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Low Speed Override of Passenger Vehicles with Heavy Trucks

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Abstract

In low speed collisions (under 15 mph) that involve a heavy truck impacting the rear of a passenger vehicle, it is likely that the front bumper of the heavy truck will override the rear bumper beam of the passenger vehicle, creating an override/underride impact configuration. There is limited data available for study when attempting to quantify vehicle damage and crash dynamics in low-speed override/underride impacts. Low speed impact tests were conducted to provide new data for passenger vehicle dynamics and damage assessment for low speed override/underride rear impacts to passenger vehicles. Three tests were conducted, with a tractor-trailer impacting three different passenger vehicles at 5 mph and 10 mph. This paper presents data from these three tests in order to expand the available data set for low speed override/underride collisions.

Introduction

The testing that is the basis for this paper provides new data points that contribute to the available data set for low speed rear override/underride collisions. These collisions commonly occur when a heavy truck impacts the rear of a passenger vehicle at speeds under 15 mph, often when the passenger vehicle is stopped at an intersection or traffic control device. These collisions have unique characteristics that make it difficult for an accident reconstructionist to accurately calculate vehicle impact speeds and delta Vs, which in turn make determining vehicle accelerations and forces challenging. Override/underride impacts often have longer impact durations and lower peak and average accelerations than similar bumper-level impacts due to differences in vehicle structures at varying impact heights. Reconstructing override/underride impacts with traditional methods utilizing stiffness coefficients can result in overestimations of vehicle impact speeds, and therefore higher delta Vs, accelerations, and impact forces. The data captured during this testing provides additional information for low speed override/underride collisions, including data for vehicle impact speeds and delta Vs, accelerations, impact durations, and coefficients of restitution, all of which can be referenced when determining impact forces in similar collisions.

Rear override/underride impact research is important because, as mentioned in Tanner's 1997 SAE paper on occupant response in rear heavy truck to car impacts, rear impacts account for a higher percentage of injured occupants in relation to the percentage of accidents that are rear impacts. However, override/underride impacts often impart lower accelerations and forces to the occupants of the struck vehicle than bumper-level impacts [1]. This suggests that analysis of override/underride impacts will provide more accurate reconstruction information in relation to actual vehicle accelerations and forces than analysis techniques referencing typical bumper-level collisions.

Existing testing data and literature on override/underride collisions is limited, and reconstruction analysis techniques may not apply as effectively to these collisions. Testing and research performed in the field of rear override/underride collisions, specifically with low impact speeds, was published in Goodwin's SAE paper 1999-01-0442, which presented testing results from repeated front and rear impacts of passenger cars into both a standard flat barrier and a modified barrier intended to recreate override/underride impact conditions. Impact speeds were from 3-8 kph (2-5 mph), and each test vehicle was impacted into the barrier multiple times without repairing previous impact damages. The paper's conclusion states, "These tests encompassed too small a sample to make any sweeping conclusions concerning occupant response in bumper contact versus override collisions [2]".

A crush energy analysis method was proposed in Croteau's SAE paper 2001-01-1170, which attempted to provide a calculation method applicable to override/underride rear impact collisions to determine closing speed of such impacts. This method involved determining coefficients of a combined bumper-level and above-bumper damage energy sum equation through testing and data analysis, in order to quantify the additional energy absorbed in above-bumper damages to the target vehicle [3]. However, this method was developed with testing that used higher impact speeds of the bullet vehicle (greater than 25 mph), and as such may not be directly applicable to low speed (under 15 mph) override/underride impacts, which often result in no contact or induced damage at bumper-level structures.

This theory was expanded upon in the literature review performed in Marine's SAE paper 2002-01-0556, however the conclusion states that there is insufficient data to confirm the accuracy of crush energy analysis in override/underride collisions: "The current state of override/underride impact data is very limited… The above-bumper data presented thus far is not sufficient to assist us in defining a general approach (if one is even possible) to estimate the crush energy associated with override/underride residual damage profiles [4]."

Additional newer rear override/underride data was presented in Asay's SAE paper 2017-01-1423, which focused on rear override/underride impacts where the target vehicle is a light truck or SUV. However, impact speeds were higher than in the testing presented in this paper, and its conclusion states, "It is recognized that additional testing and research in this area is warranted to expand understanding and help to explore the physical parameters associated with stiffness, energy absorption, and crash severity [5]."

There is considerable research published on low speed collisions between similar passenger cars, which result in bumper-level impacts. This type of impact is relevant to low speed override/underride collisions for comparison purposes. Three SAE papers reviewed for this publication [6, 7, 8] performed low speed bumper-level impact testing and reported pre- and post-impact speeds and impact durations in the test data. Analysis of this data shows that low speed bumper-level collisions have impact durations ranging from 100-235 milliseconds and coefficients of restitution ranging from 0.20-0.73. There is little correlation between closing speed and resulting impact duration and restitution shown in bumper-level impact test data, which is demonstrated in the large ranges of reported values above. However, average impact duration from this data is under 160 milliseconds, and average restitution is over 0.4. The average impact duration and coefficient of restitution values are important for comparison to override/underride test data published in this paper. Table 1 summarizes the testing data in order to provide a clearer picture of the results.

This paper presents testing intended to expand the understanding of rear override/underride collisions, specifically in the case of low speed rear impacts to passenger cars. Although the data is limited to three tests, the results from the three tests show similarities in the impact durations and resulting accelerations. This paper will present the testing setup of the vehicles, impact configurations, data acquisition, and a summary of the collected data set from both bullet and target vehicles.

TABLE 1 Low Speed Bumper-Level Impact Testing Data Summary

Low Speed Bumper-Level Impact Tests Summary (SAE 980298, 2002-01-0540, 2007-01-0728)				
Closing Speed [mph]		Number of Tests	Average Impact Duration [sec]	Average Coefficient of Restitution
Low	High			
1.8	5.0	27	0.173	0.47
5.0	7.0	16	0.157	0.43
7.0	10.0	15	0.143	0.39
10.0	13.0	8	0.116	0.33
Total/Average		**66**	**0.156**	**0.42**

Methods

Testing Facility

Testing was performed at Karco Engineering in Adelanto, CA, which is a vehicle crash testing facility that meets NHTSA and FMVSS standards for crash testing [9]. The Karco Engineering facility includes a purpose-built crash testing track with a level concrete runway that utilizes a cable and pulley system for vehicle towing, and vehicle tracking is accomplished with a recessed monorail system. Figure 1 shows an aerial of the Karco facility with testing tracks highlighted.

Figure 2 is a graphic depicting the test track and facility layout, which is the highlighted region on the aerial.

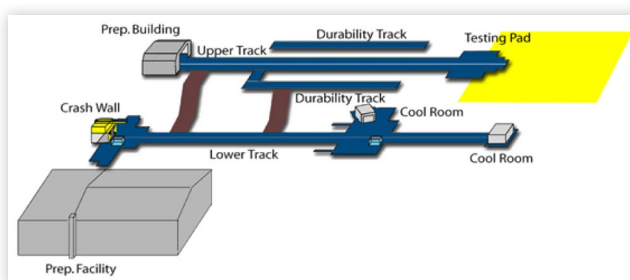
Three impact tests were performed to research low speed rear override-underride collisions. Closing speeds for the three tests were five, five, and ten mph respectively, which were obtained by towing the tractor-trailer with the track's cable and pulley system toward the stationary target vehicle. For each test, the front of the tractor-trailer struck the rear of the passenger car straight-on with no lateral offset.

Vehicles

In order to analyze rear override impacts to passenger cars, the test vehicles were selected to replicate this impact

FIGURE 1 Karco Engineering Facility Aerial

FIGURE 2 Karco Engineering Test Track Layout [9]



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configuration. The bullet vehicle was a tractor-trailer combination chosen based on availability and ease of repair of the front end components after testing. The target vehicles were selected based on rear bumper beam height from the ground; the rear bumper beam on the target vehicle had to be lower than the bottom of the heavy truck's frame rails to create the override/underride impact configuration. The target vehicles were from two different vehicle classes as well: the Nissan is a midsize sedan, and the Ford is a full size sedan. Additionally, all the target vehicles selected were four-door sedans with the typical trunk configuration. The Nissan utilized a unibody frame design, and the Fords utilized a body-on-frame configuration.

