

Comparison of Quasistatic Bumper Testing and Dynamic Full Vehicle Testing for Reconstructing Low Speed Collisions

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ABSTRACT

It has been proposed that low speed collisions in which the damage is isolated to the bumper systems can be reconstructed using data from customized quasistatic testing of the bumper systems of the involved vehicles. In this study, 10 quasistatic bumper tests were conducted on 7 vehicle pairs involved in front-to-rear collisions. The data from the quasistatic bumper tests were used to predict peak bumper force, vehicle accelerations, velocity changes, dynamic combined crush, restitution, and crash pulse time for a given impact velocity. These predictions were compared to the results measured by vehicle accelerometers in 12 dynamic crash tests at impact velocities of 2 - 10 mph. The average differences between the predictions using the quasistatic bumper data and the dynamic crash test accelerometer data were within 5% for bumper force, peak acceleration, and velocity change, indicating that the quasistatic bumper testing method had no systematic bias compared to dynamic crash testing. The root mean square differences were 21% - 23% for peak vehicle accelerations and 12% for vehicle velocity changes. The root mean square differences when comparing crash test accelerometer data from one vehicle to the other using Newton's second law and assuming the vehicles to be rigid bodies were 11% - 18% for all parameters. We conclude that quasistatic bumper testing is an effective tool for reconstructing low speed collisions because it replicates the results of dynamic full vehicle crash testing with good accuracy.

CITATION: Funk, J., Bonugli, E., Guzman, H., and Freund, M., "Comparison of Quasistatic Bumper Testing and Dynamic Full Vehicle Testing for Reconstructing Low Speed Collisions," *SAE Int. J. Passeng. Cars - Mech. Syst.* 7(3):2014, doi:10.4271/2014-01-0481.

INTRODUCTION

Traditional accident reconstruction methods that rely on an analysis of vehicle crush cannot be readily applied to low speed collisions in which there is little or no crush damage to the involved vehicles. Nevertheless, the basic principle behind the crush analysis methodology can still be applied; namely, that the severity of a collision can be determined by comparing the damage sustained by a vehicle in a real world crash to the damage sustained by similar vehicles during physical testing in a similar impact configuration. Commonly used accident reconstruction methods rely on testing that often differs from the real world crash under investigation in potentially important ways. First, nearly all publicly available crash test data involve a collision of a vehicle into some sort of barrier, whereas many real world cases involve a collision between two vehicles. Second, most publicly available crash test data are conducted at a few discrete closing speeds (such as 5, 30, and 35 mph), so the level of damage to the test vehicles may differ substantially from the subject vehicles in the real world crash. Over the years, various analytical methods have been developed to allow the investigator to account for these differences and reach accurate conclusions [1, 2, 3, 4, 5].

In 2010, Scott et al. [6] proposed a method for reconstructing low speed collisions based on quasistatic testing of the bumper systems of the vehicles involved in the collision. This methodology has several appealing features. Bumpers from the same make, model, and year range of both vehicles are used in the testing. The offset, alignment, and angle between the bumpers can be customized to match witness statements or damage patterns specific to the subject case. In addition, because the testing is conducted quasistatically, it can be stopped whenever the investigator observes that the level of damage achieved in the testing has matched the level of damage documented in the subject vehicles.

On the other hand, quasistatic bumper tests differ from real world collisions in at least two respects. First, real world crashes happen dynamically, not quasistatically. It is possible that the mechanical response of the bumper systems depends on the rate at which they are loaded, although previous research has shown that loading rate has a negligible effect on the mechanical response of a vehicle [7-8]. Second, real world collisions involve full vehicles, not just bumper systems. The

method of Scott et al. [6] assumes that the vehicles are rigid bodies with all of the compliance contained in the bumper systems.

The methodology that might be considered the gold standard for reconstructing a particular crash is to conduct a full-scale dynamic crash test using similar vehicles that replicates the damage sustained by the involved vehicles. However, such an approach is often neither feasible nor necessary. Furthermore, accelerometers in dynamic crash tests capture not only the low frequency whole-body response of the vehicle, but also the higher frequency vibration of the particular structure to which the accelerometers are mounted. Scott et al. [9] showed that the higher frequency vibrations measured by onboard accelerometers in low speed rear end vehicle crash tests are generally not observed in the bumper force when it is measured directly by load cells. A potential advantage of quasistatic bumper testing over dynamic full vehicle testing is that the quasistatic data do not contain high-frequency vibrations that would not be felt by the occupant.

The purpose of the present study was to investigate the accuracy of quasistatic bumper testing and dynamic full vehicle testing for purposes of low speed accident reconstruction. The mechanical response of the vehicles predicted using quasistatic bumper test data was compared to accelerometer measurements made during dynamic full vehicle crash testing. Both techniques were evaluated in terms of their ability to match the damage occurring in a real world collision. This paper extends the work of Scott et al. [9], who showed that the force-displacement responses of three different pairs of bumper systems were very similar in quasistatic bumper testing and dynamic crash testing with a vehicle buck.

METHODOLOGY

Matched quasistatic bumper testing and full vehicle dynamic crash testing was conducted on seven different vehicle pairs (Table 1). The tested vehicles were generally representative of passenger vehicles currently driven in the US. All of the vehicle pairs were initially tested in order to reconstruct real world collisions that were the subject of litigation. In some cases, quasistatic bumper testing was conducted first in order to determine the appropriate impact speed for a subsequent full vehicle dynamic crash test in which biomechanical data were collected from human or ATD test occupants. In other cases, additional quasistatic or dynamic testing was conducted independently as necessary in order to complete the test matrix for this research project.

All of the cases involved in-line ($<10^\circ$ obliquity) low speed collisions in which the front bumper of the striking (bullet) vehicle collided with the rear bumper of the struck (target) vehicle, which was stationary prior to impact. Except for case 7, there was full overlap between the bumpers with less than 1 foot (25 cm) of offset between the centerlines of the vehicles. In case 7, the left side of the front bumper of the Crown Victoria struck the right side of the rear bumper of the PT Cruiser with

approximately 60% overlap. There were no cases in which one bumper overrode or underrode the other. In two cases (vehicle pairs 3 and 4), the target vehicle was equipped with a trailer hitch and the rear bumper was not contacted at all. These cases can be considered trailer hitch tests because the target vehicle essentially provided only a mass and attachment point for the trailer hitch. In case 2, the target vehicle was equipped with a trailer hitch receiver, and both the receiver end and the rear bumper were loaded during the test.

Table 1. Vehicle pairs subjected to matched quasistatic bumper testing and dynamic crash testing. Vehicle model years and masses reflect the test vehicles used in the dynamic crash testing.

