DELTA VS FOR IIHS SIDE IMPACT CRASH TESTS AND THEIR RELATIONSHIP TO REAL-WORLD CRASH SEVERITY

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ABSTRACT

The Insurance Institute for Highway Safety (IIHS) began publishing side impact crashworthiness evaluations for consumer information in 2003. The test on which the evaluations are based uses a barrier representing the ride height and front-end geometry of a pickup truck or sport utility vehicle. In this test a stationary vehicle is struck laterally by a 1,500 kg moving deformable barrier traveling at 50 km/h. In determining the impact severity for the test, the goal was to select an impact velocity that would both drive improvements in side impact protection and discriminate between vehicles in the current fleet offering varying levels of protection.

In the present study the Simulating Motor Vehicle Accident Speeds on the Highway (SMASH) computer program was used to obtain delta Vs for vehicles tested in the IIHS side impacts. These were compared with delta V estimates calculated using the principle of conservation of momentum. The delta Vs calculated from the IIHS tests were compared with those from injury-producing side crashes in the National Automotive Sampling System (NASS) to see how the severity of the IIHS test compares with real-world side crashes.

Analysis of 49 side crashes conducted by IIHS indicates that, overall, SMASH calculations produced delta Vs within 5 km/h of the delta V determined using the conservation of momentum principle. The SMASH delta Vs ranged from 18 to 31 km/h, and the average delta V was 24 km/h. The maximum occupant compartment crush in these tests ranged from 27 to 46 cm. Comparison of delta Vs and maximum crush measures from the 1998-2003 NASS data files indicates that 30-55 percent of real-world front-to-side crashes with seriously injured nearside occupants and 10-25 percent of the crashes with fatal injuries to nearside occupants are less severe than the IIHS side impact test.

INTRODUCTION

Between 1992 and 2001 the demand for pickup trucks and sport utility vehicles (SUVs) pushed their sales up from 26 to 41 percent of all vehicles sold in the United States (Automotive News, 1993, 2002). By 2003 pickups and SUVs comprised almost one-third of the registered passenger vehicles in the U.S. fleet (R.L. Polk & Co., 2004). In 2004 these vehicles represented 45 percent of the vehicles sold in the United States (Crain Communications Inc, 2005).

Data from the Fatality Analysis Reporting System (FARS) from 1998 to 2003 show two-vehicle side impact crashes result in approximately 4,000 struck vehicle occupant fatalities per year in the United States (National Highway Traffic Safety Administration, 2004). In 2003 pickups and SUVs comprised 59 percent of the striking vehicles in these fatal crashes. Real-world crash investigations also have shown that pickups, SUVs, and vans are disproportionately involved as striking vehicles in side impact crashes in which the occupants of the struck vehicle sustained serious and fatal injuries (Augenstein et al., 2000; Lund et al., 2000; Thomas and Frampton, 1999; Zaouk et al., 2001). Previous research by Nolan et al. (1999) and Rattenbury et al. (2001) suggests the elevated ride height of pickups and SUVs contributes to their overrepresentation in real-world side impact crashes where the struck vehicle occupants sustain serious or fatal injuries.

In 1999 the Insurance Institute for Highway Safety (IIHS) began developing a new side impact test to evaluate occupant protection in passenger vehicles struck by a truck-like barrier. The moving deformable barrier (MDB) used in this side impact test, the IIHS barrier (Figure 1), was designed to match the front-end geometry and ride height of pickups and SUVs (Arbelaez et al., 2002). By the end of 2002 IIHS began evaluating vehicles in its side impact consumer information program. In the IIHS test a 1,500 kg barrier strikes a stationary vehicle at 50 km/h. The impact severity for the test was established through a series of tests in which the impact angle, velocity, and mass of the striking MDB was varied (Dakin et al., 2003). The impact mass and velocity selected for the IIHS test were chosen to drive improvements in side impact protection while still providing discrimination among vehicles in the current fleet offering varying levels of protection.