Bullet Vehicle The bullet vehicle used during all rear override/underride impact tests was a 2001 Mack CH612 tractor hauling a 1998 Stoughton dry van trailer. The Mack was a 4x2 conventional day cab tractor, and the Stoughton trailer was a 45-foot tandem axle dry van trailer. The combined as-tested weight of the tractor-trailer was 28,220 pounds. Figure 3 shows the bullet vehicle in as-tested configuration.

The front bumper of the Mack is comprised of a plastic aerodynamic bumper cover mounted to metal supports on the front of the frame rails. The plastic bumper cover is not a structural element on the front of the truck; the frame rails behind the bumper cover sit approximately 27 inches above the ground. Figures 4 and 5 show the tractor's front bumper exterior, including height measurements from the ground.

Figures 6 and 7 show the frame rails and metal supports behind the plastic bumper cover, including major components identification in Figure 7.

A. Passenger side frame rail
B. Metal bumper cover hanger
C. Plastic bumper cover
D. Aluminum oil cooler and mounting bracket

Figure 8 shows a measurement from the bottom of the frame rail to ground level of approximately 27". The bottom

FIGURE 3 Bullet vehicle: 2001 Mack CH612 and 1998 Stoughton 45' tandem-axle trailer

FIGURE 4 Bullet vehicle bumper cover

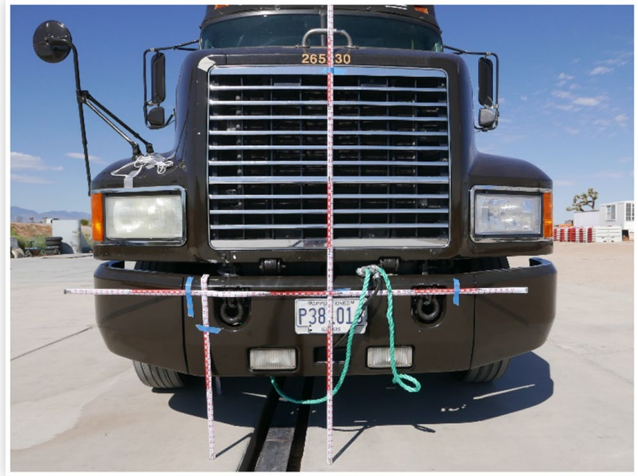


FIGURE 5 Bullet vehicle front bumper exterior measurements

FIGURE 6 Internal view of bullet vehicle bumper and frame rails

FIGURE 7 Bullet vehicle front end components identification

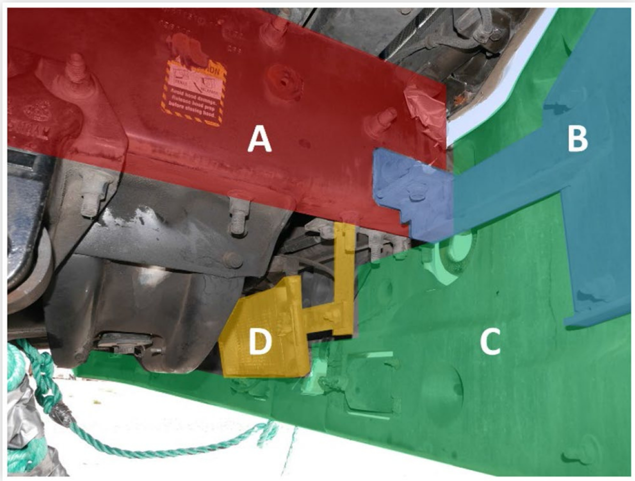


FIGURE 8 Height measurement from ground level to bottom of frame rails of bullet vehicle (27” approx.)

FIGURE 9 Front of bullet vehicle with metal structure highlighted

TABLE 2 Test 1 Target Vehicle inertial parameters

Test 1 Target Vehicle: 2008 Nissan Altima 2.5 S	
VIN: IN4AL21E48N539050	
Overall Length [in.]	182.5
Overall Width [in.]	70.7
Overall Height [in.]	55.3
Wheelbase [in.]	105.3
Front Overhang [in.]	37.8
Front Track Width [in.]	60.7
Rear Track Width [in.]	60.7
Tire Size [xxx/xxRxx]	215/60R16
Curb Weight [lb]	3214
Hybrid II 50% Male ATD Weight [lb]	171.3
Total Weight [lb]	3385
Front Axle Loaded Weight [lb]	2082
Front Axle Load Ratio	0.62
CG from Front Axle [in.]	40.5

of the frame rails is the lowest point of the metal structure on the front of the bullet vehicle, and it is the bottom boundary of where significant energy will be imparted to the target vehicle.

Figure 9 highlights the location of the frame rails as a reference on the outside of the plastic bumper cover. The bottom of the frame rails is approximately 27” above ground level as seen in Figure 8.

Minor damage the front aerodynamic bumper cover sustained during the three tests did not significantly affect the damage height or location to the target vehicles during subsequent tests.

Target Vehicles

The three tests performed each used individual target vehicles, in order to produce unique damages and data for each test.

Test 1: Nissan Altima, 5 mph Closing Speed. The target vehicle for the first test was a 2008 Nissan Altima 2.5 S four-door sedan with VIN 1N4AL21E48N539050. The target vehicle’s inertial parameters are outlined in Table 2.

Figures 10 and 11 show the Nissan prior to testing.

Measurements of the target vehicle’s bumper beam structure were also taken by removing the bumper cover prior to testing. The top of the target vehicle’s bumper beam was found to be 20” above ground level. Figures 12 and 13 show the bumper beam of the Nissan, including height measurements from the ground. Note that the powder covering the Nissan is laser scanner revealer spray to improve reflectivity of the black paint.

Test 2: Ford Crown Victoria, 5 mph Closing Speed. The target vehicle for the second test was a 2004 Ford Crown Victoria LX four-door sedan with VIN 2FAFP74W84X127704. The target vehicle’s inertial parameters are outlined in Table 3.

Figures 14 and 15 show the Ford prior to testing.

FIGURE 10 Test 1 Target Vehicle: 2008 Nissan Altima 2.5 S

FIGURE 11 Test 1 Target Vehicle: 2008 Nissan Altima 2.5 S

FIGURE 12 Test 1 Target Vehicle with bumper cover removed

FIGURE 13 Test 1 Target Vehicle bumper beam height from ground

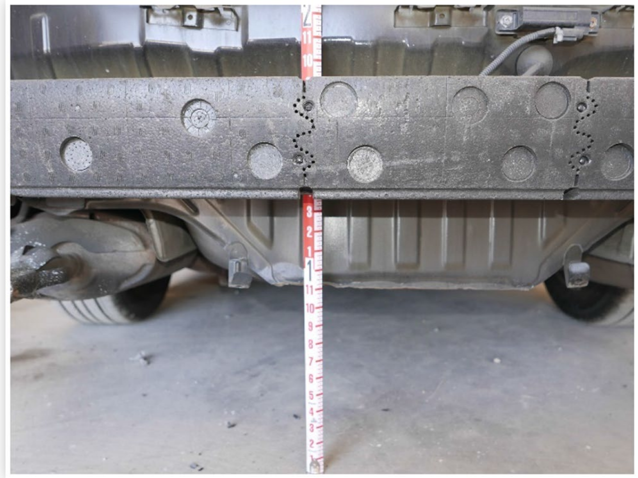


TABLE 3 Test 2 Target Vehicle inertial parameters

Test 2	Target Vehicle: 2004 Ford Crown Victoria LX
	VIN: 2FAFP74W84X127704
Overall Length [in.]	212.0
Overall Width [in.]	78.2
Overall Height [in.]	58.3
Wheelbase [in.]	114.6
Front Overhang [in.]	42.6
Front Track Width [in.]	63.4
Rear Track Width [in.]	65.6
Tire Size [xxx/xxRxx]	225/60R16
Curb Weight [lb]	4101
Hybrid II 50% Male ATD Weight [lb]	171.3
Total Weight [lb]	4272
Front Axle Loaded Weight [lb]	2433
Front Axle Load Ratio	0.57
CG from Front Axle [in.]	49.3

FIGURE 14 Test 2 Target Vehicle: 2004 Ford Crown Victoria LX

FIGURE 15 Test 2 Target Vehicle: 2004 Ford Crown Victoria LX

FIGURE 16 Test 2 Target Vehicle with rear bumper cover removed

Measurements of the target vehicle's rear bumper beam structure were also taken by removing the rear bumper cover prior to testing. The top of the target vehicle's rear bumper beam was found to be 22" above ground level. Figures 16 and 17 show the rear bumper beam of the Ford, including height measurements from the ground.

