability with the 1100C vehicle was determined to be at the offset of the peak values of the simulated trajectories or 9 ft and 1 ft from the back SBP of a 46-ft and 30-ft wide ditch, respectively.

6.5 Proposed Critical Tests Identified from Bumper Trajectories in a 6H:1V V-Ditch

A summary of the critical testing scenarios for evaluating 6H:1V V-ditches (i.e., combinations of vehicle type, barrier location, and ditch width) is provided in Table 21. Note that these critical locations are purely based on considerations for underride/override and do not account for other potential vehicular instabilities or penetrations. A more comprehensive test matrix is provided in later sections of this report.

Table 21. Override/Underride Testing Scenarios for Cable Barriers Placed in a 6H:1V V-Ditch

Vehicle Type	**Critical Ditch & Location**			**Expected Potential Risk**
	Ditch Width (ft)	**Barrier Position**	**Barrier Location (ft)**	
2270P	≥ 30	Front Slope	8 from Front SBP	Override/Roll-over
1100C	30	Back Slope	19 from Front SBP (4 from Ditch Bottom)	Underride
1500A	30	Back Slope	19 from Front SBP (4 from Ditch Bottom)	Underride
1100C	46	Back Slope	37 from Front SBP (9 from Back SBP)	Override/Roll-over
1100C	30	Back Slope	29 from Front SBP (1 from Back SBP)	Override/Roll-over
2270P	≥ 30	Back Slope	15 from Ditch Bottom	Override/Roll-over

7 Proposed Test Matrices for a 6H:1V V-Ditch

7.1 Test Matrices

Similarly to the 4H:1V V-ditch scenarios, three different test matrices are proposed for 6H:1V V-ditches. Matrices A and B define a series of tests for evaluating the scenarios of a single cable barrier system placed anywhere in the ditch and within a range of 0 to 4 ft beyond the front or back ditch SBP, respectively. Matrix C included a series of tests for evaluating the scenario of two cable barrier systems placed in the ditch, each 0 to 4 ft from a SBP. The three proposed tests matrices, which were based on the simulation results provided herein, are shown in Tables 22 through 24.

7.2 Test Descriptions

7.2.1 Test No. 1

The primary evaluation factor for test no. 1 is to assess the system capability to contain the vehicle and prevent override. The 2270P vehicle was considered to be the most critical vehicle because of its large inertia, the location of its center of mass, and the highest peak reached by its bumper trajectory above the ditch surface. Similar considerations made for test no. 1 with the 4H:1V ditch are also valid for the case with a shallower 6H:1V slope. In the case of 6H:1V V-ditches, the critical barrier location for test no. 1 is closer to the front SBP because of the shallower slopes of the ditch. Specifically, the simulated bumper trajectories for the 6H:1V ditches indicated that the critical barrier placement for vehicle override is located at about 9 ft from the front SBP. At this location, the critical bumper node of the 2270P vehicle reached its maximum respect to the ditch surface.

Similar to the test matrices for the 4H:1V V-ditch, currently two ditch widths are listed for test no. 1: (1) a 30 ft (test no. 1a) and (2) a 46 ft (test no. 1b). The dual listing due to conflicting views on the identification of the critical width. On one side, the risk for override and

Table 22. Matrix A - Single Median Barrier Placed Anywhere in Ditch (6H:1V)

