INSURANCE INSTITUTE FOR HIGHWAY SAFETY SIDE IMPACT CRASHWORTHINESS EVALUATION PROGRAM: IMPACT CONFIGURATION AND RATIONALE

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Paper No. 172

ABSTRACT

The Insurance Institute for Highway Safety (IIHS) has begun a new side impact crashworthiness evaluation program using tests that represent impacts from large pickup trucks or sport utility vehicles. Such vehicles are increasingly common in the North American fleet and often are the striking vehicles in side impacts with serious injuries. Earlier reports document the research underpinning the design of the new IIHS moving deformable barrier (MDB) and the selection of the SID-IIs dummy for the driver and left rear passenger positions.

In this report, research is discussed in which alternative mass (1,500 or 1,900 kg), impact speed (48.3 or 50.0 km/h), and approach angle (crabbed or perpendicular) of the MDB were investigated. Impact speed affected dummy injury measures and kinematics more than mass or approach angle. Based on these results, the impact configuration for the side impact program specifies a 1,500 kg MDB, a perpendicular impact into the side of a stationary vehicle, and a test speed of 50.0 km/h.

INTRODUCTION

Analysis of real-world crash data indicates that pickup trucks and sport utility vehicles (SUVs) are disproportionately involved as striking vehicles in side impact crashes where the occupants of struck vehicles sustain serious or fatal injuries (Augenstein et al., 2000; Lund et al., 2000; Thomas and Frampton, 1999; Zaouk et al., 2001). Between 1992 and 2001, the rise in sales of pickups and SUVs has increased their representation in the U.S. vehicle fleet from 22 to 30 percent of all registered vehicles (R.L. Polk & Co., 2001). These vehicles typically have higher ride heights, mass, and front-end stiffness than passenger cars, which results in serious crash incompatibilities when SUVs/pickups strike the sides of passenger cars. The increased ride heights of these vehicles has been shown to be the most important factor in contributing to higher dummy injury measures in controlled crash tests (Dalmotas et al., 2001; Nolan et al., 1999; Seyer et al., 2000). The continued sales growth of these vehicles suggests there will be an increase in the number of SUV-to-car side impacts in the future. The current Federal Motor Vehicle Safety Standard (FMVSS) 214 and European Enhanced Vehicle-safety Committee (EEVC) side impact barriers used in North American and European regulatory tests are low, short, and flat; thus they do not represent the risk to car occupants posed by pickups or SUVs. As a result, car designs for side impact protection are not adequate for today's fleet.

In 1999, the Insurance Institute for Highway Safety (IIHS) began developing a new side impact test for consumer information that would evaluate the impact protection of nearside occupants in vehicles struck by pickups or SUVs. A new side impact deformable barrier, the IIHS barrier, was designed for this test to represent the front-end geometry and ride height of modern pickups and SUVs. Earlier phases in the research underpinning this program included the validation of the new IIHS barrier and the selection of the SID-IIs dummy for the driver and left rear passenger positions (Arbelaez et al., 2002a, 2002b). The final step in the development of the new IIHS side impact test was establishing the impact configuration. In this study, the mass, impact velocity, and approach angle (perpendicular vs. crabbed) of the moving deformable barrier (MDB) were investigated to determine how they influence struck vehicle dynamics, crush, dummy kinematics, and injury measures in a series of developmental crash tests.

METHODS

Seven side impact crash tests were conducted with SID-IIs dummies in the driver and left rear passenger positions. The test vehicles were all stationary 1999-2000 Ford Focus and Pontiac Grand Am four-door passenger cars with no side airbags. Each car was struck on the driver's side by an MDB that consisted of a modified FMVSS 214 test cart equipped with an IIHS barrier element (version 4). The mass, speed, and approach angle of the MDB were varied among tests (Table 1).

Tests F1 and G1 are considered the baseline tests for this series because they have the lowest MDB mass (1,500 kg) and speed (48.3 km/h). In the other six tests, the barrier mass was increased to 1,900 kg, which is representative of striking SUVs that cause serious injury (AIS 3+) to nearside occupants (National Automotive Sampling System/Crashworthiness Data System, 1995-99) (National Highway Traffic

Table 1.
Test matrix

Test number	**F1**	**F2**	**F3**	**F4**	**G1**	**G2**	**G3**
Struck vehicle							
Ford Focus	•	•	•	•			
Pontiac Grand Am					•	•	•
Barrier mass							
1,500 kg	•				•		
1,900 kg		•	•	•		•	•
Barrier velocity							
48.3 km/h	•	•			•		
50.0 km/h			•			•	
56.1 km/h				•			•
MDB approach angle							
Perpendicular (0°)	•	•	•		•	•	
Crabbed (27°)				•			•
Impact point							
30 cm aft FMVSS 214	•	•	•		•	•	
Same as FMVSS 214				•			•

Safety Administration, 2001). In tests F3 and G2, the barrier was heavier (1,900 kg) and the impact velocity was faster (50.0 km/h) than the baseline tests. In tests F4 and G3, the barrier was crabbed (27 degrees) and the impact point was 94 cm forward of the wheelbase midpoint as specified by the FMVSS 214 protocol, whereas the impact point of the perpendicular tests was 30 cm rearward of the FMVSS 214 location. The MDB velocity in the crabbed tests was increased to 56.1 km/h to achieve the same longitudinal velocity that was used in the 50.0 km/h perpendicular tests.

The University of Michigan Transportation Research Institute anthropometric test device positioning procedure (IIHS, 2002a; Reed et al., 2001) was used to position the driver seat and driver dummy prior to each test. Rear dummy positioning followed IIHS's dummy seating procedure for rear outboard positions (IIHS, 2002b). The left arm of the driver SID-IIs was placed in the click-stop position that corresponds to a 45-degree angle between the arm and torso. The rear dummy's arm was set to 45 degrees in tests F1, F2, and G1 and the neutral position (straight down) in the other four tests.

The dummies were instrumented to collect a range of measures in the head, neck, thorax, abdomen, and pelvis (Table 2). In addition to dummy instrumentation, high-speed cameras (500 frames per second) were used to document dummy kinematics and any interaction between the dummy and the vehicle interior and/or intruding IIHS barrier face.