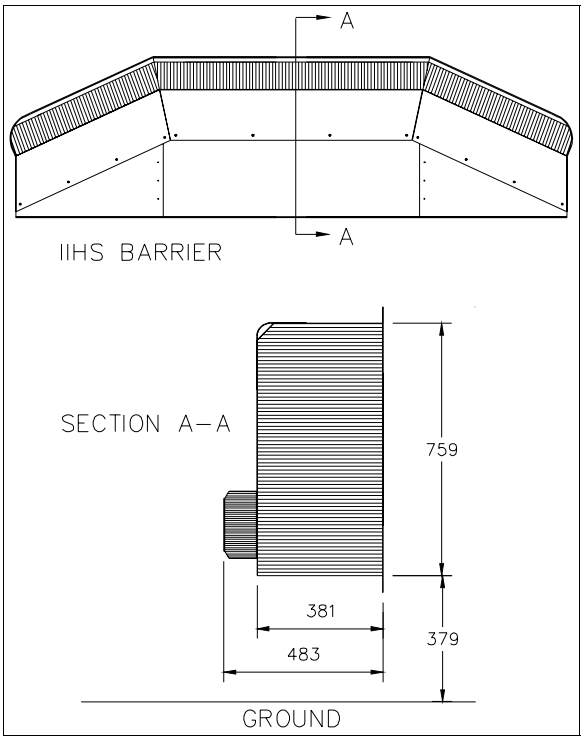

Figure 1. Top and side cross-sectional views of IIHS barrier; all measurements are in millimeters.

Crash severity often is described by a vehicle's change in velocity (delta V) during the crash; delta V is the primary metric used to quantify crash severity in the National Automotive Sampling System (NASS) database. Since 1997 delta Vs for crashed vehicles in NASS have been estimated from measures of vehicle crush using the Simulating Motor Vehicle Accident Speeds on the Highway (SMASH) computer program. In the present study SMASH was used to obtain comparable estimates of delta Vs of vehicles subjected to the IIHS side impact test. The purpose was to understand how well these field procedures estimate the actual delta Vs calculated using the conservation of momentum principle and, by comparison with NASS cases, to see how the severity of the IIHS test compares with real-world side impact crashes.

To obtain another perspective on how the IIHS test relates to real-world side impacts, maximum occupant compartment crush measures from the IIHS test were compared with crush distributions for injury-producing crashes in the NASS database.

METHODS

A total of 37 different vehicle models were subjected to 49 side impacts with the IIHS barrier at 50 km/h. These impacts were conducted according to the IIHS "Crashworthiness Evaluation Side Impact Crash Test Protocol" (IIHS, 2004). Delta Vs for these vehicles were calculated using the NASS measurement protocol and the SMASH (Version 1.3) damage-only algorithm. SMASH results were averaged for each of the 12 models subjected to repeated tests. The vehicle and barrier crush specifications and crush measures used in the SMASH program are shown in Appendices A, B, and C. The SMASH size category used to describe each vehicle was based on its wheelbase, and the SMASH stiffness value was set equal to the size category, per NASS protocol. The size and stiffness categories for the IIHS barrier were set to the values used in SMASH for "movable barriers" (size and stiffness = 10). In SMASH there is no deformation energy attributed to vehicles categorized as movable barriers (i.e., for a side impact test the delta V estimate for the struck vehicle does not take into account the deformation of the striking barrier). To correct the delta V output for the known deformation of the barrier, the energy absorbed by the deformable barrier was calculated using the measured crush at the height of the barrier's bumper element along with the known crush strength of the barrier's main core (310 kPa). The adjusted delta V for the struck vehicle, ΔV_2, was calculated using the following delta V-energy relationship:

$$\frac{\Delta V_1^2}{\Delta V_2^2} = \frac{E_1}{E_2}$$

where,

ΔV_1 = SMASH-calculated struck vehicle delta V (MDB size and stiffness = 10);

ΔV_2 = energy-adjusted delta V for struck vehicle;

E_1 = SMASH-calculated energy for struck vehicle (MDB size and stiffness = 10); and

$E_2 = E_1$ + barrier energy calculated from crush measures.

