

Reconstruction of Low-Speed Crashes using the Quasi-Static Force vs. Deformation Characteristics of the Bumpers Involved in the Crashes

William Scott, Enrique Bonugli, Herbert Guzman and Daniel Swartzendruber
Biodynamic Research Corporation

ABSTRACT

The purpose of this study was to determine if quasi-static (QS) bumper force-deformation (F-D) data could be used in a low-speed bumper-to-bumper simulation model (1) in order to reconstruct low-speed crashes. In the simulation model, the bumpers that make contact in a crash are treated as a system. A bumper system is defined as the two bumpers that interact in a crash positioned in their orientation at the time of the crash. A device was built that quasi-statically crushes the bumpers of a bumper system into each other and measures the compression force and the deformation of the bumper system. Three bumper systems were evaluated. Two QS F-D measurements were performed for each bumper system in order to demonstrate the repeatability of the QS F-D measurement. These measurements had a compression phase and a rebound phase. A series of crash tests were performed using each bumper system. In each crash test, a stationary target vehicle was struck on the rear bumper by the front bumper of a bullet vehicle. Both vehicles were instrumented with accelerometers. The bullet vehicle had load cells at the front that measured crash forces and a displacement sensor that measured the deformation of the bumper system during the crash. The crash tests were performed over a range of impact speeds for the bullet vehicle. The compression QS F-D data were used as an input to the simulation model in order to reconstruct the vehicle motions in the crash tests. The other inputs required to simulate a crash test were the impact speed of the bullet vehicle, the vehicle masses and the coefficient of restitution measured in the crash test. The study demonstrated that the simulation model with the QS F-D data accurately recreated the velocities of the target and bullet vehicle in the crash tests.

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INTRODUCTION

Quantifying the severity of low-speed bumper-to-bumper crashes has always been a challenge because most of the classical crash reconstruction techniques are intended to be used in crashes that produce significant amounts of crush (2). In a low-speed bumper-to-bumper crash, where injuries are alleged to have occurred, there may be no measureable crush or limited areas of focal damage that are difficult to quantify. In many cases the only source of information about the damage to each vehicle are photographs of the vehicles and repair estimates.

Thus far there have been two main approaches to modeling a low-speed crash. The first approach is to treat the vehicles as rigid structures, model the bumpers as spring/dashpot systems and then solve the governing differential equations with the appropriate initial conditions (3,4,5,6).

The inputs required by a spring/dashpot model to simulate a specific crash are the stiffness and damping coefficients for the bumpers that interact in the crash. These coefficients are generally not known. The accuracy of the simulation relative to the crash being analyzed cannot be determined as there is no way to correlate the simulation damage with the damage pattern of the bumpers in the actual crash. The second approach, the Momentum-Energy-Restitution (MER) method, is based on rigid body impact mechanics and uses impulse, conservation of momentum, conservation of energy and restitution to determine the change in velocity (ΔV) of the vehicles in the crash (7,8,9). In order to estimate the ΔV for a vehicle in a specific crash the MER method requires a value for the coefficient of restitution (ϵ) and an estimate of the energy absorbed by each vehicle during the crash. While there are methods to estimate ϵ for a given crash situation, it is difficult to determine the amount of energy absorbed by

both vehicles during the crash, especially if the damage to each bumper is minimal and non-uniform.

Previously, a simulation model was developed to recreate low-speed bumper-to-bumper crashes where the only damage was to the bumpers (1). The impact force used in this simulation model is directly related to the force-deformation (F-D) characteristics of the bumpers involved in the crash being investigated. The model treats the bumpers that contact in a crash as a system, which is defined as the two bumpers that interact in a crash orientated as they were at the time of contact. Previously, dynamic F-D data measured in crash tests were used as input to the simulation model in order to recreate the vehicle dynamics in those crash tests (1). In a real world crash investigation the input to the model is intended to be the quasi-static (QS) force-deformation (F-D) characteristics of the bumper system and, therefore, a basic assumption of this simulation technique is that the QS F-D characteristics of the bumper system can represent the dynamic F-D characteristics in a low-speed impact. The QS F-D measurement is also intended to create damage patterns to the bumpers that are similar to or greater than the damage to the bumpers in the crash being investigated. A comparison of the damage obtained in the QS F-D measurement with the damage to the bumpers in the crash being investigated provides a metric to determine how well the impact forces in the simulation represent the impact forces in the actual crash.