Test vehicle accelerations were recorded by a triaxial accelerometer block mounted on the floor of the rear seating area along the centerline of the vehicle. Delta-V (change in velocity at impact) of the test vehicle was calculated by integrating this acceleration data.

Table 2.
Dummy instrumentation

Head (center of gravity)	A_X, A_Y, A_Z accelerations
Upper Neck	F_X, F_Y, F_Z forces M_X, M_Y, M_Z moments
Shoulder	D_Y displacement F_X, F_Y, F_Z forces
Spine (T1, T4, T12)	A_Y accelerations
Thorax (3 ribs)	A_Y accelerations D_Y displacements
Abdomen (2 ribs)	A_Y accelerations D_Y displacements
Pelvis Pubic symphysis, ilium, and acetabulum	A_X, A_Y, A_Z accelerations F_Y forces

Precrash and postcrash vertical door profiles of the front and rear doors were recorded using a coordinate measuring machine (FARO Technologies Inc.). The locations of theses profiles corresponded to the driver and passenger dummy's H-point positions (as measured prior to the test).

With the exception of thoracic and abdominal rib deflections, the dummy data in this study were collected and filtered according to Society of Automotive Engineers (SAE) J211 specifications. Thoracic and abdominal deflections were filtered at SAE CFC180. Thoracic and abdominal rib compression velocities were determined by differentiating the filtered rib deflection data. Head injury criterion (HIC) and viscous criterion were calculated by established methods (Appendix A). The combined pelvic force was the sum of the instantaneous lateral iliac force and the acetabulum force.

RESULTS

Changes in MDB mass, velocity, and approach angle had relatively little effect on the amount of postcrash static crush sustained by the Ford Focus (Figure 1). Throughout the entire vertical length at the driver H-point, all four crush contours were within 5 cm of each other, with the crabbed impact being the most intrusive. In the proximity of the rear passenger dummy, the crabbed impact appeared to have substantially less crush than the other three tests; however, this deviation was caused by the outer door skin being pulled away from the car by the MDB as it rebounded from the vehicle.

For the Grand Am, the perpendicular (1,900 kg, 50.0 km/h) test resulted in the greatest amount of crush in the driver and rear passenger compartments (Figure 2). In some places, crush differences among the three tests were up to 8 cm.

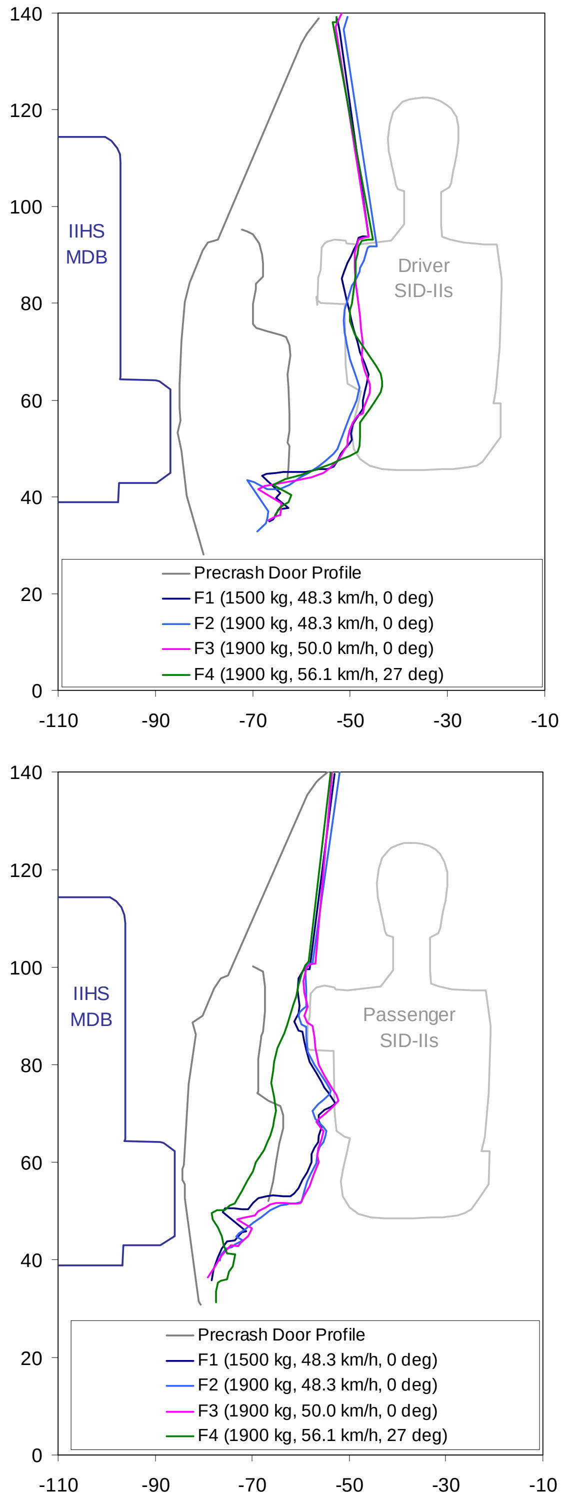

Figure 1. External door crush measured at driver and left rear passenger H-points, Ford Focus tests. X and Y axes represent distance (cm) from floor and vehicle centerline, respectively.