ID	Bullet vehicle	mass (lbs)	Target vehicle	mass (lbs)
1	2003 Dodge Ram	5907	2000 Dodge Caravan	4002
2	Vehicle buck with 2008 Ford Edge front bumper	4210	2007 Dodge Nitro with trailer hitch receiver	4151
3	1997 Ford F-150	4810	1995 GMC Yukon with trailer hitch	5556
4	2009 Pontiac Vibe	2976	2003 Ford F-150 with trailer hitch	5138
5	2005 Acura TSX	3410	2000 Oldsmobile Alero	3408
6	2004 Ford Taurus	3969	2005 Chevrolet Express van	5785
7	2005 Crown Victoria	4775	2006 Chrysler PT Cruiser	3472

Quasistatic Bumper Testing

Quasistatic bumper testing was accomplished with a custom-made device called the "bumper crusher." The bumper crusher consists of a fixed steel plate and a moveable steel plate oriented parallel to each other and perpendicular to the axis of crush (Figure 1). The movable steel plate was mounted to load-bearing rollers and powered by two 4-inch diameter hydraulic cylinders operating at 2400 psi. Only motion perpendicular to the steel plates on the test fixture was allowed; all other degrees of freedom were constrained. The movable steel plate was instrumented with two load cells (1210AO-25k, Interface, Inc.) and a displacement transducer (PT101, Celesco, Inc.) that recorded the displacement of the movable plate, which was equivalent to the combined crush of both bumper systems. The bumper systems for each vehicle, including the brackets, attachment hardware, reinforcement bar, energy absorber, plastic covers, etc., were obtained from dealers or salvage yards. In two of the quasistatic bumper tests (2Qb and 5Q), the bumpers were tested without the plastic bumper covers.

The bumper systems were mounted to the steel plates on the test fixture via rectangular steel tubing that served as surrogate frame horns. In one case (6Q), actual rear frame horns were removed from an exemplar Chevrolet Express van and welded to the attachment plate. The relative position of the bumpers on the plates was adjustable so that any necessary vertical offset

lateral offset, or oblique angle between the vehicles could be reproduced. For each test, the impact configuration was chosen to match either the real world collision being investigated or a previous full vehicle dynamic crash test. During testing, the bumpers were compressed together quasistatically (0.3 in/s) until the desired level damage was created, at which point the rams were manually stopped and reversed. Test video was obtained from overhead, side, and oblique views. A total of 10 quasistatic bumper tests were performed for this study (Table 2). In cases 1 and 2, repeated testing was conducted to progressively higher levels of force and displacement without repairing the bumper systems.

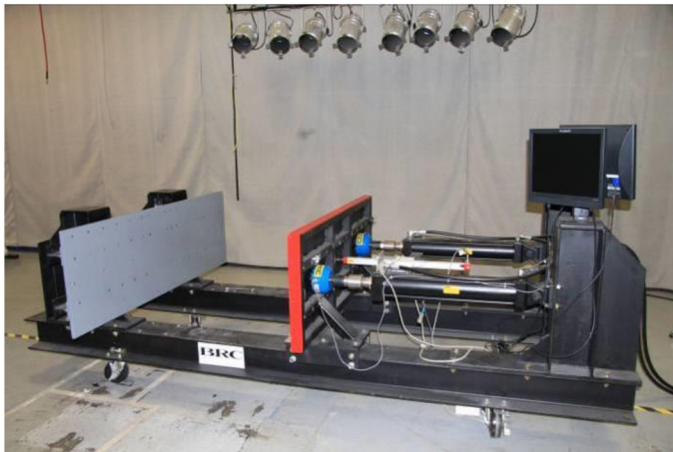


Figure 1. Photograph of the quasistatic bumper testing apparatus.

Table 2. Summary of quasistatic bumper testing. The first number of the test ID indicates which pair of bumpers was tested (Table 1). The "Q" indicates the test was conducted quasistatically. Lowercase letters "a", "b", and "c" indicate bumper pairs that were tested repeatedly. The bumpers were not repaired or replaced in between repeated tests.

ID	Peak bumper force (lbs)	Peak combined crush (in)	Equivalent impact speed (mph)	Restitution
1Qa	1557	2.3	0.9	0.79
1Qb	5026	5.0	3.3	0.42
1Qc	10751	6.5	4.6	0.43
2Qa	6020	3.2	2.6	0.59
2Qb	9296	5.0	4.6	0.47
3Q	5706	5.1	4.5	0.23
4Q	10263	12.0	7.6	0.17
5Q	12988	9.4	10.3	0.37
6Q	19837	7.6	8.0	0.39
7Q	13778	12.0	10.5	0.31

Simulation Procedure

Standard physics equations were used to transform the force-displacement response of the bumper systems measured in the quasistatic bumper testing to acceleration, velocity, and

displacement time histories for each vehicle in a simulated collision. The procedure was described in detail by Scott et al. [6] and is summarized here. Given a force-displacement response, the only additional input information that is required in order to simulate a collision is the mass of each vehicle and the impact speed (assuming the target vehicle to be initially stationary). For this study, the vehicle masses and impact speed in the simulations were matched to the values measured in the corresponding full vehicle dynamic crash tests. For the purpose of evaluating the reasonableness of the restitution values obtained from the quasistatic bumper testing, equivalent impact speeds were also calculated for each quasistatic bumper test, as described in Appendix I.

The simulation procedure was based on the equations of motion for each vehicle. It was formulated as an initial value problem, with impact speed being the initial value, and solved numerically over a series of small (1 ms) time increments. At each successive time increment following first contact between the bumpers, the displacement of each vehicle was calculated by integrating its velocity. Combined crush was then determined by subtracting the vehicle displacements. The force developed as a result of this combined crush was calculated by interpolating the force vs. displacement data measured during the quasistatic bumper test, which essentially served as a look-up table. Vehicle accelerations were then calculated by dividing the bumper force by the vehicle mass, and vehicle velocities were calculated by integrating vehicle accelerations. The process was then repeated for the next time increment and continued throughout the crush phase of the simulation.

The simulation transitioned from the crush phase to the rebound phase when the combined crush between the vehicles began to decrease. The procedure for modeling the rebound phase of the crash pulse was identical to the procedure for modeling the crush phase, but a new look-up table reflecting the force-displacement behavior of the bumper systems during unloading was required. For this study, the response of the bumper systems during rebound was assumed to remain the same regardless of how much force or crush was developed during the crush phase of the simulation. The unloading force-displacement response measured in the quasistatic bumper testing was simply shifted to the left in cases where the peak combined crush in the simulation was less than what occurred during testing. The simulation was terminated when it predicted separation of the vehicles (no bumper force). A more detailed graphical illustration of the simulation procedure is provided in Appendix I, along with an explanation of how equivalent impact speed and restitution were calculated.

