



# Validation of the Use of Quasistatic Force Deformation Measurements for Determining Collision Force in Low-Speed Override/Underride Collisions

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## Abstract

The purpose of this study was to investigate the use of quasistatic force deformation (QSFD) data to represent the collision forces in low-speed collinear collisions when there is damage to vehicle body structures as well as the bumpers. In this study five full-scale underride/override crash tests were performed and simulated with QSFD data. In each crash test a bumper or a trailer underride guard on a bullet vehicle overrode the rear or front bumper of a target vehicle and damaged structures above the bumper of the target vehicle. A QSFD measurement was performed substantially similar to the vehicle interactions in the crash using a complete exemplar target vehicle that was rigidly attached to the earth. The output of a QSFD measurement is force deflection data for the vehicle pair. Each crash test was simulated using the QSFD data, the weights of the test

vehicles, the closing speed of the test vehicles, and the restitution measured in the crash test. The output of a simulation was the velocity vs. time history of the target vehicle. The change in velocity ( $\Delta V$ ) of the target vehicle in the simulations was determined by analysis of the force deflection data. The  $\Delta V$  ranged from 3.9 to 8.6 mph. The average differences between the  $\Delta V$  measured in a crash test and the calculated in the simulation of that crash test was 0.16 mph. The crash pulses of the target vehicle in the simulations were similar to the crash pulses in the full-scale tests. In three of the full-scale crash tests a load cell array measured the force of the collision. The simulations using QSFD data were able to accurately predict the collision force during the crash. This work demonstrates the utility of the QSFD methodology to represent the collision forces in low-speed crashes when there is damage beyond the bumper systems of vehicles.

## Keywords

Accident reconstruction, Crash testing, Simulation and modeling, Override, Underride

## Introduction

A method to reconstruct bumper-to-bumper low-speed collisions was previously developed that is based on recreating the bumper damage using quasistatic force deformation (QSFD) measurements [1–3]. In this context the phrase "low-speed" refers to the closing velocity of the vehicles in the crash, not the vehicle speeds relative to earth. This method was developed because

traditional crash reconstruction techniques tend to overestimate crash severity when the amount of crush is small and is non-uniform across the horizontal and vertical aspects of the vehicles. In the analysis of real-world low-speed collisions, the only relevant crush information a reconstructionist usually has is from photographs taken before the vehicles were repaired and/or taken during the repair process. Funk et al. demonstrated that QSFD data

can be used to accurately reconstruct crashes when only the bumpers experienced damage in the crash and the damage to the bumpers created during the QSFD measurement was substantially similar to the collision damage. This study extends the work of Scott et al. (2012) as it investigates the use of QSFD data to determine the collision forces and vehicle stiffness characteristics in underride/override collisions when there is damage to the body of one of the vehicles as well as the bumpers.

Traditionally, the analysis of override/underride collisions has been accomplished using a damage or crush energy approach. Struble et al. outlined a method to account for the crush energy at the bumper level and above the bumper level using publicly available load cell barrier data collected in National Highway Traffic Safety Administration (NHTSA) compliance tests [4]. Struble's method allows for vehicle-specific calculations primarily based on force distribution obtained from high-speed frontal crash tests. Additionally, the model postulated that shear energy exists due to the shear deformation between the upper and lower structures of the vehicle during the underride/override crash. This study concluded that, in general, damage to structures above the bumper level accounted for 10% to 29% of the total crush energy.

Marine et al. reported the findings of four staged crash tests involving frontal collisions with a vertically offset barrier [5]. The crash configuration resulted in structural deformation to the front bumper and structures above-bumper level. Impact speeds varied between 10.5 and 18.3 mph. Discrete crush measurements were obtained at the bumper and at the leading edge of the vehicle's hood. These crush measurements were subsequently utilized to calculate crush energy at each level. The authors concluded that the average of the bumper and hood residual crush closely approximated full-frontal crush data.

Rear override crashes with offset were analyzed by Croteau et al. [6]. A series of four two-vehicle crash tests were conducted between a passenger vehicle and a flat rigid moving barrier or heavy vehicle. The study explored the effect of both horizontal and vertical collision offset. The tests between the rigid barrier and sedan had an impact speed of 31.6 mph and the tests between the heavy vehicle and sedan had a nominal impact speed of 25.7 mph. The results of the tests were compared with EDSMAC4 simulations. The study suggested adjusting stiffness coefficients to better model the acceleration profile of the crash being investigated. The results also indicated that the damage energy can be estimated using 100% of the energy from the crush at the bumper and 50% of the energy from the structures above the bumper level.

Danaher et al. reported the results of three low-speed override crash tests between a tractor-trailer combination and a stationary passenger vehicle [7]. The impact speeds were from 6.4 and 10.1 mph. The vehicle velocity and acceleration time histories indicated that the crash pulse durations for overrides were approximately 200 ms, and the average coefficient of restitution was 0.23.

In this study, five underride/override crash tests were investigated where the front of a bullet vehicle impacted

a stationary target vehicle. The bullet vehicle was a truck, van, or a truck tractor with a rigid impact implement attached to the front. The impact implement was either a Ford F-750 front bumper or a dry van trailer-style underride guard. When the underride guard was on the tractor the front of the tractor impacted the front of a stationary vehicle and the underride guard overrode the front bumper of the target vehicle creating damage to the upper front structures of the target vehicle. These crash tests replicated a frontal impact for the target vehicle. When the implement was the F-750 front bumper, the bullet vehicle struck the rear of the target vehicle. When the front bumper of the bullet vehicle overrode the rear bumper of the target vehicle there was damage to the rear body of the target vehicle. These tests replicated a rear impact on the target vehicle. In all of the crash tests there no measurable permanent damage to the bumper or underride guard on the bullet vehicle was observed. QSFD measurements were performed for each pair of vehicles. The quasistatic measurements were made with an undamaged bumper/underride guard and an exemplar of the target vehicle. These QSFD data were then used in a simulation program that calculated the collision force and the accelerations of the vehicles in the crash test. The algorithm in the simulation program is based on Newton's Laws of Motion and has been previously described [1]. The underlying theory in the simulation program treats each vehicle as a rigid body with a deformable spring between the vehicles [8] where the deformable spring represents structural deformation or crush. The QSFD data represented the stiffness of this deformable spring during the crushing phase of the crash in the simulation. Since the simulation algorithm is based on Newton's laws and should apply to all structures, the purpose of this study was to examine the ability of the QSFD data to represent the collision forces in low-speed crashes where there is damage to the body structures and components of vehicles above the impact bar.

The state of the literature to date suggests that the application of a QSFD-informed reconstruction of an override-type collision may be valid; however, no such data has yet been published. The goal of this study was to investigate the use of QSFD data to represent the collision forces in low-speed collinear collisions when there is damage to vehicle body structures and components of vehicles as well as the bumpers. This paper demonstrates our analysis of the hypothesized utility of the QSFD methodology in such circumstances.

## Methods

### Crash Tests

Five crash tests were used to evaluate the ability of QSFD data to represent the collision forces in a low-speed crash. In all crash tests the bumper/underride guard of the bullet vehicle overrode the bumper on the target

vehicle. In each crash test a three-axis accelerometer (MSI Inc. Model 53A) was placed near the target vehicle's center of gravity (CG). Multiple video cameras documented the vehicle motions in the crash tests. There was a three-axis accelerometer in the bullet vehicle. The target vehicle was always stationary at impact, and the impact speed of the bullet vehicle was measured with a GPS datalogging system (Racelogic Video VBOX). The post-impact speed of the target vehicle was calculated via the integration of the CG acceleration data. The measured accelerometer data were filtered according to SAE J211 recommended practices. The coefficient of restitution ( $\epsilon$ ) was determined from the crash tests by defining the end of the crash pulse for the target vehicle. The crash was over once the target vehicle accelerations went to zero or near zero if there were small vibrations present. The restitution was then calculated using the target ( $V_T$ ) and bullet vehicle ( $V_B$ ) velocities at the time the crash pulse ended with the following equation,

$$\epsilon = (V_T - V_B) / (\text{Closing velocity})$$

In crash tests #3, #4, and #5 a dynamic force deformation (DYFD) curve was generated based on the vehicle acceleration data and the load cell data. The measured load cell data were filtered according to SAE J211 recommended practices. Deformation was computed by double-integrating the vehicle accelerations to obtain the dynamic deformation time history. Then the load cell data was matched with the deformation data at each time point to create the DYFD curve.

Table 1 shows the test matrix which includes the type of crash for the target vehicle, the vehicle weights, the impact speed of the bullet vehicle, the restitution, and the  $\Delta V$  experienced by the target vehicle in each crash test. In crash tests #3, #4, and #5 the bullet vehicle was a 1998 International 9100 class 8 tractor with a Ford F-750 bumper, or a dry van trailer-style underride guard mounted to the front frame rails in line with a load cell array that measured the collision force. The load cell array consisted of four load cells sandwiched between two 3/4 in. thick steel plates. The rear plate was bolted to the frame rails of the tractor and the front plate carried the bumper or underride guard. The collision forces in crash

tests #3, #4, and #5 were directly measured with the load cells (Interface model 1220) and the measured data were inertially compensated to account for the mass of the load cells and the hardware in front of the load cells. The load cell data had to be inertially compensated since there was a steel plate and a bumper/underride guard between the load cells and the surface where the impact forces were generated. The mass of the plate and the bumper/underride guard ( $M_p$ ) experienced the acceleration of the International 9100 tractor ( $A_{IT}$ ), the bullet vehicle, so an additional force, calculated with Newton's second law, had to be added to the summed force measured by the four load cells ( $F_{LC}$ ).

$$\text{Inertially compensated collision force} = M_p * A_{IT} + F_{LC}$$

After each crash test the damage on the target vehicle was documented with digital still photography and a 3D laser scanner (FARO Inc., Focus S70). The maximum dynamic engagement between the two vehicles in each crash test was determined by double integrating the vehicle accelerations and obtaining the system crush as a function of time. The dynamic engagement represents the combined crush of both vehicles during the crash, and maximum crush occurred when the vehicles achieved common velocity. Figure 1 shows pre-crash alignment of the vehicles in the crash tests.

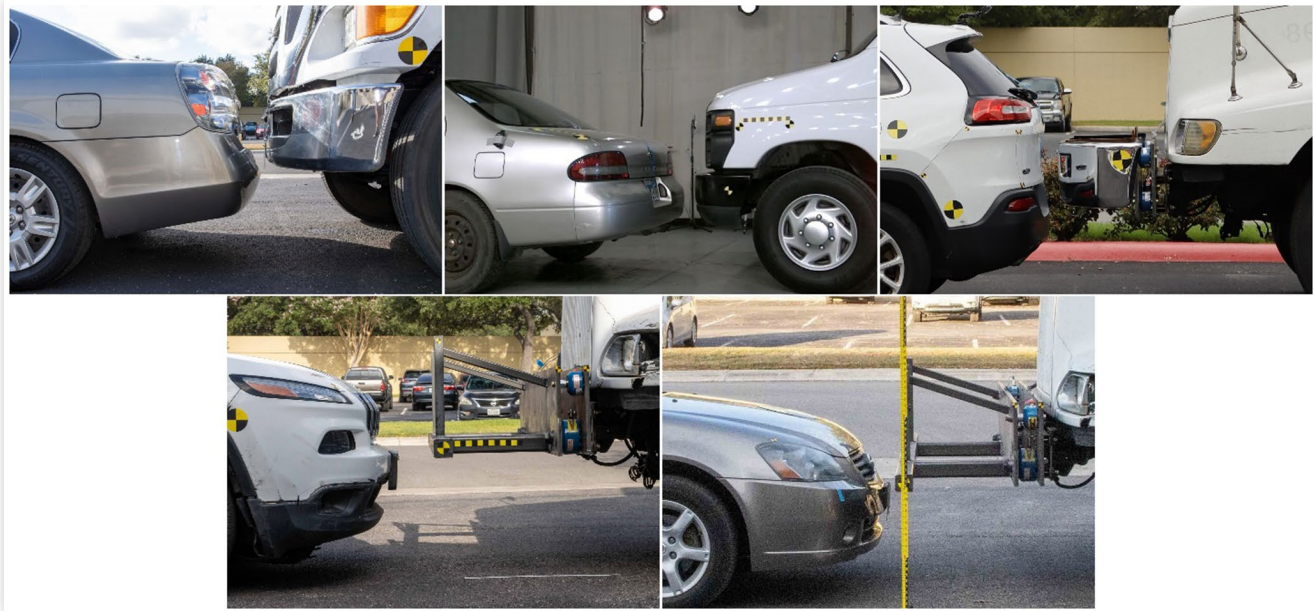
Figure 1 shows pre-crash alignment for each crash test. In crash test #1 a 2011 Ford F-750 Truck impacted the rear of a 2006 four-door Nissan Altima. The front bumper on the F-750 overrode the Altima's rear bumper reinforcement bar (re-bar). The impact alignment was centerline to centerline.

In crash test #2 a 1997 Nissan Altima was impacted in the rear by a 2010 Ford E-350 Van. The van was offset to the right relative to the Altima such that the centerline of the van lined up with the right side of the Altima. There was approximately 0.5 in. of vertical engagement between the van's front bumper and the Altima's rear bumper reinforcement bar at the moment of impact.

In crash test #3 the bullet vehicle was a 1998 International 9100 tractor. The tractor had a Ford F-750 Truck bumper mounted on the front. The target vehicle

**TABLE 1** Crash test information and the measured coefficient of restitution.

Crash test #	Impact location	Target vehicle	Target vehicle weight (lb)	Bullet vehicle weight (lb)	Bullet vehicle	Impact speed (mph)	Restitution
1	Rear	2006 Nissan Altima	3,410	16,229	2011 Ford F-750	3.9	0.30
2	Rear	1997 Nissan Altima	3,230	6,768	2012 Ford E-350	8.6	0.17
3	Rear	2014 Jeep Cherokee	4,147	17,920	International 9100 w/ Ford F-750 front bumper	4.8	0.35
4	Front	2014 Jeep Cherokee	3,902	17,867	International 9100 w/ underride guard	6.9	0.29
5	Front	2005 Nissan Altima	3,302	17,867	International 9100 w/ underride guard	5.4	0.29

**FIGURE 1** The pre-crash alignment for crash tests #1–#3 (top row), #4, and #5 (bottom row).

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was a 2014 Jeep Cherokee. The F-750 bumper overrode the rear bumper of the Jeep and impacted the lift gate. The impact was centerline-to-centerline.

Crash test #4 represented an impact between the front of a 2014 Jeep Cherokee and the rear underride guard of a dry van semi-trailer. In order to recreate this type of crash an underride guard was mounted on the front of the International 9100 tractor. The tractor impacted the front of a stationary 2014 Jeep Cherokee, and the tractor was offset to the right of the Jeep centerline by 0.5 ft. The underride guard interacted with the structure of the Jeep above its front bumper and was not damaged.

Crash test #5 was also set up to represent an impact between the front of a passenger vehicle and the rear underride guard of a tractor-trailer. The same underride guard used in crash test #4 was used in crash test #5. The target vehicle was a 2005 Nissan Altima. The tractor impacted the stationary 2005 Nissan Altima, and the tractor was offset to right of the Altima centerline 0.5 ft. The underride guard interacted with the Altima's structure above the front bumper bar and it was not damaged.

## QSFD Measurement

The QSFD measurement was performed after each crash test. The pre-impact position of the bullet vehicle bumper/underride guard was the same relative to the target vehicle as in the crash test except for crash test #2. In the QSFD measurement for crash test #2 the vertical position of the front bumper of the bullet vehicle was raised slightly for the QSFD measurement to ensure that the front bumper of the bullet vehicle overrode the rear bumper of the 1997 Nissan Altima. In all of the QSFD measurements the test vehicle was secured to the floor

of the test facility and a hydraulic press pushed the bullet vehicle bumper/underride guard into the target vehicle. During a QSFD measurement there was always some movement of the target vehicle relative to the floor, so a string potentiometer was placed on the end of the vehicle that was not crushed in order to measure its longitudinal movement with respect to earth. This movement was subtracted from the displacement measurement of the bumper on the hydraulic press at each time step in order to obtain the actual system deformation as a function of time.