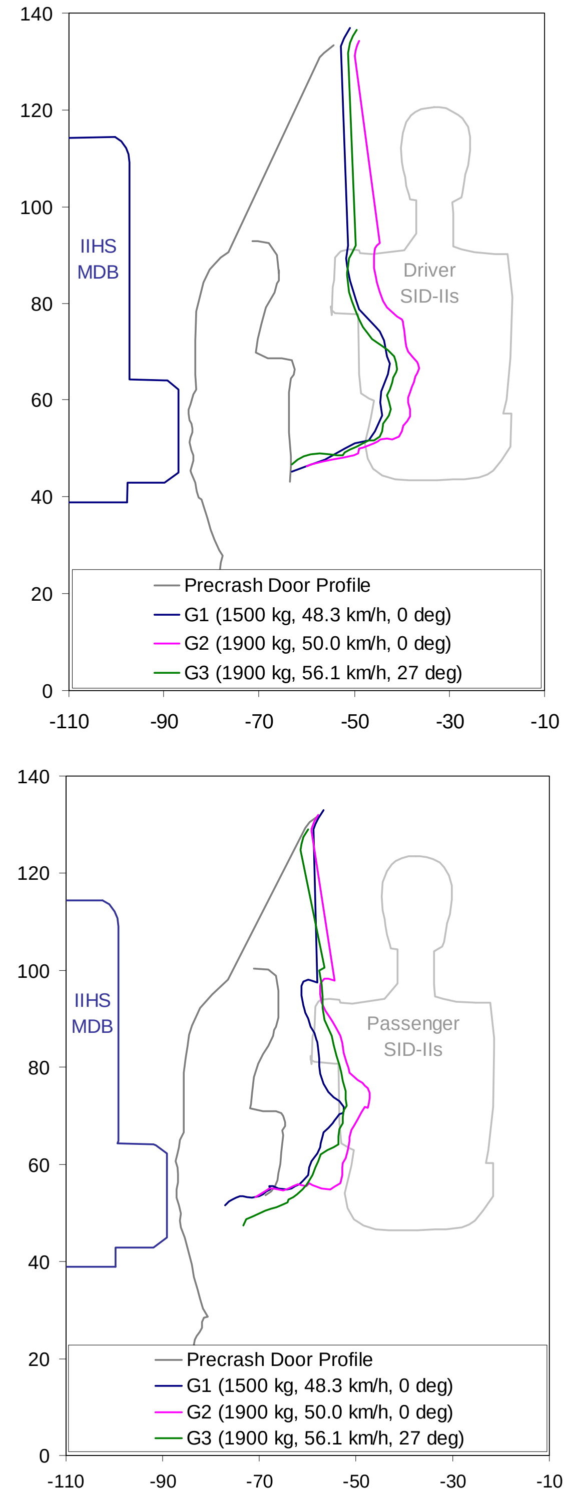

Figure 2. External door crush measured at driver and left rear passenger H-points, Pontiac Grand Am tests. X and Y axes represent distance (cm) from floor and vehicle centerline, respectively.

In general, increasing the mass and speed of the MDB caused a concatenate increase in the target vehicle delta-V (Figures 3 and 4). The crash tests all produced similar shaped lateral vehicle velocity curves, whereas the crabbed impacts produced distinct longitudinal vehicle velocity in comparison with the perpendicular tests. At 75 ms (a time that many of the dummy injury measures had peaked) the vehicle longitudinal and lateral delta-V responses varied as much as 7 km/h depending on impact configuration.

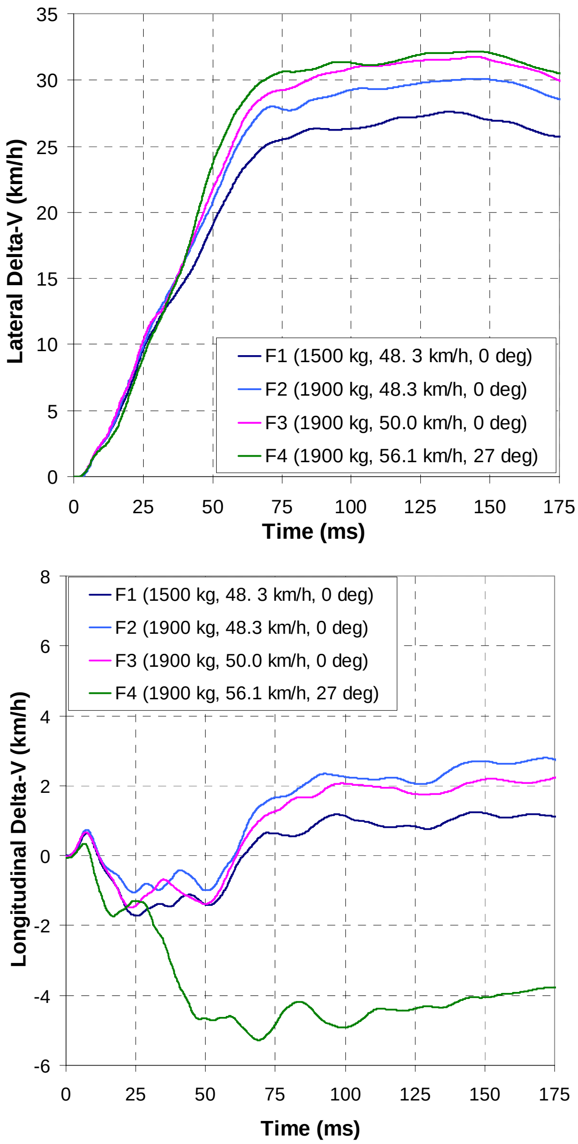

Figure 3. Lateral and longitudinal struck vehicle delta-Vs, Ford Focus tests.

Driver Dummy Kinematics and Injury Measures

In the baseline Focus and Grand Am tests (F1 and G1), the driver dummy's head rotated outboard during the crash, swiped across the face of the intruding barrier, then continued to rotate until it contacted the window sill (Appendix B). When the barrier mass was increased to 1,900 kg for test F2, the dummy head kinematics and contact location on the window sill were nearly identical to the 1,500 kg Focus test (F1).