The adjusted delta V estimates from SMASH then were compared with the delta V calculated using the principle of conservation of momentum and the maximum vehicle delta V recorded by on-board vehicle accelerometers.

Delta Vs from real-world crashes were extracted from the 1997-2003 NASS data files for side impacts involving two vehicles in which there were no ejections of struck vehicle occupants or rollovers. NASS cases were selected based on the following criteria:

- Struck vehicles were restricted to 1990+ model years;
- Collision Deformation Classification (CDC) coding that represents crashes with struck vehicle damage distribution to the occupant compartment;

this includes CDC lateral damage classifications areas D (distributed), P (occupant compartment), Y (occupant compartment and front one-third of vehicle), and Z (occupant compartment and rear one-third of vehicle);

- Principle direction of force was limited to 8-10 o'clock for impacts to the left side of the vehicle and 2-4 o'clock for the right side impacts; and
- Crashes in which struck-side occupants sustained injuries.

The 1997-2003 NASS data contained a total of 9,993 vehicles with reported side structure damage, of which 1,799 met the crash conditions described above. Of those 1,460 vehicles had delta Vs computed using the SMASH damage-only algorithm. In this study the NASS data were used to relate SMASH delta Vs to injury levels.

RESULTS

Delta Vs calculated using the SMASH damage-only algorithm for the IIHS side impact crashes are listed by vehicle type in Tables 1-3, along with delta Vs calculated using conservation of momentum and actual delta Vs recorded by vehicle accelerometers. Figures 1-3 show postcrash side deformation on vehicles from each of the three vehicle categories used in this study. For all but two of the vehicle models tested, the delta V calculated using the principle of conservation of momentum was within 1 km/h of the maximum lateral delta V recorded by on-board vehicle accelerometers. Overall, the SMASH delta Vs computed for the vehicles in this study were within 5 km/h of the delta Vs calculated using the conservation of momentum and those recorded by the accelerometers mounted in the occupant compartment of the struck vehicles. The SMASH delta Vs for the small and midsize cars and small SUVs tested in the IIHS side crashworthiness evaluation program ranged from 18 to 31 km/h; the average SMASH delta V was 24 km/h.

Table 1.
Delta Vs calculated for small four-door cars in side crashes with a 1,500 kg IIHS barrier at 50 km/h

	Delta V (km/h)		
Year, make, and model	Conserv. of momentum	Vehicle accel.	SMASH
2004 Kia Spectra	25	25	29
2004 Nissan Sentra	26	26	31
2005 Dodge Neon	26	26	28
2005 Ford Focus	26	27	26
2005 Saturn Ion*	26	27	24
2005 Toyota Corolla*	26	27	28
Average	26	26	28

*Based on average results of two tests

Table 2.
Delta Vs calculated for midsize four-door cars in side crashes with a 1,500 kg IIHS barrier at 50 km/h

	Delta V (km/h)		
Year, make, and model	Conserv. of momentum	Vehicle accel.	SMASH
2004 Acura TL	23	23	24
2004 Chevrolet Malibu*	24	24	24
2004 Dodge Stratus	24	21	26
2004 Honda Accord*	24	24	25
2004 Hyundai Sonata	24	24	27
2004 Jaguar X-Type	23	23	24
2004 Lexus ES 330*	23	22	21
2004 Mazda 6	24	24	28
2004/05 Mitsubishi Galant*	23	24	22
2004 Saab 9-3	24	25	22
2004 Saab 9-5	23	22	23
2004 Saturn L Series	24	24	25
2004 Suzuki Verona	23	23	26
2004 Toyota Camry*	24	25	26
2005 Mercedes C 240	23	24	20
2005 Nissan Altima	24	23	28
2005 Subaru Legacy*	24	25	21
2005 Volvo S40	24	24	21
Average	24	24	24

*Based on average results of two tests

Table 3.
Delta Vs calculated for small SUVS in side crashes with a 1,500 kg IIHS barrier at 50 km/h

