

Characterization of Force Deflection Properties for Vehicular Bumper-to-Bumper Interactions

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ABSTRACT

This is the complete manuscript and replacement for SAE paper 2014-01-0482, which has been retracted due to incomplete content.

This paper reports on 76 quasi-static tests conducted to investigate the behavior of road vehicle bumper systems. The tests are a quasi-static replication of real world low speed collisions. The tests represented front to rear impacts between various vehicles. Force and deflection were captured in order to quantify the stiffness characteristics of the bumper-to-bumper system.

A specialized test apparatus was constructed to position and load bumper systems into each other. The purpose was to replicate or exceed damage that occurred in actual collisions. The fixture is capable of positioning the bumpers in various orientations and generates forces up to 50 kips. Various bumper-to-bumper alignments were tested including full overlap, lateral offset, and override/underride configurations. Force and displacement were recorded and the data was analyzed to develop system stiffness and crush parameters. These parameters can be used in a collision-based model to calculate vehicle delta-v (ΔV) and acceleration. The simulation uses an impact mechanics-based numerical algorithm published by Scott [6]. The paper reports on the test results of various combinations of vehicle categories. Vehicle type includes passenger, light transport and heavy vehicle bumper systems.

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INTRODUCTION

Assessing impact severity in low-speed collisions is often difficult using current accident reconstruction methods. In many cases vehicle specific crush stiffness data is not applicable or difficult to incorporate when dealing with vehicles that have little to no residual crush. Reconstructionists are routinely given sparse information regarding the accident vehicles which may or may not be available for inspection. Photographs, witness testimony and repair estimates are frequently the primary source of vehicle information regarding damage.

Traditional vehicle stiffness properties were first studied by Campbell [5] which defined the plastic deformation of vehicle structures in terms of equivalent barriers speed (EBS) and residual crush. The stiffness theory was further developed and uses what are currently known as stiffness coefficients. Campbell also described a non-zero intercept term that took into account the initial energy absorbed with no residual crush. The theory allows calculation of damage energy which can be used in conjunction with conservation of momentum and

conservation of energy to determine the ΔV of the vehicles. However, the stiffness coefficients and intercept have limited application in low-speed impacts with minimal residual damage.

Strother et al. examined the use of deformation energy as an accident reconstruction tool to determine vehicle dynamics for a specific crash [10]. The method required vehicle specific crash data to establish deformation energy estimates. Various force models including the constant force, force saturation, and bilinear crush force model were explored. He stated the need for additional testing to supplement the low energy level data. He cautioned that the use of 30 to 35 mph barrier test data to estimate low speed collision could yield unrealistic stiffness estimates.

Another approach has been called the Momentum-Energy-Restitution (MER) method. This method is based on rigid body impact mechanics and uses impulse, conservation of momentum, conservation of energy and restitution to determine the ΔV of the vehicles in a low-speed crash [2,3,7].

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. An analysis of a low-speed crash with the MER method provides a ΔV for the crash but does not provide the acceleration vs. time information for the vehicles during the crash.

A third approach is to treat the vehicles as rigid structures and model the bumpers as a spring/dashpot systems and then solve the governing differential equations with the appropriate initial conditions [2,7,12]. The solution gives the accelerations of both vehicles during the crash. In order to simulate a specific crash with a spring/dashpot model the appropriate stiffness and damping coefficients must be used.

Happer et al. [6] described a method for using the IIHS low speed crash test reports to establish an upper limit for crash severity. A comparison of damaged components between the test vehicle and the vehicle being investigated is made. If lesser damage is demonstrated on the vehicle being investigated when compared to the test vehicle then the closing velocity for the test can be used as an upper limit BEV for the subject vehicle. The BEV can in turn be used in the Carpenter [3] single-degree-of-freedom (SDOF) MER method, once b_1 values have been determined. This method is useful when IIHS tests are available for a particular vehicle.