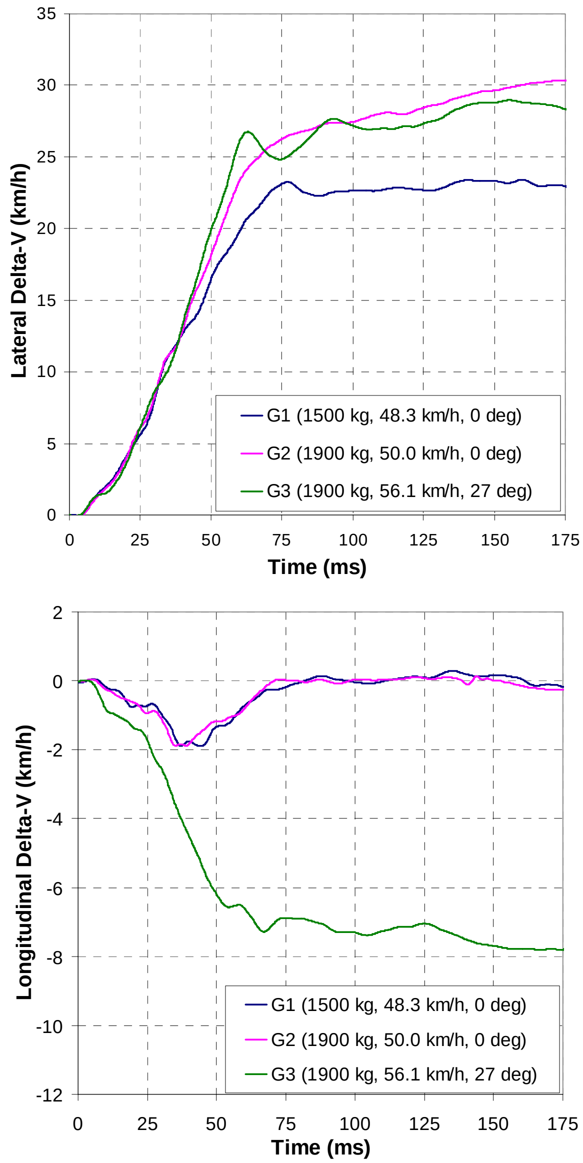

Figure 4. Lateral and longitudinal struck vehicle delta-Vs, Pontiac Grand Am tests.

In all three of these tests (F1, F2, and G1), the peak head accelerations were recorded and the HICs were calculated during an interval that corresponds with the dummy head contacting the window sill. Although head kinematics were similar between the two 48.3 km/h Focus tests, the test with the heavier barrier mass resulted in higher thoracic and abdominal deflections and viscous criterion values (Table 3).

When the velocity of the heavier barrier (1,900 kg) was increased to 50.0 km/h, the driver lateral head rotation was similar to the baseline tests; but instead of the head swiping across the barrier face, the side of the head made solid contact with the barrier, resulting in high resultant accelerations and HIC values. These tests (F3 and G2) reported higher thoracic and abdominal deflections and viscous criterion values than the baseline tests (Tables 3 and 4).

When the 1,900 kg barrier was crabbed (27 degrees) with an impact velocity of 56.1 km/h, head kinematics, thoracic injury measures, and abdominal injury measures in the Ford Focus (F4) were very similar to those in the perpendicular test of the Focus (F3) with the same mass and lateral impact velocity. The timing of the solid head contacts during these two tests were very similar (at 45 and 44 ms into the crash for tests F3 and F4, respectively; see Figure 5). The higher speed tests (F3 and F4) caused similar anterior-posterior head accelerations (Figure 6) even though the crabbed impact produced higher vehicle longitudinal velocity changes (Figure 3). The timing of the driver thoracic loading is shown in Figure 7 for the Focus tests. The crabbed impact (F4) deflection timing is very similar to the other tests at the same impact mass (F2 and F3).

In the Grand Am tests, the crabbed impact (G3) produced similar kinematics and dummy injury measures to the perpendicular impact (G2), with the exception of higher thoracic injury measures. The timing of the driver thoracic loading is shown in Figure 8 for the Grand Am tests. The crabbed impact (G3) deflection timing falls between the perpendicular test at the higher mass and speed (G2) and the lower mass and speed (G1). The hard head contacts in tests G2 and G3 occurred within 1 ms of each other and followed similar trends as those observed in the Focus head acceleration data.

Table 3.
Ford Focus driver SID-IIs maximum injury measures

Test number	F1	F2	F3	F4
Barrier mass (kg)	1,500	1,900	1,900	1,900
Barrier speed (km/h)	48.3	48.3	50.0	56.1
Approach angle	0°	0°	0°	27°
Head				
HIC-15	1281	1428	2992	3215
Resultant accel (g)	266	198	274[a]	260[a]
Neck				
Tension (kN)	3.6	3.5	2.4	2.3
Compression (kN)	0.0	0.0	3.0	3.0
X moment (Nm)	135	144	75	66
Thorax				
Deflection (mm)	45	62	57	59
Deflection rate (m/s)	7.6	6.8	6.5	7.1
Viscous criterion	1.1	1.9	1.5	2.1
Abdomen				
Deflection (mm)	44	53	52	50
Deflection rate (m/s)	8.3	6.1	7.4	7.0
Viscous criterion	1.2	1.5	1.8	1.7
Pelvic forces				
Pubic (kN)	-0.7	-0.7	-0.5	-0.7
Iliac (kN)	4.9	3.8	3.9	3.2
Acetabulum (kN)[b]	2.4	0.6	2.8	3.7
Combined (kN)[b]	7.0	4.2	6.5	6.8

[a]Hard head contact with the barrier face.
[b]Prototype upper femur brackets (provided by FTSS) were used in tests F3 and F4 (see text).

Table 4.
Pontiac Grand Am driver SID-IIs maximum injury measures

Test number	G1	G2	G3
Barrier mass (kg)	1,500	1,900	1,900
Barrier speed (km/h)	48.3	50.0	56.1
Approach angle	0°	0°	27°
Head			
HIC-15	520	1677	2020
Resultant accel (g)	93	248[a]	228[a]
Neck			
Tension (kN)	2.2	2.7	2.5
Compression (kN)	0.0	3.1	2.8
X moment (Nm)	48	50	53
Thorax			
Deflection (mm)	41	45	55
Deflection rate (m/s)	5.9	6.0	5.9
Viscous criterion	0.9	1.1	1.3
Abdomen			
Deflection (mm)	56	60	57
Deflection rate (m/s)	8.9	9.9	10.1
Viscous criterion	2.5	2.7	2.5
Pelvic forces			
Pubic (kN)	-0.7	-0.4	-0.6
Iliac (kN)	3.4	3.9	3.1
Acetabulum (kN)[b]	2.4	2.5	2.9
Combined (kN)[b]	5.7	6.2	5.7

[a]Hard head contact with the barrier face.
[b]Prototype upper femur brackets (provided by FTSS) were used in tests G2 and G3 (see text).