	Delta V (km/h)		
Year, make, and model	Conserv. of momentum	Vehicle accel.	SMASH
2002/03 Land Rover Freelander*	23	24	24
2003 Ford Escape*	23	24	20
2003 Honda CR-V*	23	25	21
2003 Honda Element	23	23	21
2003 Hyundai Santa Fe	22	22	18
2003 Mitsubishi Outlander	23	23	22
2003 Saturn VUE	23	24	20
2003 Subaru Forester*	24	25	23
2003 Suzuki Grand Vitara	24	25	24
2003 Toyota RAV4	24	25	24
2004 Toyota RAV4	24	24	23
2005 Ford Escape	23	24	19
2005 Honda CR-V	23	24	20
Average	23	24	21

*Based on average results of two tests

Figure 1. Example of postcrash deformation of small car (2005 Dodge Neon) following IIHS test

Figure 2. Example of postcrash deformation of midsize car (2004 Toyota Camry) following IIHS test

Figure 3. Example of postcrash deformation of small SUV (2003 Ford Escape) following IIHS test.

Maximum struck vehicle crush measured in the IIHS crash tests ranged from 27 to 46 cm, with an average maximum crush of 37 cm for all vehicle models. Table 4 shows the crush ranges for the small and midsize cars and the small SUVs tested.

Table 4.
Distribution of maximum vehicle crush

	Maximum crush (cm)		
Vehicle type	**Range**	**Average**	**± st. dev**
Small cars	37-42	40	2
Midsize cars	27-46	38	6
Small SUVs	29-40	34	4
All IIHS tests	27-46	37	5

The delta Vs, maximum vehicle crush, and occupant injury data from the 1997-2003 NASS data files were weighted according to NASS guidelines. Figure 4 shows the cumulative distribution of the delta Vs from the weighted NASS cases by maximum abbreviated injury scale (MAIS) level for nearside struck occupants. The average delta V for the vehicles tested was 24 km/h; the calculated delta V for the IIHS test using the principle of conservation of momentum would be 25 km/h, assuming that both vehicles are of the same mass and the striking vehicle is traveling at 50 km/h. Based on a 25 km/h delta V reference, the IIHS test is more severe than 45 percent of the crashes with MAIS 2+ injuries, 30 percent of the crashes with MAIS 3+ injuries, and 10 percent of the real-world front-to-nearside struck occupant fatalities (Figure 4).

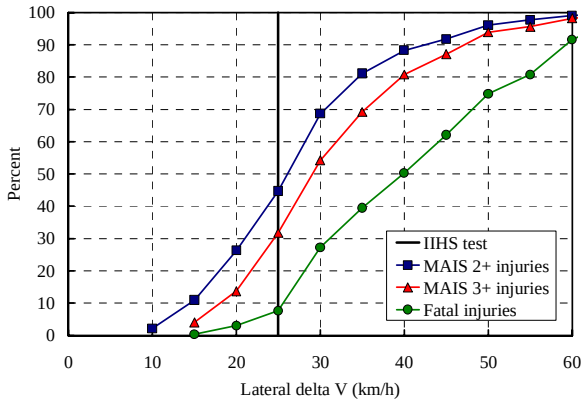

Figure 4. Cumulative distribution of delta Vs in two-vehicle front-to-nearside crashes; highlighted IIHS test delta V of 25 km/h represents the delta V for striking and struck vehicles of equal mass.

Figure 5 shows the cumulative distribution of the maximum struck vehicle crush from the weighted NASS cases by MAIS level for nearside struck occupants. The NASS cases considered for the maximum crush versus injury comparison were not restricted to cases in which delta V was determined; this restriction was used only for the delta V versus injury comparison. Given a maximum crush value of 37 cm as a reference value for the IIHS test, the IIHS side crash test is more severe than 60 percent of the crashes with MAIS 2+ injuries, 55 percent of the crashes with MAIS 3+, and 25 percent of the real-world front-to-nearside crashes with struck occupant fatalities.