The goal of the present study was to determine if the QS F-D characteristics of a bumper system can be used to reconstruct a low-speed crash with the simulation model. Three bumper systems were evaluated. The first step in this study was the measurement of the QS F-D characteristics of each bumper system. Next, a series of crash tests were performed using each bumper system. The crash tests were performed for two reasons. First, they provided data on the dynamic F-D characteristics of the bumpers. Second, the crash tests provided a known event that the simulation model and the QS F-D data could be used to reconstruct. In each crash test the dynamic F-D characteristics of the bumper system were measured and compared with the QS F-D characteristics. The QS F-D data were used as input data in the simulation model along with the test vehicle masses, and the closing velocity and the coefficient of restitution measured in the crash test. The simulation model was then used to calculate the vehicle dynamics in the crash test. Finally, the simulated vehicle dynamics were compared with the vehicle dynamics measured in the crash tests in order to validate the effectiveness of this reconstruction technique.

METHOD

QUASI-STATIC FORCE-DEFORMATION MEASUREMENTS

In this study three bumper systems were evaluated, each of which was composed of the rear bumper of the struck vehicle, the target vehicle, and the front bumper of the

striking vehicle, the bullet vehicle. The bumpers were from passenger cars, a van and SUVs. The lateral positions were set so that the centers of the bumpers were in line. The vertical orientations of the bumpers in each system were determined by performing exemplar vehicle match-ups. The same bumper orientations were used in all of the QS F-D measurements and crash tests for a given bumper system. [Table 1](#) details the origins of the bumpers in each bumper system, which are called Bumper System A, B and C.

Table 1. Target and bullet vehicle bumpers used in each test series.

Bumper System	Target Vehicle Bumper - Rear Bumper	Bullet Vehicle Bumper - Front Bumper
A	1994 Toyota Tercel	2003 Chevy Express Van
B	2002 Honda Civic	2007 Ford Escape
C	2008 Honda Civic	2005 Kia Sedona

Previous research indicated that the geometry of the surface that applies the force affects the QS F-D characteristics of an individual bumper (1), thus the best way to replicate the physical characteristics of the other bumper in the QS F-D measurement is to use that bumper. Therefore the QS F-D data for a bumper system were obtained by pushing the two bumpers of a bumper system into each other. In order to perform the QS F-D measurement a device was built that quasi-statically crushes the two bumpers into each other while they are in the proper relative orientation and measures the compression force and the deformation of the bumper system. [Figure 1](#) shows a photograph of the device, which is colloquially called the bumper crusher. The QS F-D data of each bumper system were measured twice in order to determine how repeatable the measurement was.

The bumper crusher consists of a fixed plate to which one bumper is attached and a moveable plate to which the other bumper is attached. The moveable plate is pushed along a track by two hydraulic cylinders. A load cell (1210-A0 25, Interface, Inc) attaches each hydraulic cylinder to the plate, and measures the force applied to the moveable plate by that piston. Two displacement transducers, a string pot (PT101, Celesco, Inc.) and a LVDT (E-Series, Temposonics, MTS, Inc) are attached to the moveable plate to measure its displacement. The moveable plate is kept on the track with load bearing rollers in which the only degree of freedom is along the longitudinal axis (x-axis) of the bumper crusher. Hence, the displacement transducers provided data on the deformation of the bumper system along the x-axis. During the measurement of the QS F-D data, video and sound information were also recorded.

The test bumpers were mounted on the steel plates of the bumper crusher using their original equipment brackets and attachment hardware. Rigid attachments for the bumper

brackets were bolted on the steel plates of the bumper crusher, and the bumpers and brackets were bolted to these attachments. These rigid attachments represented the frame horns or the unibody structure and were much stiffer than the bumpers and their mounting brackets. Therefore, during the QS F-D measurements the only structures that underwent measurable deformation were the bumpers.