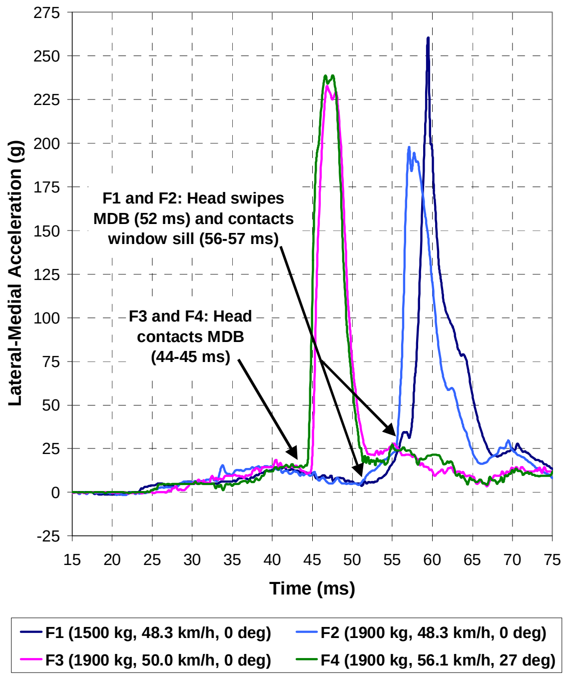

Figure 5. Lateral head motion of the driver SID-IIs in the four Focus tests was almost identical up to 44 ms. At this time, the faster MDB in tests F3 and F4 intruded further into the vehicle and contacted the dummy's head. The dummy in tests F1 and F2 swiped across the barrier face and then contacted the window sill.

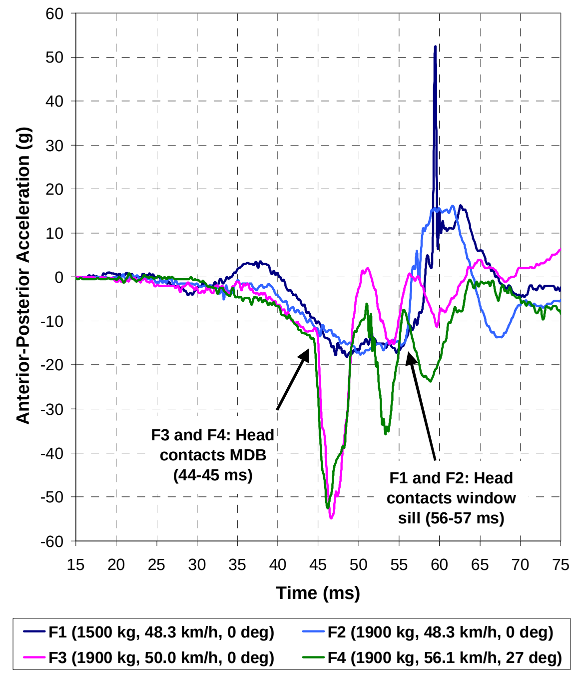

Figure 6. Higher speed tests (F3 and F4) caused similar anterior-posterior head accelerations even though the crabbed impact produced higher vehicle longitudinal accelerations. The lower speed tests (F1 and F2) followed similar acceleration patterns.

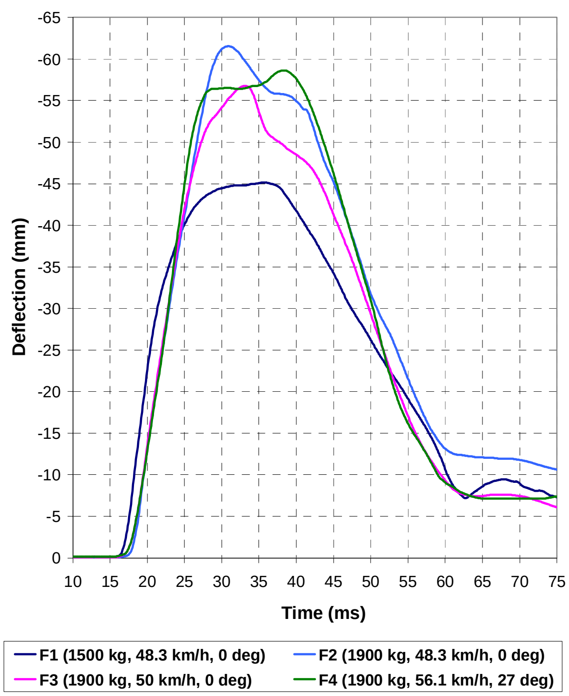

Figure 7. Comparison of driver dummy's third thoracic rib deflection in Ford Focus tests. The timing of the crabbed test (F4) is essentially identical to the perpendicular tests at the same mass (F2 and F3).

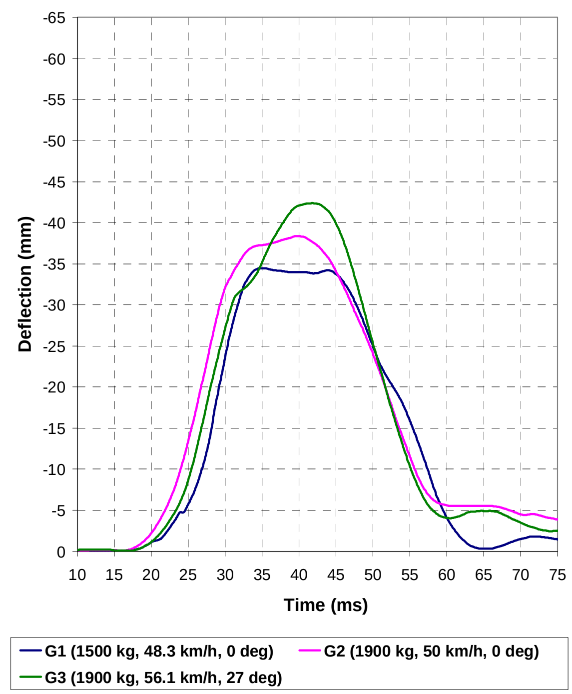

Figure 8. Comparison of driver dummy's third thoracic rib deflection in Pontiac Grand Am tests.

The acetabulum and combined pelvic loads in tests F1, F2, and G1 may be underreported because the SID-IIs dummies were instrumented with the old style upper femur brackets. These brackets are capable of contacting the back of the acetabulum load cell causing erroneous negative (tensile) acetabular loads (Arbelaez et al., 2002b). Prototype femur brackets, designed by First Technology Safety Systems (FTSS), were used in the driver and left rear passenger dummies in tests F3, F4, G2, and G3 to evaluate their effectiveness. These prototype brackets reduced the occurrence of negative loads in all but one of these tests (1 of 8 dummy exposures), thus additional modifications were made prior to the finalization of the production level design.