For the QSFD measurement for crash test #1 an undamaged exemplar Nissan Altima was rigidly attached to the cement floor of the test facility and the front bumper of a Ford F-750 Truck was mounted onto the moveable plate of the hydraulic press. Because there was very little vertical motion of the rear of the Altima in the crash test, the suspension of the Altima in the QSFD measurement was rigidly fixed to minimize vertical motion of the rear of the Altima during the measurement. The centerline of the F-750 bumper was aligned with the centerline of the Altima and the vertical height of the F-750 bumper was set at the same position as in the crash test.

The QSFD measurement for crash test #2 was made with an exemplar 1994 Nissan Altima and the front bumper of a 2012 Ford E-350 Van. In the static alignment there was 0.5 in. of vertical engagement between the front bumper of the van and the bumper reinforcement bar in the rear bumper of the Altima. In order to ensure that the override occurred in the QSFD measurement and to mimic the vertical motion of the van's front bumper relative to the rear of the Altima early in the crash, the E-350 front bumper was raised 1.5 in. relative to its static position at initial contact. For this QSFD measurement the rear suspension of the Altima was allowed to move freely so the rear of the Altima could move up and down.

The QSFD measurement for crash test #3 was made with the rear of an undamaged 2014 Jeep Cherokee and the front bumper of a Ford F-750 Truck. The Jeep was secured to the test facility floor and the F-750 bumper was pushed into the liftgate of the Jeep in the same location as the crash test.

The QSFD measurement for crash test #4 was obtained by pushing the underride guard that was used in crash test #4 into the front of an undamaged 2014 Jeep Cherokee. The Jeep was secured to the test facility floor and the underride guard was pushed into the Jeep in the same location as the crash test.

The QSFD data for crash test #5 was obtained by pushing the underride guard into the front of an undamaged 2005 Nissan Altima. The Nissan was secured to the test facility floor and the underride guard was pushed into the Nissan in the same location as the crash test.

## Simulations

The simulation of a crash test was performed using a custom MATLAB code with the measured QSFD data, the vehicle weights, the closing speed of the bullet vehicle, and the coefficient of restitution measured in the crash test. The simulation was formulated as an initial value problem, with the impact speed of the bullet vehicle being the initial value (target vehicle was always stationary) and solved numerically over a series of small (0.1 ms) discrete time steps. At each successive time step following the first contact between the vehicles, the displacement of each vehicle was calculated by integrating its velocity. Combined crush was then determined by subtracting the target and bullet vehicle displacements. The collision force developed as a result of this combined crush was calculated with the data measured during the crushing part of the QSFD measurement. Vehicle accelerations were then calculated by dividing the force by the vehicle mass, and vehicle velocities were calculated by integrating the vehicle accelerations. The process was then repeated for the next time increment and continued throughout the crushing phase of the simulation. The crushing phase ended when the vehicles reached a common velocity, and the simulation transitioned from the crushing phase into the rebound phase. The linear rebound FD curve was then calculated. The rebound curve started at the FD point where the vehicles reached the common velocity and was calculated so that it satisfied the amount of energy returned to the system as measured by the restitution in the crash test [2, 9]. The procedure for modeling the rebound phase of the crash simulation was identical to the procedure for modeling the crush phase, except that the restitution FD curve was used to calculate the collision forces. The restitution phase of the simulated crash ended when the calculated collision force was zero or less than zero. Since bullet vehicles sometimes had some slight deceleration at the start of a crash or acceleration at the end of the crash, the time history velocity of the bullet vehicle was an input to a simulation. This accounted for any braking forces or engine forces in the crash.

The output of a simulation is the crash pulse, the acceleration vs. time data, for both vehicles and the collision force vs. time data. The  $\Delta V$  of the target vehicle in the simulation was calculated by integrating the accelerations of the target vehicle in the simulated crash. The validation of the method was performed by comparing the velocity vs. time data in the simulation with the crash test velocity vs. time data. In the three crash tests with load cells, the collision force vs. time data from the crash test was compared with the collision force vs. time data from the simulation. The comparison of the  $\Delta V$  calculated in the simulation with the  $\Delta V$  in the crash test was also made. The simulations used the closing velocity and the coefficient of restitution for each crash test as inputs. Knowing the closing velocity, the restitution, and the weight (mass) of each vehicle provides all of the necessary information required to calculate the  $\Delta V$  without any consideration of time or the quantification of the collision forces [9]. The simulation algorithm is based on Newton's laws and will give the accurate  $\Delta V$  for a given closing velocity, vehicle weights, and restitution. Since these crash test inputs mean the simulation "should" obtain the same  $\Delta V$  as in the crash test, the  $\Delta V$  comparison provides a good overall check of the accuracy of the data collected in the crash tests.

Fidelity of the QSFD simulation outputs vs. time with respect to the measured crash test data was assessed using the ISO18571 standard [10]. Briefly, the ISO18571 standard compares the time history of the simulation output against the measured crash test data. Correlation of key features of the data plots ("magnitude," "phase," "slope," and "corridor") are quantified on a scale from  $R_i = 0$  (no agreement) to  $R_i = 1$  (perfect agreement). A composite score is generated to describe the overall agreement between the simulated and measured data for a given scenario, using the following equation:

$$R_{Ovr} = 0.4R_{Corridor} + 0.2(R_{Mag} + R_{Phase} + R_{Slope})$$

ISO18571 tests were performed in Python with an open-source module [11] combined with custom batch-processing scripts. Correlation analysis was performed for the velocity vs. time data for all crash tests and for the collision force in crash tests #3, #4, and #5, where load cells measured the collision force.

## Results

### Crash Test #1

In crash test #1 a 2011 Ford F-750 Truck impacted the rear of a 2006 four-door Nissan Altima. The front bumper of the F-750 overrode the bumper reinforcement bar in the rear bumper of the Altima. The left photograph in [Figure 2](#) shows the pre-impact position of the F-750 Truck and the Altima with its rear bumper cover removed. The right photograph in [Figure 2](#) shows a video frame of the

**FIGURE 2** The left photograph shows the impact position of the bumpers with the Altima's rear bumper cover removed prior to crash test #1. The right video frame shows the vehicles near maximum engagement during the crash.



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**FIGURE 3** The damage to the rear of the 2006 Altima in crash test #1.



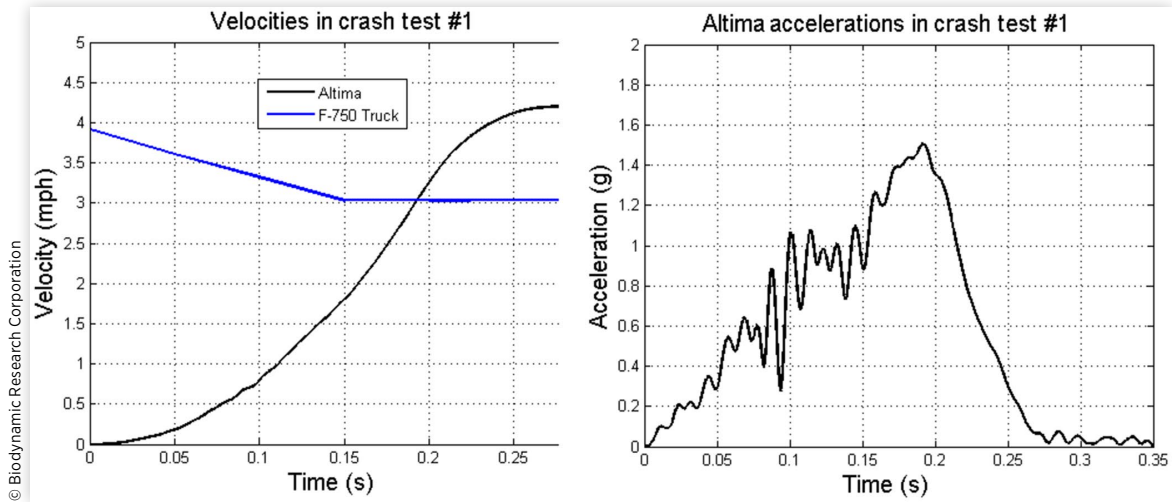
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vehicles near maximum engagement in the crash test. Analysis of the accelerometer data indicated that the deformation at maximum engagement was approximately 0.64 ft (19.5 cm). The damage created to the rear of the Nissan Altima in the crash test is shown in [Figure 3](#). The most visible damage was to the trunk lid. The primary structural damage was to the upper rear body panel which is visible with the trunk lid up in the right photograph in [Figure 3](#). There was no permanent damage to the bumper of the F-750, other than a distorted license plate. The velocities of the F-750 and the Altima during the crash are shown in the left graph in [Figure 4](#). The truck impact speed of 3.9 mph was measured with a GPS datalogging system, and velocity of the Altima was determined by integrating its CG accelerations. The accelerations experienced by the Altima are shown in the right graph of [Figure 4](#). The peak acceleration of the Altima was approximately 1.5 g and the crash pulse lasted for approximately 0.278 s. The  $\Delta V$  experienced by the Altima was 4.2 mph.

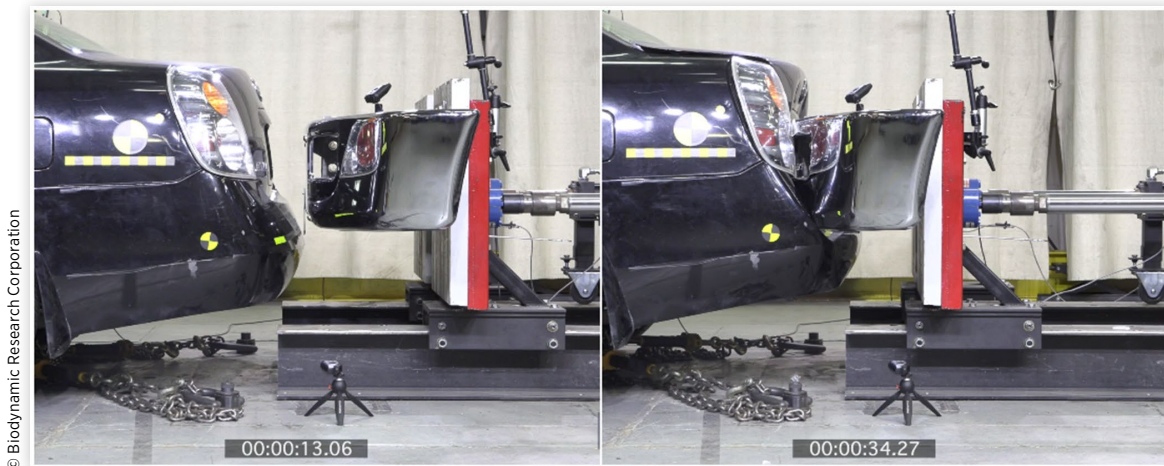
In order to measure the QSFD data for the simulation of crash test #1, an exemplar Nissan Altima was rigidly attached to the cement floor of the test facility and the front bumper of a Ford F-750 Truck was mounted onto the moveable plate of the hydraulic press. Because there

was very little vertical motion of the rear of the Altima in the crash test, the suspension of the Altima in the QSFD measurement was rigidly fixed to minimize vertical motion of the rear of the Altima during the measurement. Frames from a video of the QSFD measurement are shown in [Figure 5](#). The left frame shows the rear of the exemplar Altima and the F-750 front bumper on the hydraulic press before the QSFD measurement. The centerline of the F-750 bumper was aligned with the centerline of the Altima and the vertical height of the F-750 bumper was set at the same position as in the crash test. The right video frame in [Figure 5](#) shows the QSFD measurement near the maximum engagement of 0.65 ft (19.8 cm). The QSFD data are shown in [Figure 6](#). The peak force was 4,227 lb. The linear stiffness from 0.0 to 0.65 ft was 6,490 lb/ft. The photographs in [Figure 7](#) show a comparison of the external damage to the Altima in the crash test (top) and the Altima used in the QSFD measurement (bottom). This crash test was done for a case study and the subject driver most likely did not remove his foot from the gas pedal at the time of impact, which caused the velocity of the bullet vehicle to level out instead of continuing to decrease. This meant that there was some engine-driven force acting on the vehicle as well as the collision forces. Our solution to this problem was to make the velocity of

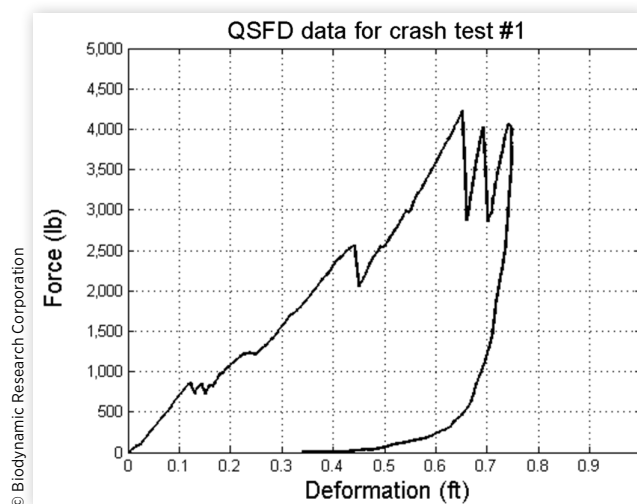
**FIGURE 4** The velocity of the 2006 Nissan Altima and the 2011 Ford F-750 in crash test #1 (left) and the accelerations of the Altima as functions of time (right).



**FIGURE 5** The apparatus used to measure the QSFD data when the front bumper of a Ford F-750 Truck is pushed into the rear of a 2006 Nissan Altima is shown before the QSFD measurement in the left frame. The right frame shows the position of the F-750 bumper relative to the rear of the exemplar Altima after approximately 0.65 ft of engagement.



**FIGURE 6** The QSFD data collected when the front bumper of a Ford F-750 Truck was pushed into the rear upper structures of a 2006 Nissan Altima.



**FIGURE 7** The top photograph shows the damage to the rear of the Altima in crash test #1 and the lower photograph shows the damage to the rear of the Altima used in the measurement of the QSFD data.



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the bullet vehicle an input in the simulation of all the crash tests. By doing this we could account for any additional forces acting on the bullet vehicle due to engine forces or braking forces.

## Crash Test #2

In crash test #2 a 1997 Nissan Altima was impacted in the rear by a 2010 Ford E-350 Van. The van was offset to the right relative to the Altima such that the centerline of the van lined up with the right side of the Altima. Even though this was not a collinear crash the torque created by the collision forces did not cause the Altima to yaw and it tracked straight ahead after the impact, therefore this crash test was considered a good candidate to simulate [12]. There was approximately 0.5 in. of vertical engagement between the front bumper on the van and the rear bumper reinforcement bar of the Altima when the vehicles were stationary. As the vehicles made contact in the crash test there was an upward movement of the front of the van and a downward movement of the rear of the Altima and this relative movement allowed the front bumper on the van to override the rear bumper reinforcement bar

on the Altima. The video frames in [Figure 8](#) show an oblique lateral view of the crash. The left frame is at initial contact and the right frame is approximately 100 ms into the crash. The upward movement of the front of the van and the downward movement of the rear of the Altima can be seen when the two frames are compared. Analysis of the vehicle accelerometers indicated that the maximum dynamic crush was approximately 1.03 ft (31.4 cm). [Figure 9](#) shows the damage to the rear of the 1997 Altima created in crash test #2. The damage was to the right side of the trunk lid, the right side of the rear body panel, and the right rear quarter panel. There was minor damage to the E-350 front bumper in the location where it interacted with the right rear quarter panel of the Altima. The left graph in [Figure 10](#) shows the velocities of both vehicles during the crash and the right graph shows the accelerations of the Altima. The impact velocity of the van was 8.6 mph. The velocity of the Altima during the crash was determined by integrating its accelerations. The crash lasted for approximately 255 ms. The vehicles reached a common velocity of 5.8 mph at 152 ms. The  $\Delta V$  experienced by the Altima was 6.8 mph. The peak acceleration of the Altima was 3.3 g at 50 ms.