Dynamic Crash Testing

Dynamic full vehicle crash tests were conducted indoors at the BRC Research Test Center (Table 3). All of the test vehicles were drivable and all were driven by employees of BRC during the tests. For test 7D, the bullet vehicle used in the dynamic crash test was actually the same vehicle that was involved in the real world crash, which was a 2005 Crown Victoria police

cruiser. The front bumper system had been repaired between the time of the accident and the time of our testing. All vehicles were inspected prior to testing to ensure that there was no damage to the bumper system that was going to be involved in the collision. In case 2, the bullet vehicle consisted of a properly weighted buck with the front bumper of a 2008 Ford Edge mounted to a steel plate in front. Each vehicle was instrumented with triaxial accelerometers (7290E-10 and 7595-10, Endevco, Inc.) mounted to the floor pan in the occupant compartment. Redundant accelerometers were often used. During the test, data were sampled at 5 kHz (16-channel TDAS-PRO, DTS, Inc. and 16-channel 6210 NI, Inc.) and filtered at 100 Hz (SAE J211 CFC 60). High speed (1 kHz) video was taken from overhead and side views. Real time (30 Hz) video was also taken from oblique views.

Table 3. Summary of vehicle velocities in the dynamic crash tests. The first number of the test ID indicates which vehicle pair was tested (Table 1). The "D" indicates the test was conducted dynamically. Lowercase letters "a" and "b" indicate vehicle pairs that were subjected to two tests. All vehicles were repaired prior to repeated testing.

ID	Impact speed (mph)	Bullet vehicle ΔV (mph)	Target vehicle ΔV (mph)	Restitution
1Da	1.9	-1.1	1.7	0.46
1Db	5.0	-2.6	3.9	0.31
2Da	3.6	-2.8	2.5	0.48
2Db	3.6	-2.6	2.4	0.39
3Da	4.5	-2.2	3.0	0.17
3Db	3.9	-2.7	2.5	0.33
4Da	4.2	-3.1	1.8	0.17
4Db	7.6	-6.3	3.5	0.29
5D	7.8	-5.6	5.5	0.42
6Da	8.2	-5.9	3.7	0.18
6Db	8.3	-6.7	4.0	0.30
7D	10.2	-5.8	7.6	0.32

Prior to each test, the two vehicles were aligned in the appropriate impact configuration, including any vertical offset, lateral offset, or oblique angle between the vehicles. If necessary, the vertical alignment between the bumpers was adjusted by lowering the air pressure in the tires or blocking the suspension. The impact configuration was chosen to match either the real world collision being investigated or a previous quasistatic bumper test. The bullet vehicle was aligned such that it could be backed up a ramp to a height necessary to achieve the desired impact speed (Figure 2). The impact speed of the bullet vehicle was measured with an infrared sensor (SM312LVMHS, Banner, Inc.) mounted to the undercarriage that passed over retro-reflective tape (Banner, Inc.) just prior to impact.



Figure 2. Dynamic crash test setup (5D).

A total of 12 dynamic crash tests were run. In five of the seven cases, the crash tests were repeated under different conditions for various reasons. If any of the structural elements of either bumper system were damaged in the first test, the damaged parts were replaced before the second test was conducted.

Although vehicle accelerations were measured in all three axes, only the longitudinal (x-axis) vehicle accelerations were analyzed. All tests were collinear bumper-to-bumper impacts, so off-axis accelerations were negligible. Because all of the vehicles rolled freely, tire forces were also negligible. Bumper force was calculated by multiplying the mass of each vehicle by its acceleration and averaging the results for the two vehicles. Velocity and displacement time histories for each vehicle were generated by integrating and double integrating, respectively, the acceleration traces. The combined crush between the vehicles was calculated by subtracting the target vehicle displacement from the bullet vehicle displacement. Restitution (ϵ) was calculated based on the post-impact velocities taken at the time of vehicle separation:

$$\epsilon = \frac{V'_t - V'_b}{V_b - V_t} \quad (1)$$

where V' indicates a post-impact velocity, V indicates a pre-impact velocity, the b subscript denotes the bullet vehicle, and the t subscript denotes the target vehicle. Because it was difficult to determine precisely when the vehicles separated using either the crash test video or the accelerometer data, the time of vehicle separation was estimated based on the results of the matched quasistatic simulation.

Comparison of Methods

In order to compare the quasistatic bumper test data to the dynamic crash test data, simulations were run to match each of the 12 crash tests in terms of impact speed and vehicle masses. The simulation results, which were based on quasistatic bumper test data, were then compared to vehicle accelerometer measurements taken during the dynamic crash tests using the dynamic crash test data as a reference:

$$e = \frac{X_{crash\ test} - X_{simulation}}{X_{crash\ test}} \quad (2)$$

where X represents any one of following parameters that were compared: peak bullet vehicle acceleration, peak target vehicle acceleration, bullet vehicle velocity change (ΔV), target vehicle ΔV , and peak bumper force.

The overall differences across all of the 12 matched tests was assessed in two ways. First, the average difference was calculated. The average difference provided an estimate of the systematic bias in the quasistatic simulation results relative to the dynamic crash test results. Second, because large overestimations and underestimations can cancel out when calculating the average difference, the root mean square (eRMS) difference was also calculated across all 12 comparisons:

$$e_{RMS} = \sqrt{\sum_{i=1}^{12} e_i^2} \quad (3)$$

The root mean square difference provided an indication of the average absolute magnitude of the difference between the quasistatic simulation results and the dynamic crash test measurements.

In addition, the data from the accelerometers in the bullet and target vehicles were compared against each other. Assuming the vehicles to be rigid bodies with compliant bumper systems, the sensors were theoretically redundant based on Newton's second law. The data from the bullet vehicle accelerometer were compared to the data from the target vehicle accelerometer using the target vehicle accelerometer data as a reference:

$$e_b = \frac{-\frac{m_b}{m_t} X_b - X_t}{X_t} \quad (4a)$$

where the b subscript denotes the bullet vehicle, the t subscript denotes the target vehicle, m is mass, and X is peak vehicle acceleration or calculated velocity change.

Likewise, the target vehicle accelerometer data were compared to the bullet vehicle accelerometer data using the bullet vehicle accelerometer data as a reference:

$$e_t = \frac{-\frac{m_t}{m_b} X_t - X_b}{X_b} \quad (4b)$$

The average and root mean square differences of the vehicle accelerometers relative to each other were calculated and compared to the differences in the quasistatic data simulations relative to the dynamic crash test results.

RESULTS

In most cases, the quasistatic bumper testing accurately captured the mechanical response of the bumper systems during a full vehicle dynamic crash test (Tables 3, 4, 5, and 6). Not only did the quasistatic bumper data accurately predict the peak vehicle accelerations measured by the crash test accelerometers, the simulations accurately predicted the shapes of the acceleration and velocity time histories, as well (Appendix IV). In two cases (S3Db and S4Da), the simulations predicted a sudden drop in bumper force that did not actually occur. This discontinuity in the acceleration traces was an artifact of the method by which the unloading curves were calculated for the simulation (Appendix I). Because the bumpers were not unloaded until after failure had occurred in the quasistatic bumper tests 3Q and 4Q, these tests did not provide enough continuous unloading data for the simulations to use.

Table 4. Summary of vehicle accelerations in the dynamic crash tests.

