SAE TECHNICAL PAPER SERIES

2001-01-0168

Rear-End Impact Testing with Human Test Subjects

Thomas A. Braun, Janet H. Jhoun, Michael J. Braun, Brad M. Wong, Thomas A. Boster, Ted M. Kobayashi, Frank A. Perez and Gary M. Hesler
Boster, Kobayashi & Associates

Reprinted From: Side Impact, Rear Impact, and Rollover (SP–1616)

The Engineering Society For Advancing Mobility Land Sea Air and Space®
INTERNATIONAL

SAE 2001 World Congress
Detroit, Michigan
March 5-8, 2001

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-5760

ISSN 0148-7191

Printed in USA

2001-01-0168

Rear-End Impact Testing with Human Test Subjects

Thomas A. Braun, Janet H. Jhoun, Michael J. Braun, Brad M. Wong, Thomas A. Boster, Ted M. Kobayashi, Frank A. Perez and Gary M. Hesler
Boster, Kobayashi & Associates

ABSTRACT

Low speed rear-end aligned bumper-to-bumper impact tests were conducted. Bullet vehicle impact speeds ranged from 3.2 – 10.5 kph (2.0 – 6.5 mph) and produced target vehicle changes in velocity ranging from 2.4 – 7.2 kph (1.5 – 4.5 mph). Seven human volunteers participated in the testing. The volunteer group included both male and female subjects ranging in age from 29 to 61 years. All participants were considered to be in good health prior to the start of the testing. Two test subjects were seated in the target vehicle and one subject drove the bullet vehicle for each of the seven tests. Occupant kinematic response was monitored via videotape and test subjects were interviewed immediately post-impact to record subjective impressions. The majority of the participants experienced no symptoms or injury as a result of this testing. Three of the participants that had multiple exposures had minor neck stiffness, but not pain, that resolved without treatment in one day. The vehicle restitution response was analyzed. The results indicate a coefficient of restitution in the range of 0.3 to 0.5 for the range of impact speeds and vehicles tested. The duration of impact was found to be in the range 0.090 – 0.124 seconds.

INTRODUCTION

Accident reconstructionists and biomechanical or biomedical engineers are frequently called upon to analyze low speed rear-end automobile impacts and assess the potential for an injury to have occurred to the occupants of the vehicle. The key issues in these types of accidents are typically the speeds and forces involved in the impact, and whether or not these speeds and forces were sufficient to cause injury. Several studies done in the 1990's have attempted to address these issues[1-8]. The database of human exposures and our understanding of human tolerance to rear-end impacts continues to grow as additional work is published. Our testing is intended to add to the growing body of research related to occupant kinematic response to low speed rear-end impacts and to further quantify the vehicle dynamic response that would be typical of the bumper systems in use on modern passenger cars.

Our first objective was to add to the human exposure database by testing human volunteers in low speed rear-end impacts at a level that was at or below the level currently associated with no significant risk of injury. It was not our intent to reach or exceed an injury threshold. From a review of the literature and human exposure database, it appears that for a normally seated healthy adult occupant with adequate head support, exposure to a change in speed of 8 kph (5.0 mph) or less does not expose the occupant to any significant risk of injury. Thus, our testing was intended to include impacts approaching but not exceeding a change in speed of 8 kph (5.0 mph) to the target vehicle.

Our second objective was to subjectively describe and characterize the severity of the impact that was experienced by the occupants. That is, in addition to being able to characterize an impact in terms of change in speed or average or peak acceleration, we were interested in determining whether or not the volunteer's subjective impressions of the forces experienced in certain low speed rear-end impacts may be appropriately compared to human head accelerations that are experienced in certain daily activities. One study published in 1994 measured human head accelerations during daily activities that included activities like sitting down in a chair, hopping off a step, and plopping backwards into a chair[9]. These types of activities are sometimes used by accident reconstructionists to describe and characterize the severity of a low speed rear-end vehicular impact. This may or may not be appropriate, of course, depending on the peak head accelerations experienced.

Our third objective was to evaluate the vehicle dynamic response to low speed rear-end impacts. We were specifically interested in determining average and peak vehicle accelerations, coefficients of restitution, and duration of impacts. In addition, we were interested in examining what correlation, if any, exists between target vehicle forward displacement and change in speed when the target vehicle is stopped and the driver has a foot resting on the brake pedal at impact.