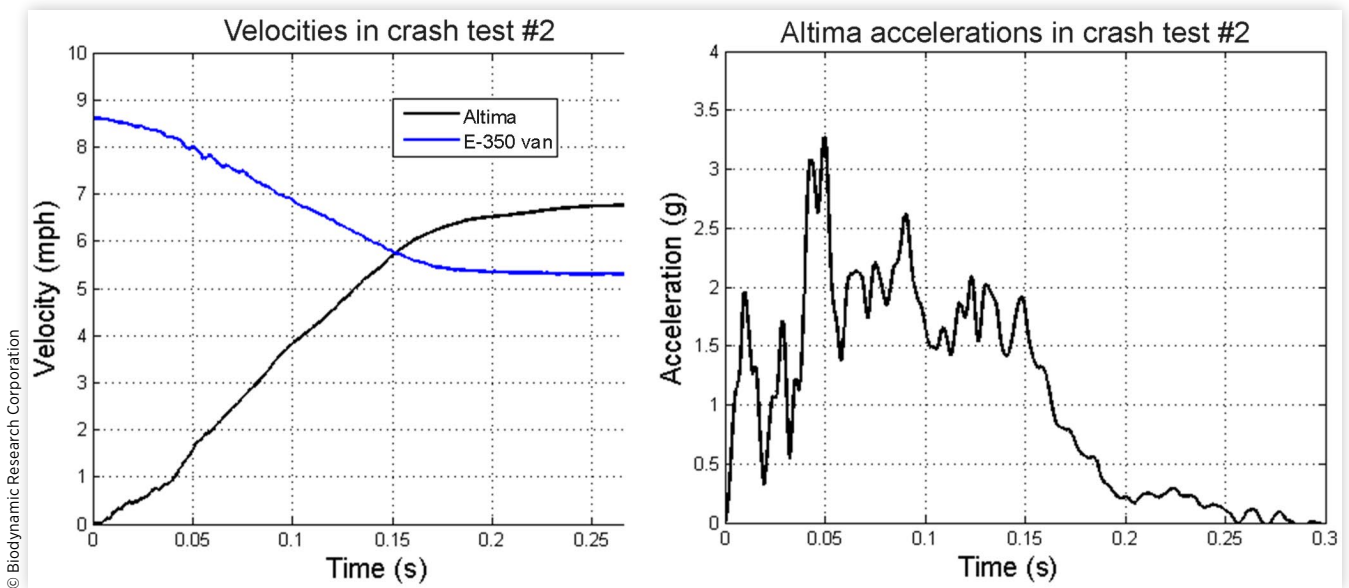
**FIGURE 8** A lateral view of crash test #2 shows the position of the vehicles at initial contact and after approximately 100 ms of engagement.



**FIGURE 9** The damage to the rear of the 1997 Nissan Altima in crash test #2.



**FIGURE 10** The velocities of the two vehicles (left) and the accelerations of the 1997 Nissan Altima in crash test #2 (right).

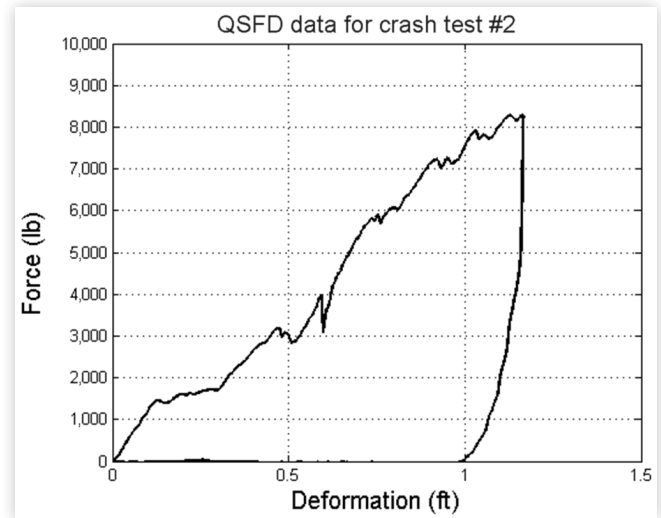


The QSFD measurement was made with a 1994 Nissan Altima and the front bumper of a 2012 Ford E-350 Van. In the static alignment there was 0.5 in. (1.3 cm) of vertical engagement between the front bumper of the van and the bumper reinforcement bar in the rear bumper of the Altima. In order to ensure that the override occurred in the QSFD measurement and to mimic the vertical motion of the van's front bumper relative to the rear of the Altima early in the crash, the E-350 front bumper was raised 1.5 in. (3.8 cm) relative to its static position at initial contact. For this QSFD measurement the rear suspension of the Altima was allowed to move freely so the rear of the Altima could move up and down. Figure 11 shows two video frames of the right side of the Altima taken during the QSFD measurement. The left frame shows the front bumper of the E-350 Van when it first contacted the rear of the Altima. The right frame shows the maximum engagement of the E-350 front bumper into the rear of the Altima during the QSFD measurement. During the measurement the rear of the Altima moved downward with respect to the E-350 front bumper approximately 0.21 ft (6.4 cm). The maximum deformation was 1.17 ft (35.7 cm) and the peak force was 8,293 lb. The QSFD data for this measurement are shown in Figure 12. The average stiffness between 0.0 and 1.0 ft was approximately 7,669 lb/ft. The photographs in Figure 13 show the damage to the crash test vehicle, the top photograph, and the damage created in the measurement of the QSFD data, the bottom photograph.

### Crash Test #3

In crash test #3 the bullet vehicle was a 1998 International 9100 tractor. The front bumper of a Ford F-750 was mounted to the front plate that had the load cell array attached to its rear surface. The F-750 bumper overrode the rear bumper of a 2014 Jeep Cherokee and impacted

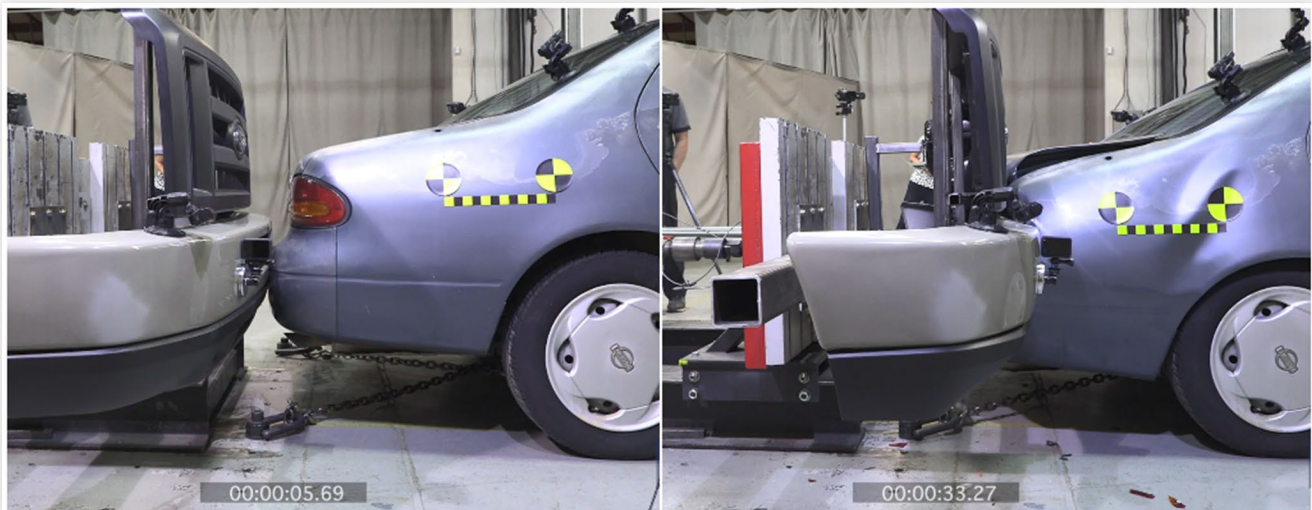
**FIGURE 12** The QSFD data measured when the front bumper of a Ford E-350 Van was pushed into the rear upper structures of a 1994 Nissan Altima.



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the liftgate. The impact was centerline-to-centerline. The video frames in Figure 14 show the vehicles at initial contact and at maximum engagement. The tractor impacted the Jeep at a velocity of 4.8 mph and the maximum dynamic crush calculated from accelerometer data was approximately 0.43 ft (13.1 cm). The photographs in Figure 15 show the damage to the liftgate on the Jeep. The data collected in the crash test is shown in Figure 16. The vehicles achieved a common velocity of approximately 4 mph at 105 ms. The  $\Delta V$  experienced by the Jeep was approximately 5.5 mph. At approximately 170 ms the velocity of the tractor increased slightly. The crash pulse was 186 ms long. The peak acceleration of the Jeep was approximately 2.5 g at 72 ms.

**FIGURE 11** Frames from a video of the QSFD measurement for crash test #2. The left frame shows the front bumper of the E-350 van as it contacts the rear of the Altima, and the right frame shows the bumper near maximum engagement with the Altima.



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**FIGURE 13** The top photograph shows the damage to the rear of the Altima in crash test #2, and the lower photograph shows the damage to the rear of the Altima as a result of the QSFJ measurement.

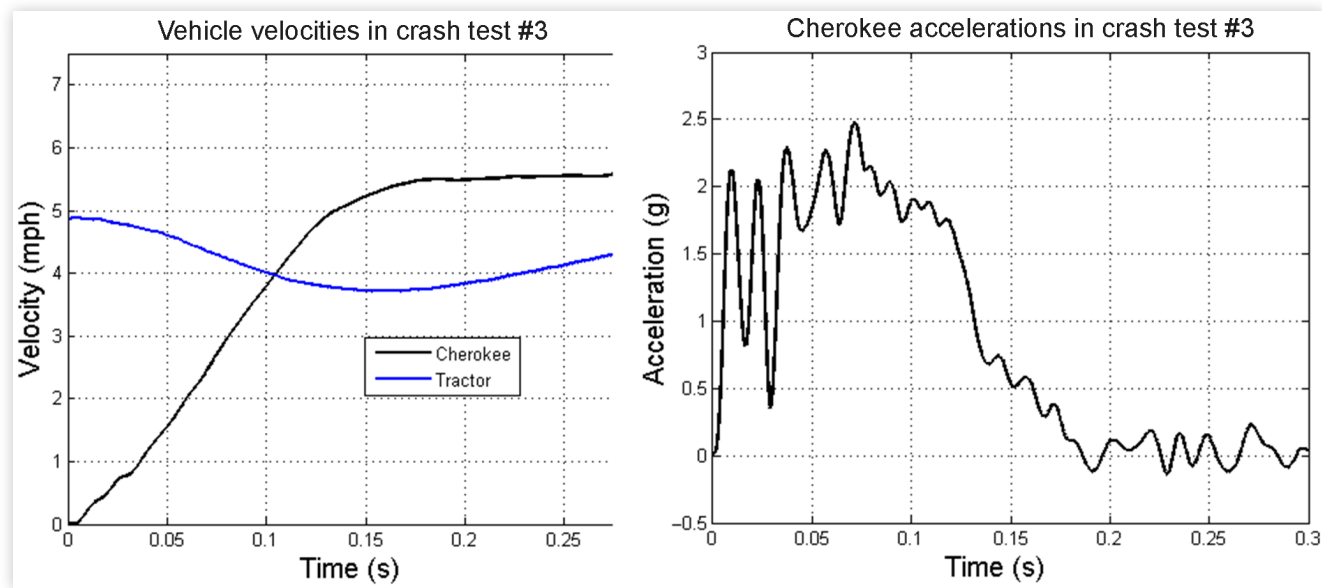


**FIGURE 14** A lateral view of crash test #3 that shows the position of the vehicles at initial contact (left) and near maximum engagement (right).



**FIGURE 15** The damage to the rear of the 2014 Jeep Cherokee in crash test #3.

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**FIGURE 16** The velocities of the two vehicles (left) and the accelerations of the 2014 Jeep Cherokee in crash test #3 (right).

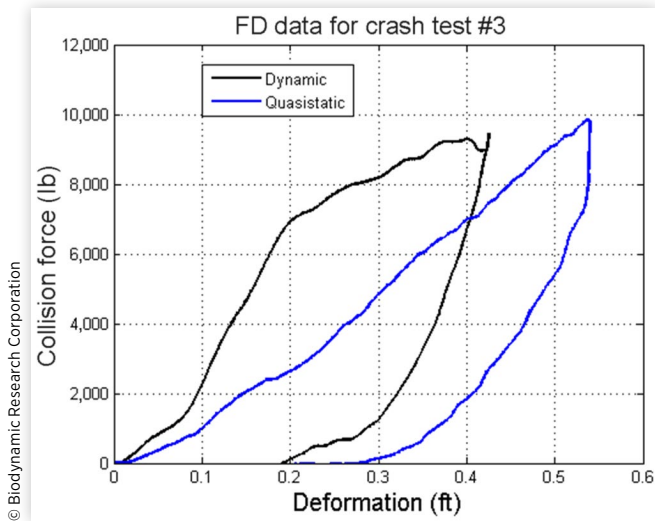
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The DYFD and QSFD data for crash test #3 are shown in [Figure 17](#). The creation of the DYFD data is described in the Methods section. The QSFD measurement was made with a 2014 Jeep Cherokee and the front bumper of a Ford F-750 Truck. The F-750 bumper was pushed into the liftgate, as shown in [Figure 18](#). The maximum deformation was approximately 0.54 ft (16.5 cm) at a peak force of 9,860 lb. The linear stiffness between 0.0 and 0.5 ft was 18,387 lb/ft. The collision forces at a given level of deformation were greater in the DYFD data compared to the QSFD data. The photographs in [Figure 19](#) show the damage to the crash test vehicle (top photograph) and the damage created in the measurement of the QSFD data (bottom photograph).

## Crash Test #4

Crash test #4 represented the front of a passenger vehicle impacting the rear underride guard on a trailer. In order to recreate this type of crash an underride guard was mounted on the front of the 1998 International 9100 tractor in line with the load cell array to measure force. The underride guard is shown in [Figure 20](#). In crash test #4 the tractor impacted the front of a stationary 2014 Jeep Cherokee at a speed of 6.9 mph in order to create a frontal impact for the Jeep. The centerline of the underride guard was offset to the right approximately 0.5 ft (15.2 cm) relative to the centerline of the Jeep and the underride guard overrode the front bumper of the Jeep

**FIGURE 17** The dynamic force deformation (DYFD) data measured in crash test #3 (black line) and the quasistatic force deformation (QSFD) data measured after crash test #3 (blue line).



during the crash. The video frames in Figure 21 show the vehicles at initial contact and maximum engagement. The maximum engagement calculated from accelerometer data was 0.96 ft (29.3 cm). There was no permanent damage to the underride guard. Figure 22 shows the damage to the front of the Jeep. The left vertical support of the underride guard made a distinct impression in the hood/grille of the Jeep and the hood/grille contacted the condenser and the radiator in the crash. The vehicle

speeds (left graph) and the accelerations of the Jeep during the crash are shown in Figure 23. The rearward velocity and acceleration of the Jeep are shown as positive values for these graphs. The vehicles had a common velocity of 5.6 mph at 141 ms. The  $\Delta V$  experienced by the Jeep was approximately 7.0 mph. The peak acceleration was 4.5 g at 126 ms and the crash pulse was 193 ms long.

The DYFD and QSFD data for crash test #4 are shown in Figure 24. The creation of the DYFD data is described in the Methods section. The QSFD data for this crash were obtained by pushing the underride guard that was used in the crash test into the front of an undamaged exemplar 2014 Jeep Cherokee. Figure 25 shows video frames of the QSFD measurement that show initial contact and maximum engagement. The peak force was 24,330 lb and the maximum deformation was 1.18 ft (33.1 cm). The maximum crush in the QSFD measurement is greater than in the DYFD data because it was the intent to exceed the damage in the crash test in the measurement. The average stiffness between 0.0 and 0.8 ft was approximately 8,557 lb/ft. There was no damage to the underride guard during the QSFD measurement. Figure 26 shows the damage to the front of the Jeep in the crash test (top photograph), and in the QSFD measurement (bottom photograph). The final state of the bumper cover is different in these two photographs because in the QSFD measurement the bumper cover was pulled forward when the top of the license plate bracket caught the underride guard as the guard was pulled away from the Jeep after the measurement was over. This engagement between the license plate bracket and the underride guard did not occur in the crash test as the vehicles separated.

**FIGURE 18** Frames from a video of the QSFD measurement for crash test #3. The left frame shows the front bumper of the F-750 front bumper as it contacts the rear of the 2014 Jeep Cherokee, and the right frame shows the bumper near maximum engagement of 0.54 ft (16.5 cm).



**FIGURE 19** The top photograph shows the damage to the rear of the Jeep in crash test #3 and the lower photograph shows the damage to the rear of the Jeep used in the measurement of the QSF data.