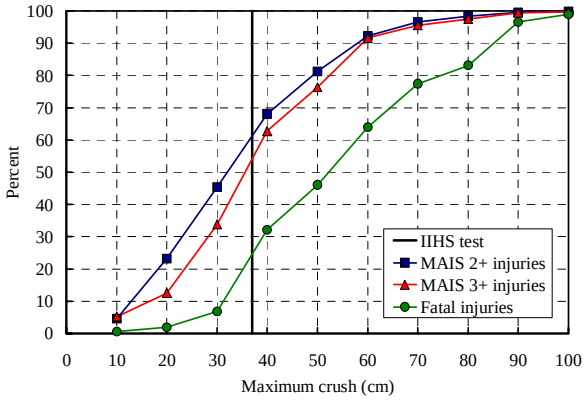

Figure 5. Cumulative distribution of maximum struck vehicle crush in two-vehicle front-to-nearside crashes; highlighted 37 cm maximum crush line represents the average maximum crush from IIHS side impact tests.

DISCUSSION

On average the SMASH delta Vs for vehicles subjected to the IIHS side impact differed from the delta Vs calculated from conservation of momentum and those recorded by vehicle accelerometers during each crash test by only 1-2 km/h. However, the SMASH

delta Vs had a much wider range (18-31 km/h) than the delta Vs based on the conservation of momentum (22-26 km/h) The SMASH reconstructions in this study indicate that the SMASH damage-only algorithm can be off by as much as 20 percent for an individual vehicle.

Analysis of delta Vs and maximum crush values from the IIHS tests indicates the test severity is on the low end of real-world crashes resulting in fatalities (75-90 percent of fatal crashes appear to be more severe), but it is well into the distribution of crash severity resulting in serious injury (30-55 percent of serious injuries occur in less severe crashes). These results indicate that the majority of serious injury and fatal side impact crashes are occurring at significantly higher crash severities than currently are being evaluated in either federal regulation or consumer information tests. Of the NASS cases included in this study with fatal nearside occupants, more than half have maximum deformation of the vehicle side structure of at least 50 cm, which corresponds to approximately one quarter of a typical vehicle width.

ACKNOWLEDGMENT

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APPENDIX A. Specifications for vehicles subjected to IIHS side crash test

Test ID	Vehicle type	Vehicle year, make, and model	Wheelbase (cm)	Length (cm)	Width (cm)	Mass (kg)
1	Small	2004 Kia Spectra	261	448	174	1,484
2	Small	2004 Nissan Sentra	254	452	171	1,375
3	Small	2005 Dodge Neon	267	444	171	1,396
4	Small	2005 Ford Focus	262	445	169	1,412
5A	Small	2005 Saturn Ion	262	469	171	1,432
5B	Small	2005 Saturn Ion	262	469	171	1,424
6A	Small	2005 Toyota Corolla	260	453	170	1,372
6B	Small	2005 Toyota Corolla	260	453	170	1,360
7	Midsize	2004 Acura TL	274	481	184	1,798
8A	Midsize	2004 Chevrolet Malibu	270	478	178	1,656
8B	Midsize	2004 Chevrolet Malibu	270	478	178	1,657
9	Midsize	2004 Dodge Stratus	274	486	179	1,612
10A	Midsize	2004 Honda Accord	274	481	182	1,635
10B	Midsize	2004 Honda Accord	274	481	182	1,615
11	Midsize	2004 Hyundai Sonata	270	475	182	1,674
12	Midsize	2004 Jaguar X-Type	271	467	179	1,816
13A	Midsize	2004 Lexus ES 330	272	486	181	1,754
13B	Midsize	2004 Lexus ES 330	272	486	181	1,747
14	Midsize	2004 Mazda 6	268	475	178	1,616
15A	Midsize	2004 Mitsubishi Galant	275	484	184	1,730
15B	Midsize	2005 Mitsubishi Galant	275	484	184	1,731
16	Midsize	2004 Saab 9-3	268	464	175	1,635
17	Midsize	2004 Saab 9-5	270	483	179	1,781
18	Midsize	2004 Saturn L Series	271	484	174	1,635
19	Midsize	2004 Suzuki Verona	270	477	182	1,721
20A	Midsize	2004 Toyota Camry	272	480	180	1,636
20B	Midsize	2004 Toyota Camry	272	480	180	1,626
21	Midsize	2005 Mercedes C 240	271	453	173	1,708
22	Midsize	2005 Nissan Altima	280	488	179	1,613
23A	Midsize	2005 Subaru Legacy	267	473	173	1,683
23B	Midsize	2005 Subaru Legacy	267	473	173	1,685
24	Midsize	2005 Volvo S40	264	447	177	1,654
25A	SUV	2002 Land Rover Freelander	256	445	180	1,780
25B	SUV	2003 Land Rover Freelander	256	445	181	1,805
26A	SUV	2003 Ford Escape	262	439	178	1,723
26B	SUV	2003 Ford Escape	262	439	178	1,736
27A	SUV	2003 Honda CR-V	262	454	178	1,703
27B	SUV	2003 Honda CR-V	262	454	178	1,700
28	SUV	2003 Honda Element	258	430	182	1,773
29	SUV	2003 Hyundai Santa Fe	262	450	182	1,955
30	SUV	2003 Mitsubishi Outlander	263	455	175	1,731
31	SUV	2003 Saturn VUE	271	461	182	1,759
32A	SUV	2003 Subaru Forester	253	445	174	1,613
32B	SUV	2003 Subaru Forester	253	445	174	1,610
33	SUV	2003 Suzuki Grand Vitara	248	418	178	1,680
34	SUV	2003 Toyota RAV4	249	425	174	1,592
35	SUV	2004 Toyota RAV4	249	426	174	1,629
36	SUV	2005 Ford Escape	262	444	178	1,800
37	SUV	2005 Honda CR-V	262	460	178	1,760