METHODOLOGY

Seven vehicle-to-vehicle rear-end impact tests were conducted at impact speeds ranging from 3.2 – 10.5 kph (2.0 – 6.5 mph). Given the relative weights of the two test vehicles, this range of impact speeds was expected to produce impacts of a severity that would not produce damage to either test vehicle and more importantly not expose the human test subjects to any significant risk of injury. The target vehicle, a 1982 Toyota Celica, was stationary prior to impact with the engine running and the vehicle transmission in neutral. One human test subject was seated in each of the target vehicle's front bucket seats for each test. The test subject in the driver's seat was instructed to apply light pressure to the brake pedal as if sitting at a normal stop for a stop sign or stop light.

The rear bumper of the target vehicle was struck by the front bumper of the bullet vehicle, a 1984 Ford Mustang. The bullet vehicle was operated by a third test subject seated in the driver's seat. This subject was instructed to release the brake on the bullet vehicle and allow the bullet vehicle to roll forward with the transmission in drive at engine idle speed over a pre-determined distance to the point of impact. An approximate impact speed for each test had been established by determining ahead of time bullet vehicle speed as a function of roll distance over the level surface upon which the tests were to be conducted. Each impact was an aligned, bumper-to-bumper rear-end impact. There was no offset or underride between target and bullet vehicle bumpers.

VEHICLES

The target vehicle was a 1982 Toyota Celica GT two-door hatchback. This vehicle has a foam core rear bumper consisting of an energy absorbing foam core sandwiched between an outer plastic cover and a metal reinforcement bar that is mounted to the body of the vehicle. Prior to the start of the testing, the bumper was partially disassembled and examined to determine the condition of the foam core and metal reinforcement bar. These components were found to be in good condition without evidence of damage prior to the start of the test. The driver's side door was removed prior to the start of the testing to allow observation and videotaping of the human test subject seated in the driver's seat. This vehicle was weighed and found to weigh approximately 1179 kg (2600 lb). The two front bucket seats were each equipped with an adjustable head restraint. A three-point lap/shoulder seatbelt was available for both seating positions.

The bullet vehicle was a 1984 Ford Mustang two-door hatchback. This vehicle has a front bumper that is mounted to the vehicle with two isolators. An isolator is a piston and cylinder assembly that will typically compress to absorb energy during an impact and then rebound back to its original position. The isolators were inspected prior to the start of the testing and appeared to be in good condition. The exposed piston tube length on these particular isolators was measured and found to be 67 mm (2.625 in.). Prior to each test, a pipe cleaner was carefully positioned around each piston tube and up against the frame bracket so that any compression that occurred during the test could be measured and recorded.

The same two vehicles were used repeatedly for all seven tests without repair or modification between tests.

TEST EQUIPMENT

Vehicle acceleration data was captured using two Instrumented Sensor Technology (IST) Model EDR-3 tri-axial accelerometers. One EDR-3 was mounted in each vehicle at approximately the vehicle's center of gravity. The EDR-3 contains a microprocessor-based data acquisition system. The microprocessor is interfaced to a 10-bit analog-to-digital converter (ADC). Sampling frequency was set to 500 Hz. The EDR-3 has an internal low-pass filter (anti-aliasing) with a 3 dB cut-off of 110 Hz. The software program DynaMax was used to analyze and plot the recorded data. The acceleration-time history of the event was used to determine vehicle change in velocity (delta-V), vehicle peak and average accelerations, and duration of impact for each test.

The bullet vehicle's speed at impact was determined in two ways. First, a Stalker Radar Gun Model ATR was positioned behind and in line with the bullet vehicle to monitor the vehicle's speed up to impact. This gun is equipped with an automatic highest speed lock feature, which was used to hold the highest recorded speed during each test. The gun also displays continuously in one-tenth mph resolution and updates about 30 times a second. Speed range is 1 to 480 kph (1 to 300 mph with an accuracy of +/- 0.1 mph). Second, speed at impact was determined by analysis of videotape taken during each test. One of the video cameras used during this testing was positioned to record a reference marker mounted to the passenger side of the bullet vehicle as it passed by reference markers positioned on the ground at known intervals. Frame-by-frame review of the videotape, taken at 30 frames per second, allowed calculation of velocity by knowing how many frames of video (and thus how much time) was required for the bullet car to travel a known distance between two markers.