Test 3: Ford Crown Victoria, 10 mph Closing Speed. The target vehicle for the third test was a 2003 Ford Crown Victoria LX four-door sedan with VIN 2FAFP74W83X103398. This target vehicle required repair to the rear suspension in order to meet testing requirements: the rear air suspension components had failed, and they were replaced with standard coil spring suspension components to restore standard ride height of the vehicle. The target vehicle's inertial parameters are outlined in Table 4.

Figures 18 and 19 show the Ford prior to testing.

Measurements of the target vehicle's rear bumper height were also taken prior to testing. The target vehicle's rear

FIGURE 17 Test 2 Target Vehicle rear bumper beam height from ground

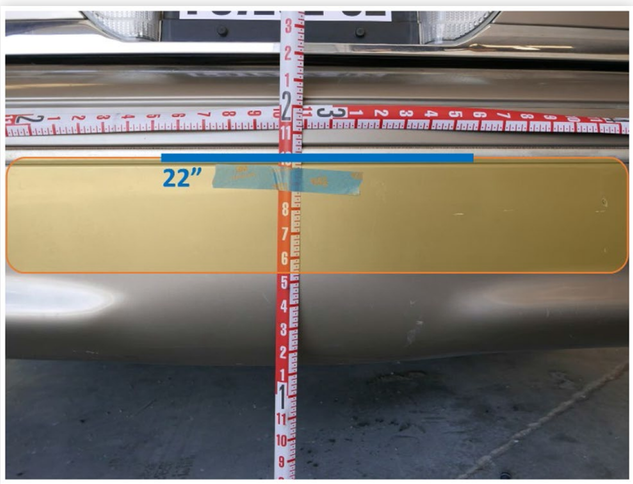
TABLE 4 Test 3 Target Vehicle inertial parameters

Test 3	Target Vehicle: 2003 Ford Crown Victoria LX
VIN: 2FAFP74W83X103398	
Overall Length [in.]	212.0
Overall Width [in.]	78.2
Overall Height [in.]	56.8
Wheelbase [in.]	114.7
Front Overhang [in.]	1
Front Track Width [in.]	63.4
Rear Track Width [in.]	65.6
Tire Size [xxx/xxRxx]	225/60R16
Curb Weight [lb]	4182
Hybrid II 50% Male ATD Weight [lb]	171.3
Total Weight [lb]	4353
Front Axle Loaded Weight [lb]	2518
Front Axle Load Ratio	0.58
CG from Front Axle [in.]	48.4

FIGURE 18 Test 3 Target Vehicle: 2003 Ford Crown Victoria LX

FIGURE 19 Test 3 Target Vehicle: 2003 Ford Crown Victoria LX

FIGURE 20 Test 2 Target Vehicle with rear bumper height measurement (22” to first bumper trim line)



bumper was found to be at the same height as Test 2’s target vehicle rear bumper, and as such the rear bumper beam was at the same height of 22”. Figure 20 shows the rear bumper of Test 2’s target vehicle including height measurement from ground; Figure 21 shows the rear bumper of Test 3’s target vehicle including height measurement from ground. Both target vehicle exterior rear bumper height measurements were identical, with the first bumper trim line from the bottom measuring 22” from ground level.

Test Procedure

The test vehicles were acquired and transported to the test facility and instrumented according to testing requirements. The target vehicle was placed in neutral and lined up with the cable track so that the impact would occur with no angle or offset. The bullet vehicle was attached to the cable and pulley track system for propulsion at set closing speed thresholds.

FIGURE 21 Test 3 Target Vehicle with rear bumper height measurement (22” to first bumper trim line)

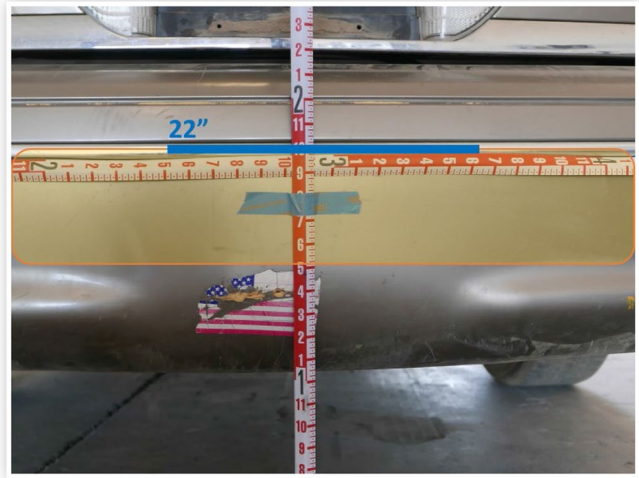


FIGURE 22 Test Vehicles Setup and Instrumentation

Figure 22 shows Test 2 vehicles being set up and instrumented on the test track.

Test Documentation

Test Vehicle Instrumentation For each test, the target vehicle was instrumented with two (2) tri-axial accelerometers. Both sets of accelerometers were mounted on the vehicle along the longitudinal centerline. The bullet vehicle was also instrumented with two (2) accelerometers located along the centerline of the Mack CH612. The accelerometers measured longitudinal (x), lateral (y), and vertical (z) acceleration. Data was recorded using the on-board Data Acquisition System DAS. The DAS software contains Society of Automotive Engineers (SAE) standard class filters. Acceleration data was captured at a 10,000 Hz acquisition rate with a hardware anti-aliasing filter of 2900 Hz, and an SAE Class 60 filter was applied to the acceleration data per Karco’s standard data acquisition procedures. All instrumentation used in the tests

FIGURE 23 Test 1 Target Vehicle Accelerometer Location

FIGURE 24 Test 2 Target Vehicle Accelerometer Location

has been calibrated through standards traceable to NIST and is maintained in a calibrated condition. See Appendix B for data acquisition system specifications. Figures 23 and 24 show the accelerometer mounting location on the transmission tunnel behind the front seats.

Test Video Documentation High-speed cameras were stationed to capture the impact from a side profile view and overhead view at the point of impact. This high-speed footage was synced to the time of impact through usage of tape triggers placed on the rear bumper of the target vehicles.

Results

Data recorded during the three impact tests was processed and filtered by the test facility as described in the instrumentation section. Accelerometer data was broken out into three directional components and also a resultant vector. Velocity of the target vehicle was obtained by integrating the accelerometer data over the time step. Impact duration was determined for each test by identifying the start of impact with the increase of accelerometer data above zero, and identifying the end of impact with the time when the resultant acceleration reached a minimum value before rising due to restitution.

Test 1: 2008 Nissan Altima 2.5 S

Impact Alignment As previously shown, the bottom of the frame rails of the bullet tractor are approximately 27" above ground level, and the top of the rear bumper beam of the Nissan is 20" above ground level; this height differential between frame and bumper structures creates a complete override impact to the back of the Nissan. Figure 25 shows a side profile view of the bullet tractor lined up with the rear of the Nissan to illustrate the frame height disparity.