Rear Passenger Dummy Kinematics and Injury Measures

Injury measures recorded by the dummy in the left rear seating position were mixed. In these tests, the dummy head contacted the interior compartment and/or the barrier face. When the barrier mass was increased to 1,900 kg, there were minor increases in resultant head acceleration and HIC. When both the barrier mass and speed were increased for tests F3 and G2, the impact between the dummy's head and the vehicle interior/barrier face produced resultant head accelerations and HIC values that were significantly higher than those in the baseline tests (Tables 5 and 6).

Postcrash data analysis revealed that the lower thoracic linear potentiometer was defective in tests F1, F2, and G1. Typically this third rib produced the highest deflections in the other tests. Thus the reported thoracic measures in these three tests, which came from the top two ribs only, may underestimate the actual injury risk in the thorax.

In the crabbed impact tests (F4 and G3), the head struck both the rear quarter window frame and the barrier face. This contact resulted in head injury measures that were significantly higher than the perpendicular tests. Thoracic and abdominal injury measures were lower than their counterpart perpendicular tests (F3 and G2).

DISCUSSION

In previous publications, IIHS has presented the research and testing underpinning the barrier design and

Table 5. Ford Focus rear passenger SID-IIs maximum injury measures

Test number	F1	F2	F3	F4
Barrier mass (kg)	1,500	1,900	1,900	1,900
Barrier speed (km/h)	48.3	48.3	50.0	56.1
Approach angle	0°	0°	0°	27°
Head				
HIC-15	484	529	1793	2788
Resultant accel (g)	85	115	219	251
Neck				
Tension (kN)	1.2	0.6	1.7	1.9
Compression (kN)	0.3	1.9	1.7	0.3
X moment (Nm)	31	33	64	55
Thorax[a]				
Deflection (mm)	33	27	49	27
Deflection rate (m/s)	2.9	2.5	5.4	6.3
Viscous criterion	0.5	0.4	0.7	0.5
Abdomen				
Deflection (mm)	53	41	52	19
Deflection rate (m/s)	4.8	4.0	5.4	4.2
Viscous criterion	1.5	0.5	0.7	0.3
Pelvic forces				
Pubic (kN)	-0.6	-0.8	-0.6	-0.3
Iliac (kN)	1.0	0.7	1.0	1.3
Acetabulum (kN)[b]	1.5	-	2.2	2.1
Combined (kN)[b]	7.0	-	2.9	2.6

[a]Thoracic measures in tests F1 and F2 may be underreported (see text).
[b]Prototype upper femur brackets (provided by FTSS) were used in tests F3 and F4 (see text).

Table 6. Pontiac Grand Am rear passenger SID-IIs maximum injury measures

Test number	G1	G2	G3
Barrier mass (kg)	1,500	1,900	1,900
Barrier velocity (km/h)	48.3	50.0	56.1
Approach angle	0°	0°	27°
Head			
HIC-15	759	1208	3607
Resultant accel (g)	104	170	282
Neck			
Tension (kN)	2.6	1.7	1.7
Compression (kN)	0.1	0.3	0.3
X moment (Nm)	25	34	96
Thorax[a]			
Deflection (mm)	26	47	36
Deflection rate (m/s)	2.1	7.3	4.6
Viscous criterion	0.2	0.7	0.5
Abdomen			
Deflection (mm)	51	49	31
Deflection rate (m/s)	6.7	6.9	5.2
Viscous criterion	1.2	1.3	0.6
Pelvic forces			
Pubic (kN)	-0.8	-0.7	-1.0
Iliac (kN)	0.7	0.4	1.1
Acetabulum (kN)[b]	1.6	1.8	0.7
Combined (kN)[b]	1.9	2.0	1.7

[a]Thoracic measures in tests F1 and F2 may be underreported (see text).
[b]Prototype upper femur brackets (provided by FTSS) were used in tests G2 and G3 (see text).

choice of anthropomorphic test device for its new side impact crashworthiness evaluation program (Arbelaez et al., 2002a, 2002b). However, additional test parameters remained to be specified. MDB masses representing the average weight of all striking vehicles (1,500 kg) and striking SUVs (1,900 kg) in serious injury producing side impacts were considered. Barrier speeds of 48.3 km/h (longitudinal component of FMVSS 214), 50.0 km/h (ECE R95), and 56.1 km/h (crabbed equivalent of ECE R95) were investigated. Barrier approach angles were either crabbed 27 degrees (FMVSS 214) or perpendicular (ECE R95).

Results from tests with the Ford Focus indicate relatively little effect of the mass difference on dummy kinematics, injury measures, or vehicle response. Although some measures increased for the higher mass barrier, as expected from the greater kinetic energy, the increases were surprisingly small compared with the effect of increasing test speed. The most obvious effect of the higher test speed was the increased likelihood of head contact by the barrier and, consequently, higher HIC scores. From these results, it seems that whether the barrier mass is 1,500 kg or 1,900 kg is relatively unimportant in evaluating the protection of near side occupants in crashes in the speed range studied. In contrast, even a small increase in speed from 48.3 to 50.0 km/h appears to significantly increase the sensitivity of the test to the presence of adequate head protection. This finding suggests that the timing of events, as they are affected by the crash speed, are more important than changes in total kinetic energy (because the kinetic energy associated with the speed change is much smaller than that of the mass difference studied).

Results for impact configuration were more complex. Both the Focus and Grand Am were impacted in each configuration by a 1,900 kg barrier with a longitudinal velocity of 50.0 km/h. The crabbed configuration resulted in higher HIC scores for both dummies in both vehicles. However, among other dummy injury measures there was no consistent effect of impact configuration: some were lower and some higher in the crabbed configuration. This inconsistency may reflect the higher impact speed of the crabbed barrier (56.1 km/h resultant velocity) and the fact that the head of SID-IIs is sensitive to this difference. That is, HIC is calculated from the resultant of the head's triaxial acceleration measurements so that if the barrier had greater retained velocity at the time of head impact, the head can register it from any angle. The lack of a consistent difference between crabbed and perpendicular impacts for other body regions could mean that SID-IIs does not adequately reflect forces applied at an angle to those regions. Thus, although the crabbed configuration has some intuitive merit in representing the likelihood that both vehicles have some forward velocity at the time of impact, the principal advantage of the crabbed configuration in forcing injury countermeasures is the potential for more severe head impacts and the other body regions of SID-IIs appear to be relatively insensitive to the crabbed configuration. Given that the perpendicular impact also produces a hard head impact with the barrier that must be mitigated by some sort of head protection, it is unclear what further advantage could be gained from a crabbed impact test procedure, in terms of producing effective countermeasures.