Four video cameras were used to record the events. These included a Panasonic PV-42 (VHS-C format), a Canon ES-80 (8 mm format), and two Sony CCD-TR700's (Hi-8 format). One video camera was positioned to observe the driver in the target vehicle. A second was used to record a side view of the vehicle-to-vehicle impact as well as to determine the bullet vehicle speed at impact. A third was used to record the radar gun readings. The fourth was used to capture an overall view of the test.

OCCUPANTS

Seven test subjects volunteered to participate in this series of tests. They included six males and one female, ranging in age from 29 to 61 years. All test subjects were considered to be in good health prior to the start of the testing. Table 1 lists the sex, age, height and weight for each test subject. All test subjects used the available seatbelt and were considered to have adequate head support. The test subjects were instructed to relax and maintain a normally seated, relaxed position prior to impact. Some test subjects participated in multiple tests.

Test subjects A and B each experienced 4 impacts of increasing severity.

The seating arrangements for each test are shown in Table 2. Test subject C operated the bullet vehicle for every test except test #4. Test subject E operated the bullet vehicle for test #4.

Subject	Sex	Age	Height (m)	Weight (kg)
A	M	34	1.88	90.7
B	M	32	1.91	96.2
C	M	29	1.70	77.1
D	M	56	1.70	74.8
E	M	40	1.70	70.3
F	F	31	1.65	61.2
G	M	61	1.85	88.5

Table 1. Test Subject Characteristics

Test #	Target Vehicle Driver Seat	Target Vehicle Passenger Seat
1	A	B
2	A	B
3	A	B
4	C	D
5	E	F
6	G	A
7	B	F

Table 2. Test Subject Seating Positions

RESULTS

The bullet vehicle impact speed and the bullet and target vehicle changes in velocity (delta-V) for each test are shown in Table 3. Bullet vehicle impact speed shown in Table 3 is based on an analysis of the videotape of each test. Change in velocity data were obtained by analyzing the acceleration history for each event. From these data, the coefficient of restitution was calculated for each impact. This value is easily derived from the known impact speed, change in speed to the target vehicle, and masses of the two vehicles as shown:

$$e = \frac{V_2'(1+\frac{m_2}{m_1})}{V_1} - 1$$

e coefficient of restitution
V_1 bullet vehicle impact speed
V_2' target vehicle post-impact speed
m_1 mass of bullet vehicle
m_2 mass of target vehicle

Coefficient of restitution values ranged from about 0.3 to 0.5 as shown in Table 4 and Figure 1. Impact durations ranged from 0.090 seconds to 0.124 seconds and are also shown in Table 4 and Figure 2. Impact duration was determined by examining the acceleration-time history graph as recorded by the EDR-3 mounted in the target vehicle.

Average and peak vehicle accelerations and target vehicle forward displacement results are shown in Table 5. Average vehicle acceleration was calculated based on the known delta-V and duration of impact. Peak vehicle acceleration was determined by reviewing the acceleration-time history as recorded by the EDR-3. The highest value recorded is reported as the peak regardless of duration. Peak vehicle accelerations were between 1.5 and 2.7 times higher than the average vehicle accelerations.

Test #	Bullet Vehicle Speed (kph)	Bullet Vehicle delta-V (kph)	Target Vehicle delta-V (kph)
1	3.22	2.74	2.41
2	6.12	4.67	4.83
3	8.21	5.95	6.28
4	10.14	7.08	7.24
5	6.11	4.83	4.18
6	10.46	7.24	7.24
7	9.17	6.4	6.60

Table 3. Impact Speed and delta-V Results

Test #	Coefficient of Restitution	Impact Duration (seconds)
1	0.44	.124
2	0.51	.114
3	0.46	.110
4	0.37	.096
5	0.31	.124
6	0.33	.090
7	0.38	.100