Scott developed a numerical collision model to simulate low-speed collinear vehicle-to-vehicle impacts. In the analysis the impact force was directly related to the physical properties of the bumpers that were involved in the crash [8,9]. The approach allows the crash severity of a low-speed crash involving specific vehicles to be estimated, including the crash pulse. This approach takes into account the variability of the force-deformation characteristics of the bumper systems. A numerical simulation is performed which satisfies Newton's Second Law at discrete time increments. The structural characteristics of both vehicles' bumpers are combined and input as a system Impact Force-Deformation (IF-D) function. The deformation is the sum of the deformation of the two bumpers involved in the crash (i.e. mutual crush). The IF-D function can be a theoretical curve, or be based on measured force-deflection data for specific bumpers. Tests were conducted to measure IF-D curves which were then used in the analysis to determine the ΔV and the acceleration vs. time information for vehicles involved in crashes.

Validation of the quasi-static bumper loading method described in this paper has been conducted by Scott et al. A series of matching quasi-static and dynamic tests were performed and compared. The study concluded that quasi-static force deflection measurement can be used to reconstruct and quantify the vehicle dynamics in low speed bumper-to-bumper collisions.

This retrospective study provides a large number of force-deformation curves taken from tests covering a wide range of bumper systems. The testing is grouped into categories and

summarized as linear IF-D functions. These functions could be used for the calculation of vehicle delta-v and acceleration in low-speed collisions when specific test data is not available. In that case the delta-v and acceleration are calculated in an analysis of the collision using a model based on Newton's Laws of Motion developed by Scott et al. The IF-D function characterizes the vehicle interaction.

METHOD

General

Bumper-to-bumper interactions were simulated using a test fixture developed to quasi-statically load two bumper systems as described by Scott [8,9]. The working model assumes each of the vehicles involved in the collision to be a rigid body with the exception of the interacting bumper and vehicle components. Many of the tests conducted were designed and modeled based on a real world low speed collision and were used to analyze the crash mechanics for that specific crash configuration. The bumper components were aligned using information available to the reconstructionist for the particular crash being investigated. Information available to the reconstructionist often included scene photographs, photographs of one or both vehicles involved in the crash, witness testimony, repair estimates, accident reports, and/or appraisal reports. For example, in some cases the front license plate or license plate fastener of the striking vehicle created an imprint onto the rear bumper cover of the struck vehicle. This physical evidence was used to align the bumper at the point of initial contact. Exemplar vehicles were procured for each bumper system in order to obtain external bumper cover and bumper reinforcement bar heights. In some instances bumper dive measurements due to heavy braking were also documented to ensure proper vertical bumper alignment.

The interacting bumpers are treated as a one system and therefore produce the stiffness characteristics for the system as a whole. The exemplar test components were fixed to the test apparatus rigidly and in a substantially similar mounting configuration when compared to their respective vehicles including all relevant bumper brackets. All tests were conducted using original equipment manufacturer (OEM) parts and brackets.

A total of 85 quasi-static force deflection bumper tests were reviewed. The bumper tests were sorted and grouped in a variety of category permutations for comparative analysis. Nine of the 85 did not form a significant category grouping and were not used in the analysis.

Each force deflection test consisted of two general phases, a compression phase and rebound phase. The front bumper system of one vehicle and the rear bumper system of another were compressed together in order replicate and/or exceed the damage seen on the vehicles being investigated. Only compression phases were comparatively analyzed for this study.

Test Apparatus

The test fixture is comprised of one fixed and one moveable steel plate as shown in [Figure 1](#). Each bumper system is mounted to one of the steel plates. The moveable plate is guided along two tracks on roller bearings and is powered by two 4 inch diameter hydraulic cylinders operating at 2400psi.

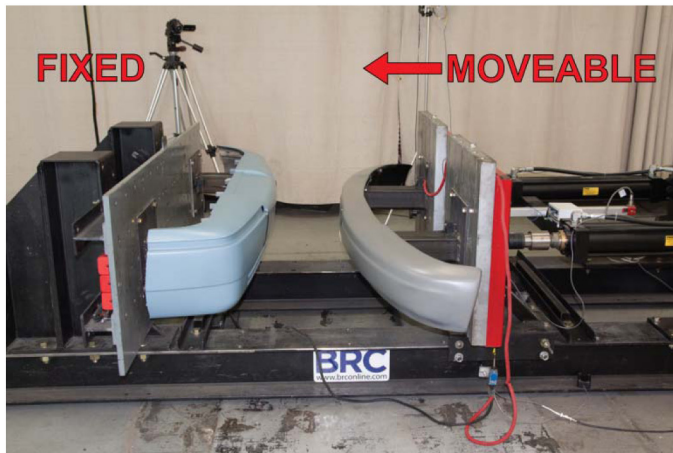


Figure 1. Photograph of the test apparatus designed to mount two bumper systems for a quasi-static compression test.