ID	Peak bumper force (lbs)	Peak bullet acceleration (g)	Peak target acceleration (g)
1Da	3130	-0.5	0.8
1Db	11642	-2.1	3.1
2Da	7744	-2.0	1.7
2Db	7380	-1.8	1.9
3Da	7138	-1.7	1.3
3Db	6841	-1.7	1.2
4Da	6462	-2.6	1.4
4Db	9856	-3.3	2.2
5D	12261	-3.4	3.9
6Da	13141	-3.4	2.5
6Db	16656	-4.5	2.8
7D	17566	-3.7	5.1

Table 5. Summary of vehicle velocities and bumper force predicted by the simulations using the quasistatic bumper data. The "S" in the test ID indicates the results are for a simulation of a particular dynamic crash test. Impact velocities in the simulations were matched to the dynamic crash tests (see Table 3).

ID	Peak bumper force (lbs)	Bullet vehicle ΔV (mph)	Target vehicle ΔV (mph)	Restitution
S1Da	3442	-1.2	1.8	0.55
S1Db	12267	-2.9	4.3	0.45
S2Da	6967	-2.7	2.7	0.51
S2Db	6967	-2.7	2.7	0.51
S3Da	5706	-2.9	2.5	0.23
S3Db	5707	-2.6	2.3	0.26
S4Da	10171	-3.5	2.0	0.32
S4Db	10260	-5.6	3.3	0.17
S5D	12749	-5.7	5.7	0.48
S6Da	20033	-6.8	4.7	0.41
S6Db	20262	-6.9	4.7	0.40
S7D	13776	-5.7	7.9	0.34

Table 6. Summary of vehicle accelerations and pulse times predicted by the simulations using the quasistatic bumper data. The "S" in the test ID indicates the results are for a simulation of a particular dynamic crash test. Impact velocities in the simulations were matched to the dynamic crash tests (see Table 3).

ID	Peak bullet acceleration (g)	Peak target acceleration (g)	Time to peak crush (s)	Pulse time (s)
S1Da	-0.6	0.9	0.136	0.250
S1Db	-2.1	3.1	0.107	0.174
S2Da	-1.7	1.7	0.093	0.140
S2Db	-1.7	1.7	0.093	0.140
S3Da	-1.2	1.0	0.146	0.261
S3Db	-1.2	1.0	0.098	0.210
S4Da	-3.4	2.0	0.081	0.189
S4Db	-3.4	2.0	0.160	0.273
S5D	-3.7	3.7	0.079	0.169
S6Da	-5.0	3.5	0.082	0.144
S6Db	-5.1	3.5	0.081	0.144
S7D	-2.9	4.0	0.102	0.206

In cases where the vehicle damage was similar in the quasistatic bumper tests and the dynamic crash tests, the mechanical response of the bumper systems was also similar.

Several of the cases studied demonstrated good matches in terms of both vehicle damage and mechanical response. In case 1, the real world accident vehicles and the quasistatically and dynamically tested vehicles all showed similar evidence of license plate stamping on the rear bumper of the Dodge Caravan, buckling of the outer portions of the lower chrome member of the Dodge Ram's front bumper, and rearward rotation of the top of the front license plate holder (Appendix V). Correspondingly, the vehicle accelerations and velocity changes predicted by the simulations based on the quasistatic data matched the crash test accelerometer data very well (Figures A4.1 and A4.2). In case 2, similar small stampings on the front bumper of the Ford Edge from the trailer hitch receiver of the Dodge Nitro were observed in all tested vehicles and the real world accident vehicles, and the mechanical response of the vehicles was nearly the same whether they were tested quasistatically or dynamically (Figures A4.3 and A4.4). In case 3, the trailer hitch buckled the lower portion of the chrome front bumper of the Ford F-150 in both the tested and the accident vehicles. However, due to some noise in the crash test accelerometer data and the artifact in the simulation of the rebound phase, there were greater differences in the quasistatic and dynamic test responses compared to other tests (Figures A4.5 and A4.6). In test 5, it was not possible to demonstrate a good match between the quasistatic bumper testing, the dynamic crash testing, and the real world accident vehicles in terms of vehicle damage because the quasistatic bumper testing was conducted without the plastic bumper covers and because the available photographs of the real world accident vehicles did not show much damage. Nevertheless, there was excellent agreement between the quasistatic and dynamic tests in terms of the mechanical response of the bumper systems (Figure A4.9).

In two of the dynamic crash tests (4Db and 7D), the damage extended beyond the bumper systems in one of the vehicles. In test 4Db, the front bumper reinforcement bar of the Pontiac Vibe buckled due to trailer hitch loading and made contact with the center of the radiator, which was initially 6 inches rearward of the bumper bar (Figure A3.20). The mechanical response of the vehicles in the dynamic crash was identical to the quasistatic bumper test for the first 6 inches crush, and then a stiffer response was observed in the dynamic crash test data compared to the quasistatic bumper test data at precisely that point because there was no radiator for the bumper to contact in the quasistatic test (Figure 3). Likewise, in test 7D, the right side of the rear bumper reinforcement bar crushed the rear body panel in the dynamic crash test (Figure A3.32), but not in the quasistatic bumper test. As a result, the bumper system response was stiffer in the full-vehicle crash test than the isolated bumper tests (Figure A4.12).

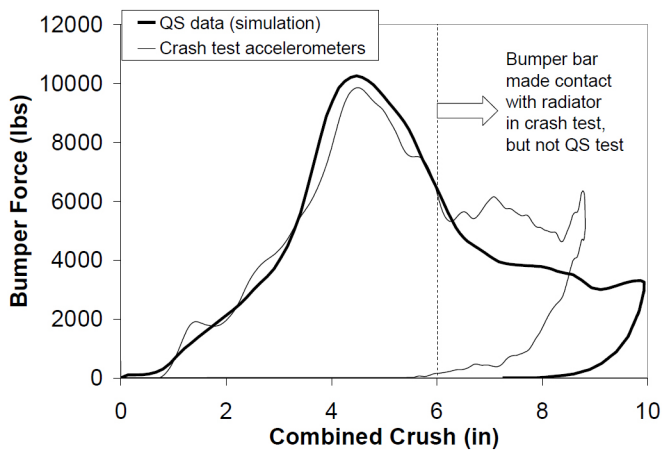


Figure 3. The force-displacement behavior of the bumper was nearly identical for the first 6 inches of crush in test 4Db, at which point the front bumper bar of the 2009 Pontiac Vibe contacted the radiator in the crash test, but not in the quasistatic test.

In case 6, the damage to the rear bumper and right rear frame horn of the Chevrolet Express van created during the quasistatic bumper testing was a good match to the accident vehicle (Figures A5.25 and A5.26). However, in the first dynamic crash test (6Da), the front bumper of the Taurus failed to engage the right rear frame horn. The resulting damage pattern was dissimilar to the quasistatic bumper test and a much softer bumper system response was measured (6Da compared to 6Q) (Figure A4.10). For the second crash test (6Db), the front bumper of the Ford Taurus was raised 1 inch to increase the engagement between the bumper systems, and the test was repeated. The resulting damage to the right rear frame horn of the Express van was greater than test 6Da, but still less than the damage that was observed on the accident vehicle and in the quasistatic test (Figures A5.25, A5.26, A5.27). The bumper response in this second crash test (6Db) was closer to the quasistatic response (6Q) than the first crash test (6Da), but still somewhat softer (Figure A4.11).

