FRONTAL OFFSET DEFORMABLE BARRIER CRASH TESTING AND ITS EFFECT ON VEHICLE STIFFNESS

Joseph M. Nolan
Adrian K. Lund
Insurance Institute for Highway Safety
United States of America
Paper No. 487

ABSTRACT

Since 1995, the Insurance Institute for Highway Safety (IIHS) has evaluated the crashworthiness of more than 120 new vehicle models in a 64 km/h (40 mi/h), 40 percent offset deformable barrier crash test. The offset test is especially demanding of the vehicle structure, requiring only 40 percent of the vehicle width to manage the crash energy. Many of the models originally tested have been redesigned and retested, with the majority producing better structural performance than their predecessors. Critics of such testing have suggested that these tests are forcing vehicle stiffness too high for compatibility with other vehicles and other crash modes. IIHS has studied the relationship between vehicle mass, stiffness, and front-end length to the structural rating in the offset test. IIHS then studied vehicle accelerations, deformation, and interior intrusion for eight pairs of vehicles whose structural performance changed in the offset test after redesign for evidence of front-end stiffness changes. The data indicate that there were no significant correlations between mass, front-end length, and stiffness to structural performance in the offset test. The data also indicate that for models that sustained catastrophic collapse of the vehicle structure in the offset test, an increase in overall stiffness was required for better structural performance. The majority of vehicles whose structural performance improved did so without significant alteration to the stiffness of the vehicle for the first half-meter of deformation. These vehicles have maintained essentially the same stiffness in the front crush zone but have rapidly increasing stiffness as the deformation approaches the occupant compartment.

INTRODUCTION

Frontal offset crash testing has gained acceptance worldwide as an assessment of the frontal crashworthiness of vehicles. In the offset test, 40 percent of the vehicle's front end strikes a deformable barrier mounted to a rigid barrier at 64 km/h (40 mi/h). The deformable barrier is intended to initiate deformation patterns seen in real car-to-car, 50 percent frontal offset impacts (Lund et al., 1995). Because the offset test forces a smaller portion of the vehicle's front end to manage crash energy, there is more localized deformation on the struck vehicle than seen in flat barrier tests such as the National Highway Traffic Safety Administration's New Car Assessment Program (NCAP).

To achieve good performance in the offset test it is necessary to minimize intrusion into the occupant compartment by absorbing the crash energy in the crush zone forward of the compartment. If a vehicle's occupant compartment is weaker than the front crush zone, the occupant compartment will be compromised before full use of the available energy-absorption capacity of the front crush zone has occurred. In this case, front-end stiffness needs to be decreased and occupant compartment stiffness increased. It is imperative to design vehicles with sufficient energy-absorption capacity in the crush zone and with an occupant compartment that can resist the forces of front-end crush without yielding. Zobel (1999) calls this strategy for occupant protection 'the bulkhead concept.'

Some are concerned that the bulkhead concept will drive vehicle front-end stiffness too high for compatibility with other vehicles (Zobel, 1999). This can be shown to be true when considering only simple models of vehicles in crashes. However, there are other possibilities to improve offset structural performance without increasing overall stiffness. In cases where occupant compartment failure occurs before full energy absorption of the front structure has been realized, a decrease in front-end stiffness is required. The front end also must be designed carefully to ensure that stiff front-end components such as engine cradles and longitudinal rails do not unnecessarily impinge on the occupant compartment before the crash energy has been absorbed.

Although not the focus of this paper, it should be noted that the effect of stiffness on injury causation in crashes remains unclear, particularly in side impact collisions (Nolan et al., 1999). The majority of research indicates that after controlling for mass, vehicle geometry is the dominant factor for compatibility in both frontal and side collisions (Meyerson and Nolan, 2001).

The Insurance Institute for Highway Safety (IIHS) has conducted more than 120 offset crashes of new vehicles available in the U.S. market since 1995, rating each vehicle's performance for consumer information. An instrumented 50th percentile male Hybrid III dummy is used to evaluate driver injury risk. Separate ratings are assigned to each vehicle in five rating categories: structural performance; head, neck, and chest injury risk; and occupant kinematics.

This paper includes two separate analyses. The first is a statistical analysis of the relationship between vehicle front-end stiffness, as calculated from full-frontal rigid barrier tests, to the structural performance of 80 vehicles in the offset test. Vehicle mass and front-end length also were included in the analysis to control for the separate effects of these physical variables.