Test No.	**Test Designation No.**	**Vehicle Type**	**Impact Conditions**		**Ditch Width (ft)**	**Barrier Position**	**Barrier Location**	**Primary Evaluation Factors**
			Speed (mph)	**Angle (deg)**				
1a	3-11(+)	2270P	62	25	46	Front Slope	9 ft from Front SBP	Vehicle containment, override prevention, & W.W.
1b	3-11(+)	2270P	62	25	30	Front Slope	9 ft from Front SBP	
2	3-10(+)	1100C	62	25	≥ 30	Front Slope	9 ft from Front SBP	Vehicle stability & A-pillar integrity
3	3-10(+)	1100C	62	25	30	Back Slope	4 ft from Ditch Bottom (19 ft from Front SBP)	Vehicle containment, ORA/OIV, & underride prevention
4a	3-10(+)	1100C	62	25	46	Back Slope	4 ft from Back SBP	Increased vehicle orientation at impact & override
4b	3-10(+)	1100C	62	25	30	Back Slope	1 ft from Back SBP	
5	TBD	1500A	62	25	Note 1	Note 1	Note 1	Vehicle penetration & A-pillar integrity
6	3-11	2270P	62	25	NA	Level Terrain	NA	Vehicle containment & W.W.
7	3-10	1100C	62	25	NA	Level Terrain	NA	Vehicle stability & A-pillar integrity
8	3-11(+)	2270P	62	25	≥ 30	Back Slope	15 ft from Ditch Bottom	Override & increased vehicle orientation at impact
9	TBD	1500A	62	25	30	Back Slope	4 ft from Ditch Bottom	Vehicle containment, ORA/OIV, & underride prevention

SBP – Slope Break Point
W.W. – Working Width
ORA – Occupant Ridedown Acceleration
OIV – Occupant Impact Velocity
NA – Not Applicable
Note 1 – Testing laboratory should determine critical barrier position on front slope of ditch or on level terrain in order to maximize propensity for front end of 1500A vehicle to penetrate between adjacent vertical cables. Critical factors may include vertical cable spacing, location and type of cable release mechanisms, vehicle projectile motion, etc.
(+) Specific test designation to be assigned

Table 23. Matrix B - Single Median Barrier Placed at 0 to 4-ft Offset from SBP (6H:1V)

Test No.	Test Designation	Vehicle Type	Impact Conditions		Ditch Width (ft)	Barrier Position	Barrier Location	Primary Evaluation Factors
			Speed (mph)	Angle (deg)				
1	3-11(+)	2270P	62	25	≥ 30	Front Slope	4 ft from Front SBP	Vehicle containment, override prevention, & W.W.
2	3-10(+)	1100C	62	25	≥ 30	Front Slope	4 ft from Front SBP	Vehicle stability & A-pillar integrity
3(*)	3-10(+)	1100C	62	25	Narrow (18 ft wide)	Back Slope	4 ft from Back SBP	Vehicle containment, ORA/OIV, & underride prevention
4a	3-10(+)	1100C	62	25	46	Back Slope	4 ft from Back SBP	Increased vehicle orientation at impact & override
4b	3-10(+)	1100C	62	25	30	Back Slope	1 ft from Back SBP	
5	TBD	1500A	62	25	Note 1	Note 1	Note 1	Vehicle penetration & A-pillar integrity
6	3-11	2270P	62	25	NA	Level Terrain	NA	Vehicle containment & W.W.
7	3-10	1100C	62	25	NA	Level Terrain	NA	Vehicle stability & A-pillar integrity
8	3-11(+)	2270P	62	25	30	Back Slope	Back SBP	Override & increased vehicle orientation at impact
9(*)	TBD	1500A	62	25	Narrow (18 ft wide)	Back Slope	4 ft from Back SBP	Vehicle containment, ORA/OIV, & underride prevention

SBP – Slope Break Point
W.W. – Working Width
ORA – Occupant Ridedown Acceleration
OIV – Occupant Impact Velocity
NA – Not Applicable
Note 1 – Testing laboratory should determine critical barrier position from 0 to 4 ft on front slope of ditch or on level terrain in order to maximize propensity for front end of 1500A vehicle to penetrate between adjacent vertical cables. Critical factors may include vertical cable spacing, location and type of cable release mechanisms, vehicle projectile motion, etc.
(*) Corresponding test from Matrix A (6H:1V) can be considered an equivalent substitute
(+) Specific test designation to be assigned

Table 24. Matrix C - Double Median Barrier Placed at 0 to 4-ft Offset from Both SBP (6H:1V)