Across all 12 dynamic crash tests, the simulation predictions based on the quasistatic bumper test data correlated extremely well with the crash test accelerometer measurements in terms of both peak vehicle acceleration (Figure 4) and vehicle velocity change (Figure 5). The average difference in the peak bumper forces, peak vehicle accelerations, and vehicle velocity changes predicted by the simulations using the quasistatic bumper test data compared measurements from the crash test accelerometers were very low ($\leq 5\%$) (Figure 6). Average differences were also very low ($\leq 4\%$) when comparing one crash test accelerometer against another. These results changed very little if the results from cases 6 and 7 were excluded from the analysis on the basis that the vehicle damage was not confined to the bumper systems in those tests.

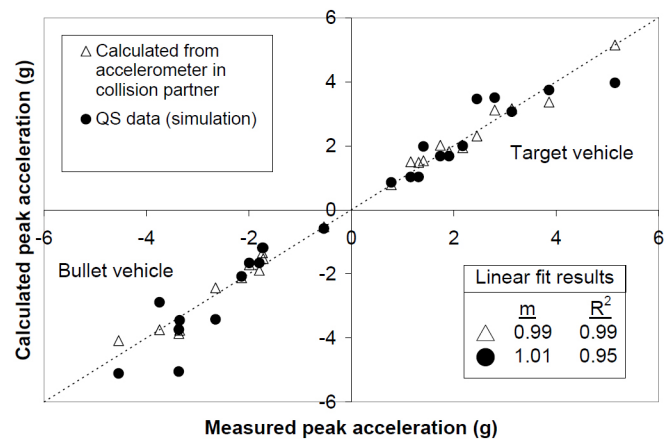


Figure 4. Comparison of calculated vs. measured peak vehicle accelerations for all 12 dynamic crash tests.

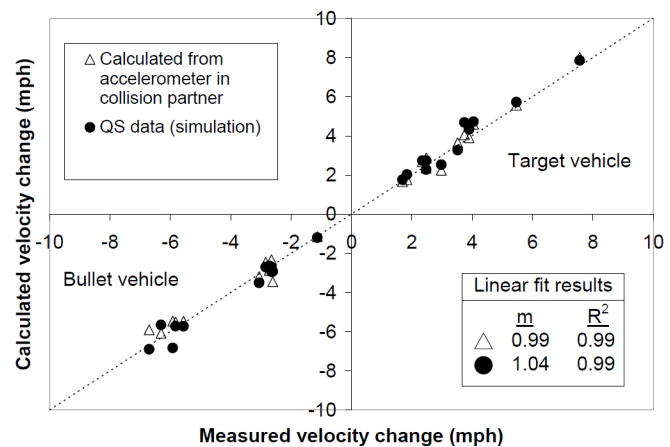


Figure 5. Comparison of calculated vs. measured vehicle velocity changes for all 12 dynamic crash tests.

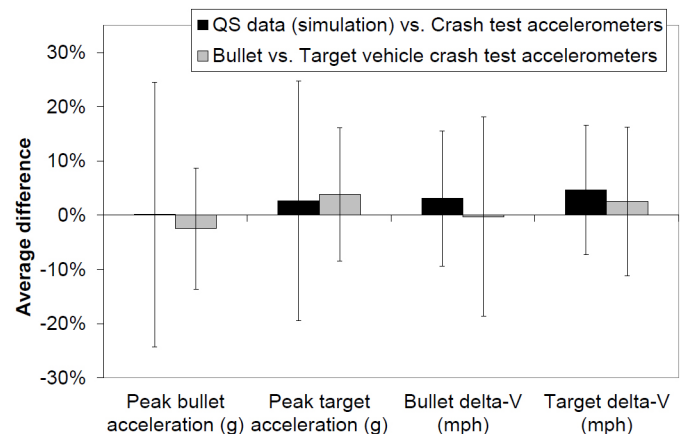


Figure 6. Average differences (± 1 SD) among all 12 dynamic crash tests in various parameters for the simulation results and the crash test accelerometers.

The root mean square differences were considerably higher than the average differences. When comparing the quasistatic data-based simulations to crash test vehicle accelerometer

measurements, the root mean square differences were 21% - 23% when predicting peak vehicle accelerations and 12% when predicting vehicle velocity changes. If the results from cases 6 and 7 were excluded from the analysis, these RMS errors were reduced to 14% - 17% when predicting peak vehicle accelerations and 9% - 11% when predicting vehicle velocity changes. When comparing one crash test accelerometer against another, root mean square differences were 11% - 12% when measuring peak vehicle accelerations and 13% - 18% when measuring vehicle velocity changes (Figure 7).

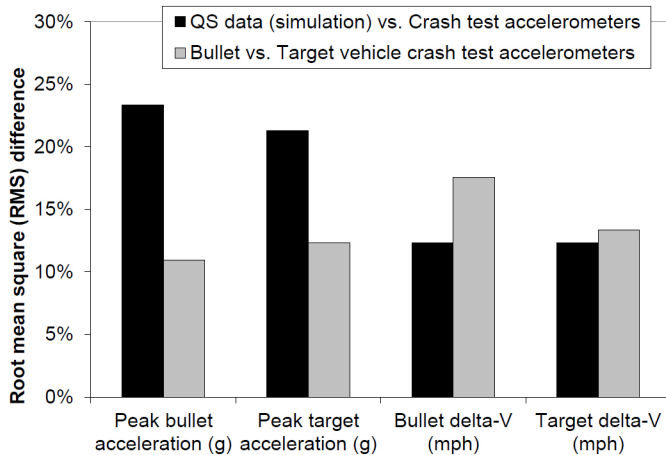


Figure 7. Root mean square differences among all 12 dynamic crash tests in various parameters for the simulation results and the crash test accelerometers.

The restitution coefficients predicted by the simulations did not correlate well with calculations made from the crash test accelerometer data (Figure 8). On average, the simulations based on quasistatic bumper test data overestimated the restitution coefficient by $18\% \pm 44\%$ compared to the coefficient of restitution calculated from the crash test accelerometers. The RMS difference in the coefficient of restitution was 46% when comparing the quasistatic and dynamic data. However, the RMS difference in the calculated restitution coefficient was 87% when comparing the bullet and target vehicle crash test accelerometers against each other (this RMS difference dropped to 33% if one outlying data point was excluded). Nevertheless, the restitution coefficients measured in both the quasistatic bumper testing and the dynamic crash testing appeared to be reasonable when compared to the results of previous studies (Figure 9). Cases 3 and 4, which both involved a trailer hitch focally loading and failing the middle of a front bumper, were associated with lower restitution values (0.28 ± 0.12) than the tests that did not involve a trailer hitch (0.41 ± 0.14). The difference was marginally significant ($p = 0.06$).