The second analysis is an examination of the acceleration and displacement of the occupant compartment measured in the offset test for eight models that were retested for evidence of stiffness changes after a major redesign. The eight models had large changes in structural performance in the offset test after the redesign, with seven scoring better and one worse. These models provided an opportunity to study specific production vehicle changes and the influence of these changes on structural test performance and front-end stiffness.

METHOD

Each vehicle subjected to the IIHS frontal offset test is assigned a structural rating of good, acceptable, marginal, or poor based on its performance in the test (IIHS, 2000a,b). The structural rating is based primarily on the vehicle's ability to maintain its occupant compartment integrity during the crash. Vehicles with minimal intrusion into the occupant compartment are rated good, vehicles with excessive intrusion are rated poor, and the gradations between these extremes are rated acceptable or marginal. The structural rating also can be affected by structural performance not directly related to intrusion such as fuel leakage during the tests, door opening during the test, etc., but such downgrades are uncommon. Occupant compartment intrusion is quantified by measuring the precrash and postcrash coordinates of various parts of the vehicle interior. Intrusion is measured at the footrest, brake pedal, three locations on the toepan, and two locations on the instrument panel. The change in driver A-to-B-pillar distance also is measured, representing the door aperture closure as a result of the impact.

Statistical Analysis

The statistical analysis includes the 120 vehicles rated by IIHS. The data set includes 74 cars, 27 utility vehicles, 14 passenger vans, and 5 pickups. Recorded for each vehicle were its structural rating, test mass, and front-bumper-to-firewall distance (front-end length). Table 1 lists the vehicles included in the analysis by vehicle type. Stiffness values were calculated for 80 vehicles in the data set that were subjected to the NCAP test using the two methods described below.

Table 1
Summary of Test Vehicle Metrics

Model Year	Vehicle	Structural Rating	Mass (kg)	Wheelbase (cm)	Overall Length (cm)	Body Type	Front Bumper to Firewall (cm)
1995	Chevrolet Cavalier	Poor	1,362	264	458	Car	112
1995	Chevrolet Lumina	Good	1,645	273	510	Car	125
1995	Chrysler Cirrus LX	Poor	1,553	274	472	Car	110
1995	Ford Contour	Marginal	1,431	271	467	Car	105
1995	Ford Taurus	Good	1,565	269	488	Car	121
1995	Honda Accord	Acceptable	1,452	272	467	Car	120
1995	Mazda Millenia	Marginal	1,593	275	482	Car	111
1995	Mitsubishi Galant	Poor	1,459	263	475	Car	121
1995	Nissan Maxima	Acceptable	1,507	270	477	Car	118
1995	Saab 900S	Poor	1,489	260	464	Car	118
1995	Subaru Legacy	Acceptable	1,380	263	459	Car	114
1995	Toyota Camry	Acceptable	1,511	262	477	Car	123
1995	Volkswagen Passat	Marginal	1,557	262	461	Car	112
1995	Volvo 850	Acceptable	1,555	266	466	Car	117
1996	Ford Taurus	Good	1,651	276	502	Car	132
1996	Hyundai Sonata	Poor	1,485	270	470	Car	117
1996	Toyota Avalon	Marginal	1,584	272	483	Car	121
1997	BMW 540i	Good	1,876	283	478	Car	129
1997	Cadillac Seville	Poor	1,910	282	519	Car	138
1997	Dodge Neon	Marginal	1,308	264	436	Car	108
1997	Ford Escort	Acceptable	1,294	250	443	Car	108