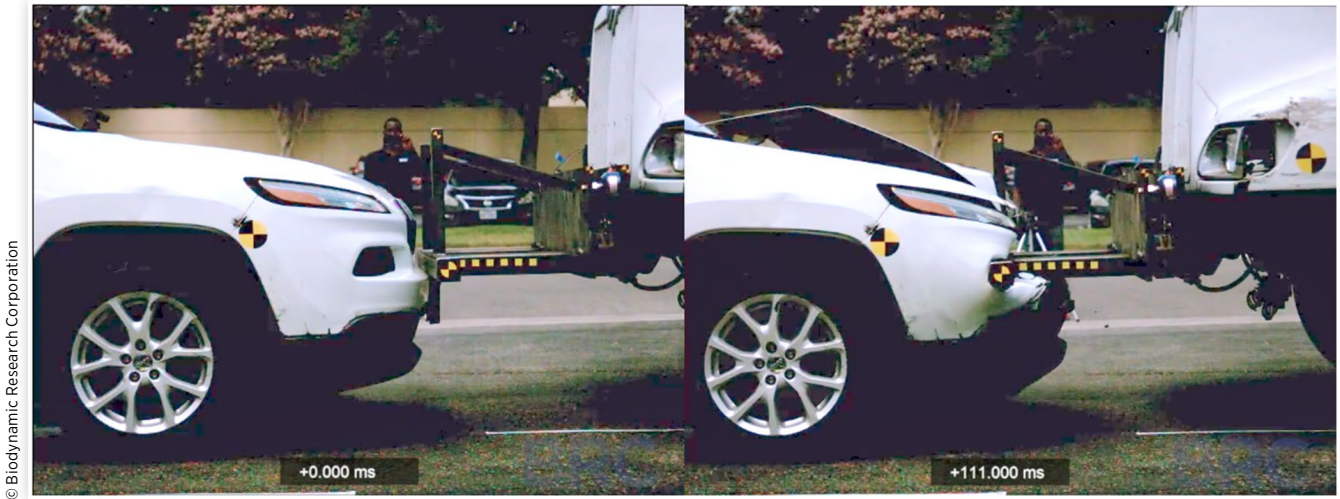
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**FIGURE 20** An underride guard was mounted on the front of the International 9100 tractor.



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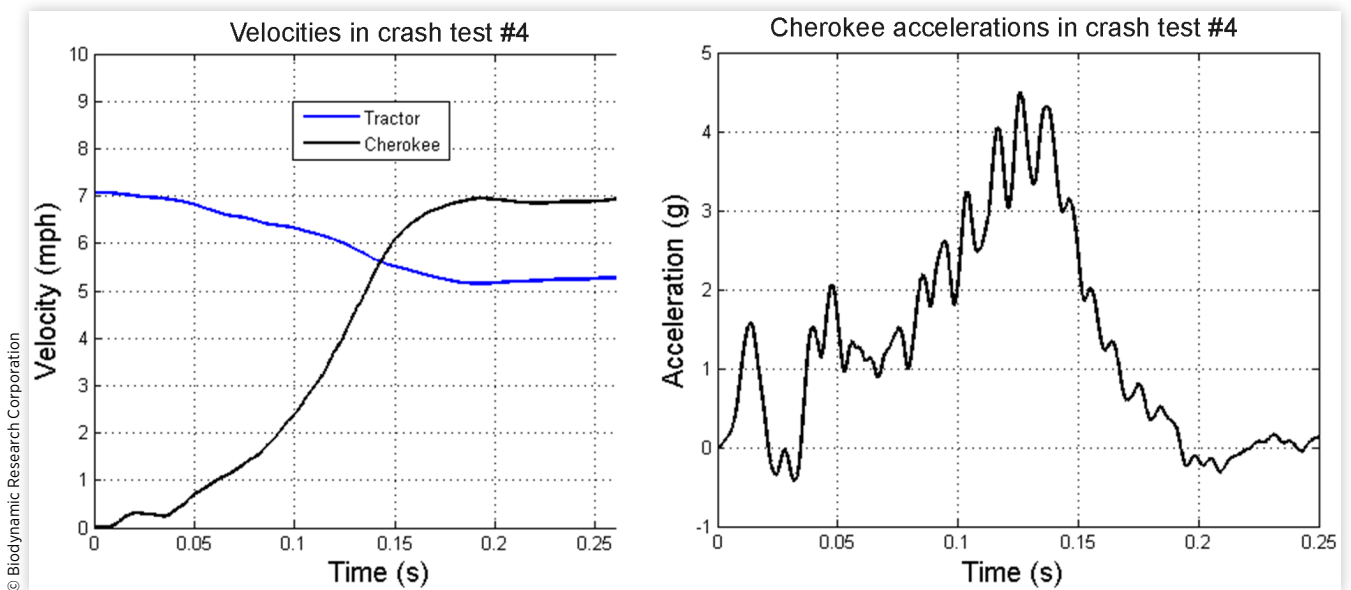
**FIGURE 21** Video frames of crash test #4 show the position of the vehicles at initial contact (left) and maximum engagement (right).



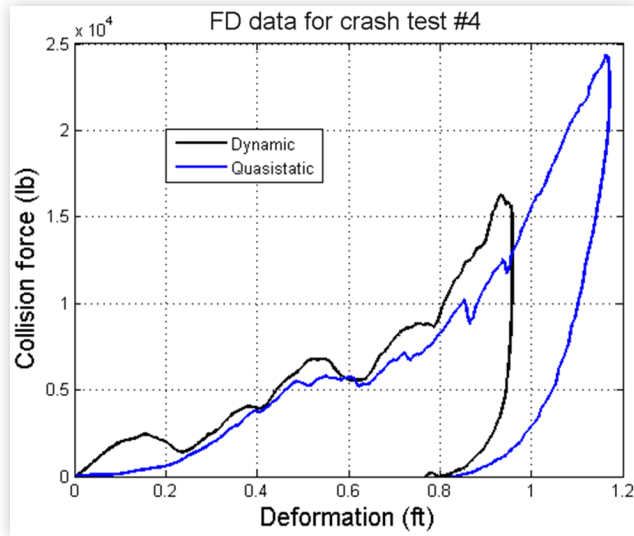
**FIGURE 22** The damage to the front of the Jeep Cherokee in crash test #4.



**FIGURE 23** The velocity of the Jeep and the tractor (left) and the accelerations of the Jeep during the crash (right). The rearward velocity and the accelerations of the Jeep have been made positive for these graphs.



**FIGURE 24** The dynamic force deformation (DYFD) data measured in crash test #4 (black line) and the quasistatic force deformation (QSFD) data measured after crash test #4 (blue line).



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## Crash Test #5

Crash test #5 was also set up to represent the front of a passenger vehicle impacting the underride guard on the rear of a trailer. The same underride guard used in crash test #4 was used in crash test #5. The tractor impacted the front of a stationary 2005 Nissan Altima at a speed of 5.4 mph. The centerline of the tractor was offset to the right about 0.5 ft (15.2 cm) relative to the centerline of the Altima. The video frames in [Figure 27](#) show the vehicles at initial contact and maximum engagement. The maximum dynamic crush determined from the accelerometer data was 0.81 ft (24.7 cm). There was no permanent damage to the underride guard. [Figure 28](#) shows

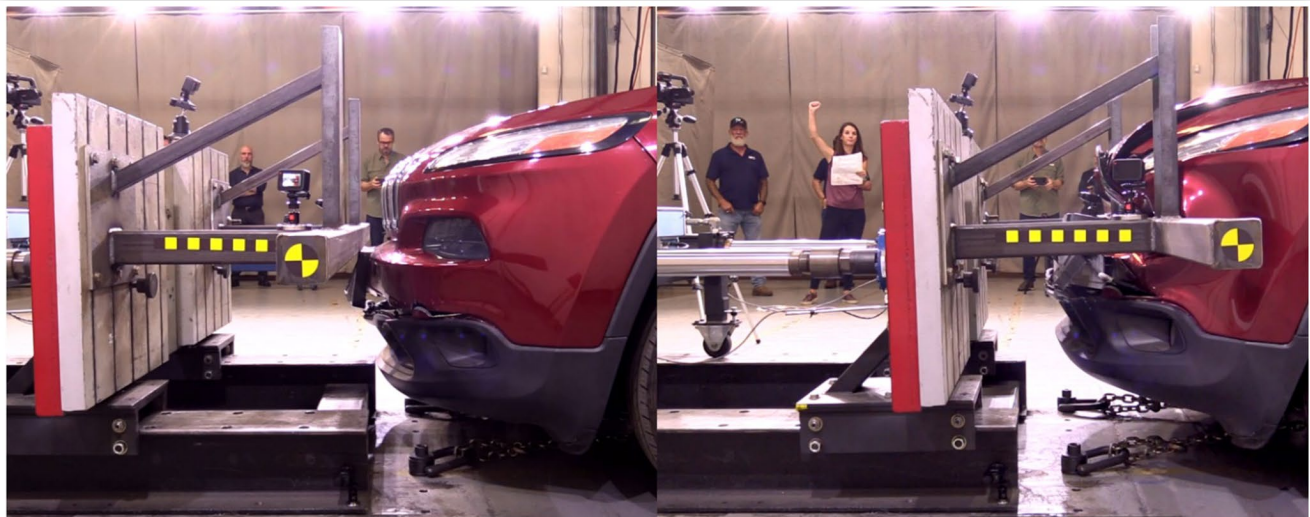
the damage to the front of the Altima. The vehicle speeds and the accelerations of the Altima during the crash are shown in [Figure 29](#). The rearward velocity and acceleration of the Altima have been made positive for these graphs. The vehicles achieved a common velocity of 4.6 mph at 162 ms. The crash pulse length was 260 ms. The peak acceleration of the Altima was 2.1 g at 171 ms.

The DYFD and QSFD data for crash test #4 are shown in [Figure 30](#). The creation of the DYFD data is described in the Methods section. The QSFD data for this crash test were obtained by pushing the underride guard into the front of an undamaged 2005 Nissan Altima. [Figure 31](#) shows video frames of this QSFD measurement. [Figure 30](#) shows the QSFD data obtained in the measurement. The peak force in the measurement was 11,003 lb and the maximum deformation was 0.98 ft (29.9 cm). The maximum crush in the QSFD measurement is greater than in the DYFD data because it was the intent to exceed the damage in the crash test. The average stiffness between 0.2 and 1.0 ft was approximately 13,754 lb/ft. There was no damage to the underride guard as a result of the QSFD measurement. [Figure 32](#) shows the damage to the front of the Nissan Altima in the crash test (top photograph), and the QSFD measurement (bottom photograph). The damage to the Nissan in the QSFD measurement was greater than the damage to the Nissan in the crash test.

## Simulation of Crash Test #1

The vehicle weights, the impact speed for the bullet vehicle, and the restitution used in the simulation of crash test #1 are shown in [Table 1](#). The graphs in [Figure 33](#) show the results of the simulation using the QSFD data shown in [Figure 6](#). The left graph shows the measured QSFD data (black line) and the QSFD data that was used in the simulation (red dashed line). The maximum engagement

**FIGURE 25** Video frames taken during the measurement of the QSFD data for crash test #4 show initial contact (left) and maximum engagement of 1.18 ft (33.1 cm) (right).



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**FIGURE 26** The top photograph shows the damage to the front of the Jeep Cherokee in crash test #4 and the bottom photograph shows the damage to the front of the Jeep used in the measurement of the QSFD data.



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**FIGURE 27** Video frames of crash test #5 show the Altima and underride guard at initial contact (left) and near maximum engagement (right).



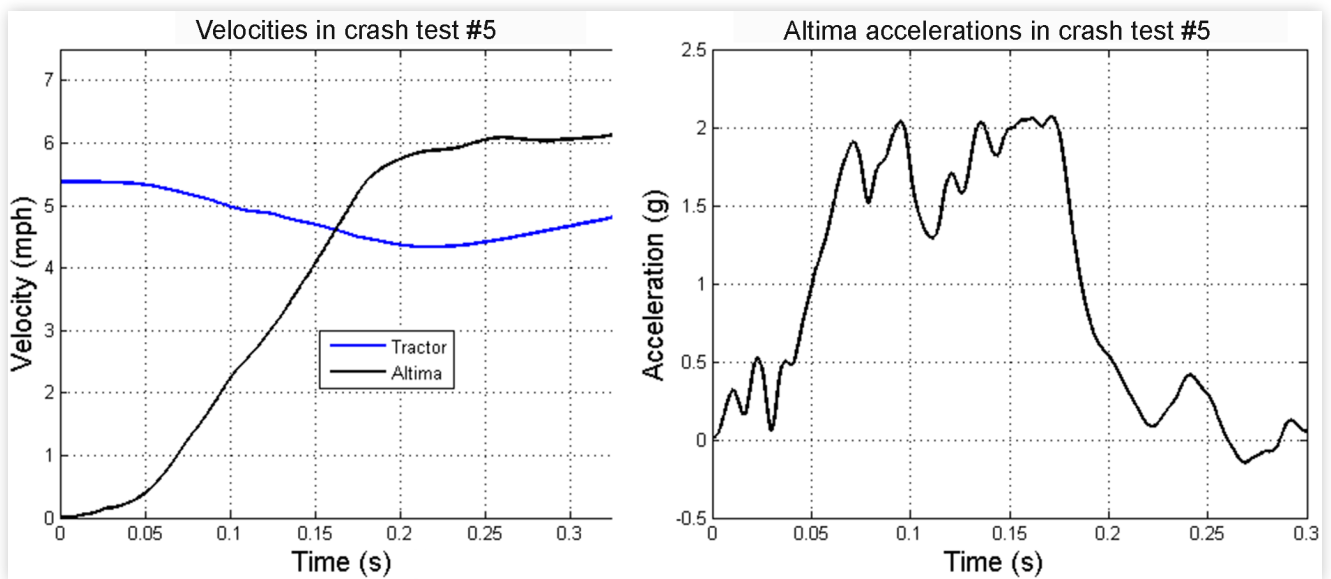
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**FIGURE 28** The damage to the front of the 2005 Nissan Altima in crash test #5.



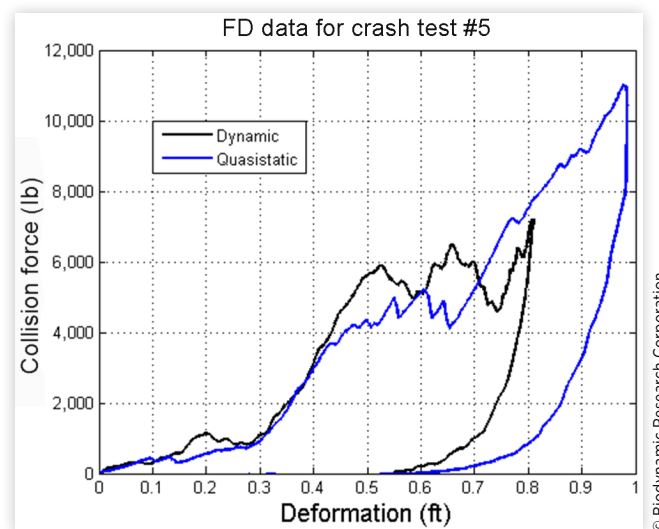
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**FIGURE 29** The velocity of the Nissan Altima and the Tractor and the accelerations of the Altima in crash test #5. The rearward velocity and acceleration of the Nissan has been made positive for this graph.



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**FIGURE 30** The dynamic force deformation (DYFD) data measured in crash test #5 (black line) and the quasistatic force deformation (QSFD) data measured for crash test #5 (blue line).



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**FIGURE 31** Video frames taken during the measurement of the QSF data for crash test #4 show initial contact (left) and maximum engagement (right).