In summary, these tests indicate that, within the ranges of speed, mass, and impact configuration studied, the most critical factor is test speed; the higher test speed produced a more consistent barrier-to-head impact for both tested vehicles. Given these findings, IIHS has elected to conduct its side impact crashworthiness evaluations using a perpendicular impact (50.0 km/h) in which a 1,500 kg MDB strikes the side of the stationary evaluated vehicle. The speed has been chosen to achieve a reasonable likelihood of head contact in vehicles that lack specific head impact countermeasures. The lower mass has been chosen in hopes that it will promote harmonization of test procedures in other parts of the globe, where 1,900 kg may be seen as unrealistically heavy — the results in this study suggest that this choice is without significant consequence for evaluating the side impact protection for struck side occupants. Finally, the perpendicular impact has been favored over the crabbed configuration because the latter is slightly more complex and offers little additional advantage for encouraging effective injury countermeasures at this time.

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APPENDIX A

Equation 1: The head injury criterion (HIC)

$$HIC = \left[\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} (t_2 - t_1)$$

Where,
a(t) = resultant head acceleration
t_1, t_2 = start and stop times of the integration, which are selected to give the largest HIC value. For the HIC analysis, t_1 and t_2 are constrained such that $(t_2 - t_1) \leq 15$ ms.

Equation 2: Rib deflection rate

$$V(t)_i = \dot{D}(t)_i$$

Where,
$D(t)_i$ = the deflection of rib *i* at time *t*, measured with linear potentiometers and filtered to SAE CFC180 (mm)

Equation 3: Viscous criterion (VC)

$$VC(t)_i = 1.0 * V(t)_i * \frac{D(t)_i}{138mm}$$

Where,
$V(t)_i$ = the velocity of rib *i* at time *t*, from Eq. 2 (m/s)
$D(t)_i$ = the deflection of rib *i* at time *t*, measured with linear potentiometers and filtered to SAE CFC180 (mm)

Equation 4: Combined pelvic force

$$F_P(t) = F_A(t) + F_I(t)$$

Where,
$F_A(t)$ = lateral acetabulum force (kN)
$F_I(t)$ = lateral iliac force (kN)

APPENDIX B

Figure B1. SID-IIs kinematics in Ford Focus test F1 (1,500 kg, perpendicular, 48.3 km/h). Top: time zero; middle: head swipes across barrier then continues to rotate laterally until it contacts window sill; bottom: following window sill contact, head rebounds inboard.

Figure B2. SID-IIs kinematics in Ford Focus test F2 (1,900 kg, perpendicular, 48.3 km/h). Top: time zero; middle: head swipes across barrier then continues to rotate laterally until it contacts window sill; bottom: following window sill contact, head rebounds inboard.

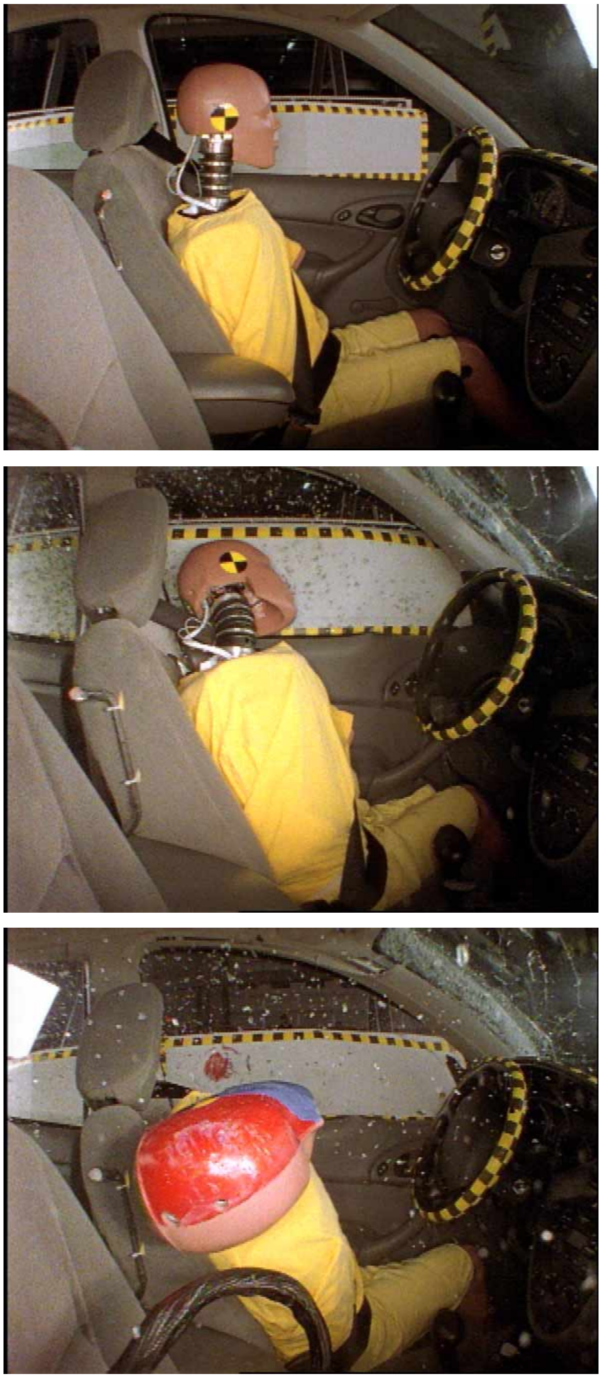

Figure B3. SID-IIs kinematics in Ford Focus test F3 (1,900 kg, perpendicular, 50.0 km/h). Top: time zero; middle: head rotates outboard and is struck by intruding barrier; bottom: following barrier contact, head rebounds inboard.