Model Year	Vehicle	Structural Rating	Mass (kg)	Wheelbase (cm)	Overall Length (cm)	Body Type	Front Bumper to Firewall (cm)
1997	Honda Civic	Acceptable	1,244	262	445	Car	100
1997	Hyundai Elantra	Acceptable	1,355	255	442	Car	104
1997	Infiniti Q45	Acceptable	1,944	283	506	Car	134
1997	Infiniti Q45	Acceptable	1,944	283	506	Car	134
1997	Kia Sephia	Poor	1,316	250	436	Car	107
1997	Lexus LS 400	Good	1,886	285	500	Car	120
1997	Lincoln Continental	Acceptable	1,914	277	524	Car	137
1997	Mazda Protege	Acceptable	1,272	261	444	Car	104
1997	Mercedes E420	Good	1,802	283	481	Car	123
1997	Mitsubishi Mirage	Marginal	1,231	250	442	Car	109
1997	Pontiac Grand Prix	Acceptable	1,711	281	499	Car	133
1997	Saturn SL	Acceptable	1,240	260	449	Car	107
1997	Toyota Camry	Good	1,558	267	478	Car	117
1997	Volkswagen Jetta	Marginal	1,365	247	440	Car	106
1998	Honda Accord	Acceptable	1,526	272	480	Car	124
1998	Nissan Maxima	Acceptable	1,550	270	481	Car	121
1998	Nissan Sentra	Marginal	1,281	254	434	Car	103
1998	Toyota Avalon	Acceptable	1,680	272	488	Car	124
1998	Toyota Corolla	Acceptable	1,284	246	442	Car	109
1998	Volkswagen Beetle	Good	1,377	251	409	Car	105
1998	Volkswagen Passat	Good	1,576	271	468	Car	113
1999	Audi A6	Acceptable	1,822	276	488	Car	100
1999	Buick Park Avenue	Good	1,840	289	525	Car	122
1999	Cadillac Catera	Acceptable	1,842	273	493	Car	136
1999	Chevrolet Malibu	Acceptable	1,500	272	484	Car	126
1999	Chrysler LHS	Marginal	1,737	287	528	Car	123
1999	Daewoo Leganza	Poor	1,574	267	467	Car	119
1999	Hyundai Sonata	Marginal	1,544	270	471	Car	122
1999	Kia Sephia	Marginal	1,308	256	443	Car	108
1999	Lexus GS 400	Good	1,824	280	480	Car	122
1999	Mazda 626	Acceptable	1,416	267	474	Car	124
1999	Mazda Protege	Acceptable	1,302	261	442	Car	110
1999	Mitsubishi Galant	Acceptable	1,511	264	477	Car	122
1999	Pontiac Grand Am	Marginal	1,513	272	474	Car	128
1999	Saab 9-3	Acceptable	1,567	260	463	Car	125
1999	Saab 9-5	Acceptable	1,734	270	480	Car	117
1999	Volkswagen Jetta	Acceptable	1,455	251	438	Car	110
2000	BMW 328i	Good	1,620	272	447	Car	116
2000	Buick LeSabre	Good	1,728	285	508	Car	128
2000	Cadillac Seville	Good	1,916	285	510	Car	138
2000	Chevrolet Impala	Good	1,676	281	508	Car	134
2000	Dodge Intrepid	Acceptable	1,692	287	517	Car	124
2000	Dodge Neon	Marginal	1,319	267	443	Car	110
2000	Ford Taurus	Good	1,622	276	502	Car	127
2000	Lincoln LS	Good	1,837	291	492	Car	126
2000	Nissan Altima	Marginal	1,512	262	472	Car	116
2000	Nissan Maxima	Acceptable	1,624	275	484	Car	118
2000	Nissan Sentra	Acceptable	1,324	254	450	Car	108
2000	Saturn LS	Acceptable	1,565	270	484	Car	122
2000	Subaru Legacy	Good	1,600	265	468	Car	115