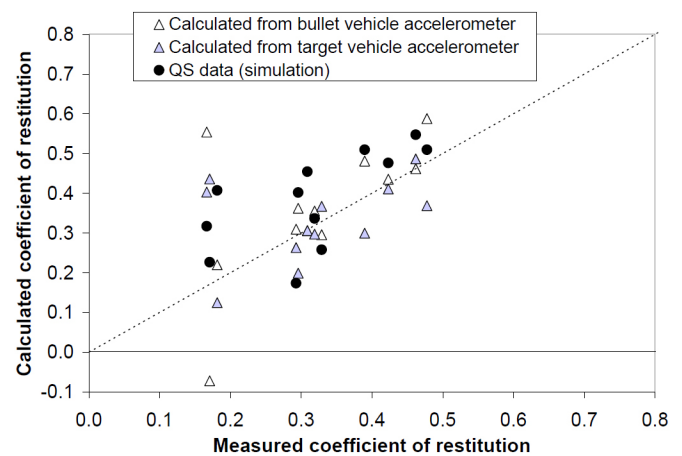


Figure 8. Comparison of calculated vs. measured restitution coefficients for all 12 dynamic crash tests.

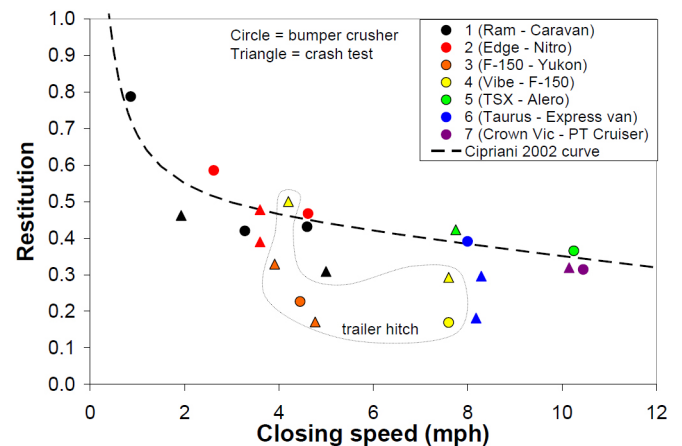


Figure 9. Comparison of calculated vs. measured restitution coefficients for all 12 dynamic crash tests. The curve from Cipriani et al. [4] characterized foam core-to-foam core bumper systems.

DISCUSSION

The current study provides an extensive validation of quasistatic bumper testing as a method for reconstructing low speed impacts. A total of 22 tests involving 7 vehicle pairs were conducted for this research, including 10 quasistatic bumper tests and 12 full vehicle dynamic crash tests. The test matrix included vehicles from a wide range of classes, including small to full-sized passenger cars, pickup trucks, sport utility vehicles, minivans, and full-sized vans (Table 1). Most of the vehicles were manufactured in the 2000s. This study investigated impact speeds ranging from 2 - 10 mph, which led to vehicle velocity changes of 1 - 8 mph and peak vehicle accelerations of 1 - 5 g. This study was designed to provide a direct comparison between the collision parameters that would be derived from quasistatic bumper testing versus dynamic full vehicle crash testing. The evaluation focused on peak vehicle accelerations and vehicle velocity changes, because these parameters are most commonly used to assess the potential for injury in a crash.

There are several differences between quasistatic bumper testing and dynamic full vehicle crash testing that are potential sources of error. First, the bumper systems were loaded slowly in the quasistatic tests and rapidly in the crash tests. However, since all of the bumper systems that were tested involved solid metal, plastic, and foam components (no piston isolators), no rate dependence was expected, and none was observed. Second, the bumper systems were mounted to rigid plates in all of the quasistatic tests and two of the dynamic tests (2Da and 2Db), whereas the bumpers were integrally attached to full vehicles in the rest of the dynamic tests. It was hypothesized that the body of the vehicle could provide some resistance or compliance that would not be captured in a test involving only the bumper systems. In fact, this issue did create error in two cases (S4Db and S7D), but the errors were relatively small. We would not normally use the quasistatic bumper test methodology to reconstruct crashes 4Db and 7D, because the damage extended beyond the bumper systems. These cases were included in the analysis to help define the useful limits of the quasistatic bumper testing methodology. Third, the bumpers were rigidly constrained in the vertical direction in the quasistatic tests but only inertially constrained in the vertical direction in the dynamic crash tests. We hypothesize that the looser vertical constraint in the dynamic crash test allowed the front bumper of the Ford Taurus to move downward relative to the rear bumper of the Chevrolet Express van in test 6Da (and possibly 6Db to some extent), thus avoiding the desired engagement with the rear frame horn. In this case, the quasistatic bumper test (6Q) accurately reproduced the vehicle damage from a real world accident, but the dynamic crash tests (6Da and 6Db) did not (Figures A.4.25 - A.4.27).

In spite of all these concerns, however, the quasistatic bumper test data proved to be similar to the dynamic full vehicle crash test data when similar patterns of damage were produced in the quasistatic and dynamic tests. Importantly, there was no systematic bias in the quasistatic bumper test method, and the scatter error was within the range of other techniques that are commonly accepted in accident reconstruction and other fields. Very large percentage errors were found with respect to the calculation of restitution. However, these errors are inconsequential, because restitution is only important for calculating delta-V, and the delta-V calculations were found to be quite accurate in spite of the restitution error.

It is important to remember that perfect agreement between the two methodologies was not expected. Vehicle accelerometers in dynamic crash tests are sensitive to localized vibration of the structure to which they are mounted, whereas quasistatic bumper testing measures the compliance of the bumper systems without any superimposed vibration. These phenomena were evident in several tests in which the crash test accelerometer data followed the general shape of the response predicted from the quasistatic data, but with superimposed higher frequency vibration (Appendix IV). This is the reason that better agreement between the quasistatic and dynamic data was observed with respect to vehicle velocity changes than peak accelerations. Calculating velocity change

involves integration, which effectively filters out the higher frequency vibrations in the dynamic crash test accelerometer data, thereby rendering it more similar to the quasistatic bumper test data.

Perhaps the most important result of this study pertains to relationship between vehicle damage and mechanical response of the bumper systems. We found that if the vehicle damage generated in the quasistatic bumper test replicated the vehicle damage produced in the corresponding full vehicle dynamic crash test in terms of the location and extent of deformation, then the measured mechanical response of the bumper systems was replicated, as well. Therefore, we conclude that quasistatic bumper testing is a reliable method for reconstructing low speed collisions, provided that the test accurately reproduces the vehicle damage that occurred in the real world collision. All of the cases examined here involved front-to-rear collisions. However, the methodology would presumably be just as accurate in other situations, such as low speed front-to-front, rear-to-rear, or bumper-to-fixed object impacts.