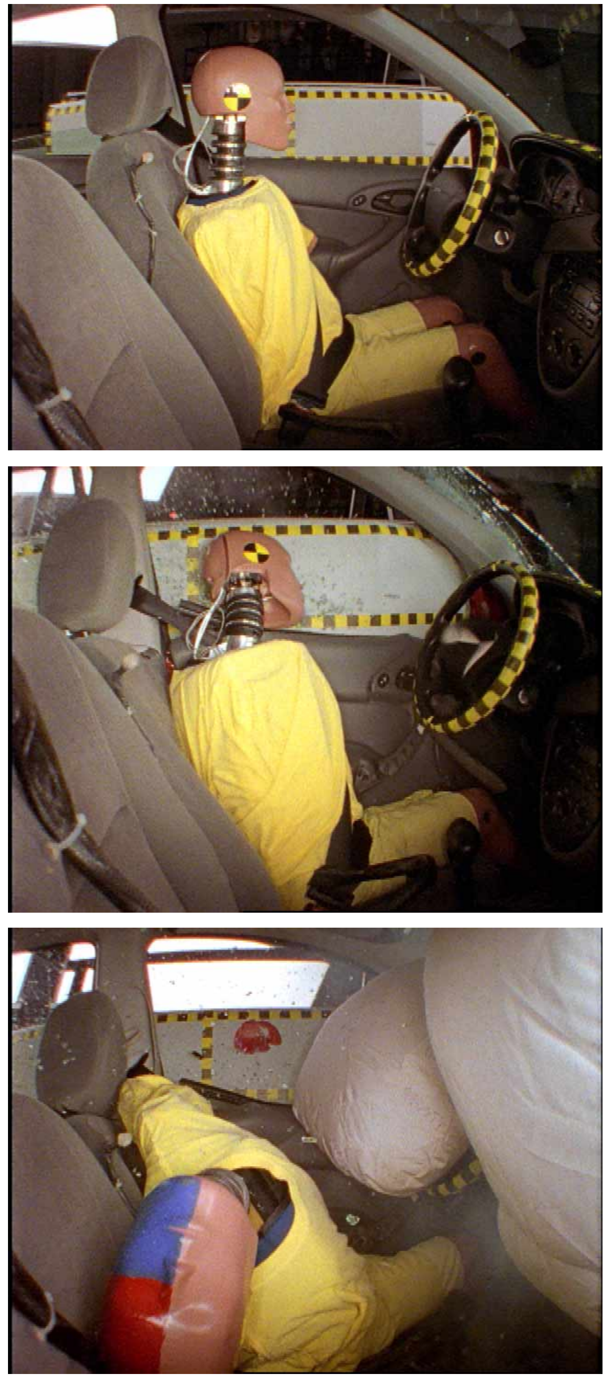

Figure B4. SID-IIs kinematics in Ford Focus test F4 (1,900 kg, crabbed, 56.1 km/h). Top: time zero; middle: head rotates outboard and is struck by intruding barrier; bottom: following barrier contact, head rebounds inboard.

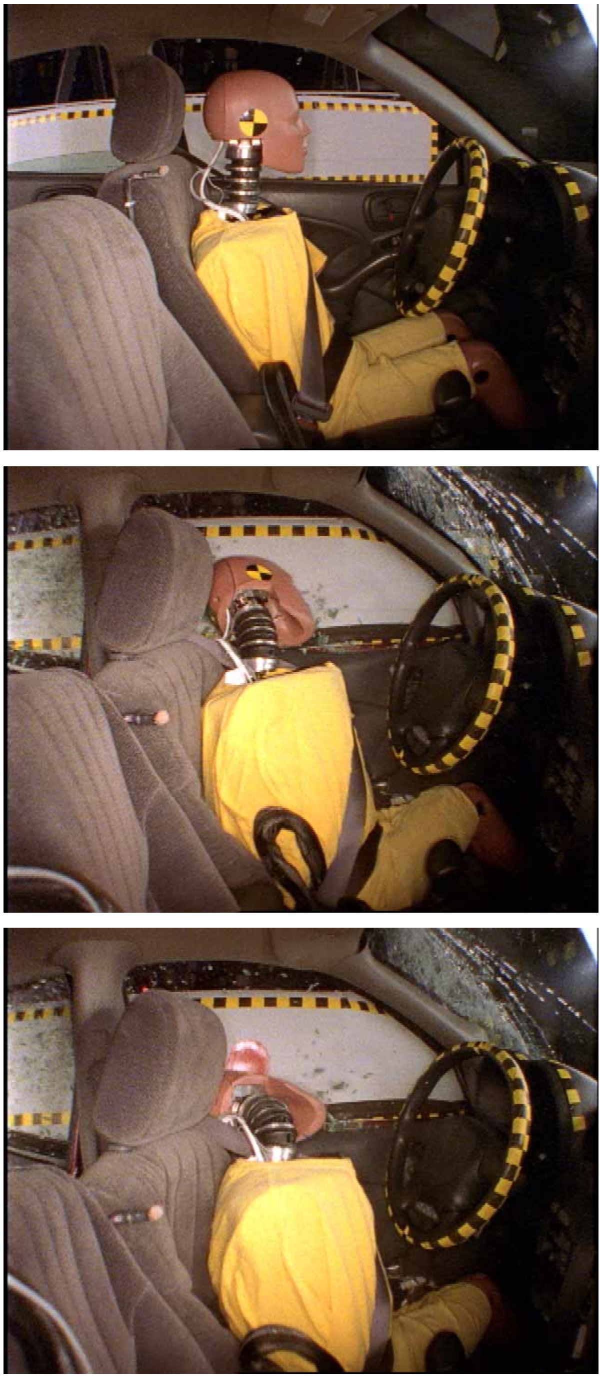

Figure B5. SID-IIs kinematics in Pontiac Grand Am test G2 (1,900 kg, perpendicular, 50.0 km/h). Top: time zero; middle: head rotates outboard and is struck by intruding barrier; bottom: following barrier contact, head contacts window sill.

Figure B6. SID-IIs kinematics in Pontiac Grand Am test G3 (1,900 kg, crabbed, 56.1 km/h). Top: time zero; middle: head rotates outboard and is struck by intruding barrier; bottom: following barrier contact, head rebounds inboard.