Test No. (*)	**Test Designation**	**Vehicle Type**	**Impact Conditions**		**Ditch Width (ft)**	**Barrier Position**	**Barrier Location**	**Primary Evaluation Factors**
			Speed (mph)	**Angle (deg)**				
1	3-11(+)	2270P	62	25	≥ 30	Front Slope	4 ft from Front SBP	Vehicle containment, override prevention, & W.W.
2	3-10(+)	1100C	62	25	≥ 30	Front Slope	4 ft from Front SBP	Vehicle stability & A-pillar integrity
5	TBD	1500A	62	25	Note 1	Note 1	Note 1	Vehicle penetration & A-pillar integrity
6	3-11	2270P	62	25	NA	Level Terrain	NA	Vehicle containment & W.W.
7	3-10	1100C	62	25	NA	Level Terrain	NA	Vehicle stability & A-pillar integrity

SBP – Slope Break Point
W.W. – Working Width
NA – Not Applicable
Note 1 – Testing laboratory should determine critical barrier position from 0 to 4 ft on front slope of ditch or on level terrain in order to maximize propensity for front end of 1500A vehicle to penetrate between adjacent vertical cables. Critical factors may include vertical cable spacing, location and type of cable release mechanisms, vehicle projectile motion, etc.

* Tests 3, 4, 8, 9 defined in Matrices A and B not necessary for a double system
(+) Specific test designation to be assigned

containment issues is maximized if the 2270P is allowed to continue down the foreslope of a wider ditch. On the other side, vehicle contact with the backslope surface while being redirected by the system may cause some instability. As such, in order to identify the critical ditch width, it will be necessary to initially run test no. 1 on the same cable system in both a 30-ft and 46-ft wide ditches. The feedback provided by testing experience will create the basis for identifying which width is worse. Eventually, one selected width will be recommended for future testing under test no. 1.

For Matrices B and C, the critical location is limited to the maximum placement offset for these matrices, i.e., 4 ft from the front SBP.

7.2.2 Test No. 2

The primary evaluation for test no. 2 is to assess the system capability to prevent vehicle instability and rollover while capturing and redirecting a small car (1100C) which is traveling into the ditch. The risk of vehicle rollover for the small car is the result of the combination of three different factors: (1) the relatively small rotational inertia; (2) the roll and pitch rotations obtained by the vehicle while traveling into the ditch before it contacts the barrier; and (3) the potential instability caused by the redirecting forces acting on the vehicle while it is still airborne. To maximize the airborne interaction time, the critical barrier location was set where the 1100C vehicle reaches the maximum height above the ditch surface, at 12 ft from the front SBP. Test no. 2 should be performed in a ditch width equal or greater than 30 ft.

For Matrices B and C, the critical location is limited to the maximum placement offset for these matrices, i.e., 4 ft from the front SBP.

7.2.3 Test Nos. 3 and 9

Test nos. 3 and 9 assess the potential risk for passenger vehicles to underride the cable system. Similarly to the case with 4H:1V V-ditches, both the 1100C and 1500A vehicles have been proposed in test nos. 3 and 9, respectively. The 1500A vehicle is heavier than the 1100C vehicle and reached a lower minimum bumper height in the numerical simulations, so it has a higher risk to underride the system. However, the front-end geometry of the 1100C may also lead to vehicle underride. Additionally, the 1100C passenger car is typically characterized as having a weaker A-pillar compared to the 1500A passenger sedan. Thus, a test with the 1100C vehicle is deemed necessary to evaluate crushing of the A-pillar or penetration into the occupant compartment of the cables.

With a steepness of 6H:1V, the vehicles landed on the back slope only for ditches equal or narrower than 30 ft. As landing on the back slope may increase the compression of the suspension as well as the potential penetration of the vehicle front end into the soil, a 30-ft wide ditch was suggested for both test nos. 3 and 9 in Matrix A. The critical barrier location for both test nos. 3 and 9 was identified to be 4 ft from the bottom of the ditch. Since the main evaluation criteria are vehicle containment and underride prevention, the impact point for test no. 9 with the 1500A vehicle should be at the midspan instead of 12 in. upstream of a barrier post as suggested by MASH for this type of vehicle.