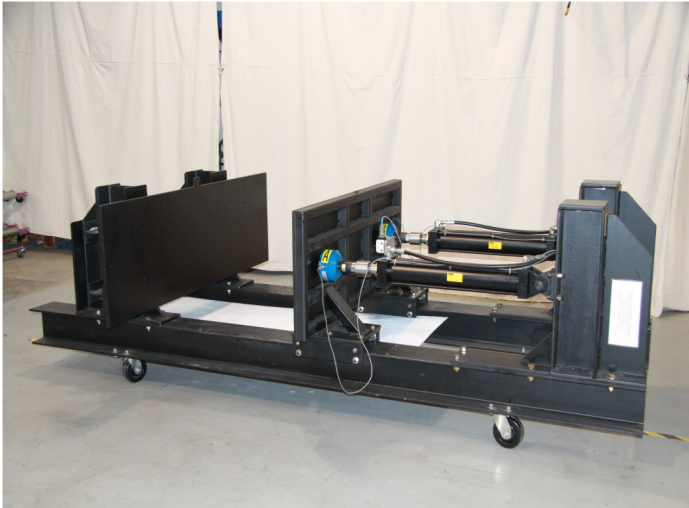


Figure 1. A photograph of the bumper crusher, the device used to quasi-statically crush the bumpers of a bumper system into each other.

Bumpers for older vehicles were obtained from salvage yards, and the bumpers for newer vehicles were obtained from dealers. The bumpers from the salvage yards were inspected to make sure there was no damage. Only original equipment bumpers (OEM) were used. The QS F-D measurements were performed with the bumper covers and any energy absorbing components in place and measurements were conducted up to a maximum deformation that produced notable damage to at least one of the bumpers. The displacement transducers documented the overall deformation to the system and video documented the overall and localized deformations. The sound information was useful in that many of the bumper component failures created noise and this audio data could be correlated with the force data to determine the failure force of a particular component.

Bumper System A was composed of the rear bumper of a 1994 Toyota Tercel and the front bumper of a 2003 Chevrolet Express Van. The Tercel's rear bumper is shown in [Figure 2](#) with the bumper cover removed. The Tercel's rear bumper has a steel impact bar (bumper beam) with four steel cover supports welded to the rear upper surface which support the bumper cover along with two small expanded polypropylene (EPP) pads. The two inboard supports extend rearward approximately 3.8 cm (1.5 inches) from the surface of the impact bar. The Tercel's rear bumper had a cover made of polypropylene (PP). The Chevy Express Van's front bumper has a steel face bar with a PP cover on the top 5 cm (2 in.) of

the front surface of the face bar, and, when the two bumpers engaged, the cover supports on the Tercel's bumper made the first hard contact with the van's bumper. The bumpers of Bumper System A are shown on the bumper crusher in [Figure 3](#) prior to a QS F-D measurement.



Figure 2. The top photograph shows the impact bar on the rear bumper of a 1994 Toyota Tercel. The lower photograph shows the left side cover supports welded to the top rear surface of the impact bar which support the bumper cover (not shown).

Bumper System B was composed of the rear bumper of a 2002 Honda Civic Sedan and the front bumper of a 2007 Ford Escape. The impact bars for Bumper System B are shown on the bumper crusher prior to a QS F-D measurement in the upper photograph in [Figure 4](#). The Civic bumper had a convex steel impact bar with a rectangular shaped steel section welded to the center that extended approximately 2 cm (0.8 in) from the impact bar. As shown in the lower photograph in [Figure 4](#), an EPP impact absorber fitted over the rear surface of the impact bar with a cutout for the center extension. The impact absorber had a thickness that varied from approximately 1.5 to 2.5 cm (0.6 to 1.0 in). The steel brackets that attached the impact bar to the unibody structure of the Civic were welded to the impact bar. The Civic's rear

bumper had a PP bumper cover. The 2007 Ford Escape had a convex steel impact bar and the brackets that attached the impact bar to the unibody structure were welded around the impact bar. The Escape's front bumper had no impact absorber located between the impact bar and the PP cover.

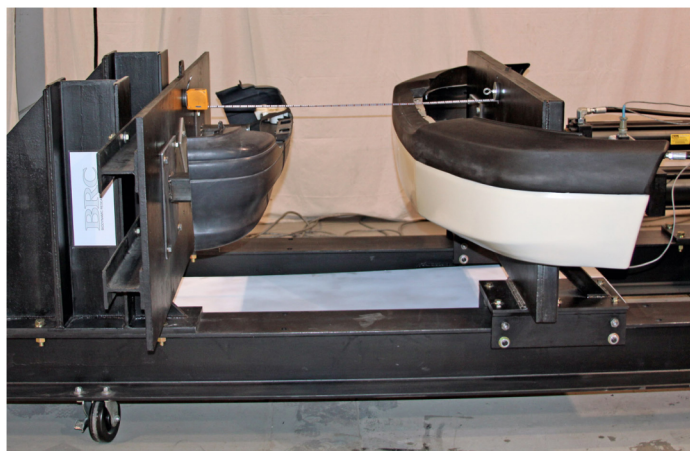


Figure 3. Bumper System A prior to a QS F-D measurement with the Tercel's bumper on the fixed plate (left side) and the Chevy Express Van's bumper on the moveable plate (right side).