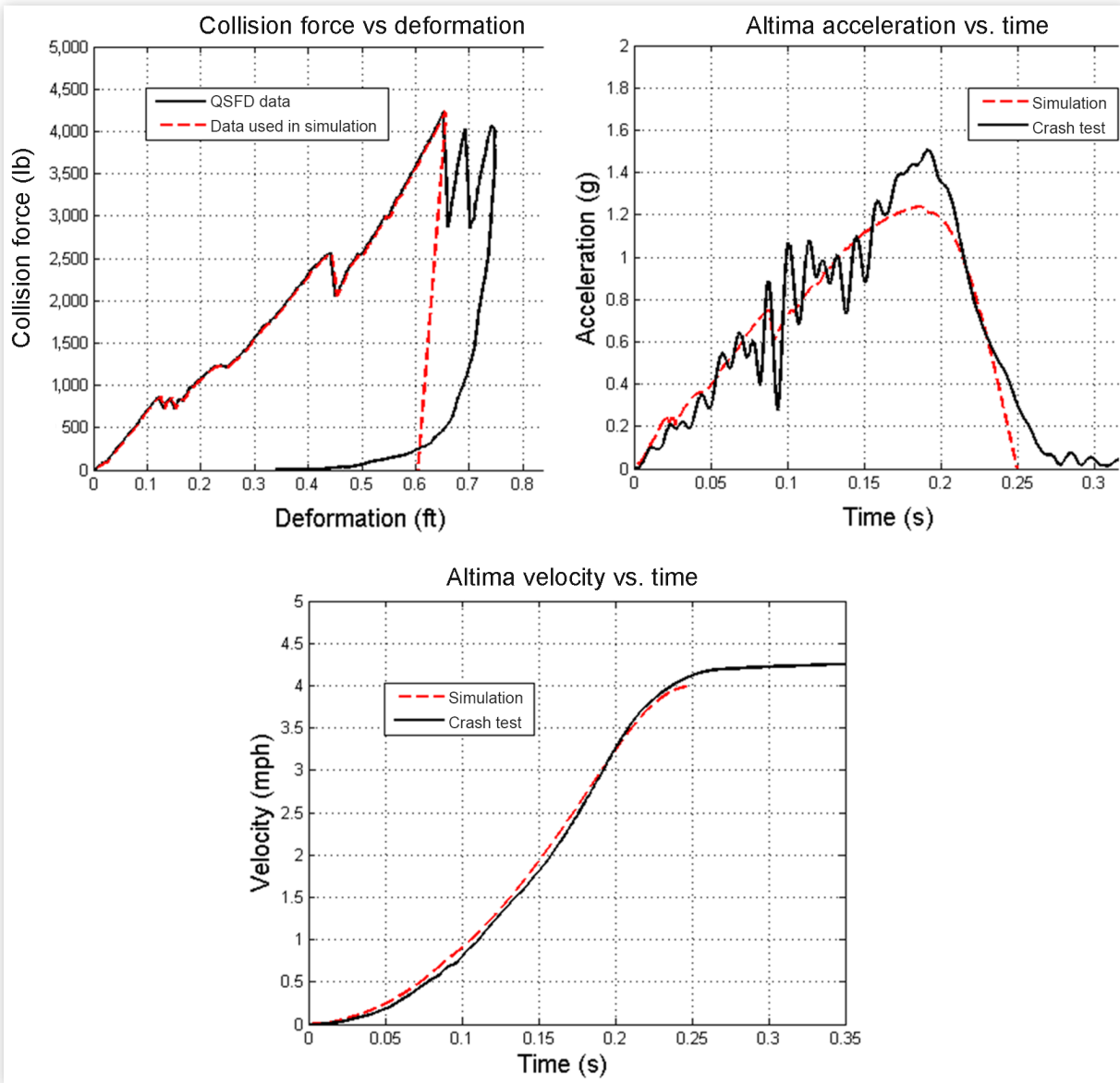
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**FIGURE 32** The top photograph shows the damage to the front of the Altima in crash test #5 and the lower photograph shows the damage to the front of the Altima used in the measurement of the QSF data.



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**FIGURE 33** The left graph shows the measured QSF data (black line) and the QSF data used in the simulation (red dashed line). The center graph shows the accelerations of the Altima in crash test #1 (black line) and the accelerations of the Altima in the simulation (red dashed line). The right graph shows the velocity of the Altima in the crash test (black line) with the velocity calculated in the simulation (red dashed line).



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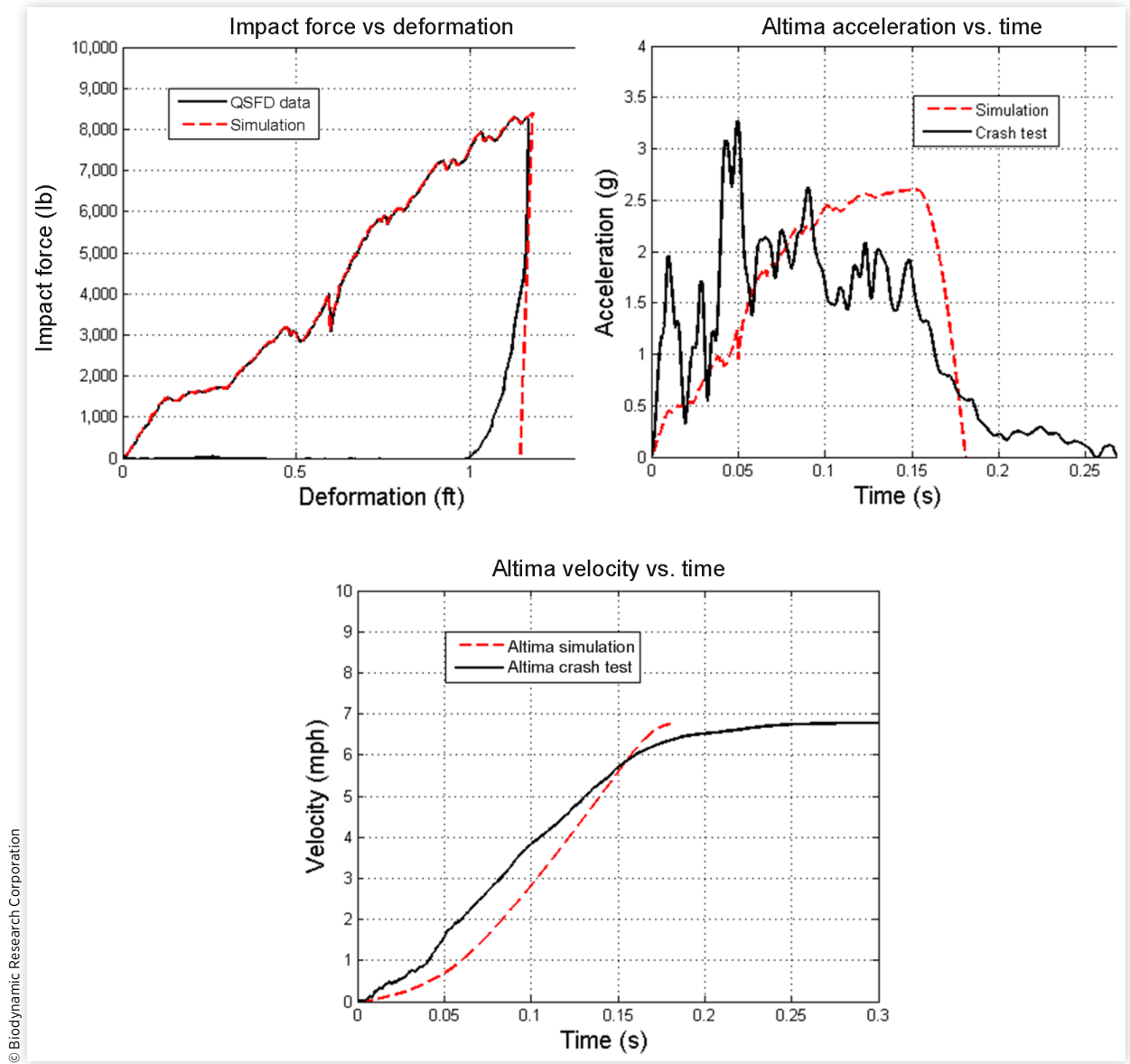
in the simulation was 0.65 ft (19.8 cm) and the peak force was 4,224 lb. The restitution segment of the red dashed curve is the straight line that descends from point (0.65 ft, 4,224 lb) to point (0.60 ft, 0.0 lb). The acceleration vs. time data for the Altima is shown in the center graph. The accelerations in the simulation are similar to the measured accelerations in crash test #1, although the simulation acceleration data did not have the high-frequency vibrations during the compression phase of the crash, the first part of the curve. The peak acceleration measured in crash test #1 was 1.5 g and the peak acceleration in the simulation was 1.2 g. The duration of the crash in the simulation was shorter than in the crash test and the crash pulse in the simulation ended more abruptly than in the crash test. The Altima vehicle speeds in the

simulation (red dashed line) and crash test #1 (black line) are shown in the right graph. The calculated Altima velocities were similar to the velocities measured in crash test #1 over the crash pulse. The  $\Delta V$  of the Altima in the simulation was 4.0 mph and the  $\Delta V$  of the Altima in crash test #1 was 4.2 mph.

## Simulation of Crash Test #2

The vehicle weights, the impact speed for the bullet vehicle, and the restitution used in the simulation of crash test #2 are shown in [Table 1](#). The graphs in [Figure 34](#) show the results of the simulation using the QSF data shown in [Figure 12](#). The left graph shows the force vs.

**FIGURE 34** The left graph shows the measured QSF data (black line) and the QSF data used in the simulation (red dashed line). The center graph shows the accelerations of the Altima in crash test #2 (black line) and the accelerations of the Altima calculated in the simulation (red dashed line). The right graph shows the velocity of the Altima in the crash test (black line) with the velocity calculated in the simulation (red dashed line).



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deformation data used in the simulation (red dashed line) along with the measured QSF data (black line) for crash test #2. There was not enough crush energy in the measured QSF curve to account for the crash as the vehicles were not able to reach a common velocity with the measured QSF data. In order to simulate crash test #2, the QSF data was extended by 0.14 in. from point (1.17 ft, 8,293 lb) with a constant stiffness of 7,764 lb/ft to point (1.18 ft, 8,384 lb). The straight line in the graph that descends from point (1.18 ft, 8,384 lb) to point (1.14 ft, 0 lb) represents the restitution segment of the FD data in the simulation. The Altima accelerations in the simulation and the accelerations measured in crash test #2 are shown in the middle graph as a function of time. The accelerations of the Altima in the crash test rose more

quickly than in the simulation and had large high-frequency vibrations in the compression phase of the crash that were not present in the simulation. The lower accelerations in the simulation compared to the crash test were most likely a result of the bumper reinforcement bar of the Altima and the front bumper of the E-350 being positioned so that they did not engage in the QSF measurement, whereas these components interacted early in crash test #2. The length of the crash pulse in the simulation was 181 ms and in crash test #2 the length was approximately 255 ms. The peak acceleration of the Altima in crash test #2 of 3.3 g occurred at 50 ms. The peak acceleration of the Altima in the simulation occurred at 157 ms and was 2.5 g. The right graph in [Figure 34](#) shows the velocity of the Altima in the crash test #2 and

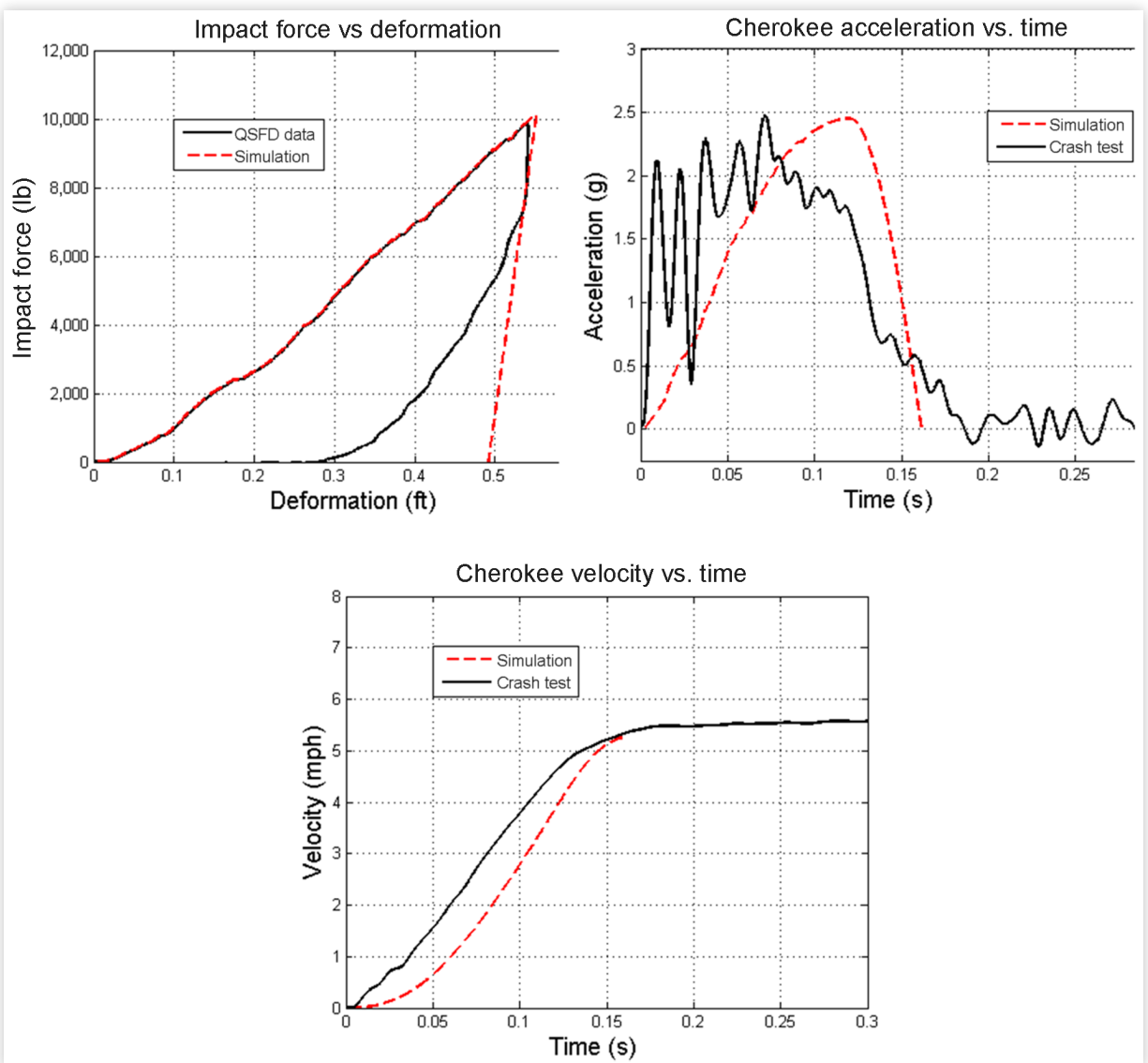
the simulation as functions of time. The  $\Delta V$  of the Altima in the simulation was 6.7 mph and in the crash test it was 6.8 mph.

## Simulation of Crash Test #3

The vehicle weights, the impact speed for the bullet vehicle, and the restitution used in the simulation of crash test #3 are shown in Table 1. The graphs in Figure 35 show the results of the simulation using the QSF data shown in Figure 18. The left graph shows the force vs. deformation data used in the simulation (dashed red line) along with the measured QSF data (black line) for crash test #3. When comparing the energy required to match the crash test using a momentum, energy, and restitution

analysis with the area under the force deflection curve, there was not enough crush energy in the measured QSF data to simulate crash test #3. The QSF data was therefore extended by extrapolation of the last data points in the loading curve. The extension was 0.15 in. (0.39 cm) from the point (0.54 ft, 9,860 lb) to the point (0.55 ft, 10,148 lb) with a stiffness of 23,077 lb/ft. The straight line in the graph that descends from point (0.55 ft, 10,148 lb) to point (0.49 ft, 0 lb) represents the restitution segment of the FD curve in the simulation. The acceleration vs. time data for the Jeep Cherokee in the simulation and crash test #3 are shown in the middle graph. The accelerations in the crash test rose more quickly than in the simulation and had large high-frequency vibrations in the compression phase of the crash that were not present in the simulation. The peak acceleration of the

**FIGURE 35** The left graph shows the measured QSF data (black line) and the QSF data used in the simulation (red dashed line). The center graph shows the accelerations of the Jeep in crash test #3 (black line) and the accelerations of the Jeep calculated in the simulation (red dashed line). The right graph shows the velocity of the Jeep in the crash test (black line) with the velocity calculated in the simulation (red dashed line).