Figure 26 shows a closeup view of the impact alignment, with frame and bumper structure heights highlighted for clarity.

FIGURE 25 Test 1 impact alignment (side view)

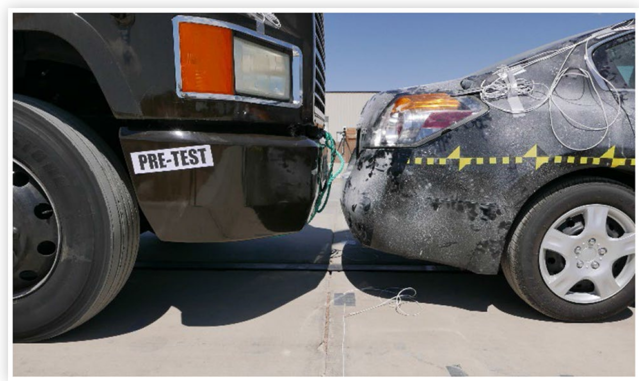


FIGURE 26 Test 1 impact alignment with structures highlighted

FIGURE 27 Trunk area of Test 1 target vehicle

FIGURE 28 Inside of trunk lid of Test 1 target vehicle

FIGURE 29 Test 1 Target Vehicle Impact Damage

FIGURE 30 Test 1 Target Vehicle Impact Damage

As seen in Figure 23, the bottom of the bullet tractor frame rail is approximately 7" above the top of the Nissan rear bumper beam. With this impact alignment, there is no energy transferred to the frame of the target vehicle by the impact, and all energy is absorbed by the above-bumper structures, which are composed mainly of sheetmetal. Figures 27 and 28 show the rear of the target vehicle with the trunk lid open and the inside of the trunk lid, respectively.

Test Summary The bullet vehicle was attached to the cable and pulley towing system and centered over the test track guide rail. It was towed to impact straight without offset or angle. The target vehicle was also positioned centered and aligned with the guide rail to ensure a rear impact without offset or angle. The target vehicle was stationary and placed in neutral. The target impact speed of the bullet vehicle into the target vehicle was 5 mph; the actual recorded impact speed was 5.39 mph.

Target Vehicle Impact Damage The impact to the above-bumper structures of the target vehicle resulted in damages to the trunk lid, taillights, upper bumper cover, and the underlying sheetmetal structure of the body. Figures 29 and 30 show overall views of the impact damage to the rear of the target vehicle.

As seen in the above post-test photographs, the trunk lid of the Nissan is dented inward in the area surrounding the license plate mount. Additionally, the passenger side taillight lens is cracked, the driver side taillight lens is no longer attached, and both taillight housings are displaced slightly outward at the leading edges. Figures 31 and 32 show driver and passenger side views of the rear of the Nissan.

Side perspectives better illustrate the displacement of the taillight housings outside of the quarter panels. Furthermore, these photographs show the upper edge of the trunk lid pushed forwards so that it slightly overlaps the sheetmetal, and show the bumper cover clips that detached along the leading edge where it meets the quarter panels on both sides. This deflection of the bumper cover is consistent with the minimal contact made by the bullet vehicle to the top of the bumper cover, but no contact was made to the bumper beam itself under the cover. As with the whole vehicle, the unibody experienced indirect forces as a result of the impact. However, those

FIGURE 31 Test 1 Target Vehicle Impact Damage (Driver Side Rear)

FIGURE 32 Test 1 Target Vehicle Impact Damage (Passenger Side Rear)

indirect forces were insufficient to create permanent deformation anywhere but the trunk and body panels. Figure 33 shows the rear damage to the Nissan with the scanner revealing spray partially removed for clarity.

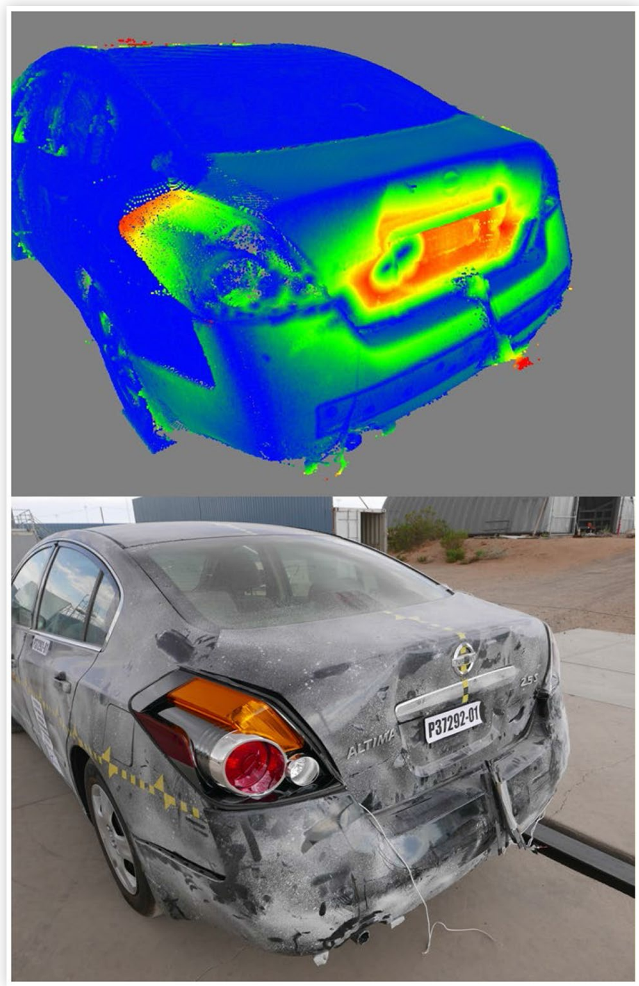
This photograph more clearly shows the damaged region in the center of the trunk lid, and it also shows the minor scratches and paint cracking present on the bumper cover from the contact with the bullet tractor's front bumper cover.

The target vehicle was scanned with a FARO Focus 3D laser scanner before and after the impact test. Data collected by the laser scanner was processed for comparison between pre- and post-test scans of the Nissan. Figure 34 shows a deviation map of the rear of the Nissan, with pre- and post-test scans aligned based on the undamaged sections of the vehicle. A post-test photograph of the Nissan is included for comparison purposes.

As seen in the above comparison, the maximum crush on the back of the Nissan was located in the center of the trunk lid around the license plate mounting area.

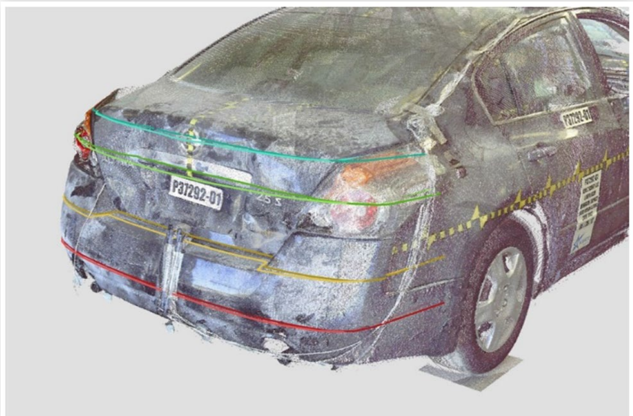
FIGURE 33 Test 1 Target Vehicle Impact Damage

FIGURE 34 Nissan Scan Data Deviation Comparison



Appendix A includes a summary table of crush measurements taken from the laser scan data of the pre- and post-test Nissan. Crush measurements were taken at four different levels on the rear of the Nissan: at bumper beam height, at the bottom edge of the trunk lid, at the trim piece above the

FIGURE 35 Test 1 Post-Test Scan Data with Crush Measurement Lines



license plate mounting area, and at the height of the badge on the trunk lid. The crush measurement data shows that there is very little deformation to the rear bumper cover of the Nissan, with a maximum crush measurement of 0.86 inches at bumper beam height. Maximum recorded crush depth was 3.22 inches, and this crush is seen at the measurement level above the license plate mounting area. Figure 35 shows the post-test scan data of the Nissan with the pre- and post-test crush lines at each measurement level overlaid on the scans.