For Matrix B, simulation results with a narrow 24-ft wide ditch (Figure 6) indicated that the location with the maximum potential for underride with all the three cars (820C, 1100C, and 1500A) was at about 8 ft from the back SBP. Hence, a narrower ditch with a width between 16 to 18 ft becomes critical for underride potential with the cable system placed 3 to 4 ft from the back SBP, as indicated in test nos. 3 and 9 in Matrix B. Table 25 shows the height of the critical bumper node reached by the 1100C and 1500A vehicles computed at a 4-ft offset from the back SBP of a 18-ft wide 6H:1V V-ditch. In case an 18-ft wide ditch is not available, test nos. 3 and 9 in Matrix B can be substituted by the corresponding tests in Matrix A which require a 30-ft wide ditch.

Test nos. 3 and 9 are not required for Matrix C as there would be a barrier on both sides of the ditch, thus preventing vehicle contact with the back slope.

Table 25. Height of Critical Bumper Node 4 ft from Back SBP of an 18-ft Wide Ditch (6H:1V)

Vehicle Type	Height (in.)
1100C	13.1
1500A	7.3

7.2.4 Test Nos. 4 and 8

Both test nos. 4 and 8 aim to evaluate potential risks associated with impacts after the vehicle travels across the center of the ditch and up the back slope. In particular, two different circumstances can arise that may lead to a critical system test: (1) increased vehicle orientation and (2) override of the system.

The possibility of the front tires steering up the back slope increases the vehicle heading and/or impact angles. This phenomenon, which has been seen in previous full-scale crash testing, may result in a significant increase in impact severity and may cause instability during the redirection of the vehicle as well. To maximize the possibility for increased vehicle orientation, test no. 4a involves an 1100C vehicle with a 46-ft wide ditch. The relatively low rotational inertia of the small car and the longer airborne time while the vehicle traverses a wider ditch will maximize the potential for an increased vehicle orientation. Further, for a 6H:1V 46-ft wide V-ditch, the 1100C vehicle landed on the front slope, thus allowing the vehicle to keep more momentum as opposed to landing on the back slope of a narrower ditch. Thus, for test no. 4a, a 46-ft wide ditch was selected, with the most critical barrier location defined at 4 ft from the back SBP, matching the critical test location of the corresponding test in the test matrices for 4H:1V V-ditches. For a 6H:1V 30-ft wide V-ditch, vehicles landed in the back slope. Landing directly in the back slope may cause considerable vehicle rebound, especially for a small vehicle. Thus test no. 4b was also proposed, which involves narrower 30-ft wide ditches with the barrier located 4 ft from the back SBP.

The potential for overriding the system is a consequence of the vehicle bouncing after impacting the back slope and becoming airborne again. According to the simulation results, this behavior was maximized with the 1100C vehicle entering a 30-ft wide ditch. Although the vehicle models used for the simulations could not be validated due to the lack of full-scale crash testing, the general vehicle behavior was assumed to be accurate. Thus, test no. 4b involves an 1100C vehicle impacting the barrier placed 1 ft from the back slope SBP of a 30-ft wide V-ditch.

Although there are currently two combinations of ditch width and critical location listed for test no. 4, it is envisioned that one of these will prove to be more critical. Future full-scale testing results from both test nos. 4a and 4b on similar systems shall be used to determine which of these two ditch widths is more critical, thus resulting in the selection of a single test.