Bumper System C was composed of the rear bumper of a 2008 Honda Civic Sedan and the front bumper of a 2005 Kia Sedona. The impact bars for Bumper System C are shown on the bumper crusher prior to a QS F-D measurement in the upper photograph in [Figure 5](#). The Civic's bumper had a convex aluminum impact bar with a rectangular extension welded to the center that extended approximately 1 cm (0.4 in) from the rear surface of the impact bar. As shown in the middle photograph of [Figure 4](#), there was an EPP impact absorber that covered part of the rear surface of the impact bar. The impact absorber had a thickness that ranged from approximately 1.0 to 1.5 cm (0.4 to 0.6 in). The mounting brackets were steel and were bolted onto the impact bar. The Civic's bumper had a PP cover. The Sedona's bumper had a glass mat thermoplastic (GMT) impact bar. As shown in the lower photograph of [Figure 5](#), a white EPP impact absorber covered the entire rear surface of the impact bar and extended over the top surface as well. The section of the impact absorber that covered the rear surface of the impact bar had a thickness that ranged from approximately 1.0 to 2.0 cm (0.4 to 0.8 in). A PP cover support on the impact bar's top surface extended above the impact absorber and provided support for the Sedona's PP bumper cover. The steel mounting brackets were attached to the GMT impact bar with bolts.

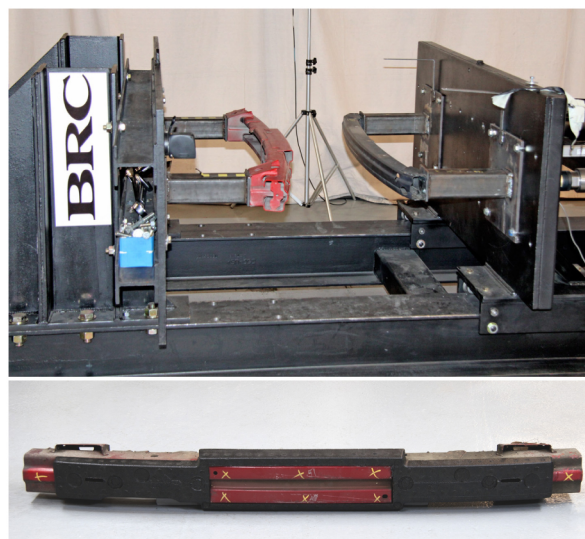


Figure 4. The top photograph shows the impact bars of Bumper System B prior to a QS F-D measurement, with the Civic's impact bar on the fixed plate (left side) and the Escape's impact bar on the moveable plate (right side). The lower photograph shows the Civic's black impact absorber on the impact bar.

CRASH TESTS

A series of crash tests were performed with each bumper system. In each crash test the dynamic F-D characteristics of the bumper system and the vehicle dynamics were measured. The bullet vehicle in each crash test was a buck that had the front bumper of the bumper system attached to it. The target vehicle in each crash test was a production vehicle with an OEM rear bumper. The target vehicle was always stationary pre-crash with the transmission in neutral and the bullet vehicle, the buck, was accelerated to the impact speed by rolling down a ramp. A schematic of the test setup for the crash tests is shown in [Figure 6](#).

The buck was made from a pickup's chassis and suspension and the buck's weight could be adjusted to represent the weight of the vehicle whose bumper was mounted on the front. The adjustable weights were rigidly attached to the frame of the buck. The buck had a vertically oriented steel plate rigidly attached to the front of the frame and six load cells (Model 1210AO, Interface, Inc.) were attached to this plate. A second steel plate, the bumper plate, was attached to the other end of the load cells at the front of the buck. The front bumper of the bumper system was mounted on the bumper plate with attachment hardware similar to the hardware used on the bumper crusher. The front bumper on the buck was positioned on the bumper plate such that when it contacted the rear bumper on the target vehicle, it was in the same orientation as the bumpers in the QS F-D measurements. A string potentiometer (T2A, Celesco, Inc) was attached to the bumper plate and the string was attached to a moveable rod that extended past the bumper on the buck.