Override/underride configurations were tested in addition to the bumper-to-bumper interactions. The test fixture was modified by removing the fixed steel plate from the I-beam track. An exemplar vehicle, in its entirety, is then rigidly anchored to the fixture and ground as shown in [Figure 2](#). In this configuration the suspension of the vehicle was allowed to respond normally in the vertical direction.



Figure 2. Photograph of the test apparatus modified for an override/underride condition. The fixed steel plate has been removed and a whole vehicle is rigidly anchored to the ground and fixture.

Instrumentation

The test machine was instrumented with two force transducers (1210AO-25k, Interface, Inc.) and a displacement transducer (Temposonics, E-Series, MTS, Inc.). The data acquisition system consisted of a 16-channel board (PCIMIO16E2, NI,

Inc.) inside a Dell® workstation connected to a 3-channel bridge conditioner and amplifier system (136-1DC, Endevco, Inc.).

Documentation

All tests were documented using real-time digital video. The video cameras were synchronized in time with the force displacement data. Digital still photography was used to document the pre- and post-test condition of the bumper components. Comparative photographs were taken at similar angles and focal distances as the photographs of the vehicles being investigated.

Test Categories

Each test was categorized by vehicle type, vertical bumper alignment, horizontal bumper alignment, and whether or not the struck vehicle was equipped with a trailer hitch ball mount. The vehicle type was defined by the vehicle the bumper system originated from. The categories chosen were cars, which included passenger vehicles such as two or four door sedans and coupes, light transport vehicles (LTV's) including pickups, sport utility vehicles (SUV), and minivans, and heavy vehicles which included all commercial vehicles with a GVRW of 10,000 lbs or greater. For each test there was a striking and struck vehicle. [Table 1](#) lists the test categories and the number of tests in each category.

Table 1. Test categories organized by vehicle type, vertical and horizontal alignment.

Vehicle Type Striking Vehicle	Vehicle Type Struck Vehicle	Alignment		Number of Tests
		Vertical	Horizontal	
Car	Car	Bumper-to-Bumper	Full Overlap (> 50%)	18
LTV	LTV	Bumper-to-Bumper	Full Overlap (> 50%)	6
Car	LTV	Bumper-to-Bumper	Full Overlap (> 50%)	8
LTV	Car	Bumper-to-Bumper	Full Overlap (> 50%)	8
Heavy Veh.	Car/LTV	Bumper-to-Bumper	Full Overlap (> 50%)	5
All	All	Bumper-to-Trailer Hitch	Focal	8
All	All	Override/Underride	All	13
All	All	Bumper-to-Bumper	Offset (< 50%)	10

RESULTS

Car-to-Car (CC), Full Vertical Overlap, Full Horizontal Overlap

The car-to-car, full overlap category included a total of 18 tests as shown in [Figure 3](#). Manufacturers represented within this category were General Motors, Ford, Chrysler, Honda, Toyota, Suzuki, Mercedes, Mitsubishi, Hyundai, Jaguar, Volkswagen, Nissan and Volvo. A linear best fit slope for each test was

determined based on a zero y-intercept to peak force criterion. In many cases, the peak force may represent a global maximum rather than the force at peak deformation as shown in Figure 4. The maximum values located within the compression phase of a force deformation test often represented the collapse of a bumper component. The overall slope of the compression phase is the bumper system stiffness measured in pounds (force) per foot. The numerical average and one standard deviation of the bumper stiffness values were then used to create a bumper stiffness corridor. The average stiffness for this category was 29,591 lbf/ft with a standard deviation of 10,524 lbf/ft.