Table 4. Coefficient of Restitution and Impact Duration

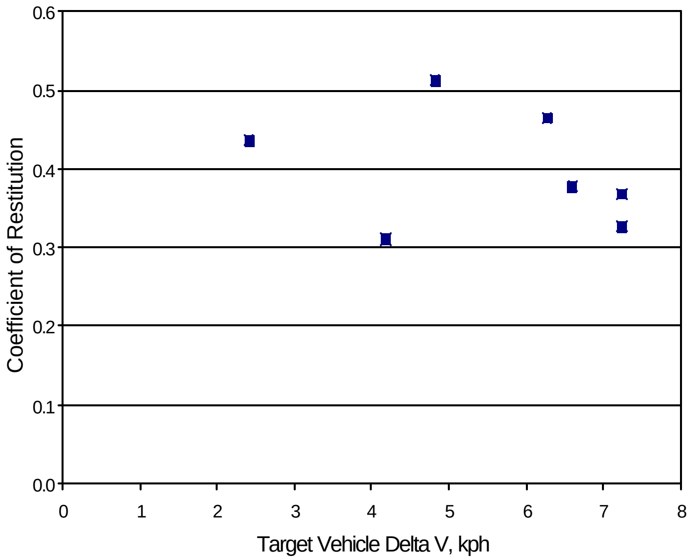

Figure 1. Coefficient of Restitution v. Target Vehicle Delta V, kph

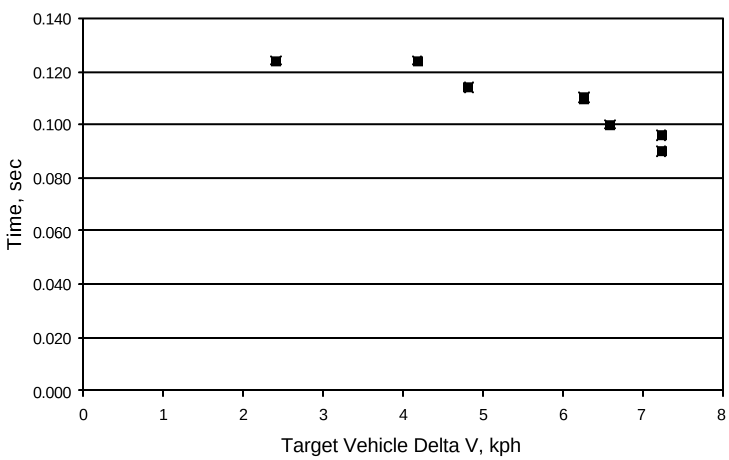

Figure 2. Duration of Impact v. Target Vehicle Delta V, kph

Test #	Average Acceleration (g)	Peak Acceleration (g)	Forward Displacement (m)
1	0.6	0.9	0.254
2	1.2	3.2	0.381
3	1.6	3.8	0.584
4	2.1	4.3	3.66
5	1.0	1.9	.457
6	2.3	4.4	1.09
7	1.9	4.0	2.72

Table 5. Target Vehicle Accelerations and Displacement

DISCUSSION

OCCUPANT RESPONSE

Each test subject underwent similar head/neck motions as a result of this series of impacts. In general, the occupant's torso was first contacted by the advancing seatback as the target vehicle was pushed forward by the impact. The occupant moved rearward relative to the forward moving seat as the torso compressed the seatback. In response, the torso accelerated forward while the head lagged behind. For impacts of sufficient severity, the forward acceleration of the head lagged behind the torso, causing a rearward bending of the neck. Contact with the headrest prevented significant cervical extension in those cases where the impact was severe enough to cause contact with the headrest. This first phase was followed by a rebound phase in which the occupant's head/neck moved forward relative to the vehicle, a result of the elastic energy stored in the compressed seatback during the first phase. This forward motion returned the torso to approximately its original position and caused the head to continue forward a distance dependent on the severity of the rear-end impact. This relative forward movement of the head put the neck in flexion. Finally, the head settled back into approximately the same position as before the impact.

Three of the seven test subjects reported minor neck stiffness the day after the test was conducted. None experienced any actual pain and all had no symptoms two days after the test. These subjects (A, B and F from Table 1) were exposed to multiple impacts of increasing severity over the course of the testing. Test subject A experienced a total of four rear-end impacts ranging in severity from 2.4 – 7.2 kph (1.5 – 4.5 mph) delta-V; test subject B also experienced four rear-end impacts from 2.4 – 6.6 kph (1.5 – 4.1 mph) delta-V; test subject F experienced two impacts with delta-V's of 4.2 and 6.6 kph (2.6 and 4.1 mph). None of the other test subjects experienced any neck symptoms. No medical treatment or medication was required by any of the test subjects.

In test #1, the target vehicle delta-V was 2.4 kph (1.5 mph). This was described by both test subjects as a trivial impact. It was characterized as a light bump with no significant noise or noticeable forward displacement of the vehicle. The target vehicle was pushed forward 25 cm and the bullet and target vehicles were touching at rest. Neither test subject had contact with the head restraint. Neither subject experienced any symptoms of pain or discomfort immediately following this test.