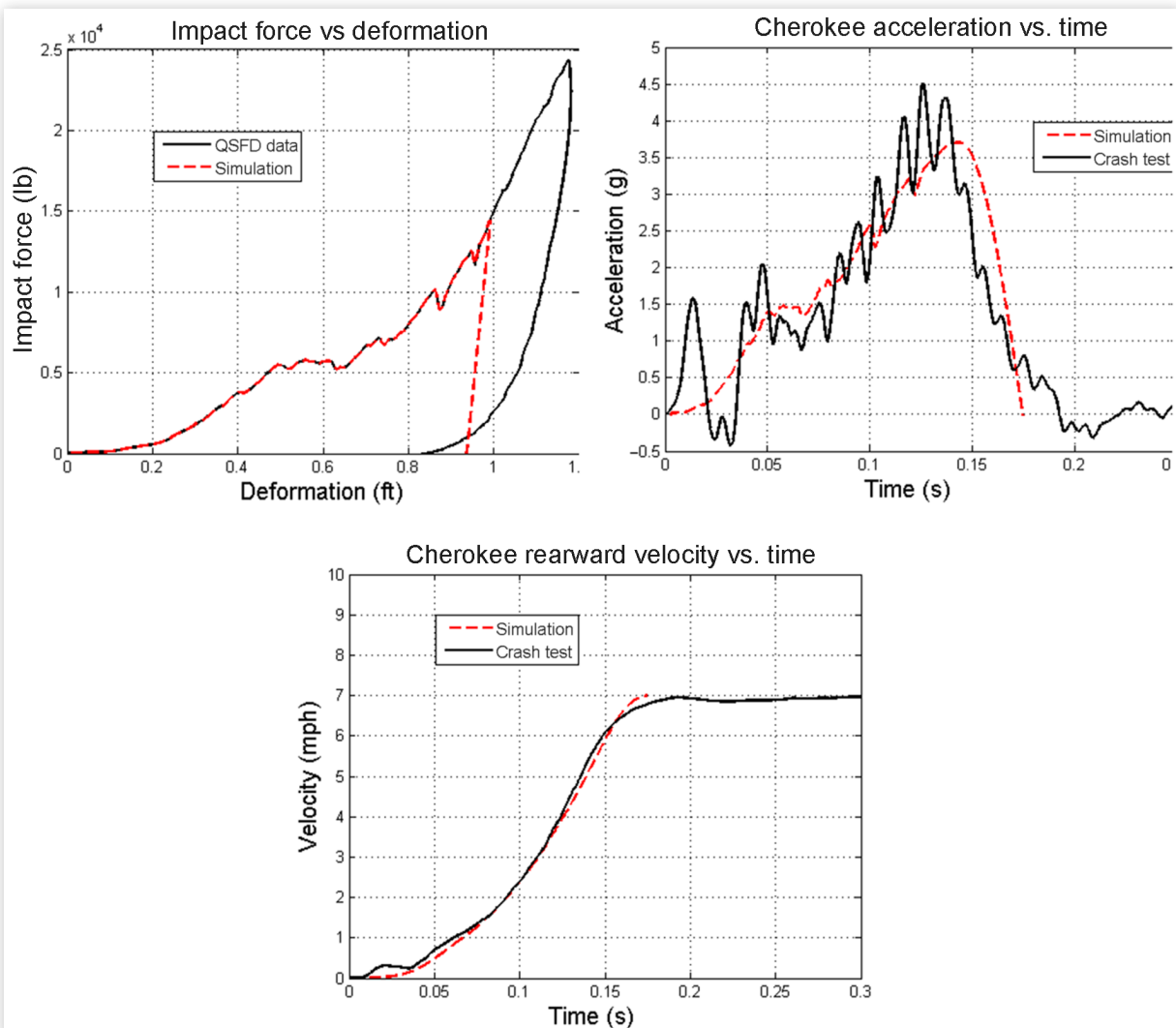
Jeep in the crash test was approximately 2.5 g at 72 ms and the peak acceleration in the simulation was approximately 2.5 g at 120 ms. The length of the crash pulse was 162 ms in the simulation and 186 ms in the crash test. The right graph in [Figure 35](#) shows the velocity of the target vehicle in the crash test and the simulation. The  $\Delta V$  of the Jeep in the crash test was 5.5 mph at 187 ms and in the simulation it was 5.3 mph at 162 ms.

maximum engagement in the simulation was 0.99 ft (30.17 cm) and the peak force was 14,443 lb. The restitution part of the simulation FD curve is represented by the red dashed line that goes from point (0.99 ft, 14,443 lb) to point (0.94 ft, 0 lb). The acceleration vs. time data is shown in the center graph. The acceleration pulse in the simulation is similar in shape to the measured accelerations in crash test #4 but it is shorter in duration. The crash pulse in the simulation had a duration of 175 ms compared to a duration of 193 ms in crash test #4. There were vibrations present in the compression phase of the crash test acceleration data that were not present in the simulation accelerations. The peak acceleration in the crash test data was approximately 4.5 g at 126 ms and in the simulation the peak acceleration was approximately 3.7 g at 144 ms. The Jeep Cherokee velocity in the simulation (red dashed line) and crash test #4 (black line) are shown in the right graph. The rearward velocity of the Jeep in crash test #4 and the simulation is treated as a positive number for the purposes

## Simulation of Crash Test #4

The vehicle weights, the impact speed for the bullet vehicle, and the restitution used in the simulation of crash test #4 are shown in [Table 1](#). The graphs in [Figure 36](#) show the results of the simulation using the QSFD data shown in [Figure 24](#). The left graph shows the force vs. deformation data used in the simulation (dashed red line) along with the measured QSFD data (black line) for crash test #4. The

**FIGURE 36** The left graph shows the measured QSFD data (black line) and the QSFD data used in the simulation (red dashed line). The center graph shows the accelerations of the Jeep in crash test #4 (black line) and the simulation (red dashed line). The right graph shows the rearward velocity of the Jeep in crash test #4 (black line) and the simulation (red dashed line).



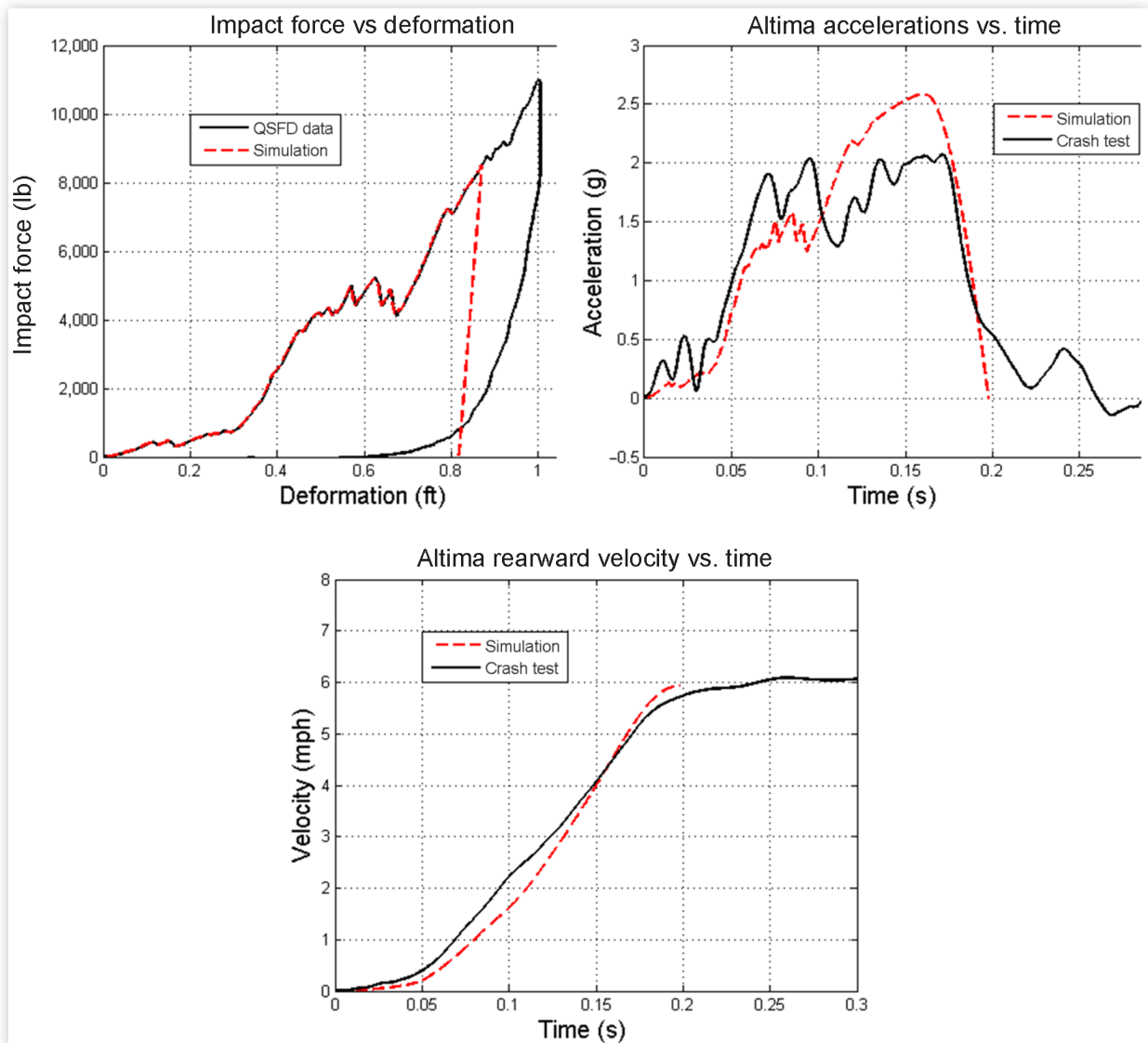
of this graph and the remainder of the study. The  $\Delta V$  of the Jeep in the simulation was 7.0 mph at 175 ms and in the crash test #4 it was 7.0 mph at 193 ms.

## Simulation of Crash Test #5

The vehicle weights, the impact speed for the bullet vehicle, and the restitution used in the simulation of crash test #5 are shown in Table 1. The graphs in Figure 37 show the results of the simulation using the QSF data shown in Figure 30. The left graph shows the force vs. deformation data used in the simulation (dashed red line) along with the measured QSF data (black line) for crash test #5. The peak dynamic crush in the simulation was 0.87 ft (26.5 cm) and the peak force was 8,521 lb. The

restitution part of the FD data is the red dashed line that descends from point (0.87 ft, 8,521 lb) to point (0.82 ft, 0 lb). The accelerations of the Altima in the simulation (red dashed line) and the crash test (black line) are shown in the center graph. The peak acceleration in the crash test was approximately 2.1 g at 171 ms and the peak acceleration in the simulation was approximately 2.6 g at 161 ms. The crash pulse in the simulation was shorter than in the crash test. The crash pulse length was 198 ms in the simulation and 260 ms in the crash test. The Altima rearward velocity in the simulation (red dashed line) and crash test #5 (black line) are shown in the right graph in Figure 37. The rearward velocity of the Altima is treated as a positive number for the purposes of this graph. The  $\Delta V$  of the Altima in the simulation was 5.9 mph in the simulation and 6.1 mph in the crash test.

**FIGURE 37** The left graph shows the measured QSF data (black line), and the part of these data used in the simulation (red dashed line). The center graph shows the accelerations of the Nissan Altima in crash test #5 (black line) and the accelerations of the Altima in the simulation (red dashed line). The right graph shows the rearward velocity of the Altima in the crash test (black line) and the rearward velocity in the simulation (red dashed line).



## Summary of Crash Test Results

Table 2 shows the  $\Delta V$ s measured in the crash tests and calculated in the simulation. The average difference between the  $\Delta V$  in the crash test and the simulation is 0.14 mph. Table 3 shows a comparison of the peak acceleration in the crash and the simulation along with percentage difference. The average difference was approximately 0.5 g. Table 4 shows the maximum dynamic crush in the crash test and the simulation. The average difference was 0.07 ft (2.1 cm), or 9.0%.

Figure 38 shows the crash test accelerations, and the accelerations calculated in the simulation of that crash test for all of the crash tests. The simulation accelerations are generally similar to the crash test accelerations, except for crash tests #2 and #3. The reasons that these differences are thought to occur are presented in the discussion.

In crash tests #3, #4, and #5 the collision force was measured with load cells. Figure 39 shows the collision force measured by the load cells, the collision force calculated with the vehicle CG accelerations (and Newton’s 2nd Law) and the collision force calculated in the simulation. The load cell data closely follows the shape of the forces calculated with the CG accelerometer data but without the vibrations during the crushing phase of the crash. The

collision force in the simulation, which is calculated with the QSFD data during the crushing phase, follows the load cell data very well in crash tests #4 and #5, but lags behind the load cell force in crash test #3. The reason this response lag is thought to happen is given in the discussion. The comparisons between the load cell data and collision forces calculated in the simulations are quantified in the correlation analysis that follows.

The availability of the load cell data in crash tests #3, #4, and #5 allowed the dynamic force deformation (DYFD) data to be calculated. Figure 40 shows the graphs of the DYFD data for each crash test along with the QSFD data and the restitution FD data used in the simulation of that crash test. The DYFD data and the simulation FD data are similar in crash tests #4 and #5. In crash test #3 the collision forces in the DYFD data were greater than the collision forces in the simulation at a given level of deformation during the crushing phase of the crash. The reason that the DYFD forces are thought to be higher than the QSFD forces is presented in the discussion.

**TABLE 2** The  $\Delta V$  of the target vehicle in each crash tests and the simulation of that crash test.

Crash test #	Crash test $\Delta V$ (mph)	Simulation $\Delta V$ (mph)	Difference (mph)
1	4.2	4.0	0.2 (4.8%)
2	6.8	6.7	0.1 (1.5%)
3	5.5	5.3	0.2 (3.6%)
4	7.0	7.0	0.0 (0.0%)
5	6.1	5.9	0.2 (3.3%)

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**TABLE 3** The peak acceleration in the crash test and the simulation of that crash test.

Crash test#	Crash test peak (g)	Simulation peak (g)	Difference in peak (g)
1	1.5	1.2	0.3 (20%)
2	3.3	2.5	0.8 (23%)
3	2.5	2.5	0.0 (0.0%)
4	4.5	3.7	0.8 (18%)
5	2.1	2.6	-0.5 (-24%)

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**TABLE 4** The maximum dynamic crush in the crash test and the simulation in feet.

Crash test #	Crash test (ft)	Simulation (ft)	Difference (ft)
1	0.64	0.65	0.02 (1.5%)
2	1.03	1.18	0.15 (14.8%)
3	0.43	0.55	0.12 (21.8%)
4	0.96	0.98	0.02 (2.0%)
5	0.81	0.85	0.04 (4.7%)

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## Correlation Velocity

Goodness-of-fit assessments of the simulated velocities compared to the measured velocities demonstrated “good” overall correlation, as defined by ISO18571 standards ( $R_{Ovr}$ :  $0.812 \pm 0.156$ ; Table 5, Figure 41). Considering the individual components of the ISO18571 rating, “magnitude” showed the best average agreement between simulation and crash test velocities ( $R_{Mag}$ :  $0.934 \pm 0.091$ ), while “phase” showed the worst overall agreement, with a marked increase in variability ( $R_{Phase}$ :  $0.482 \pm 0.428$ ).