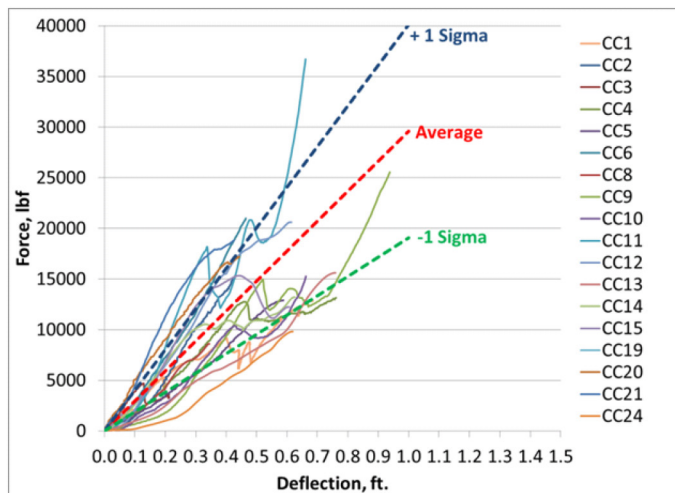


Figure 3. Force vs. deflection plot for the car-to-car full overlap tests. The average slope and standard deviation are overlaid on the test data.

The test shown below in Figure 4 is an example of a force deflection plot in which the front bumper system (striking vehicle) collapsed and could no longer support the compressive forces. In this case, the left bumper bracket and front reinforcement bar were compromised. The stiffness for this test was determined from the peak force rather than the peak deflection to better represent the resistance prior to collapse. The average slope would have been underestimated had the peak deflection been used as a stiffness determinant.

Two-thirds (12 of 18) of the tests in this category had a bumper reinforcement bar or bumper brackets that collapsed. A list of damaged components for these tests is detailed in Table 2. The average force for bumper reinforcement bar collapse was 12,800 lbf. Of the twelve tests that included bumper bar collapse, nine were front bumper systems. It was postulated that the front bumper systems for road vehicles are softer than rear bumper system because of the airbag system. The front bumper systems are possibly tuned with the deployment sequence of the vehicle. It was also observed that bumpers constructed from aluminum had a tendency to be stiffer than any other material tested.

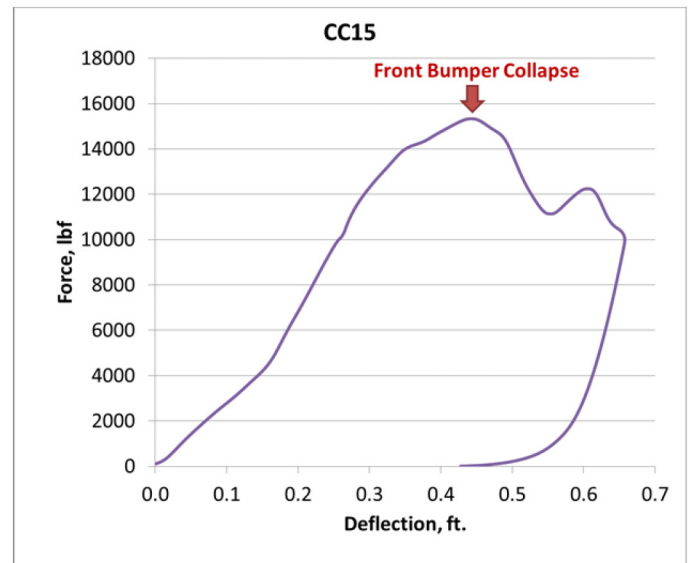


Figure 4. Force vs. deflection plot for test CC15 including the compression and rebound phase. The front bumper system permanently deforms at approximately 15,300 lbf.

Table 2. List of test components that permanently yielded in the car-to-car full overlap category.

Test I.D.	Material Type	Yield Force (lbf)	Description of Damaged Components
CC2	Steel	15300	Scion brackets permanently deform
CC3	Fiberglass Composite	4637	Buick bumper reinforcement bar collapsed
CC4	Steel	12749	Acura bumper reinforcement bar collapsed
CC5	Steel	12863	Hyundai bumper reinforcement bar collapsed
CC8	PE	7000	Impala honeycomb energy absorber deformed
CC9	Steel	15000	Malibu bumper reinforcement bar collapsed
CC10	Steel	10300	Mitsubishi bumper reinforcement bar collapsed
CC11	Steel	17557	Toyota bumper reinforcement bar collapsed
CC13	Steel	15600	Ford bumper reinforcement bar collapsed
CC14	PE	10300	Pontiac bumper brackets and rebar collapsed
CC15	Fiberglass Composite	15168	Suzuki bumper reinforcement bar collapsed
CC21	Steel	17900	Honda bumper reinforcement bar collapsed

LTV-to-LTV (LL), Full Vertical Overlap, Full Horizontal Overlap

The LTV-to-LTV, full overlap category included a total of 6 tests as shown in Figure 5. Manufacturers included Chrysler, Ford, General Motors and Honda. The average stiffness for this category was 32,145 lbf/ft with a standard deviation of 11,387 lbf/ft.