Lastly, we note that the analysis presented in this paper and the paper by Scott et al. [9] includes every test involving a vehicle pair in which matched quasistatic bumper testing and dynamic crash testing has been conducted by our company. We have not chosen to present only tests with good results; every test has been included.

CONCLUSIONS

Quasistatic bumper testing is an effective tool for reconstructing low speed collisions because it replicates the results of dynamic full vehicle crash testing with good accuracy. In this series of matched quasistatic and dynamic testing, the average difference in the peak vehicle accelerations and velocity changes obtained by the two methods was less than 5%. The mechanical response of the bumper systems in this study was not affected by loading rate or attachment to a full vehicle. The closeness of the match in the mechanical response between quasistatic and dynamic tests was related to the closeness of the match in the vehicle damage. Based on these observations, we conclude that testing that accurately replicates the damage to the vehicles involved in a collision, whether it be quasistatic bumper testing or full vehicle dynamic crash testing, will also accurately replicate the mechanical response of the accident vehicles and should be considered reliable for crash reconstruction purposes.

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APPENDIX

APPENDIX I - CRASH SIMULATION USING QUASISTATIC BUMPER TEST DATA

The crash simulation process will be illustrated graphically using the quasistatic bumper testing data from case 1 as an example. In this case, three separate quasistatic bumper tests were conducted to progressively increasing levels of crush (Figure A1.1). Because the bumpers were not repaired between tests, the displacement at which contact initiated progressively increased. A composite force-displacement response curve was constructed by taking the maximum value from all of the loading curves and the minimum value from all of the unloading curves at each displacement value. The composite curve was essentially an envelope of the test data.

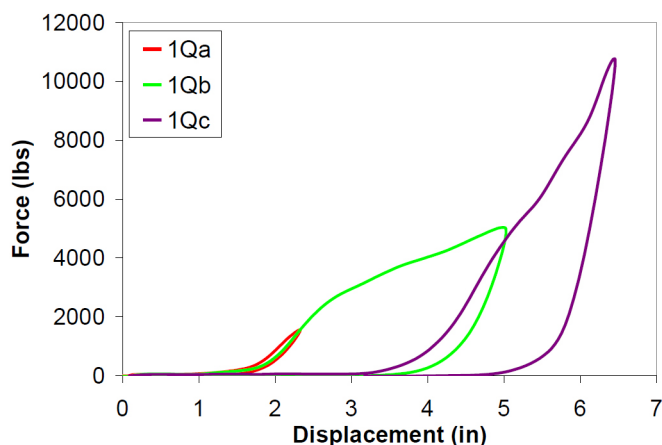


Figure A1.1. Raw data from the three quasistatic bumper tests performed for case 1. The envelope of the test data (not shown separately) comprised the composite force-displacement curve for this vehicle pair. It is shown as a dotted black line overlaid by a red line in Fig. A1.2.

To understand the procedure, it is helpful to observe the results of simulations conducted at progressively higher impact speeds. For example, at a simulated impact speed of 1 mph, the procedure predicted that maximum engagement between the vehicles would occur at a peak bumper force of 1970 pounds and a combined crush of 2.5 inches (Figure A1.2). This simulation went on to predict a high restitution value of 0.77 based on the rebound behavior of the bumper system below 1970 pounds during the third quasistatic test (1Qc) (black arrow in Figure A1.2). Simulations of progressively higher impact speeds resulted in predictions of progressively higher peak bumper forces and combined crush values, as well as higher predicted vehicle accelerations and shorter crash pulses in the time domain (Figure A1.3). At an impact speed of 4.6 mph, the simulated force-displacement response (red curve in Figure A1.2) overlaid the envelope of the measured force-displacement responses from the three quasistatic bumper tests and matched the peak force and combined crush from test 1Qc. Therefore, 4.6 mph was considered the equivalent impact speed for test 1Qc.

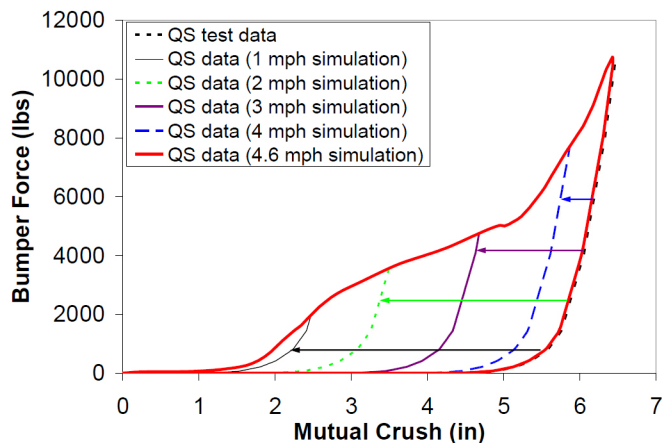


Figure A1.2. Simulations assuming various impact speeds based on the composite quasistatic bumper force-displacement curve for case 1.

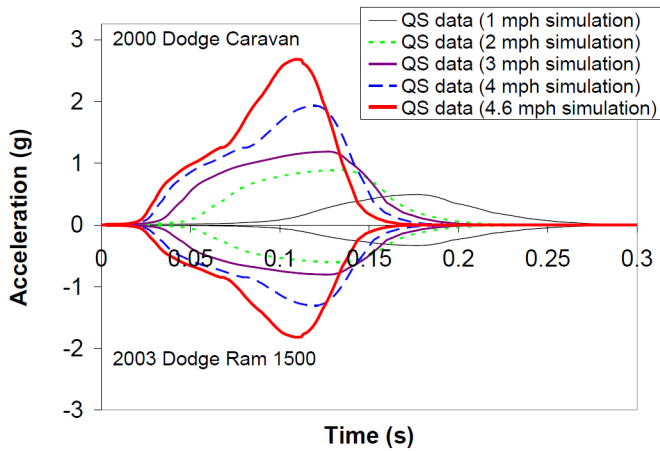


Figure A1.3. Simulated vehicle acceleration time based on the composite quasistatic bumper force-displacement curve for case 1.

Equivalent impact speeds were iteratively determined in this manner for each of the 10 quasistatic bumper tests (Table 2). In all cases but one, the equivalent impact speeds from the quasistatic bumper test data were greater than actual impact speeds used in the corresponding dynamic crash tests. This means that the simulations in these cases did not utilize the full range of quasistatic data obtained, and the damage energy predicted in the simulations was less than the damage energy imparted to the bumpers in the quasistatic testing. In case 1Db, the situation was reversed. The impact velocity in the crash test was slightly higher than the equivalent impact speed of the corresponding quasistatic bumper testing. In this instance, the quasistatic bumper data was extrapolated to an additional ½" of combined crush in order to complete the simulation.