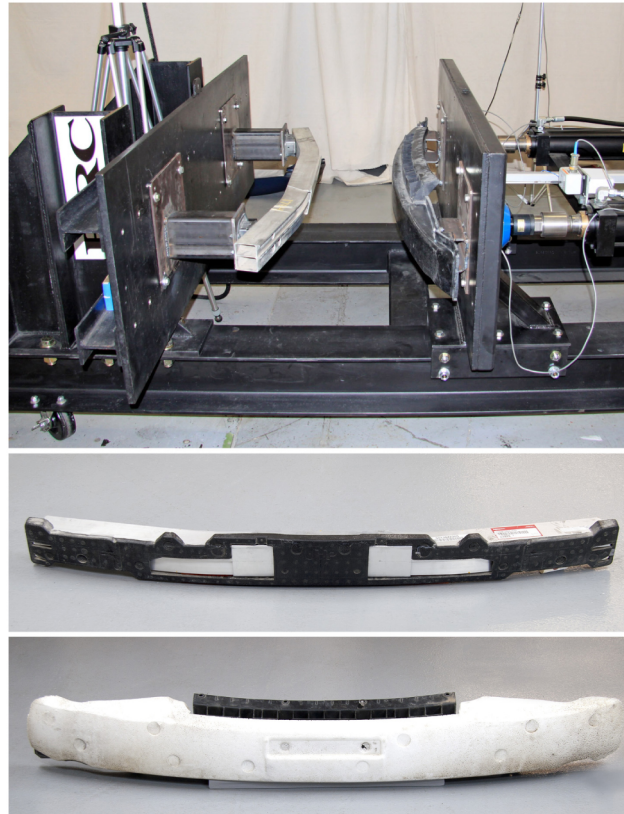


Figure 5. The top photograph shows the impact bars of Bumper System C prior to a QS F-D measurement, with the Civic's aluminum impact bar on the fixed plate (left side) and the Sedona's impact bar on the moveable plate (right side). The middle photograph shows the Civic's black impact absorber on the impact bar. The lower photograph shows the Sedona's white impact absorber on the impact bar.

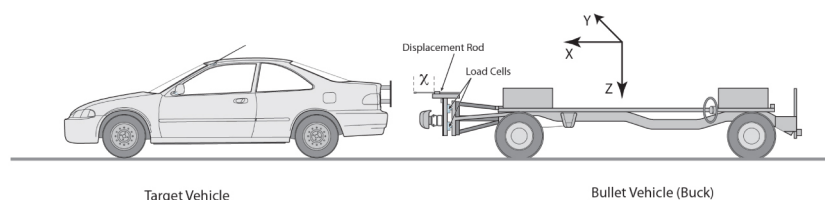


Figure 6. A schematic of the test set up used in the low-speed crash tests.

During a crash the rod contacted a flat plate above the rear bumper of the target vehicle, as shown in Figure 6, before the bumpers contacted each other and the relative movement of the rod with respect to the bumper plate during the crash was measured by the string pot. During the crash the displacement sensor measured the distance (χ) between the plate on the rear of the target vehicle and the bumper plate on the buck, as shown in Figure 6. Since the rod contacted the plate on the target vehicle before the bumpers made contact, χ is set to zero at the time an impact force is recorded by the load cells and χ represents the longitudinal deformation of the bumper system.

The buck had tri-axial accelerometers rigidly attached to the frame and the target vehicle had tri-axial accelerometers

rigidly attached to the floor pan and the unibody structure under the vehicle. Redundant accelerometers were used in case one set of accelerometers failed during a crash test. The x-axis is along the direction of travel of the bullet vehicle. During a crash test all sensor signals were sampled at a frequency of 5000 Hz (16-channel TDAS-PRO, DTS, Inc. and 16-channel 6210 NI, Inc.) and filtered at 100 HZ (SAE J211 CFC60). The impact speed of the bullet vehicle was measured with an infra-red sensor (SM312LVMHS, Banner, Inc.) and retro-reflective tape (Banner, Inc.) and also with high-speed digital video recordings (1000 frames/sec). High speed and normal video cameras were used to document the deformation of the bumpers and the vehicle behavior during the crash tests.