The simulated trajectories for the critical bumper node indicated that the 2270P bounced off the back slope greater than observed the 1100C. Although the suspension rebound/bounce effect cannot be verified due to lack of testing, assuming that the general trend of the simulated trajectories are representative of the actual suspension rebound/bounce effect, there is a risk for the 2270P to override the barrier due to bouncing off the backslope. Test no. 8 was added to matrices A and B to evaluate this potential risk. The difference in the maximum height of the 2270P trajectories for ditch widths of 30 ft and 46 ft was minimal, as summarized in Table 18. Additionally, the maximum rebound height for the 2270P occurred in a range of 14.5 ft to 17 ft from the bottom of the ditch for these three widths. Therefore, the critical barrier location for test no. 8 was identified as15 ft from the bottom of a V-ditch which is at least 30-ft wide.

For evaluations under Matrix B, the same barrier location would apply for test no. 8 but limited to only a 30-ft wide V-ditch. As for wider ditches, the barrier would be otherwise located outside the 0-to-4 ft offset if placed 15 ft from the bottom of the ditch. In case only ditches wider than 30 ft were available for testing, test no. 8 from Matrix A can be considered as an alternative due to the higher severity.

Test nos. 4 and 8 do not apply to matrix C as the barrier on the foreslope would prevent the impacting vehicle from traveling up the backslope.

7.2.5 Test No. 5

Test no. 5 is meant to evaluate the risk of vehicle penetration through a cable barrier. As cable heights are raised to prevent the potential for override of installations on slopes, the increased vertical spacing between cables may induce the vehicle penetration through the cables. The 1500A sedan was selected to evaluate penetration due to its larger inertia over the 1100C, while maintaining a small front-end profile. Additionally, a recent study has shown that sedans are the most common vehicles in cable barrier penetrations [15]. Since the main evaluation criteria are vehicle penetration and A-pillar integrity, the impact point should be at the midspan instead of the barrier post as suggested by MASH for this type of vehicle.

Although full vehicle penetration is the main concern for test no. 5, a partial penetration may pose potential risks such as a crushing of the A-pillar by a cable sliding over the vehicle hood or instability caused by a cable going under the bumper and tripping the vehicle. Either of these events would result in a test failure.

The critical placement will be dependent on the specific barrier design, including factors such as cable spacing, vertical location of largest cable gap, cable-to-post connection, and height relative to the 1500A vehicle bumper. As such, the testing agency should determine the critical barrier placement as the location which maximizes the probability of front end penetration between adjacent cables. Either placement on level terrain or on a ditch foreslope such that the vehicle projectile motion off the front SBP results in an impact at the critical height can be considered.

7.2.6 Test Nos. 6 and 7

Test nos. 6 and 7 represent the present MASH test designation nos. 3-10 and 3-11, respectively, for testing longitudinal barrier systems on level terrain, including cable barriers. As cable systems placed on slopes will likely be taller than previous level terrain systems, the top cable(s) may pose an increased risk to the integrity of the occupant compartment (e.g. the vehicle A-pillar). Thus, test no. 6 with the 1100C may prove to be critical. Additionally, test no. 7 with the 2270P addresses containment and working width issues.

8 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This white paper proposes a series of critical tests for the full-scale crash testing of cable median barriers placed into a symmetric V-ditch. Using finite element simulations, the trajectory of a critical node located on the corner of the bumper was plotted for five different vehicle models while traversing both 4H:1V and 6H:1V V-ditches with widths varying from 24 ft to 46 ft. The maxima and minima of these trajectories provided useful indication to determine the most critical locations where the vehicle may override/underride a cable system. In addition to the three vehicles indicated in MASH (1100C, 1500A, and 2270P), vehicle models of the 820C and 2000P vehicles prescribed in NCHRP Report No. 350 were also included in the simulation effort to obtain a more complete overview of any potential problems with these smaller and lighter vehicles as well.