Test 2: 2004 Ford Crown Victoria LX

Impact Alignment The bottom of the frame rails of the bullet tractor are approximately 27” above ground level, and the top of the rear bumper beam of the Ford is 22” above ground level; this height differential between frame and bumper structures creates a complete override impact to the back of the Ford. Figure 36 shows a side profile view of the bullet tractor lined up with the rear of the Ford to illustrate the frame height disparity.

Figure 37 shows a closeup view of the impact alignment, with frame and bumper structure heights highlighted for clarity.

FIGURE 36 Test 2 impact alignment (side view)

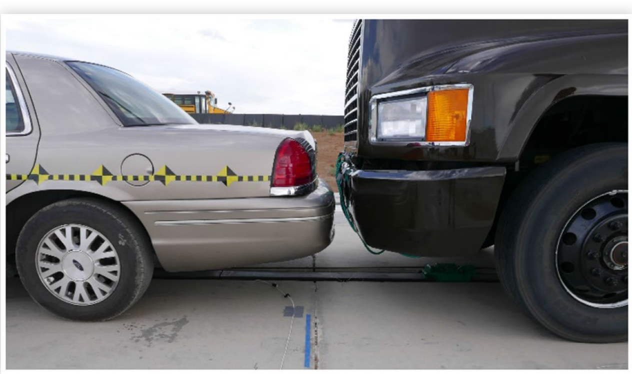


FIGURE 37 Test 2 impact alignment with structures highlighted

As seen in Figure 37, the bottom of the bullet tractor frame rail is approximately 5” above the top of the Ford rear bumper beam. With this impact alignment, there is no energy transferred to the frame of the target vehicle by the impact, and all energy is absorbed by the above-bumper structures.

Test Summary The bullet vehicle was attached to the cable and pulley towing system and centered over the test track guide rail. It was towed to impact straight without offset or angle. The target vehicle was also positioned centered and aligned with the guide rail to ensure a rear impact without offset or angle. The target vehicle was stationary and placed in neutral. The target impact speed of the bullet vehicle into the target vehicle was 5 mph; the actual recorded impact speed was 5.51 mph.

Target Vehicle Impact Damage The damage imparted to the above-bumper structures of the target vehicle resulted in damages to the trunk lid, taillights, upper bumper cover, and the underlying sheetmetal structure of the body. Figures 38 and 39 show overall views of the impact damage to the rear of the target vehicle.

As seen in the above post-test photographs, the trunk lid of the Ford is dented inward in the area surrounding the badge, and it is bowed upward laterally across the top sheet-metal. Additionally, the passenger side reverse light lens next to the license plate is cracked and both taillight housings are displaced slightly outward at the leading edges, although they are not cracked in this test. Two divots in the upper area of the bumper cover are visible, which is from contact from the tow hooks mounted to the end of the bullet vehicle’s frame rails. Figures 40 and 41 show driver and passenger side views of the rear of the Ford.

Side perspectives show the bowed sheetmetal of the trunk lid, and the enlarged gap between the leading edge of the tail-light housings and the rear quarter panels. Figure 42 shows a close-up view from the rear of the damage to the Ford with tape measures for scale.

This photograph more clearly shows the damaged region in the upper portion of the trunk lid, and it also shows the

FIGURE 38 Test 2 Target Vehicle Impact Damage

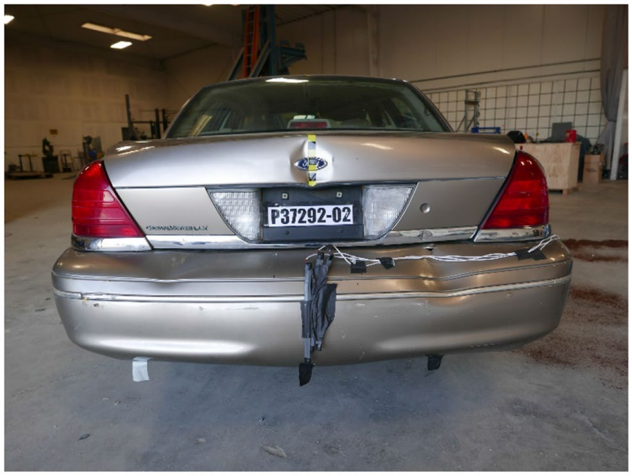


FIGURE 39 Test 2 Target Vehicle Impact Damage

FIGURE 40 Test 2 Target Vehicle Impact Damage (Driver Side Rear)

FIGURE 41 Test 2 Target Vehicle Impact Damage (Passenger Side Rear)

FIGURE 42 Test 2 Target Vehicle Impact Damage

minor scratches and divots present on the bumper cover from the contact with the bullet tractor's front tow hooks. These divots from the front of the bullet vehicle's frame rails are above the top of the Ford's bumper beam. As with the whole vehicle, the frame of the target vehicle experienced indirect forces as a result of the impact. However, those indirect forces were insufficient to create permanent deformation anywhere but the trunk and body panels.

The target vehicle was scanned with a FARO Focus 3D laser scanner before and after the impact test. Data collected by the laser scanner was processed for comparison between pre- and post-test scans of the Ford. Figure 43 shows a deviation map of the rear of the Ford, with pre- and post-test scans aligned based on the undamaged sections of the vehicle. A post-test photograph of the Ford is included for comparison purposes.

As seen in the above comparison, the maximum crush on the back of the Ford was located in the center of the trunk lid around the license plate mounting area.

FIGURE 43 Ford Scan Data Deviation Comparison

Appendix A includes a summary table of crush measurements taken from the laser scan data of the pre- and post-test Ford. Crush measurements were taken at four different levels on the rear of the Ford: at bumper beam height, at the bottom edge of the trunk lid, at the trim piece above the license plate mount, and at the height of the badge on the trunk lid. The crush measurement data shows that there is very little deformation to the rear bumper cover of the Ford, with a maximum crush measurement of 0.25 inches at bumper beam height. Maximum recorded crush depth was 2.92 inches, and this crush is seen at the measurement level at the bottom edge of the trunk lid. Figure 44 shows the post-test scan data of the Ford with the pre- and post-test crush lines at each measurement level overlaid on the scans.

FIGURE 44 Test 2 Post-Test Scan Data with Crush Measurement Lines

Test 3: 2003 Ford Crown Victoria LX

Impact Alignment As with the alignment in Test 2, the bottom of the frame rails of the bullet tractor are approximately 27” above ground level, and the top of the rear bumper beam of the Ford is 22” above ground level. Figure 45 shows a side profile view of the bullet tractor lined up with the rear of the Ford to illustrate the frame height disparity.

Figure 46 shows a closeup view of the impact alignment, with frame and bumper structure heights highlighted for clarity.

As seen in Figure 46, the bottom of the bullet tractor frame rail is approximately 5” above the top of the Ford rear bumper beam. With this impact alignment, there is no energy transferred to the frame of the target vehicle by the impact, and all energy is absorbed by the above-bumper structures.

Test Summary The bullet vehicle was attached to the cable and pulley towing system and centered over the test track guide rail. It was towed to impact straight without offset or angle. The target vehicle was also positioned centered and aligned with the guide rail to ensure a rear impact without

FIGURE 45 Test 3 impact alignment (side view)

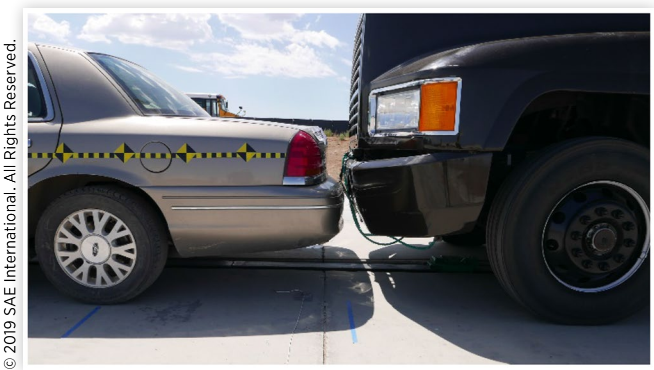


FIGURE 46 Test 3 impact alignment with structures highlighted

offset or angle. The target vehicle was stationary and placed in neutral. The target impact speed of the bullet vehicle into the target vehicle was 10 mph; the actual recorded impact speed was 10.07 mph.