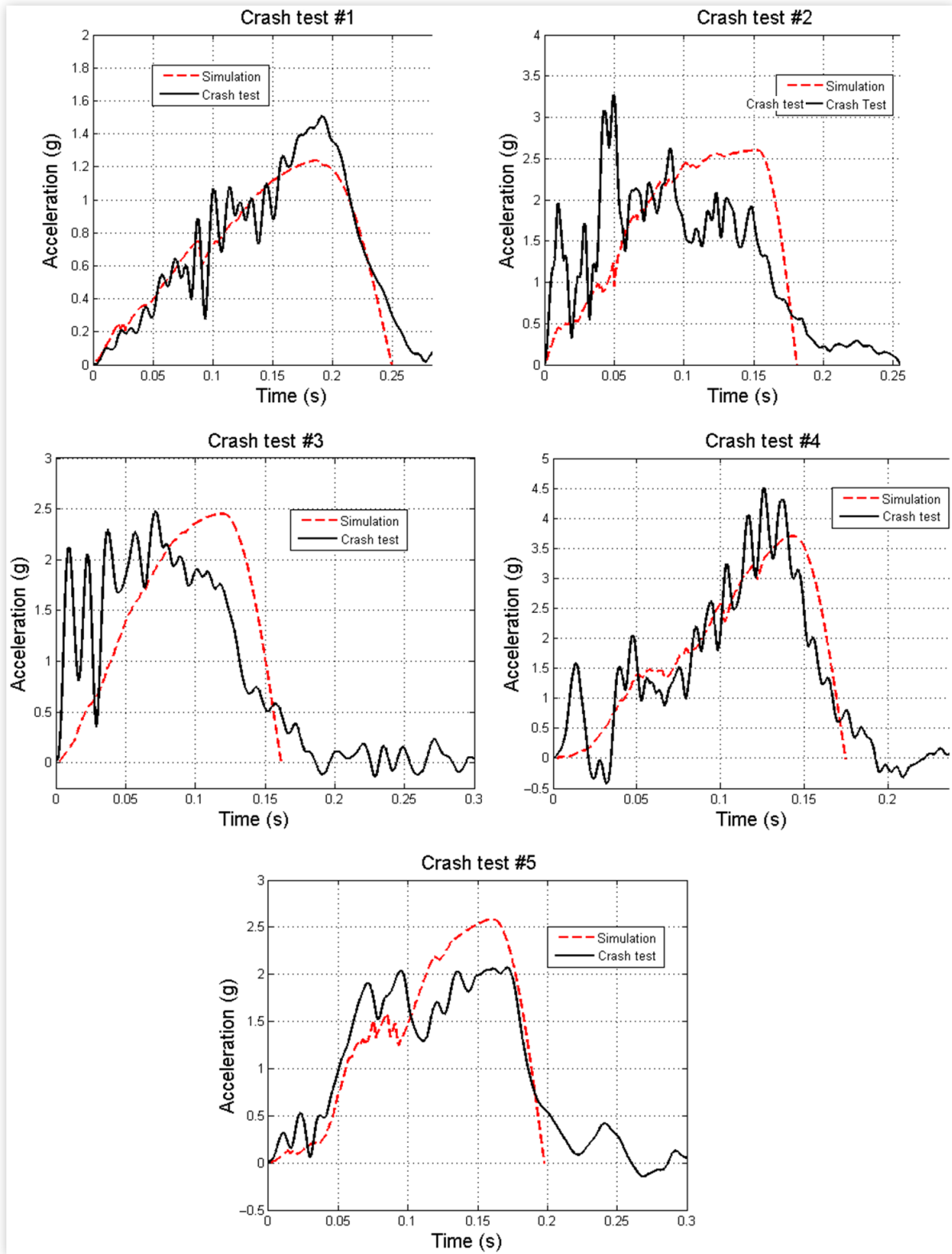
## Collision Force

Goodness-of-fit assessments of the simulated collision forces compared to the measured collision force in a crash demonstrated “fair” overall correlation, as defined by ISO18571 standards ( $R_{Ovr}$ :  $0.742 \pm 0.060$ ; Table 6, Figure 42). Considering the individual components of the ISO18571 rating, “magnitude” showed the best average agreement between simulation and instrumented tests ( $R_{Mag}$ :  $0.919 \pm 0.023$ ), while “slope” showed the worst overall agreement ( $R_{Slope}$ :  $0.574 \pm 0.024$ ).

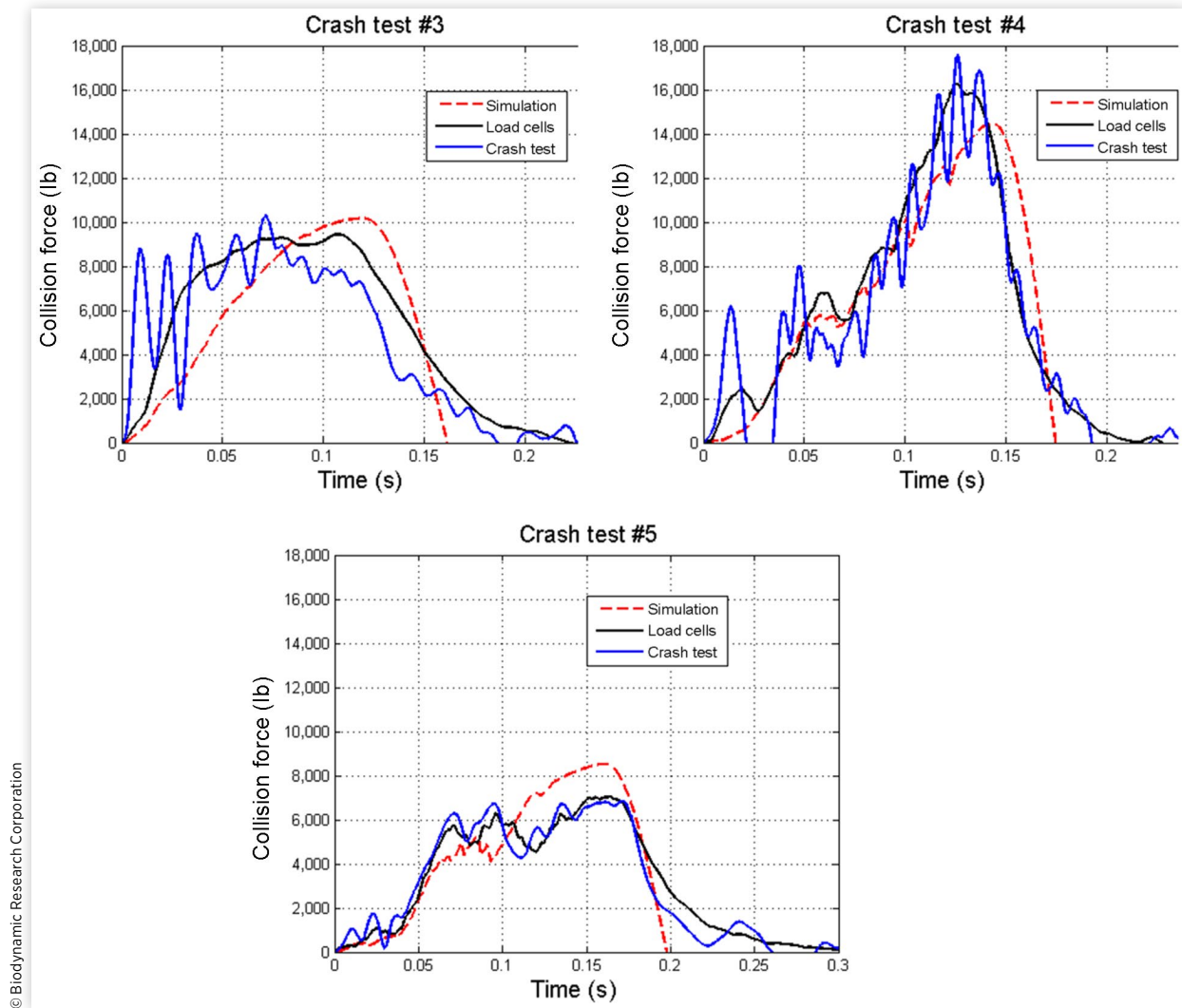
## Discussion

The goal of this study was to determine if QSFD data can represent the collision force in simulations of low-speed impacts when there is damage to vehicle body structures adjacent to the bumpers. Five crash tests with override damage were performed and then simulated with measured QSFD data. The inputs to each crash test simulation were the QSFD data, the impact speed of the bullet vehicle in the crash test (target vehicle was always stationary), the weights of both vehicles, and the restitution measured in the crash test. Table 2 shows that the  $\Delta V$ s of the target vehicle in the simulations were very

**FIGURE 38** The target vehicle accelerations measured in each crash test (solid black line) and the accelerations calculated in the simulation (red dashed line) with the QSF data are shown as functions of time.



**FIGURE 39** The collision force calculated in the simulation (red dashed line), based on the target acceleration data (black line) and measured with the load cells (black line) in crash tests #3, #4, and #5 are shown as functions of time.



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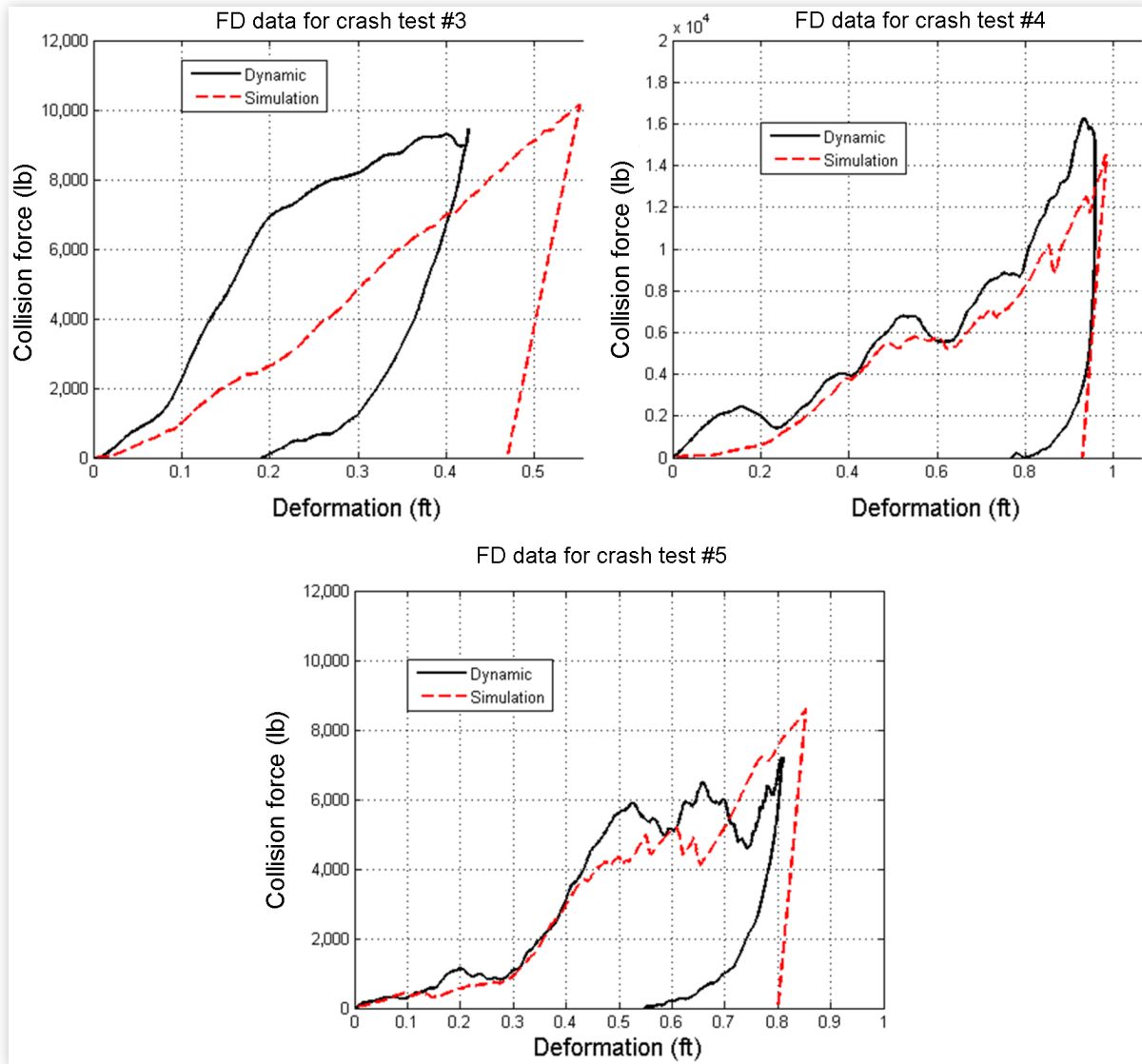
similar to the  $\Delta V$ s experienced by the target vehicle in the crash tests. The average differences between the simulation and crash test  $\Delta V$  was 0.14 mph. As discussed earlier, the good agreement between the measured and calculated  $\Delta V$ s does not validate the use of QSFD data to represent the impact forces, but it does provide a check on the overall accuracy of the crash test measurements. The good agreement between the measured and simulation  $\Delta V$ s indicates that the experimental measurements in the crash tests were accurate.

The simulations demonstrated good overall target vehicle velocity time history correlation for both front and rear-impact low-speed collisions with an override component. This agreement between simulation velocity and measured velocity was largely driven by the close agreement in "magnitude," "corridor," and "slope" ratings. Disagreement in the "phase" metric led to lower scores for crash tests #2 and #3. Phase disagreement was likely driven by the difference in concavity between the

simulated (consistent upward concavity until  $t \sim 0.15$  s) and measured (neutral-to-downward concavity across the same timespan) velocity data. The reasons for the poor correlation between the simulation velocities and the measured crash test velocities in Crash Tests #2 and #3 are discussed below.

Crash test #2 had high accelerations early in the compression phase which were not present in the simulation. This was most likely a result of raising the Ford E-350 front bumper 1.5 in. (3.8 cm) in order to ensure an override in the QSFD measurement. In crash test #2 there was approximately 0.5 in. (1.3 cm) of engagement between the E-350 bumper and the bumper reinforcement bar in the rear bumper of the Altima when the vehicles first made contact. The forces created by this engagement most likely led to the high accelerations early in crash test #2 that were not present in the simulation. In retrospect it would have been better to perform the QSFD measurement with the static alignment and an unblocked

**FIGURE 40** The dynamic FD (DYFD) data for each crash test (black line) and the FD data used in the simulation of that crash test (red dashed line) are shown for crash tests #3, #4, and #5.



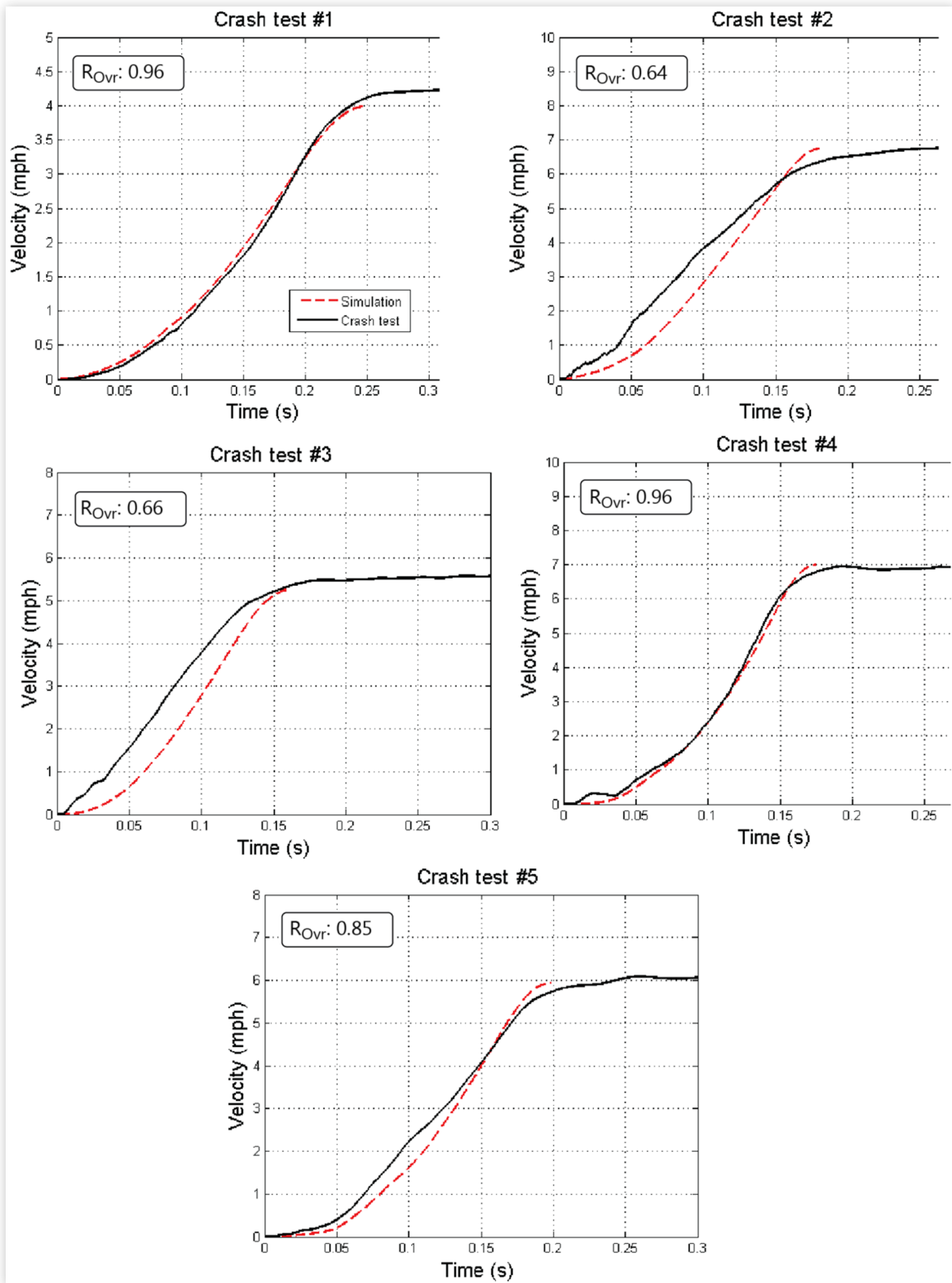
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**TABLE 5** ISO18571 ratings for simulated vs crash test velocities.