In test #2, the target vehicle sustained a delta-V of 4.8 kph (3.0 mph). This impact was significantly more forceful in nature and was near the limit of what both subjects A and B would associate with head accelerations that might be experienced in daily activities. Test subject A noted contact with the head restraint, but subject B was not sure if his head had contacted the head restraint or not. The target vehicle was pushed forward 38 cm and the bullet and target vehicles were touching at rest. Neither subject experienced any symptoms of pain or discomfort immediately following this test.

In test #3, the target vehicle underwent a delta-V of 6.3 kph (3.9 mph). This impact was quite forceful and generated a significant crashing sound at impact as described by the subjects in the vehicle. Both subjects noted that their heads were displaced rearward into the head restraints with a noticeable impact to the head restraint. Both subjects agreed the severity of this impact exceeded forces or accelerations that they had experienced in daily activities. The target vehicle was pushed forward 58 cm. Neither subject experienced any symptoms of pain or discomfort immediately following this test.

In test #4, the target vehicle sustained a delta-V of 7.2 kph (4.5 mph). This impact also generated a significant crashing sound at impact as described by the subjects in the vehicle. Both subjects noted that their heads were displaced rearward into the head restraints with a noticeable impact to the head restraints. Both subjects agreed the severity of this impact exceeded forces or accelerations that they had experienced in daily activities. The target vehicle rolled forward 366 cm. Test subject C's foot came up off the brake as a result of the impact, and the vehicle rolled forward a considerable distance before the brake was reapplied. Neither subject experienced any symptoms of pain or discomfort immediately following this test.

In test #5, the target vehicle underwent a delta-V of 4.2 kph (2.6 mph). Both subjects noted that their heads were displaced rearward into the head restraints as a result of the impact. The target vehicle rolled forward 46 cm. Neither subject experienced any symptoms of pain or discomfort immediately following this test.

In test #6, the target vehicle sustained a delta-V of 7.2 kph (4.5 mph). This impact was quite forceful in nature and generated a significant crashing sound at impact as described by the subjects in the vehicle. Both subjects noted that their heads were displaced rearward into the head restraints with a noticeable impact to the head restraints. Both subjects agreed the severity of this impact exceeded forces or accelerations that they had experienced in daily activities. The target vehicle was pushed forward 109 cm. Test subject A reported a transient headache immediately following the test which lasted for several minutes and then went away. Test subject B did not experience any symptoms of pain or discomfort immediately following this test.

In test #7, the target vehicle underwent a delta-V of 6.6 kph (4.1 mph). This impact was characterized as quite forceful and generated a significant crashing sound at impact as described by the subjects in the vehicle. Both subjects noted that their heads were displaced rearward into the head restraints with a noticeable impact to the head restraints. Both subjects agreed the severity of this impact exceeded forces or accelerations that they had experienced in daily activities. The target vehicle rolled forward 272 cm. Test subject B's foot came up off the brake as a result of the impact, and the vehicle rolled forward some distance before the brake was reapplied. Neither subject experienced any symptoms of pain or discomfort immediately following this test.

For impacts that produced a delta-V to the target vehicle of 4.8 kph (3.0 mph) or less, the test subjects subjectively agreed that these impacts produced forces on the head, neck, and torso that were within the range of forces that can be experienced in daily activities. To the extent that these impacts even produced contact between the head and the head restraint, it was not a significant contact but more of an awareness on the part of the test subject that contact had occurred. For impacts that produced a delta-V in excess of 4.8 kph (3.0 mph), the force of the impact as perceived by the test subjects exceeded forces normally experienced in daily activities.

Given that none of the test subjects experienced any symptoms other than minor neck stiffness that resolved on its own in 1 day or transient headache that resolved in minutes after the impact, it appears that normally seated healthy adults can tolerate delta-V's of 7.2 kph (4.5 mph) or less without significant risk of injury. This is consistent with the findings of previous research into occupant response to low speed rear-end impacts using human volunteers.

VEHICLE RESPONSE

Post-test inspection of the target vehicle did not reveal any damage to the vehicle as a result of this series of tests other than superficial impressions on the plastic cover that were considered cosmetic in nature and barely noticeable. However, when the rear bumper on this vehicle was partially disassembled and examined after the completion of the testing, cracking was noted along the top edge of the foam core in the relatively thin area where the foam core wraps over the top of the bumper face bar. This cracking appeared to be due to buckling of the relatively thin top edge of the foam core in compression. The cracking did not extend into the area of the foam core positioned directly between the face bar and the outer cover, and therefore should have had no effect on the vehicle dynamic response. There was no evidence of damage to any of the other bumper components.