The bumper construction and mounting differs between pickups and sedans. Pick-ups tend to lack bumper covers and energy absorbers. Additionally, the mounting structure consisted of brackets that are directly fastened to a box frame. Because of these differences in design, component yielding occurred within the compliance of the brackets. In some tests the rear bumper pitched instead of causing the bumper reinforcement bar to permanently deform. In other cases the bumper may not collapse but rather deform through the ends of the bumper fascia.

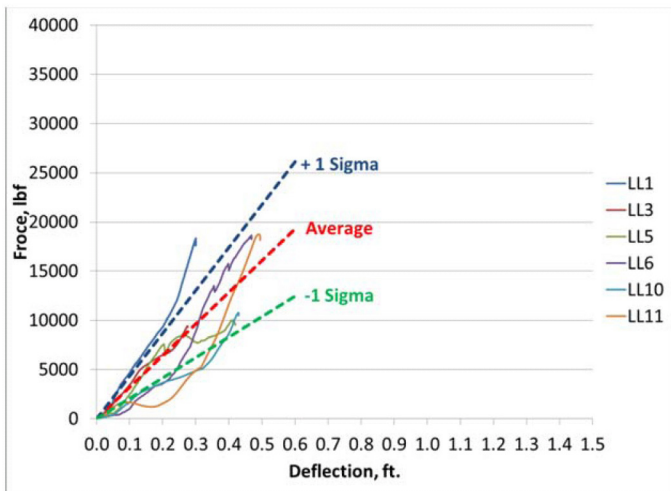


Figure 5. Force vs. deflection plot for the LTV-to-LTV full overlap tests. The average slope and standard deviation are overlaid on the test data.

Car-to-LTV (CL), Full Vertical Overlap, Full Horizontal Overlap

The car-to-LTV, full overlap category included a total of 8 tests as shown in Figure 6. Manufacturers included Ford, General Motors, Toyota, Isuzu and Honda. The average stiffness for this category was 28,296 lbf/ft with a standard deviation of 11,608 lbf/ft.

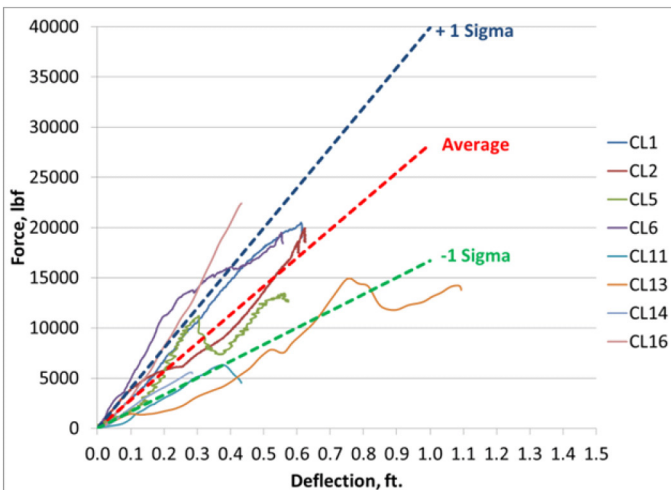


Figure 6. Force vs. deflection plot for the car-to-LTV full overlap tests. The average slope and standard deviation are overlaid on the test data.

This category had similar damage results when compared to the LTV-to-LTV category. This is in part due to the fact that the rear bumper systems are mostly pick-up bumpers. Yielding occurred when the rear bumper system rotated rather than plastically deforming. Three of the eight tests (CL1, CL2, and CL6) involved the front bumper system of a Ford Taurus. The Ford Taurus front bumper was noted as being relatively stiff

and did not permanently deform. All three Ford Taurus tests resulted in similar stiffness slopes near the upper limit of the corridor.

LTV-to-Car (LC), Full Vertical Overlap, Full Horizontal Overlap

The LTV-to-car, full overlap category included a total of 8 tests as shown in Figure 7. Manufacturers included Ford, General Motors, Toyota, Isuzu and Honda. The average stiffness for this category was 29,245 lbf/ft with a standard deviation of 13,446 lbf/ft.