The impact forces during a crash test were calculated from three different transducer data sets and compared to ensure that the transducers operated properly during that crash test. The three transducer data sets were the load cells on the bullet vehicle and the x-axis accelerometers on the bullet and target vehicles. The load cells have a mass between their location on the buck and the surface where the impact force is acting on each bumper. The mass (M_{BP}) is made up of the bumper plate (139.5 kg, (307.5 lbs)), the bumper hardware and the steel that represents the frame or unibody structure of the bullet vehicle that is bolted onto the bumper plate. The force required to accelerate M_{BP} must be added to the crash forces measured by the load cells ($F_{LC}(t)$) in order to obtain the impact force ($IF_{LC}(t)$) acting on the bumpers;

$$IF_{LC}(t) = |A_B(t)| M_{BP} + F_{LC}(t) \quad (1)$$

where t is time and $A_B(t)$ is the x-axis acceleration of the buck (bullet vehicle). The absolute value of $A_B(t)$ is used for this analysis because the accelerations of the buck were negative in the crash tests, but all forces have been made positive for the comparison. $F_{LC}(t)$ is the sum of the six load cells on the buck. The mass of the target and bullet vehicles and the mass of the plate, bumper and hardware on the front of the buck used with each bumper system are listed in [Table 2](#).

Table 2. The masses of the target vehicles, bullet vehicles and attachment hardware.

Bumper System	Target Vehicle Mass (M_T)	Bullet Vehicle Mass (M_B)	M_{BP}
A	977 kg	2453 kg	190 kg
B	1257 kg	1490 kg	167 kg
C	1330 kg	1874 kg	161 kg

The impact forces calculated using the accelerometer data from the target vehicle ($IF_T(t)$) and the bullet vehicle ($IF_B(t)$) are;

$$IF_T(t) = M_T A_T(t) \quad (2)$$

$$IF_B(t) = M_B |A_B(t)| \quad (3)$$

where M_T is the mass of the target vehicle, M_B is the mass of the bullet vehicle and $A_T(t)$ is the x-axis acceleration of the target vehicle. [Equations \(Eqs.\) 2 and 3](#) assume that the target and bullet vehicles are rigid-bodies and therefore, the measured accelerations represent the uniform acceleration of the entire mass of the vehicle.

The velocities of the bullet vehicle ($V_B(t)$) and the target vehicle ($V_T(t)$) during a crash were obtained by integrating the x-axis accelerations of the bullet and target vehicle and using the initial velocities;

$$V_B(t) = V_{\text{impact}} + \int A_B(t) dt \quad (4)$$

$$V_T(t) = \int A_T(t) dt \quad (5)$$

where V_{impact} is the impact velocity of the bullet vehicle and the integration is from the start of the crash to time t in the crash. As previously mentioned, the target vehicle was always stationary prior to impact by the bullet vehicle. [Eqs. 4 and 5](#) assume that the target and bullet vehicle are rigid masses and the measured acceleration represents the uniform acceleration of the entire mass of the vehicle.

An analysis of the energy available for crush in a collision was used to evaluate the performance of the displacement sensor and the load cells on the buck in each crash test. In order to do this evaluation, the energy available for crush was determined using two different methods. The first method was to use the pre-crash and post-crash velocities of the vehicles to determine the energy available for crush ([10](#)). The energy available for crush (E_{afc}) using the pre-crash and post-crash velocities is;

$$E_{afc} = 1/2 M_B M_T V_{\text{impact}}^2 / (M_B + M_T) \quad (6)$$

The second method was to determine the energy required to crush the bumpers to the maximum deformation in the crash tests, which should be equal to E_{afc} ([1](#)). The work done deforming the bumpers up to the maximum crush is called the energy available for crush measured in the crash test (E_{afcm}) and was calculated for each crash test, thus;

$$E_{afcm} = \int IF_{LC}(\chi) d\chi \quad (7)$$

where χ is the deformation of the bumper system (see [Figure 6](#)) and the integration was performed from initial contact up to the maximum deformation. The magnitude of E_{afcm} should be close to E_{afc} if the displacement sensor and the load cells operated properly in each crash test.

The impact speeds of the bullet vehicle in each series of crash tests are shown in [Table 3](#). Each crash test is referred to by the bumper system letter and the crash test number for that bumper system. The impact speed in the crash tests for each bumper system was varied in order to look at the dynamic performance of the bumper system over a range of impact speeds. After the first crash test in a series the bumpers were checked for any deformation and replaced if damaged or