The bullet vehicle did not sustain any damage in this series of tests. As expected, isolator compression was found to correlate with impact severity once the impact threshold of isolator compression was exceeded. Isolator compression did not begin to occur until a delta-V in excess of 4.8 kph (3.0 mph) was reached. There was no measurable isolator compression in the first two tests conducted, which produced bullet vehicle delta-V's of 2.7 and 4.7 kph (1.7 and 2.9 mph). Initially it was suspected that the isolators may be frozen or seized. However, there was also no compression in test #5, which produced a 4.8 kph (3.0 mph) delta-V to the bullet vehicle. The isolator compression as a function of bullet vehicle delta-V is shown in Figure 3.

Coefficient of restitution values were found to range between 0.3 and 0.5 for this series of vehicle-to-vehicle impacts. This was in the range expected based on testing and studies published by others[2,3,10]. Impact durations were found to be in the range of 0.090 to 0.124 seconds. These values were also in the range expected for these types of impacts[11]. As shown in Figure 2, the general trend was for decreasing impact duration with increasing impact severity over the range of speeds tested.

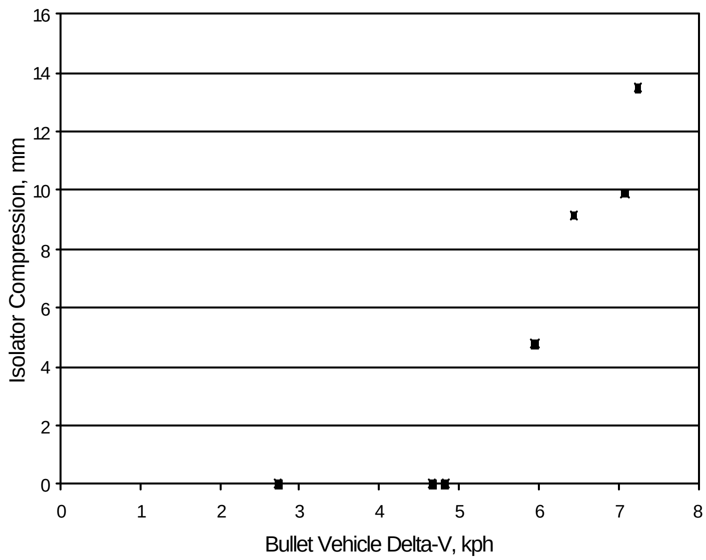

Figure 3. Bullet Vehicle Isolator Compression Results

Target vehicle forward displacement was found to be a weak indicator of impact severity for this series of rear-end impacts. Prior to the test the test subjects were instructed to relax and maintain light pressure on the brake pedal prior to impact as if simulating a normal stop for a stop sign or stop light. However, test subject response to the rear-end impact varied in terms of the time delay between impact and reapplying the brake in those cases where the impact was severe enough to cause the test subject's foot to come up off the brake. Post-impact distance traveled was therefore dependent on the brake pedal pressure before impact and to a much greater extent on the test subject reaction and response to the rear-end impact. As shown in Figure 4, impacts in the 6.3 to 7.2 kph (3.9 to 4.5 mph) delta-V range were found to produce quite different vehicle displacements with different test subjects seated in the driver's seat.