Five of the eight tests included a bumper system that collapsed, all of which were front bumpers. A majority of these front bumpers were from sport utility and minivan vehicles that closely resemble the construction of sedans. Two of the five bumpers were constructed from a fiberglass composite material. The average force for bumper reinforcement collapse for the five tests was 9,786 lbf.

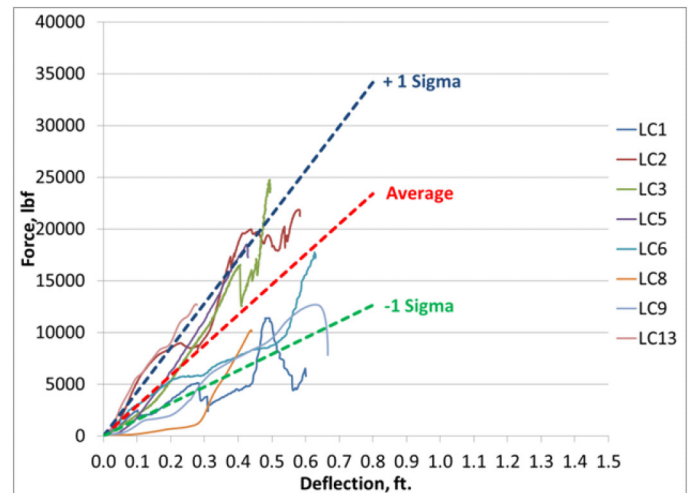


Figure 7. Force vs. deflection plot for the LTV-to-car full overlap tests. The average slope and standard deviation are overlaid on the test data.

Heavy Vehicle-To-Car/LTV (HC) (HL), Full Vertical Overlap, Full Horizontal Overlap

The heavy vehicle-to-car/LTV, full overlap category included a total of 5 tests as shown in Figure 8. Manufacturers included Ford, General Motors, Toyota, Peterbilt, International, Freightliner and Honda. The average stiffness for this category was 51,799 lbf/ft with a standard deviation of 29,699 lbf/ft.

In general, the heavy vehicle front bumper systems were stiffer than their car and LTV counterparts. Tests HC2 and HC4 were Peterbilt front bumpers and followed a distinctly similar force deflection characteristic. Both of these tests involved subject vehicles in which the struck car was left with only bumper fastener (bolt) impressions onto the rear bumper covers. This allowed for precise alignment of the bumpers at the time of impact. Preliminary tests were first conducted to create the bolt

impression onto the bumper covers before proceeding with the tests shown in Figure 8. The subsequent tests were then performed with the intent of grossly exceeding the damage documented on the subject vehicle to present a worst case scenario. Tests HC3 and HC4 followed a different pattern in both stiffness and damage. The bumper systems of the struck vehicles were comparatively less stiff than the heavy vehicle front bumpers and deformed to a greater extent. This created a large variation in the standard deviation for this category. It should be noted that in all five tests the heavy vehicle bumper fascia's plastically deformed. The stiffness of the front bumper system was generated from the interaction with the box frame and underlying bumper brackets rather than the bumper fascia which were all constructed from a thin gauge metal.

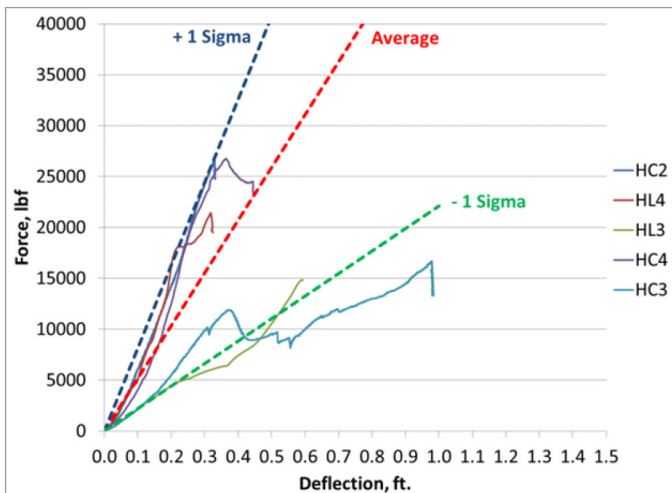


Figure 8. Force vs. deflection plot for the heavy vehicle-to-car/LTV full overlap tests. The average slope and standard deviation are overlaid on the test data.