Target Vehicle Impact Damage The damage imparted to the above-bumper structures of the target vehicle resulted in damages to the trunk lid, taillights, bumper cover, and the underlying sheetmetal structure of the body. Figures 47 and 48 show overall views of the impact damage to the rear of the target vehicle.

As seen in the above post-test photographs, the 10 mph override/underride impact left significantly more contact damage than the 5 mph impacts. The trunk lid of the Ford is bent inward and upward, and it was bent enough to be separated from the trunk latch during impact. Additionally, the sheetmetal at the rear of the trunk opening where the latch is mounted is dented inward significantly. The taillights on both sides are cracked and displaced outward. The bumper cover is pulled upwards and inwards at the upper edge where it meets the bottom of the trunk lid. The damage to the bumper cover is from the bullet vehicle's front end pushing the upper portion of the cover over the top of the bumper beam, and it is not indicative of direct contact with the Ford's bumper beam. As with the whole vehicle, the frame of the target vehicle experienced indirect forces as a result of the impact. However, those indirect forces were insufficient to create permanent deformation anywhere but the trunk and body panels. Figures 49 and 50 show driver and passenger side views of the rear of the Ford.

Side perspectives show the bent and displaced trunk lid, the crushed taillights, and the deformed upper portion of the bumper cover. Figure 51 shows a close-up view from the rear of the damage to the Ford.

This photograph more clearly shows the damage profile of the rear of the Ford from the 10 mph impact. The damage is concentrated in the center of the rear end of the Ford, around the area where the license plate is mounted in the trunk lid. The

FIGURE 47 Test 3 Target Vehicle Impact Damage

FIGURE 48 Test 3 Target Vehicle Impact Damage

FIGURE 49 Test 3 Target Vehicle Impact Damage (Driver Side Rear)

FIGURE 50 Test 3 Target Vehicle Impact Damage (Passenger Side Rear)

FIGURE 51 Test 3 Target Vehicle Impact Damage

crush depth tapers down toward the sides of the vehicle as seen in the final position of the cracked taillights, which is consistent with the shape of the front end of the bullet vehicle.

The target vehicle was scanned with a FARO Focus 3D laser scanner before and after the impact test. Data collected by the laser scanner was processed for comparison between pre- and post-test scans of the Ford. Figure 52 shows a

FIGURE 52 Ford Scan Data Deviation Comparison

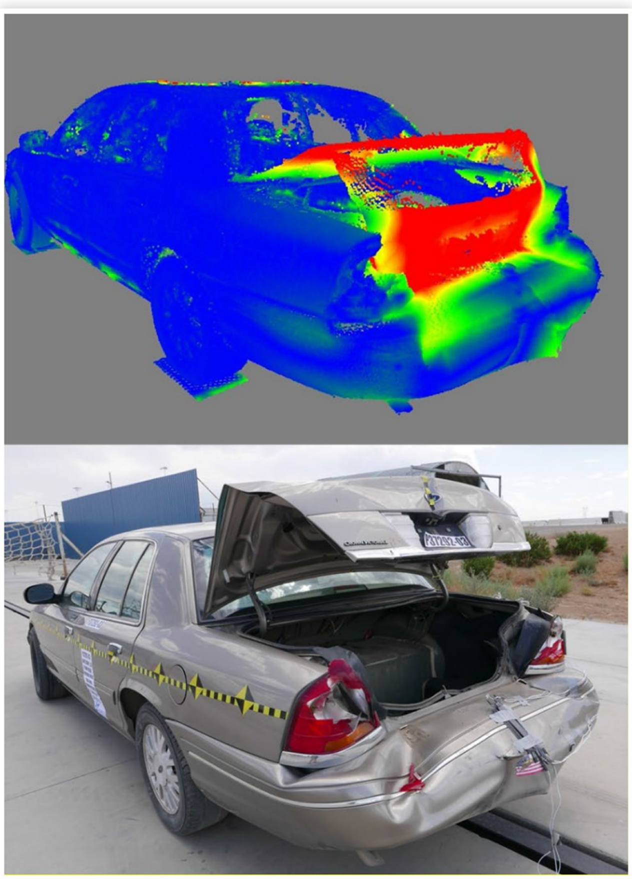


FIGURE 53 Test 3 Post-Test Scan Data with Crush Measurement Lines

deviation map of the rear of the Ford, with pre- and post-test scans aligned based on the undamaged sections of the vehicle. A post-test photograph of the Ford is included for comparison purposes. After the 10 mph crash test, the Ford's trunk lid was buckled and would no longer close; the scan data for the trunk lid was digitally rotated closed to its approximate original position for relevant crush measurements and deviation comparison.

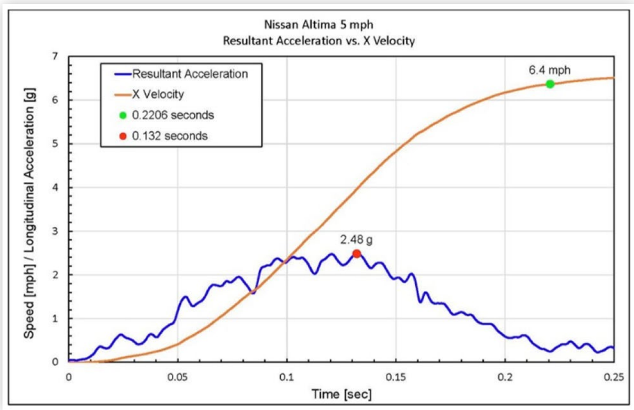
As seen in the above comparison, the maximum crush on the back of the Ford was located in the center of the bottom edge of the trunk lid.

Appendix A includes a summary table of crush measurements taken from the laser scan data of the pre- and post-test Ford. Crush measurements were taken at four different levels on the rear of the Ford: at bumper beam height, at the bottom edge of the trunk lid, at the trim piece above the license plate mount, and at the height of the badge on the trunk lid. The bumper cover of the Ford did experience some deformation during the 10 mph impact test as seen in the crush measurements, but the bumper beam underneath the cover did not absorb any impact energy. Maximum recorded crush depth on the Ford was 10.87 inches, and this crush is seen at the measurement level at the bottom edge of the trunk lid. Figure 53 shows the post-test scan data of the Ford with the pre- and post-test crush lines at each measurement level overlaid on the scans.

Summary

Testing data provides insight into the unique damage patterns and dynamic characteristics of low speed rear override/underride collisions. Data from each test was processed to determine impact duration and changes in velocity for both the bullet and target vehicles, from which peak and average accelerations and coefficients of restitution were calculated. The following graphs show the target vehicles' resultant acceleration data plotted with their respective velocities across the same time interval. End of crash pulse for each test was chosen at the point where the target vehicle's resultant acceleration reached a minimum value before rising due to restitution.