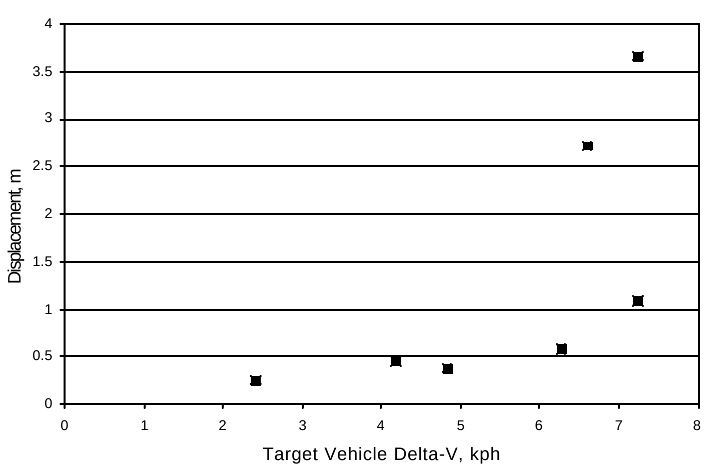

Figure 4. Target Vehicle Forward Displacement Results

CONCLUSION

1. Human volunteers were exposed to delta-V's of up to 7.2 kph (4.5 mph) in this series of tests. Normally seated healthy adults with adequate head support can tolerate delta-V's of 7.2 kph (4.5 mph) or less without significant risk of injury. This is consistent with the published data regarding human volunteer exposures in which human test subjects have been exposed to delta-V's of up to 8 kph (5.0 mph) without sustaining injury.

2. For impacts that produced a delta-V to the target vehicle of 4.8 kph (3.0 mph) or less, the nature of the impact in terms of force and severity can reasonably be related to activities of daily living. Subjectively, these impacts produced forces on the head, neck, and torso that the test subjects would agree are within the range of forces that can be experienced in daily activities.

3. For impacts that produced a delta-V in excess of 4.8 kph (3.0 mph), the test subjects consistently noted that their heads were displaced rearward into contact with the head restraints. For impacts below this level, head contact with the head restraint either did not occur or was so minor that the subjects had only a mild awareness that contact had occurred.

4. Vehicle-to-vehicle coefficient of restitution values were calculated and found to be in the range of 0.3 to 0.5.

5. The impact durations ranged from 0.090 to 0.124 seconds for these bumper-to-bumper impacts, and tended to decrease with increasing impact severity over the range of speeds tested.

6. Peak vehicle accelerations were between 1.5 and 2.7 times higher than the average vehicle accelerations.

7. Target vehicle forward displacement was found to be a weak indicator of impact severity for this series of rear-end impacts. Test subject reaction and braking response to the rear-end impact significantly influenced target vehicle rollout distance in some tests.

CONTACT

Boster, Kobayashi and Associates

REFERENCES

1. Szabo, Thomas J., Welcher, Judson B., Anderson, Robert D., Rice, Michelle M., Ward, Jennifer A., Paulo, Lori R., Carpenter, Nicholas J., "Human Occupant Kinematic Response to Low Speed Rear-End Impacts", SAE 940532
2. Siegmund, Gunter P., Bailey, Mark N., King, David J., "Characteristics of Specific Automobile Bumpers in Low-Velocity Impacts", SAE 940916
3. Bailey, Mark N., Wong, Bing C., Lawrence, Jonathan M., "Data and Methods for Estimating the Severity of Minor Impacts", SAE 950352
4. McConnell, Whitman E., Howard, Richard P., Van Poppel, John, Krause, Robin, Guzman, Herbert M., Bomar, John B., Raddin, James H., Benedict, James V., Hatsell, Charles P., "Human Head and Neck Kinematics After Low Velocity Rear-End Impacts – Understanding Whiplash", SAE 952724
5. Szabo, Thomas J., Welcher, Judson B., "Human Subject Kinematics and Electromyographic Activity During Low Speed Rear Impacts", SAE 962432
6. West, D.H., Gough, J.P., Harper, G.T.K., "Low Speed Rear-End Collision Testing Using Human Subjects", Accident Reconstruction Journal, May/June 1993
7. Nielsen, G.P., Gough, J.P., Little, D.M., West, D.H., Baker, V.T., "Repeated Low Speed Impacts with Utility Vehicles and Humans", Accident Reconstruction Journal September/October 1996
8. Nielsen, G.P., Gough, J.P., Little, D.M., West, D.H., Baker, V.T., "Low Speed Rear-End Impact Test Summary – Human Test Subjects", Accident Reconstruction Journal September/October 1996
9. Allen, Murray E., Weir-Jones, Iain, Motiuk, Darren R., Flewin, Kevan R., Goring, Ralph D., Kobetitch, Robert, Broadhurst, Andrew, "Acceleration Perturbations of Daily Living – A comparison to Whiplash", SPINE, Volume 19, Number 11
10. Howard, Richard P., Bomar, John, Bare, Cleve, "Vehicle Restitution Response in Low Velocity Collisions", SAE 931842
11. Szabo, Thomas J., Welcher, Judson, "Dynamics of Low Speed Crash Tests with Energy Absorbing Bumpers", SAE 921573