Rating	Avg (SD)	Crash test #1	Crash test #2	Crash test #3	Crash test #4	Crash test #5
Magnitude	0.934 (0.091)	0.995	0.775	0.962	0.988	0.950
Corridor	0.892 (0.136)	1.000	0.810	0.693	1.000	0.958
Phase	0.482 (0.428)	0.878	0.001	0.084	0.908	0.540
Slope	0.858 (0.056)	0.927	0.778	0.878	0.877	0.830
Overall	0.812 (0.156)	0.960	0.635	0.662	0.955	0.847

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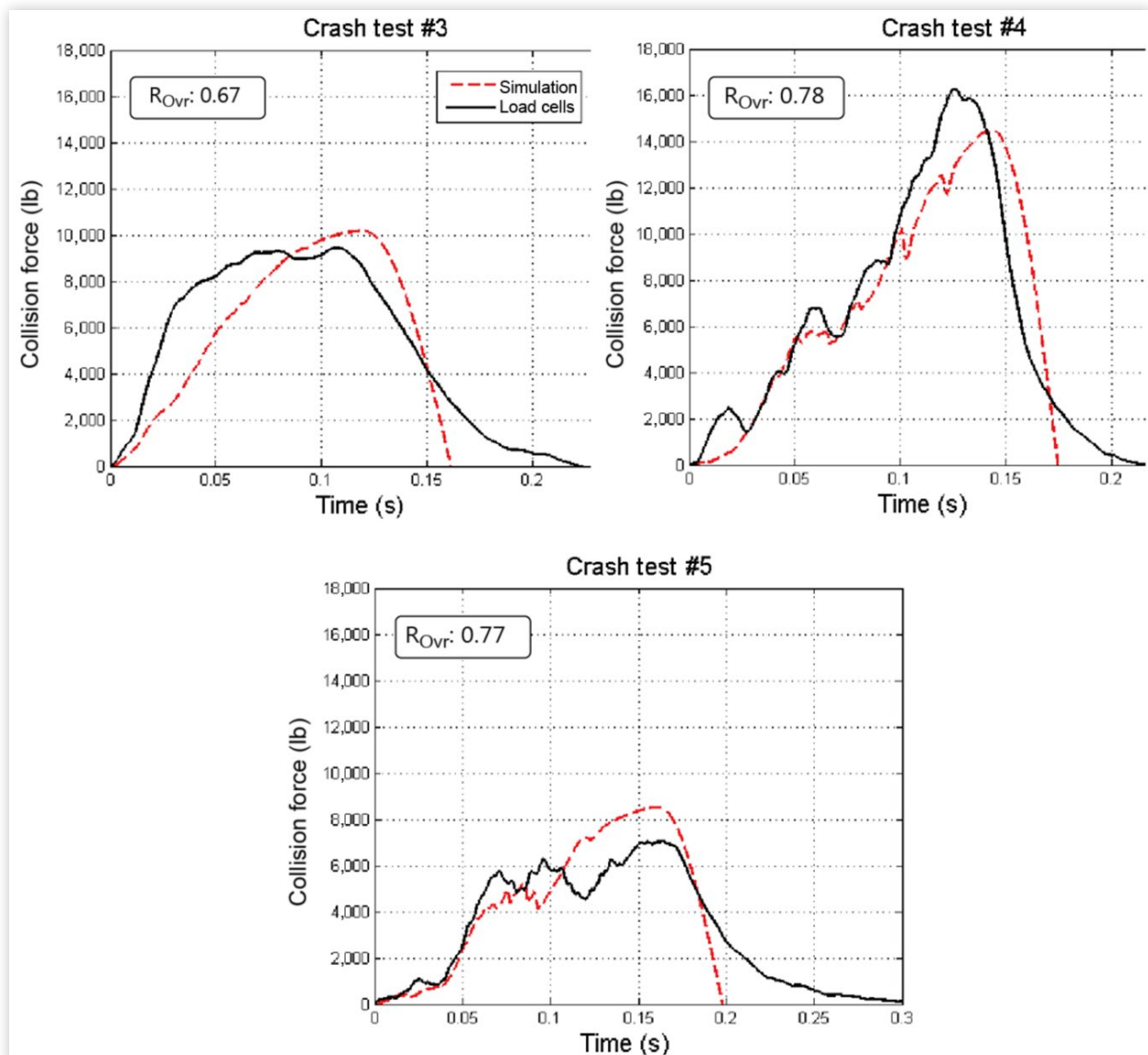
**FIGURE 41** The velocity of the target vehicle in each crash test and the simulation of that crash test.



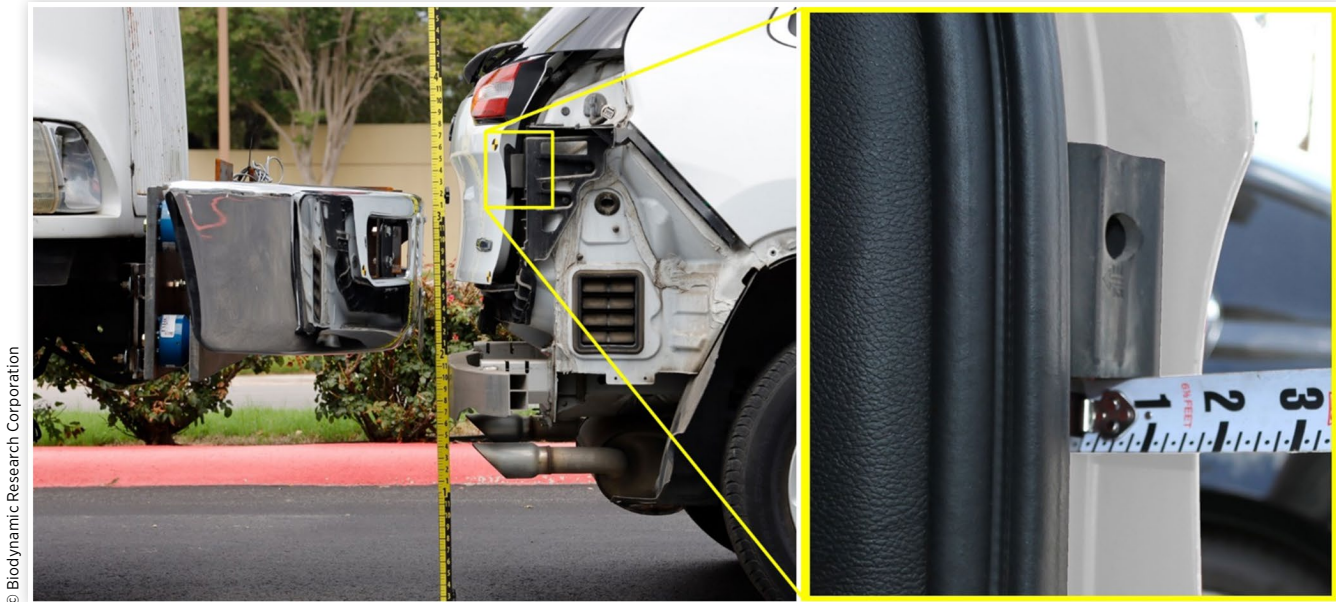
**TABLE 6** ISO18571 ratings for simulated vs. measured crash test forces.

Rating	Avg (SD)	Test 1	Test 2	Test 3	Test 4	Test 5
Magnitude	0.919 (0.023)	-	-	0.923	0.939	0.894
Corridor	0.705 (0.109)	-	-	0.590	0.808	0.717
Phase	0.810 (0.164)	-	-	0.681	0.754	0.995
Slope	0.574 (0.024)	-	-	0.582	0.593	0.547
Overall	0.742 (0.060)	-	-	0.673	0.780	0.774

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**FIGURE 42** Combined plots of tests 3–5 showing agreement between simulated (dashed line) and recorded (solid line) collision forces.

**FIGURE 43** The rubber isolator on the right side of the lift gate of the Jeep Cherokee that was used in Crash Test #3. This isolator had a thickness of about 0.063 ft (1.91 cm).



suspension on the Altima to allow the vertical forces generated between the Altima's rear bumper reinforcement bar and the E-350 front bumper push the Altima down on its suspension and create the observed override. The early high accelerations in the crash test led to an earlier rise in velocity compared to the simulation.

The collision force was measured with a load cell array in crash tests #3, #4, and #5. The simulations for these tests demonstrated fair overall collision force correlation. The agreement between simulated and instrumented crash tests is largely driven by the close agreement in "magnitude" and "phase" ratings and confounded by the "corridor" disagreement in crash test #3. In crash test #3 it is likely that the collision forces calculated with the QSFDD lagged the load cell forces in time is because the lift gate of the 2014 Jeep Cherokee is not rigidly attached to the vehicle body. The lift gate is hinged along the roof rail but is separated from the vehicle body by rubber isolators on each side of the lift gate. The rubber isolators are compressed when the lift gate is pushed into toward the vehicle body. The lower right isolator is shown in [Figure 43](#). These rubber isolators most likely have rate-dependent force deformation characteristics and therefore exhibited greater stiffness in the crash test than in the QSFDD measurement [13]. The rate-dependent behavior of the isolators was also demonstrated in the DYFD curve for crash test #3, that is shown in [Figure 17](#). The collision force in the DYFD curve was always significantly higher at a given level of deformation than in the QSFDD curve, most likely a result of the rate-dependent nature of the rubber isolators.

The crash pulses ended more abruptly in the simulations when compared to the crash tests. There was always

a low level of acceleration present in the crash tests, 0.6 g or less, after the simulated crash had ended. The abrupt end of the crash pulse in the simulations was due to the use of a straight line to represent the restitution phase of the FD data in the simulations. The positioning of this line in the QSFDD data satisfied the energy requirements of the coefficient of restitution measured in the crash test [2, 9], but the linear shape created an abrupt end to the crash pulse in the simulations. The shape of the restitution part of the crash pulse could be changed to extend out the crash pulse, but the new shape would not affect the  $\Delta V$  and the peak acceleration calculated in the simulation. Therefore, a linear representation of the restitution FD data was used to simplify the calculations.

The impact speeds (closing velocities) in these crash tests ranged from 3.9 to 8.6 mph and the rate that the QSFDD measurements were made was approximately 0.03 mph. During a crash the structures on the bullet vehicle would initially crush at the impact speed and then the speed of the crush would decrease to zero as the vehicles reached a common velocity. This study indicates that the crush characteristics of the front and rear body structures of the vehicles used in this study did not exhibit any significant rate dependency at closing speeds of 8.6 mph or below (other than the rubber isolators on the Jeep's liftgate). The finding that vehicle structures are not rate-dependent at crash speeds has been a consistent finding in analyzing crash test data [2, 3, 8].

[Table 4](#) compares the dynamic crush measured in the crash test and the calculated dynamic crush in the simulation of that crash test. The maximum dynamic crush in the crash tests was determined from double integration of the vehicle accelerometers. The maximum

dynamic crush in the simulations was the system crush when the bullet and target vehicle reached a common velocity. The crash test and simulation dynamic crush had an average difference of 9.0%, or about 0.07 ft (2.1 cm). The small difference indicates that the QSFD data can accurately represent the amount of crush (at least during the compression phase) and the collision forces in low-speed underride/override crashes.

The methodology in this study did not require that the maximum amount of crush in the QSFD measurement match the dynamic crush in the crash test, although we did try to come close in the QSFD measurements for crash tests #1 through #3. When analyzing an unknown crash event, the reconstructionist doesn't know what the dynamic crush is, but the reconstructionist can measure the permanent crush on the actual crash vehicles or estimate it by comparing photographs of the subject vehicles with exemplar vehicles. During the QSFD measurement the reconstructionist can then compare the permanent deformation on the test vehicle with the photographs of the subject vehicle to determine a crush level at which to stop the measurement. When reconstructing a crash where there are legal implications one procedure is to use QSFD data that overestimates the permanent crush, and therefore overestimates the crush energy in the crash, so that the simulation of the case crash provides an upper limit of the closing velocity and  $\Delta V$ s in the case crash.

The use of an entire vehicle in the QSFD measurement presents logistical problems as there are limits to the magnitude of the force that can be applied to the vehicle during this measurement. The force applied during the QSFD measurement must be great enough to crush the structures that deformed in the crash being studied but not great enough to damage the structures that are used to attach the vehicle to earth. Once these supporting structures start to fail, the QSFD measurement is no longer viable and must be stopped. In the series of QSFD measurements made for this study there were no failures of the supporting structures. It has been our experience that once the forces in a QSFD measurement exceed 25,000 lb, the structures attaching the vehicle to the earth may start to deform.

Another logistical problem in the measurement of the QSFD data is whether or not to block off the suspension of the target vehicle. Since there is a large difference in the time duration required to make a QSFD measurement (time > 15 s) and the duration of a crash (time ~ 0.15–0.30 s), the target vehicle can move a large vertical distance on its suspension if any vertical forces are present during the QSFD measurement. Therefore, if the vehicle suspension is not locked out there may be more vertical movement in the QSFD measurement than the actual crash because there is more time for that movement to occur. When conducting a QSFD measurement, the decision must be made as to whether or not to lock the suspension of the test vehicle and how to handle the early engagement of the bumpers that may occur before override develops. In the QSFD measurement for crash test #2 an override of the bumper on the bullet vehicle was created by raising the front bumper of

the bullet vehicle and eliminating the initial contact with the rear bumper reinforcement bar on the target vehicle. As stated earlier, in retrospect would have been better to have used the crash test orientation with an unlocked suspension on the target vehicle, and allowed the override to occur naturally during the QSFD measurement.

The methodology used to validate our hypothesis in this study is different from the methodology that would be used to perform an accident reconstruction. In an accident reconstruction the closing velocity and the restitution are unknown variables. When using QSFD data to reconstruct a real-world crash an estimate is made of the maximum crush on the subject vehicles and the simulation is used to obtain the closing velocity that gives this amount of crush. Restitution can be ranged or estimated from closing velocity using data from this study or previous studies [7, 14]. In order to investigate the validity of our hypothesis, we had to recreate the crash test as close as possible, which required the closing velocity from the crash test to be an input into the simulation. The accuracy of the simulation (and the use of the QSFD data) was then determined by comparing the accelerations and forces predicted by the simulation with the data measured in the crash test. Therefore, the validation process is not the same as the process of performing an accident reconstruction.

Another limitation of this study is that the QSFD data was measured on only five vehicle bumper override interactions. Two were front overrides and three were rear overrides. The rear overrides involved two crashes where a bumper went into the rear body panel/trunk lid of a sedan and in the other a bumper impacted the liftgate on an SUV. The data from these measurements will be added to the database of QSFD measurements, which was last published in 2017 [14]. In that publication all of the override/underride data were combined and the average stiffness was  $7,089 \pm 3,659$  lb/ft. The linear stiffnesses for the two frontal override measurements in crash tests #1 and #2 were 6,490 lb/ft and 7,669 lb/ft and are very close to published average stiffness, although crash test #2 involved an offset. The QSFD data for the two frontal overrides, crash test #4 and #5, had linear stiffness values of 8,557 lb/ft and 13,754 lb/ft. The stiffest structure in this study was the Jeep Cherokee liftgate that had a stiffness of 18,667 lb/ft.

## Conclusions

In conclusion, this study demonstrated that QSFD data can reliably represent collision forces in low-speed crashes involving above-bumper body structure engagement. The good output agreement between the crash test results and simulations demonstrates that override collision forces are rate-independent and can be modeled with the QSFD methodology. Special care needs to be taken when the QSFD measurement is made by pushing on a liftgate or any vehicle structure that is isolated from the body by some non-metal structures. Taken together, the

results of the current set of instrumented crash tests show that the QSFD method yields a reasonably accurate characterization of post-collision velocities and crash severity in low-speed crashes with override damage.

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