FIGURE 54 Test 1: Nissan Altima 5 mph



Test 1 - Nissan Altima 5 mph

- Target vehicle (Nissan) initial velocity: 0 mph
- Bullet vehicle (Mack) initial velocity: 5.39 mph
- Crash duration: 0.221 seconds
- Delta V: 6.4 mph
- Target vehicle peak acceleration: 2.48 g at 0.132 seconds
- Target vehicle average acceleration: 1.2 g

Test 2 - Ford Crown Victoria 5 mph

- Target vehicle (Ford) initial velocity: 0 mph
- Bullet vehicle (Mack) initial velocity: 5.51 mph
- Crash duration: 0.187 seconds
- Delta V: 6.6 mph
- Target vehicle peak acceleration: 3.01 g at 0.113 seconds
- Target vehicle average acceleration: 1.37 g

FIGURE 55 Test 2: Ford Crown Victoria 5 mph

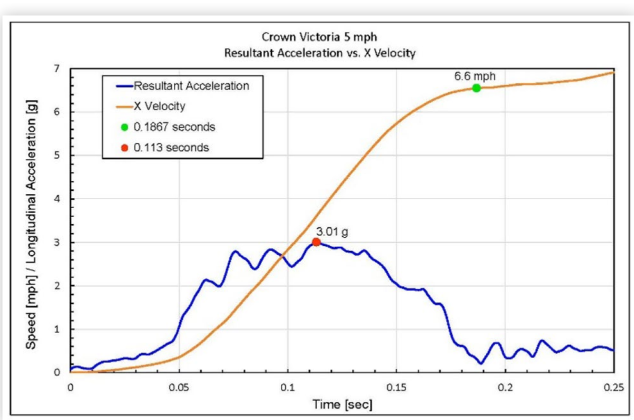
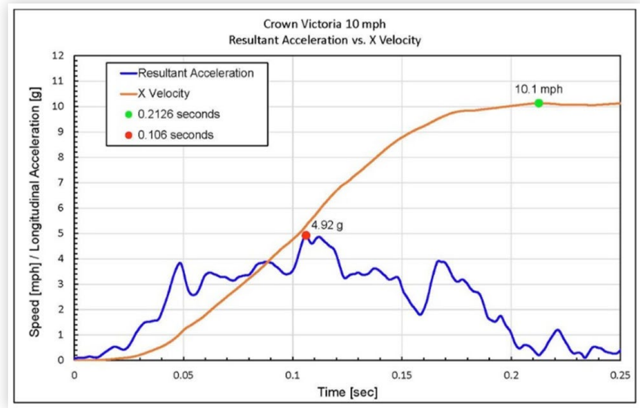


FIGURE 56 Test 3: Ford Crown Victoria 10 mph



Test 3 Ford Crown Victoria 10 mph

- Target vehicle (Ford) initial velocity: 0 mph
- Bullet vehicle (Mack) initial velocity: 10.07 mph
- Crash duration: 0.213 seconds
- Delta V: 10.1 mph
- Target vehicle peak acceleration: 4.92 g at 0.106 seconds
- Target vehicle average acceleration: 2.28 g

Table 5 summarizes the crash testing data for all three tests, including speeds for the bullet and target vehicles, peak and average accelerations, and restitution and impact duration

TABLE 5 Crash Testing Data Summary

CRASH TESTING DATA SUMMARY								
		Bullet Vehicle		Target Vehicle			Test Results	
Test No.	Target Closing Speed	Initial Speed [mph]	Final Speed [mph]	Final Speed [mph]	Peak Accel [g]	Average Accel [g]	Coefficient of Restitution	Impact Duration [sec]
1	5 mph	5.39	5.16	6.37	2.48	1.20	0.22	0.2206
2	5 mph	5.51	4.85	6.55	3.01	1.37	0.31	0.1867
3	10 mph	10.07	8.69	10.13	4.92	2.28	0.14	0.2126

FIGURE 57 Test 3 Video Overlay: Initial Contact

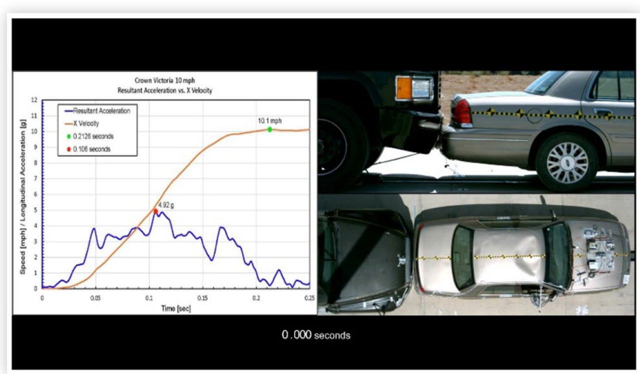


FIGURE 58 Test 3 Video Overlay: Maximum Resultant Acceleration

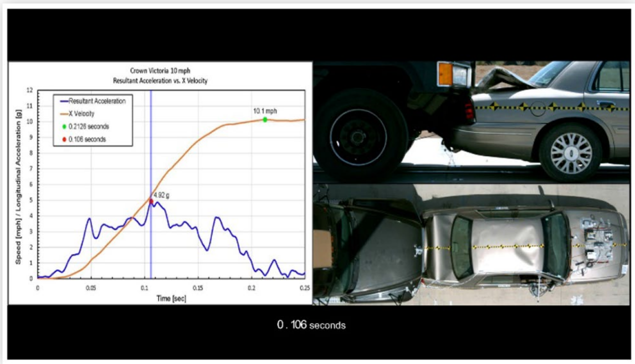


FIGURE 59 Test 3 Video Overlay: End of Crash Pulse

for the impacts. The target vehicle was stationary at the start of each test.

As seen in the above table, the restitution range for all three tests was 0.14-0.31, and the impact duration range was 0.19-0.22 seconds. Furthermore, the peak accelerations to the target vehicle ranged from 2.5-5 g, and average accelerations ranged from 1.2-2.3 g.

High speed video obtained during the tests was overlaid with the summary graphs for each test to visually display initial contact, maximum resultant acceleration, and end of crash pulse in the high speed footage. The following figures show these three key frames in the video overlay from Test 3, the 10 mph Ford Crown Victoria test, as an example.

Conclusions

The testing and data outlined in this paper contributes new information to the research into rear impacts, specifically in the case of a low speed rear override/underride impact associated with a heavy truck striking a passenger car. The testing was limited in sample size, however it provides important data that can be utilized in accident reconstruction when analyzing impacts related to low speed rear override/underride collisions. Two classes of vehicles (midsize and full-size) were tested at two closing speed thresholds, and the results can be applied to other low speed override/underride accidents.

As seen in the test data summary, the restitution range for the three tests was 0.14-0.31 with an average restitution of 0.23, and the impact duration range was 0.19-0.22 seconds with an average duration of 0.21 seconds. For tests 1 and 2, the 5 mph closing speed resulted in a 6-6.5 mph Delta V to the target vehicle, and the 10 mph closing speed in test 3 resulted in a Delta V of 10 mph to the target vehicle. The peak accelerations for the 5 mph tests were 2.5-3 g, and average accelerations were 1.2-1.4 g. The 10 mph test resulted in peak acceleration of 4.9 g and average acceleration of 2.3 g.

The data obtained during this testing shows that low speed rear override/underride collisions have longer impact durations and lower coefficients of restitution than similar bumper-level collisions. Reviewed low speed bumper-level impact testing literature resulted in average impact duration of less than 160 milliseconds and average coefficient of restitution over 0.4. This low speed override/underride testing produced average impact duration of approximately 200 milliseconds and average restitution of 0.23. Longer impact durations and lower restitution result in lower delta Vs and lower peak and average accelerations and forces to the target vehicle. Reduced impact forces in turn reduce the accelerations and forces experienced by occupants of the target vehicle.

When using traditional crush energy analysis methods to analyze low speed override/underride collisions, it is likely that the closing speed and delta Vs will be overestimated because of the difficulties associated with estimating damages, stiffness values, and coefficient of restitution. However, the longer impact durations of approximately 200 milliseconds presented in this paper, compared to bumper-to-bumper durations of under 160 milliseconds, will result in a reduction of at least 25% of calculated accelerations without altering any part of the traditional crush energy analysis. Furthermore, the testing shows that actual delta Vs will be lower than what is calculated when using traditional crush energy analysis due to the different characteristics of override/underride collisions. Additional testing to increase the sample size of target vehicles and vehicle classes at measured closing speeds is planned, along with development of an alternate analysis method for low speed override/underride collisions. Further testing and analysis will be presented in a future technical paper.