Model Year	Vehicle	Structural Rating	Mass (kg)	Wheelbase (cm)	Overall Length (cm)	Body Type	Front Bumper to Firewall (cm)
2000	Toyota Avalon	Good	1,677	272	488	Car	118
2000	Volvo S80	Good	1,715	279	482	Car	116
1996	Chevrolet Astro	Poor	2,131	282	482	Passenger van	74
1996	Dodge Grand Caravan	Acceptable	2,002	303	507	Passenger van	106
1996	Ford Aerostar	Poor	1,815	302	444	Passenger van	86
1996	Ford Windstar	Good	1,920	307	511	Passenger van	123
1996	Honda Odyssey	Poor	1,702	283	475	Passenger van	118
1996	Mazda MPV	Marginal	1,852	280	466	Passenger van	118
1996	Nissan Quest	Acceptable	1,862	285	482	Passenger van	119
1996	Toyota Previa	Marginal	1,874	287	475	Passenger van	89
1997	Pontiac Trans Sport	Poor	1,852	284	476	Passenger van	114
1998	Toyota Sienna	Good	1,928	290	492	Passenger van	120
1999	Ford Windstar	Acceptable	1,992	307	511	Passenger van	121
1999	Honda Odyssey	Acceptable	2,078	300	511	Passenger van	117
1999	Nissan Quest	Poor	1,936	285	495	Passenger van	120
2000	Mazda MPV	Acceptable	1,775	284	475	Passenger van	112
1998	Chevrolet S-10	Marginal	1,569	275	480	Pickup	120
1998	Dodge Dakota	Marginal	1,758	284	497	Pickup	119
1998	Ford Ranger	Marginal	1,584	283	476	Pickup	121
1998	Nissan Frontier	Acceptable	1,518	265	468	Pickup	111
1998	Toyota Tacoma	Acceptable	1,380	262	469	Pickup	109
1996	Chevrolet Blazer	Poor	2,013	272	461	Utility vehicle	124
1996	Ford Explorer	Acceptable	2,048	283	479	Utility vehicle	110
1996	Isuzu Rodeo	Poor	2,030	276	468	Utility vehicle	101
1996	Jeep Grand Cherokee	Acceptable	1,850	269	449	Utility vehicle	130
1996	Land Rover Discovery	Acceptable	2,134	254	452	Utility vehicle	127
1996	Mitsubishi Montero	Acceptable	2,162	272	470	Utility vehicle	119
1996	Toyota 4-Runnner	Acceptable	1,924	268	454	Utility vehicle	107
1997	Nissan Pathfinder	Poor	2,060	270	453	Utility vehicle	106
1998	Honda CRV	Acceptable	1,577	262	451	Utility vehicle	108
1998	Isuzu Amigo	Poor	1,758	246	427	Utility vehicle	108
1998	Jeep Cherokee	Marginal	1,701	258	425	Utility vehicle	106
1998	Jeep Wrangler	Acceptable	1,594	237	386	Utility vehicle	123
1998	Kia Sportage	Marginal	1,652	265	432	Utility vehicle	113
1998	Toyota RAV4	Acceptable	1,498	241	416	Utility vehicle	100
1999	Dodge Durango	Acceptable	2,312	294	491	Utility vehicle	108
1999	Jeep Grand Cherokee	Marginal	1,920	269	461	Utility vehicle	128
1999	Land Rover Discovery	Acceptable	2,314	254	470	Utility vehicle	126
1999	Lexus RX300	Acceptable	1,900	262	458	Utility vehicle	114
1999	Mercedes ML320	Good	2,125	282	459	Utility vehicle	122
1999	Mitsubishi Montero Sport	Marginal	1,990	272	453	Utility vehicle	100
1999	Subaru Forester	Acceptable	1,549	252	445	Utility vehicle	110
1999	Suzuki Grand Vitara	Acceptable	1,593	248	418	Utility vehicle	113
2000	Isuzu Rodeo	Good	1,946	270	451	Utility vehicle	107
2000	Isuzu Trooper	Poor	2,100	276	471	Utility vehicle	113
2000	Nissan Xterra	Good	1,998	265	452	Utility vehicle	108
2001	BMW X5	Good	2,168	282	467	Utility vehicle	126
2001	Mitsubishi Montero	Good	2,264	278	480	Utility vehicle	110

Stiffness Determination Method 1 The crush characteristics of vehicle front structures have typically been modeled as simple mass-spring systems based on the empirical data from full-frontal rigid barrier crash tests (Nash, 1987; Park, 1999; Prasad, 1990a,b). In these tests, the extent of frontal deformation is approximately a linear function of impact speed. This observed linear relationship suggests that vehicle front structure can be modeled as an energy-dissipating linear spring, as shown in Equation 1. Using this model, the initial kinetic energy of a vehicle of mass *M* moving at a velocity of *V* can be equated to the energy dissipated by a linear spring with a spring constant *K* and maximum crush *x*. This model allows for a simple computation of a front-end linear stiffness value based on data from crash tests.

$$\tfrac{1}{2} MV^2 = \tfrac{1}{2} Kx^2 \qquad (1)$$

It should be noted that mass-spring models are not exact for vehicle front-ends in crashes. The model mass that is attached to the spring does not change during the impact, whereas in crash tests the moving mass changes as a function of frontal deformation. The observed linear relationship between impact speed and deformation in full-frontal crash tests is actually a combination of nonlinear stiffness and changing mass. The model approximates these two parameters with a single linear value. Despite their simplicity, mass-spring models continue to be the basis for estimating real-world crash severity (National Highway Traffic Safety Administration, 1981, 1999). These models, when appropriately applied, have been shown to produce reasonable estimates of crash severity for frontal offset deformable barrier crashes (O'Neill et al., 1996).