All Car/LTV-to-Trailer Hitch

The car/LTV-to-trailer hitch, full overlap category included a total of 8 tests as shown in Figure 9. Manufacturers included Ford, General Motors, Toyota, Honda, and Nissan. The average stiffness for this category was 24,052 lbf/ft with a standard deviation of 4,163 lbf/ft.

All tests were conducted with the intent of collapsing the front bumper reinforcement bars. Trailer hitch ball mount collisions are a common crash type. They often lead to a distinct focal damage pattern ideal for aligning the vehicles at impact as shown in Figure 10. No test exceeded a peak force of 11,200 lbf. The average force for bumper collapse was 8,323 lbf. Test TH5 was the only test that did not involve a ball mount and only included the receiver box tubing although the data followed the same pattern as the remaining 7 tests. Ideally a bi-phasic slope would be used in the simulation to calculate ΔV and acceleration. The linearity of the average slope would tend to over predict the calculated values.

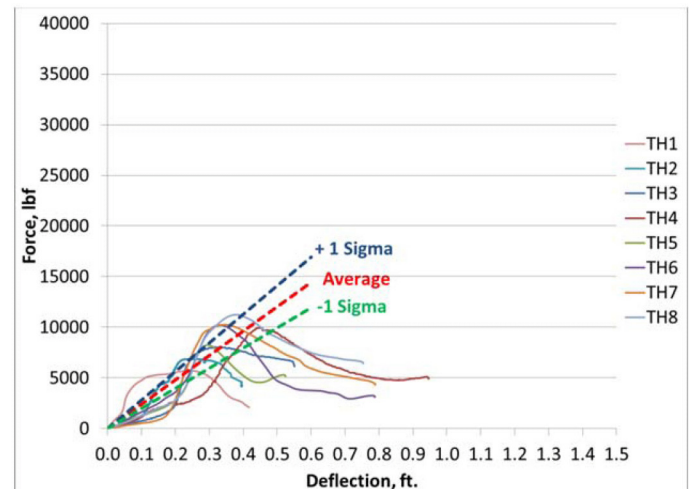


Figure 9. Force vs. deflection plot for all car/LTV-to-trailer hitch tests. The average slope and standard deviation are overlaid on the test data.

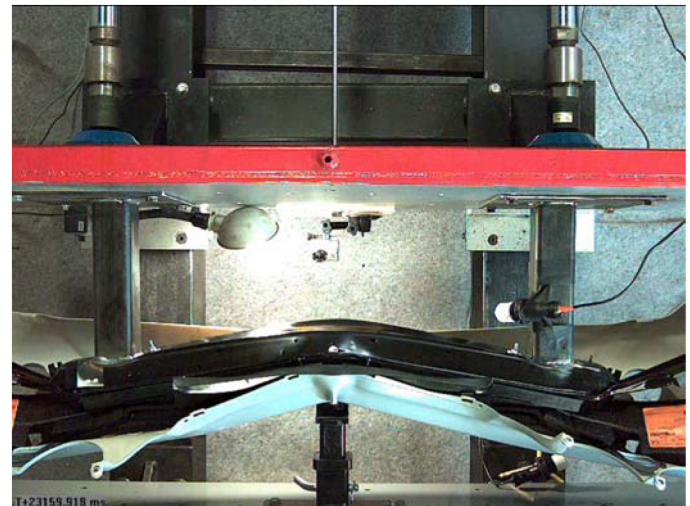


Figure 10. Overhead view of a trailer hitch equipped with a ball mount intruding into the front bumper system in test TH3 at maximum compression.

All Override/Underride

The Override/Underride category included a total of 14 tests as shown in Figure 11. Manufacturers represented within this category were General Motors, Ford, Lexus, Saturn, Hyundai, Hino, Chrysler, Nissan, Sterling and Toyota. The average stiffness for this category was 7,089 lbf/ft with a standard deviation of 3,764 lbf/ft.

During the tests the bumpers engaged and usually then slid over one another resulting in damage to components including the hood, grill, headlights, radiator support, truck lid, body panels, bumper and bumper covers. As the stiff structures were generally not damaged during the testing, the average stiffness is much lower than the other categories. There was a large variation in the vehicles tested, which included cars and LTV's. This may explain the relatively large standard deviation.