References

1. Tanner, C.B., Chen, H.F., Wiechel, J.F., and Brown, D.R., "Vehicle and Occupant Response in Heavy Truck to Car Low-Speed Rear Impacts," SAE Technical Paper 970120, 1997, doi:10.4271/970120.
2. Goodwin, V., Martin, D., Sackett, R., Schaefer, G. et al., "Vehicle and Occupant Response in Low Speed Car to Barrier Override Impacts," SAE Technical Paper 1999-01-0442, 1999, doi:10.4271/1999-01-0442.
3. Croteau, J.J. and Werner, S.M., "Determining Closing Speed in Rear Impact Collisions with Offset and Override," SAE Technical Paper 2001-01-1170, 2001, doi:10.4271/2001-01-1170.
4. Marine, M.C., O'Neill, B., Wirth, J.L., and Thomas, T.M., "Crush Energy Considerations in Override/Underride

Impacts," SAE Technical Paper 2002-01-0556, 2002, doi:10.4271/2002-01-0556.

5. Asay, A., Armstrong, C., Higgins, B., and Steiner, J., "Rear Override Impact Analysis of Full-Size and Light Duty Pickup Trucks for Crash Reconstruction," SAE Technical Paper 2017-01-1423, 2017, doi:10.4271/2017-01-1423.
6. Anderson, R., Welcher, J., Szabo, T., Eubanks, J. et al., "Effect of Braking on Human Occupant and Vehicle Kinematics in Low Speed Rear-End Collisions," *Society of Automotive Engineers, Paper No. 980298*, 1998, doi:10.4271/980298.
7. Cipriani, A., Bayan, F., Woodhouse, M., Cornetto, A. et al., "Low Speed Collinear Impact Severity: A Comparison between Full Scale Testing and Analytical Prediction Tools with Restitution Analysis," SAE Technical Paper 2002-01-0540, 2002, doi:10.4271/2002-01-0540.
8. Kress, T., Hungerford, J., Richards, S., Han, L. et al., "Bumper Paint Damage in Low Speed Impacts," SAE Technical Paper 2007-01-0728, 2007, doi:10.4271/2007-01-0728.
9. Karco Engineering website, 2017.

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Appendix A

The following tables summarize the crush measurements calculated through comparison of pre-test and post-test scan data of each target vehicle. Four horizontal levels were chosen across the back of each target vehicle: at the center of the bumper beam, the bottom edge of trunk lid, the trim above license plate mounting location, and the manufacturer badge on the trunk lid. Measurements of these levels above ground level is included in each table. The final column includes trapezoidal averages of the crush measurements for each level. All measurements are recorded in inches.

Test 1: Nissan Altima 5 mph

	Height above ground	C1	C2	C3	C4	C5	C6	C7	Average Crush
Level 4	40	-0.09	0.74	1.49	2.03	1.26	0.68	-0.21	1.01
Level 3	35	1.01	1.95	3.20	3.22	3.02	1.88	0.92	2.37
Level 2	25	0.86	2.22	2.51	2.48	2.54	2.12	1.05	2.14
Level 1	18	0.52	0.59	0.62	0.76	0.79	0.86	0.62	0.70

Test 2: Ford Crown Victoria 5 mph

	Height above ground	C1	C2	C3	C4	C5	C6	C7	Average Crush
Level 4	39	-0.08	0.41	0.66	0.95	0.51	0.22	-0.46	0.41
Level 3	36	0.88	1.06	1.60	1.58	1.38	1.09	0.84	1.26
Level 2	28	1.37	2.29	2.73	2.78	2.92	2.15	0.97	2.34
Level 1	20	0.25	0.08	0.19	0.09	0.07	0.24	-0.01	0.13

Test 3: Ford Crown Victoria 10 mph

	Height above ground	C1	C2	C3	C4	C5	C6	C7	Average Crush
Level 4	39	4.76	5.23	5.76	6.26	5.11	4.50	4.44	5.24
Level 3	36	7.56	7.58	8.03	8.90	7.50	6.76	6.60	7.64
Level 2	28	4.50	9.93	10.74	10.87	10.28	9.34	5.06	9.32
Level 1	20	0.54	0.46	-0.08	-1.29	-1.27	-0.83	0.70	-0.40

Appendix B

The following product specifications for the DTS TDAS G5 32-channel standalone data recorder with docking station were provided by Karco Engineering. They provide detailed information on the data acquisition system utilized for the crash tests.

Specifications

PHYSICAL	
Module Size:	25 x 54 x 85 mm (0.98 x 2.13 x 3.35")
Weight:	200 g (7.05 oz)
Connectors:	1. Gold plated PCB contact method 2. In-line connector options 3. LEMO connectors with Vehicle Docking Station 4. 4 D-Sub with Docking Port

ENVIRONMENTAL	
Operating Temp.:	0-60°C (32-140°F)
Shock:	500 g peak, 4 msec half sine (TDAS G5) 100 g peak, 12 msec (docking options)

ANALOG INPUTS (32)	
Type:	Differential, individually programmable
Maximum Input Range:	0.5-4.5 V
Bandwidth:	D.C. to 4 kHz
Protection:	EM, RFI, ESD
Gain Range:	1.0-4000
Gain Accuracy:	0.2% - Automatically checked each use by precision voltage insertion
Auto Offset Range:	100% of effective input range
Bridge Support:	Yes, under software control

CALIBRATION	
Features:	Software controlled voltage insertion and shunt emulation
Voltage Insertion:	
Type:	16-bit DAC
Accuracy:	0.1%, 100 ppm/°C, software compensated
Shunt Checks:	
Type:	16-bit shunt emulation
Accuracy:	0.1%, 100 ppm/°C, software compensated

EXCITATION	
Method:	Independent, current-limited sources
Voltage levels:	5.0 V (Vehicle Docking Station 2.0 V, 5.0 V)
Accuracy:	0.1%
Rated Current:	20 mA per channel
Short Circuit Recovery:	<1 msec
On/Off Control:	Excitation sources turned on/off by software control to minimize power consumption

ANTI-ALIAS FILTERS	
Fixed Low Pass:	4-pole Butterworth, standard knee frequency of 4.0 kHz (HB option = 40 kHz)
Adjustable Low Pass:	5-pole Butterworth set under software control, 50-5000 Hz (HB option = 40 kHz)
Overall Response:	Both filters may be used together to achieve 9-pole effective response
SAE J211:	System response exceeds SAE J211 requirements

DIGITAL INPUTS (32)	
Type:	5 V logic input or contact closure with built-in pull-up resistor
Propagation Delay:	<0.05 msec
Protection:	EM, RFI, ESD

DIGITAL COMMUNICATION BUS	
Number of Avail. Lines:	One per channel plus 2 extra
Methodology:	Dallas (Maxim) 1-Wire®
Typical Uses:	Silicon serial number, TEDs, etc.

ANALOG-TO-DIGITAL CONVERSION	
Type:	One SAR ADC per channel
Resolution:	16-bit
Max. Sampling Rate:	100k samples/sec/channel
Relative Accuracy:	± 4 LSB
Storage Technique:	Recorder or circular buffer modes available. Any portion of the memory may be allocated to pre-trigger data.
Memory Type/Capacity:	150 seconds at 10k samples/sec

TRIGGERING	
TDAS G5:	Optically isolated input with trigger received LED indicator
Level Triggering:	Available from any channel(s) within each DAS module
Trigger Synchronization:	Control architecture supports multiple module installations

STATUS OUTPUTS	
Recording:	5 V, 20 mA driver (for LED or opto-couplers)

POWER	
Supply Voltage:	13.8 V nominal (11-15 V)
Maximum Power:	Approximately 800 mA per 32-channel system with 350 ohm bridges at 5.0 V excitation (depends significantly upon connected sensors)
Protection:	EM, RFI, ESD, reverse current
Power Control:	Remote power control line for switching unit on/off

CONTROL SOFTWARE	
Interface:	Ethernet 100BaseTX
Compatibility:	Standard TDAS Control Software
Operating Systems:	Windows® XP/Vista/7/8 (32/64-bit)

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