Values for stiffness were calculated using the NCAP published impact speed, test mass, and maximum dynamic displacement, as determined by double-integration of the rear-seat acceleration recorded in the NCAP test, and inputting the data into Equation 1.

Stiffness Determination Method 2 A second linear stiffness estimate was made for the same 80 vehicles subjected to the NCAP test. When Equation 1 is rewritten in its differential form, it is easily shown that the solution for x and $\dot{x}$ is sinusoidal (see Equation 2). This second method is slightly different from the first method in that it forces the actual velocity-time history to be sinusoidal to fit the model. Method 2 results in lower stiffness estimates than in method 1, because it does not account for the variable moving mass throughout the impact.

$$\tfrac{1}{2} M\dot{x}^2 = \tfrac{1}{2} Kx^2 \qquad (2)$$

Solving Equation 2 for velocity yields the following general solution (Equation 3), where *A* is the initial speed of the vehicle and ω is the natural frequency of the mass spring system. Equation 4 is the natural frequency of the system, expressed in the form of the linear stiffness, *K*, and mass, *M*.

$$V = A\,Cos\,(\omega t + \beta) \qquad (3)$$

$$\omega = \sqrt{K/M} \qquad (4)$$

The second stiffness estimate was calculated by first determining the vehicle longitudinal velocity versus time for the 80 vehicles subjected to the NCAP test. Velocity was determined by integrating the data from longitudinal accelerometers located on the rear-seat crossmember. A quarter-cosine was fit to the data from the time of impact until the time when the vehicle velocity was zero (beginning of rebound). The actual test impact speed was fixed (*A*), and ω was varied to achieve the best fit using a least-square error criteria. The resulting values for ω were then used in Equation 4 to determine the curve-fit stiffness value. Table 2 lists the two calculated stiffness estimates for the 80 vehicles.

For the 120-vehicle data set (all vehicles), average mass and front-end length values were computed for each of the four structural rating categories (good, acceptable, marginal, poor), and a multiple regression was conducted to assess the combined effects of mass and front-end length.

A similar analysis was conducted using the 80-vehicle subset containing stiffness estimates. Average mass, front-end length, and stiffness values were calculated for each structural rating category, and a weighted regression analysis was conducted. A multivariate regression analysis also was conducted to isolate effects of stiffness from mass and front-end length.

To eliminate any possible problems with combining results from various vehicle types, the above analyses were repeated using cars only. There were 74 cars in the 120-vehicle data set and 47 cars in the 80-vehicle data set.

Table 2
Stiffness for 80 Vehicles Tested in NCAP

Model Year	Make	Model	Structural Rating	Stiffness Energy Method (kN/m)	Stiffness Curve Fit (kN/m)
1995	Chevrolet	Cavalier	Poor	706	658
1995	Chevrolet	Lumina	Good	536	513
1995	Chrysler	Cirrus	Poor	940	881
1995	Ford	Contour	Marginal	937	848
1995	Ford	Taurus	Good	793	707
1995	Honda	Accord	Acceptable	742	696
1995	Mazda	Millenia	Marginal	885	796
1995	Mitsubishi	Galant	Poor	651	619
1995	Nissan	Maxima	Acceptable	758	700
1995	Saab	900	Poor	668	630
1995	Subaru	Legacy	Acceptable	608	566
1995	Toyota	Camry	Acceptable	671	603
1995	Volkswagen	Passat	Marginal	884	813
1996	Chevrolet	Astro	Poor	1,108	1,108
1996	Chevrolet	Blazer	Poor	898	870
1996	Dodge	Grand Caravan	Acceptable	739	707
1996	Ford	Explorer	Acceptable	1,253	,107
1996	Ford	Taurus	Good	780	722
1996	Ford	Windstar	Good	777	689
1996	Honda	Odyssey	Poor	850	766
1996	Hyundai	Sonata	Poor	649	641
1996	Jeep	Grand Cherokee	Acceptable	1,050	989
1996	Land Rover	Discovery	Acceptable	1,015	1,005
1996	Mazda	MPV	Marginal	1,139	1,023
1996	Mitsubishi	Montero	Acceptable	1,715	1,394
1996	Nissan	Quest	Acceptable	976	932
1996	Toyota	4-Runner	Good	1,299	1,113
1996	Toyota	Avalon	Marginal	776	710
1996	Toyota	Previa	Marginal	1,385	1,299
1997	Dodge	Neon	Marginal	606	588
1997	Ford	Escort	Acceptable	688	667
1997	Honda	Civic	Acceptable	563	529
1997	Hyundai	Elantra	Acceptable	737	702
1997	Kia	Sephia	Poor	792	774
1997	Mazda	Protege	Acceptable	700	663
1997	Nissan	Pathfinder	Poor	1,124	979
1997	Pontiac	Grand Prix	Acceptable	645	602
1997	Pontiac	Trans Sport	Poor	784	687
1997	Saturn	SL	Acceptable	408	383
1997	Toyota	Camry	Good	810	713
1997	Volkswagen	Jetta	Marginal	852	809
1998	Chevrolet	S-10	Marginal	777	745
1998	Dodge	Dakota	Marginal	1,147	1,071
1998	Ford	Ranger	Marginal	1,011	806
1998	Honda	Accord	Acceptable	759	702
1998	Honda	CR-V	Acceptable	1,079	1,056
1998	Jeep	Cherokee	Marginal	1,125	1,014
1998	Jeep	Wrangler	Acceptable	861	667
1998	Nissan	Frontier	Acceptable	1,223	1,105