In order to test whether the simulation procedure accurately modeled the unloading response of the vehicles, the measured restitution of the bumper systems was compared to the predicted restitution in the two cases (1 and 2) in which repeated quasistatic bumper testing was conducted. For all 10 quasistatic bumper tests, the measured restitution (ϵ) of the bumper systems was calculated using the standard equation:

$$\epsilon = \sqrt{\frac{E_{\text{unloading}}}{E_{\text{loading}}}} \quad (\text{A1.1})$$

where E_{loading} was the energy absorbed during loading and $E_{\text{unloading}}$ was the energy returned during unloading, both of which were calculated as the area under the respective force-displacement curves.

In cases 1 and 2, the restitution of the bumper systems was predicted using the simulation procedure over a range of impact velocities in 0.1 mph increments using the composite force-deflection curve obtained from the repeated tests. For these cases, the restitution values predicted by the simulations using the unloading data from the higher severity quasistatic testing closely matched the restitution values measured in the lower severity quasistatic testing (Figure A1.4). Therefore, it was concluded that the unloading response of the bumper systems during rebound remained the same over the range of severities tested.

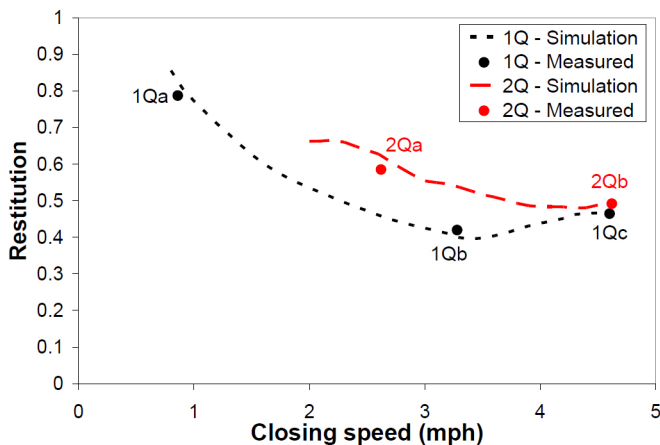


Figure A1.4. Comparison of restitution values measured in repeated quasistatic bumper tests to simulation results.

APPENDIX II - PHOTOGRAPHS OF QUASISTATIC BUMPER TESTING

Test 1Qa

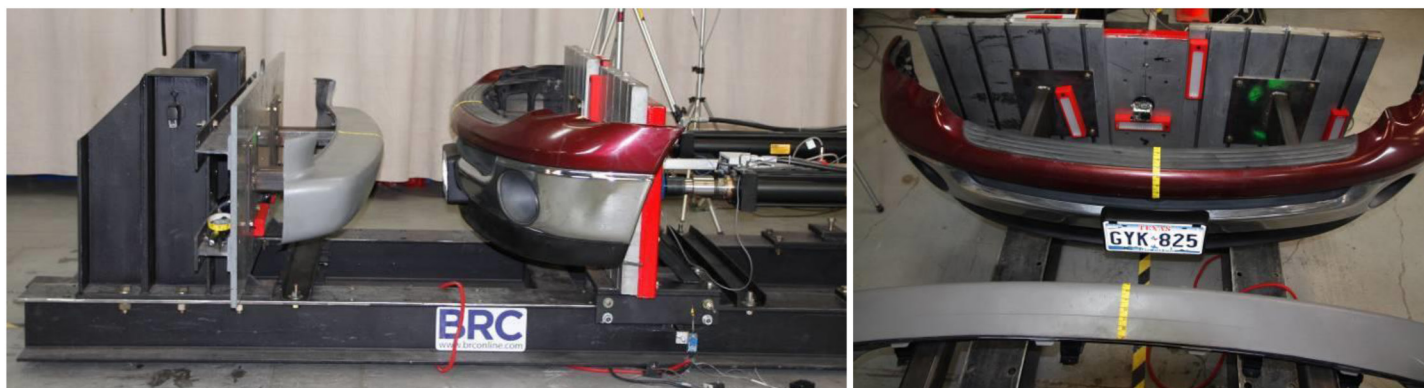


Figure A2.2. Photographs of the test setup for test 1Qa.



Figure A2.2. Photographs of damage to the front bumper of the Dodge Ram 1500 after test 1Qa.



Figure A2.3. Photographs of damage to the rear bumper of Dodge Caravan after test 1Qa.

Test 1Qb

Figure A2.4. Photographs of damage to the front bumper of the Dodge Ram 1500 after test 1Qb.

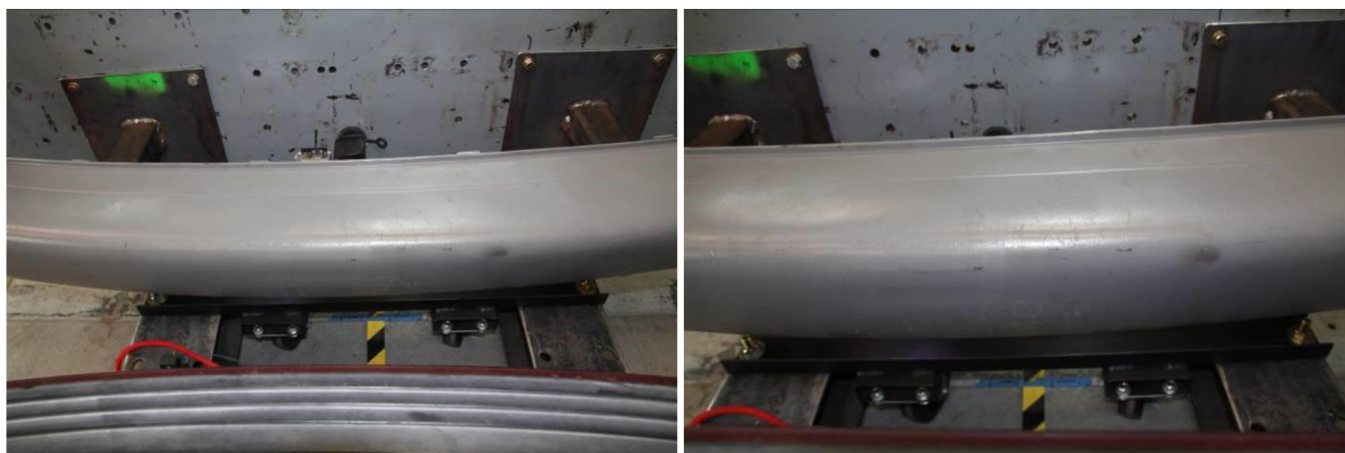


Figure A2.5. Photographs of damage to the rear bumper of Dodge Caravan after test 1Qb.

Test 1Qc

Figure A2.6. Photographs of damage to the front bumper of the Dodge Ram 1500 after test 1Qc.



Figure A2.7. Photographs of damage to the rear bumper of Dodge Caravan after test 1Qc.

Test 2Qa



Figure A2.8. Photographs of the test setup for test 2Qa.



Figure A2.9. Photographs of damage to the front bumper of the Ford Edge after test 2Qa.



Figure A2.10. Photographs of the undamaged trailer hitch receiver on the rear bumper of the Dodge Nitro after test 2Qa.