The simulated trajectories confirmed the critical width and location previously proposed for test nos. 1, 3, and 4 in the previous test matrices for 4H:1V V-ditches. Although simulation results predicted a magnitude of the rebound for the 1100C vehicle smaller than what was experienced during a recent full-scale crash test, the trend of the simulated trajectories still confirmed the critical location originally proposed. In addition, two new tests, test nos. 8 and 9, were proposed for Matrices A and B on 4H:1V V-ditches based on the analysis of the bumper trajectories, indicating a risk of override for the 2270P and underride for the 1500A vehicles, respectively. For test nos. 5 and 9, which involve the 1500A vehicle and evaluate vehicle penetration and underride, respectively, the impact point should be at the midspan instead of near the barrier post as suggested by MASH for this type of vehicle.

Similar test matrices were proposed for the testing of barriers in 6H:1V V-ditches. As expected, the peaks of the bumper trajectories through 6H:1V V-ditches were lower than those measured for the corresponding cases of a steeper 4H:1V ditch. Similarly, the minimum height of the tracked bumper point with respect to the ditch surface was higher in 6H:1V ditches due to a shorter vertical drop of the slope, causing less compression of the vehicle suspensions. The reduction in the vertical drop contributed to a consequent reduction of the vehicles' rebound after contacting the back slope of the ditch. However, the reduction in override/underride severity associated with the 6H:1V ditches was not enough to negate any of the tests from the evaluation matrices proposed for the steeper 4H:1V slopes. Therefore, the only differences between the test matrices proposed for the 4H:1V and the 6H:1V slopes were in the critical ditch widths and barrier locations.

The simulated trajectories used to assess the critical testing conditions of cable barriers in ditches were limited to symmetric 4H:1V and 6H:1V V-ditches with a width ranging between 24 and 46 ft. For asymmetric geometries, such as stepped ditches or different steepness for front and back slopes, different critical conditions may likely arise and further evaluation may be necessary. However, if a system is successfully tested under the proposed conditions for symmetric V-ditches, it is likely to perform safely for wider trapezoidal ditches, which are characterized by a flat bottom. In flat-bottom ditches, the barrier safety performance on the front slope, as assessed by test nos. 1 and 2, are expected to be similar to the case with a V-ditch, while the critical evaluation factors assessed by test nos. 3, 4, 8, and 9 on the back slope will likely be less severe. In fact, for test nos. 3 and 9, landing onto a flat-bottom ditch rather than on the back slope would likely reduce the potential for the vehicle to steer up and/or the wheels and the vehicle's front end to dig into the soil. Further, for test nos. 4 and 8, a ditch wider than 46 ft would mitigate the consequences of the impact against the cable system, since the extra distance before hitting the barrier will reduce the vehicle height at the impact location and allow the vehicle to reach a more stable and controlled configuration.

Although results obtained from the numerical simulations proved to be generally reliable and representative of the behavior of vehicles traversing V-ditches, they were based on the simplified assumption that the slope surfaces were ideally uniform and rigid. In real-world conditions, slopes may present random irregularities and wheels may dig into the soil when landing in the ditch. Either of these two factors could potentially affect the vehicle kinematics. Also, the lack of testing for vehicles traversing a ditch limited the validation of the vehicle numerical models. Without validation of the suspension system of the vehicle models, only the general trend of the simulated trajectories after the impact with the ditch slope could be assumed accurate. Accurate rebound heights would require further modeling validation and verification.

Finally, the matrices proposed in this report are not to be considered as final. Feedback provided by initial testing experience will help to understand which condition is more critical for the two variations initially proposed for both test nos. 1 and 4. Also, testing experience may help identify new critical situations not yet considered or rule out some conditions included in the proposed test matrices. Further simulations may be instrumental for this purpose as well. Definitively, an open discussion within the roadside safety community, including test facilities, state and federal agencies, and manufacturers, will be essential to develop a common consensus on this topic. As an example, one of such future discussions could consider the influence that the nominal tension of the cables may have on the severity of the primary evaluation factors. In fact, a high cable tension would be expected to increase the potential for a cable to crush the A-pillar of a 1100C or a 1500A vehicle. However, a low cable tension may delay the release of the top cable away from the post while the post while being pushed down by the impacting vehicle, thus increasing the potential for vehicle override and/or rollover.

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