Model Year	Make	Model	Structural Rating	Stiffness Energy Method (kN/m)	Stiffness Curve Fit (kN/m)
1998	Nissan	Maxima	Acceptable	836	779
1998	Nissan	Sentra	Marginal	733	668
1998	Toyota	Avalon	Acceptable	928	851
1998	Toyota	Corolla	Acceptable	692	632
1998	Toyota	RAV4	Acceptable	1,125	1,049
1998	Toyota	Sienna	Good	940	862
1998	Toyota	Tacoma	Acceptable	1,336	1,112
1998	Volkswagen	New Beetle	Good	1,129	1,022
1998	Volkswagen	Passat	Good	929	820
1999	Chevrolet	Malibu	Acceptable	723	654
1999	Chrysler	LHS	Marginal	895	837
1999	Dodge	Durango	Acceptable	1,366	1,267
1999	Ford	Windstar	Acceptable	804	717
1999	Honda	Odyssey	Acceptable	833	762
1999	Jeep	Grand Cherokee	Marginal	1,394	1,308
1999	Mazda	626	Acceptable	754	711
1999	Mazda	Protege	Acceptable	782	748
1999	Mitsubishi	Galant	Acceptable	623	642
1999	Nissan	Quest	Poor	980	892
1999	Pontiac	Grand Am	Marginal	610	545
1999	Subaru	Forester	Acceptable	921	841
1999	Volkswagen	Jetta	Acceptable	1,062	942
2000	Buick	LeSabre	Good	784	710
2000	Chevrolet	Impala	Good	709	636
2000	Dodge	Neon	Marginal	760	717
2000	Ford	Taurus	Good	850	794
2000	Isuzu	Rodeo	Good	1,164	1,077
2000	Mazda	MPV	Acceptable	1,386	1,233
2000	Nissan	Altima	Marginal	654	620
2000	Nissan	Maxima	Acceptable	771	744
2000	Subaru	Legacy	Good	1,077	990

Vehicle Redesign Analysis

Included among the 120 vehicles are 16 models whose structural ratings changed in the offset test after the vehicle structure was redesigned. Of the 16 models retested, 14 of the redesigns scored better structural ratings than did their predecessors. Eight of the 16 redesigns had structural rating changes of two or more rating categories; seven were improvements, and one was a downgrade. These eight vehicles provided the opportunity to study specific examples of the stiffness changes required to obtain significantly better structural ratings in the offset test (or a downgrade in one case). The measured acceleration and calculated displacement in the offset test were compared for these eight models for evidence of stiffness changes. For this analysis, longitudinal vehicle acceleration was measured on the center tunnel in the rear seat, and displacement was calculated by double-integrating this acceleration. Unfortunately load cell barrier data was not available from the NCAP tests both before and after redesign for any of these models.

RESULTS

Statistical Analysis

There was no evident relationship between stiffness (using either method) and the offset structural performance when looking at all vehicles or cars alone (Figures 1 and 2). The effect of stiffness was estimated after controlling for mass and front-end length in multiple regressions, but still no significant correlation to test performance was found.