APPENDIX B. Struck vehicle crush measures for vehicles subjected to IIHS side crash test

Test ID	Vehicle year, make, and model	Struck vehicle crush measures (cm)						Damage length (cm)
		C1	C2	C3	C4	C5	C6	
1	2004 Kia Spectra	7	33.5	41	41	37	0	194
2	2004 Nissan Sentra	11	35.5	41	41.5	37.5	7	171
3	2005 Dodge Neon	16	33	40.5	40	34	0	177
4	2005 Ford Focus	16	31	36	37	30	14	164
5A	2005 Saturn Ion	5	36.5	39.5	34.5	26	0	161
5B	2005 Saturn Ion	6	33	40	25.5	15	0	182
6A	2005 Toyota Corolla	17	33	38	38	32	0	176
6B	2005 Toyota Corolla	16	32	37.5	38	35	4	175
7	2004 Acura TL	0	34.5	38	38	26	0	204
8A	2004 Chevrolet Malibu	2	31	37	38	29	0	182
8B	2004 Chevrolet Malibu	6	32	37	38	32	0	182
9	2004 Dodge Stratus	20	38	40	38	27	0	180
10A	2004 Honda Accord	7	36	43	39	33	3	185
10B	2004 Honda Accord	8	38	42	39	31	0	185
11	2004 Hyundai Sonata	8	38	44	43	33	0	187
12	2004 Jaguar X-Type	10	37	40	41	29	0	183
13A	2004 Lexus ES 330	4	27.5	38	30	25	0	186
13B	2004 Lexus ES 330	4	30	38	30	28	0	175
14	2004 Mazda 6	26	41	45	42	37	12	163
15A	2004 Mitsubishi Galant	2	24	30	31	29	15	177
15B	2005 Mitsubishi Galant	13	28	30.5	33	26.5	0	186
16	2004 Saab 9-3	0	24	31	32	24	6	184
17	2004 Saab 9-5	0	35	42	37.5	31.5	0	177
18	2004 Saturn L Series	8	36	42	31	20	0	173
19	2004 Suzuki Verona	3	36	43	41	32	0	190
20A	2004 Toyota Camry	10	34	42	41	31	0	188
20B	2004 Toyota Camry	7	27	37	36	30	1	194
21	2005 Mercedes C 240	0	22	24	27	21.5	0	184
22	2005 Nissan Altima	8	38	44	46	36	0	178
23A	2005 Subaru Legacy	4	26	27	26.5	23.5	0	184
23B	2005 Subaru Legacy	6	27.5	29.5	29	24.5	15	177
24	2005 Volvo S40	8	24.5	33	33	29	0	177
25A	2002 Land Rover Freelander	19	33	39	37	23	2	181
25B	2003 Land Rover Freelander	19	32	41	38	27	3	169
26A	2003 Ford Escape	10	24.5	30.5	29	22	0	176
26B	2003 Ford Escape	11	24	31	29	21.5	0	178
27A	2003 Honda CR-V	12	28	32	28	20	1	193
27B	2003 Honda CR-V	0	19	30	32	21	0	191
28	2003 Honda Element	5	22	29	29	19	0	193
29	2003 Hyundai Santa Fe	10	24	32	31	22	0	176
30	2003 Mitsubishi Outlander	15	31	38	36	28	0	185
31	2003 Saturn VUE	19	28	33	28	19	0	180
32A	2003 Subaru Forester	10	28	30	30	19	2	195
32B	2003 Subaru Forester	10	29	30	28	18	4	195
33	2003 Suzuki Grand Vitara	21	38.5	40	36	25	0	163
34	2003 Toyota RAV4	19	30	28	37	23	1	192
35	2004 Toyota RAV4	15	28.5	30.5	31.5	28	0	171
36	2005 Ford Escape	12	24.5	30	28	21.5	0	171
37	2005 Honda CR-V	8	24	34	32	26.5	15.5	172