There also was no significant relationship between mass and test performance when looking at all vehicles or cars alone (Figure 3). However, there was a trend evident in the data toward longer front-end-length vehicles performing better in the offset test (Figure 4). This trend was most apparent (and statistically significant) when all vehicles were included in the analysis, but among cars alone there were some models with longer front ends that performed poorly.

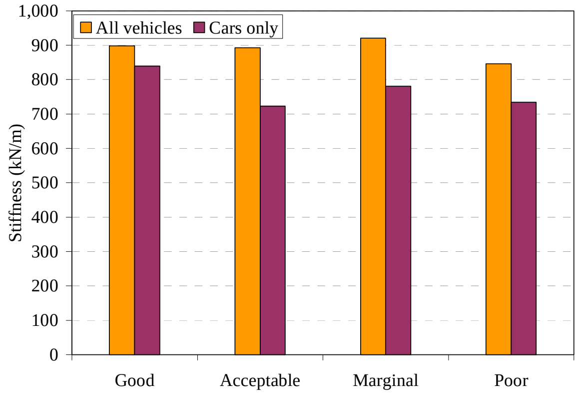

Figure 1. Average Stiffness (Method 1) by Rating Category

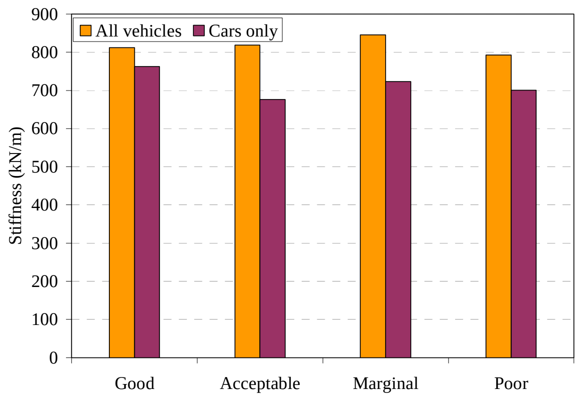

Figure 2. Average Stiffness (Method 2) by Rating Category

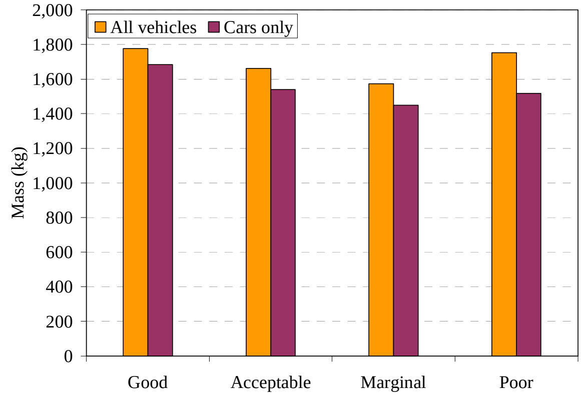

Figure 3. Average Mass by Rating Category

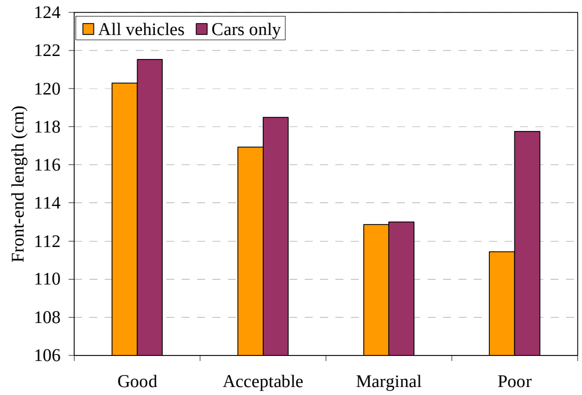

Figure 4. Average Front-End Length by Rating Category

Vehicle Redesign Analysis

Table 3 lists the 16 vehicle models that were tested before and after a major redesign. Listed for each vehicle is the maximum forward movement of the occupant compartment during the test, stiffness measures from the NCAP test, maximum footwell intrusion, and door aperture closure as a result of the crash. The eight models with significant structural rating changes after redesign are shaded. Figures 5-12 show acceleration versus displacement for the eight models that had large differences in structural ratings after redesign.