APPENDIX C. Moving deformable barrier crush measures for IIHS side crash tests

	Moving deformable barrier crush measures (cm)						Damage Length
Test ID	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**(cm)**
1	11	6	8	6	3	2	160
2	8	3	5	5	6	9	160
3	8	2	2	0	0	6	160
4	9	6	8	8	5	10	160
5A	5	4	4	4	4	6	160
5B	7	6	6	4	5	8	160
6A	6	5	6	6	5	3	160
6B	5	5	7	6	4	4	160
7	10	9	8	8	8	5	160
8A	10	8.5	9	8	9.5	17	160
8B	10	5.5	6	5	6.5	11	160
9	8.5	4	5	5	2	6	160
10A	3	1	0	2	-1	1	160
10B	7.5	3	5	7	7	7.5	160
11	12	7	6	5	5	8.5	160
12	9.5	4	7	8	8	14	160
13A	6	5	8	9	10	13.5	160
13B	4	4	6	8	9	12	160
14	6	7.5	8.5	10	9	10	160
15A	10	13.5	16	16	13.5	10	160
15B	10	11	13	14	12	10	160
16	13	8	10	10	10	13	160
17	16	6	7	6	8	10.5	160
18	7	4.5	4.5	5	8	17	160
19	8.5	6.5	7.5	7.5	5.5	9.5	160
20A	8.5	6	7	8	8	8.5	160
20B	8.5	9.5	11	11	10.5	11	160
21	15	12	14	17	14	13	160
22	6	3.5	2	1.5	2	3	160
23A	8	10	14.5	14	9	8	160
23B	2	7	11	11	6	9	160
24	12	6	8	8	8	5	160
25A	6	2.5	2	3.5	4.5	7	160
25B	10.5	4.5	3.5	4.5	7	8	160
26A	6	5.5	10.5	13	14.5	14.5	160
26B	5.5	5.5	9	11.5	13.5	14.5	160
27A	8.5	10	11	12	13	10	160
27B	7.5	9	10.5	12	13.5	13	160
28	12	7.5	11	13	9.5	16.5	160
29	6.8	4	8.5	10.5	12	13.5	160
30	4.5	1	1	1.5	3.5	10.5	160
31	3.5	3	5	7	8.5	8.5	160
32A	6	4	4.5	6	8.5	10.5	160
32B	6	3	4	4.5	7	12	160
33	6.5	1	0.5	0	3	12	160
34	0	-1	0.5	2	5	4.5	160
35	8	5	6	6	8	6	160
36	11	10	16	16	15	10	160
37	0	0	2	4	6	3	160