Table 3.
Vehicles Tested Before and After Redesign

Model Year	Make	Model	Structural Rating	Total Dynamic Crush (including Barrier) (cm)	Maximum Toepan Intrusion (cm)	Door Aperture Closure (cm)	Stiffness Method 1 (kN/m)	Stiffness Method 2 (kN/m)
1997	Cadillac	Seville	Poor	159	37	9	—	—
2000	Cadillac	Seville	Good	145	17	3	—	—
1996	Ford	Windstar	Good	186	18	9	777	689
1999	Ford	Windstar	Acceptable	155	22	3	804	717
1996	Honda	Odyssey	Poor	140	38	9	850	766
1999	Honda	Odyssey	Acceptable	147	22	0	833	762
1996	Hyundai	Sonata	Poor	140	31	17	649	641
1999	Hyundai	Sonata	Marginal	131	25	10	—	—
1996	Isuzu	Rodeo	Poor	137	39	16	—	—
2000	Isuzu	Rodeo	Good	129	14	1	1,164	1,077
1996	Mazda	MPV	Marginal	154	35	11	1,139	1,023
2000	Mazda	MPV	Acceptable	129	29	7	1,386	1,233
1995	Mitsubishi	Galant	Poor	138	32	25	651	619
1999	Mitsubishi	Galant	Acceptable	136	25	5	623	642
1996	Nissan	Quest	Acceptable	139	32	11	976	932
1999	Nissan	Quest	Poor	150	40	19	980	892
1998	Nissan	Sentra	Marginal	130	28	11	733	668
2000	Nissan	Sentra	Acceptable	128	20	5	—	—
1995	Saab	900	Poor	140	34	21	668	630
1999	Saab	9-3	Acceptable	141	26	11	—	—
1995	Subaru	Legacy	Acceptable	137	30	8	608	566
2000	Subaru	Legacy	Good	128	18	1	1,077	990
1996	Toyota	Avalon	Marginal	125	26	9	776	710
1998	Toyota	Avalon	Acceptable	139	27	2	928	851
2000	Toyota	Avalon	Good	131	15	5	—	—
1995	Toyota	Camry	Acceptable	131	25	5	671	603
1997	Toyota	Camry	Good	131	12	2	810	713
1996	Toyota	Previa	Marginal	133	29	3	1,385	1,299
1998	Toyota	Sienna	Good	135	10	1	940	862
1997	Volkswagen	Jetta	Marginal	127	34	10	852	809
1999	Volkswagen	Jetta	Acceptable	127	25	3	1,062	942
1995	Volkswagen	Passat	Marginal	141	36	4	884	813
1998	Volkswagen	Passat	Good	147	16	7	929	820

— No measurement was recorded

The Cadillac Seville (Figure 5) went from a poor structural rating for the 1997 model to a good rating for the 2000 model. Both models have similar mass and available crush space, but the 1997 model experienced major collapse of the occupant compartment whereas the redesigned model did not. The accelerations recorded were similar until more than 100 cm of combined vehicle and barrier deformation had occurred (the deformable barrier is 54 cm deep in the offset test and is crushed completely in all tests). There was evidence of increasing acceleration in the 2000 model test as total deformation reached 110 cm. Maximum dynamic deformation was reduced by 14 cm, and intrusion into the toepan was reduced by 20 cm with the redesigned model.

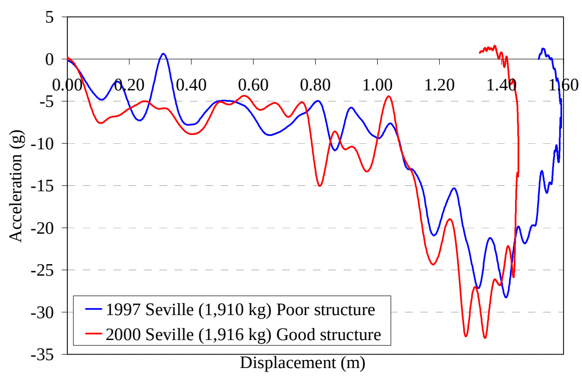

Figure 5. Acceleration vs. Displacement 1997 and 2000 Cadillac Seville

The Honda Odyssey (Figure 6) went from a poor structural rating for the 1996 model to an acceptable rating for the 1999 model. The 1999 model is significantly heavier than its predecessor (2,078 vs. 1,702 kg), but the front crush space is similar for both models. Despite allowing 7 cm more dynamic deformation, the redesigned model resulted in 16 cm less intrusion than its predecessor. Peak accelerations recorded were the same for both models but occurred much later in the redesigned model. Stiffness coefficients calculated from NCAP tests for the 1999 and 1996 models also showed the redesigned model to be less stiff.

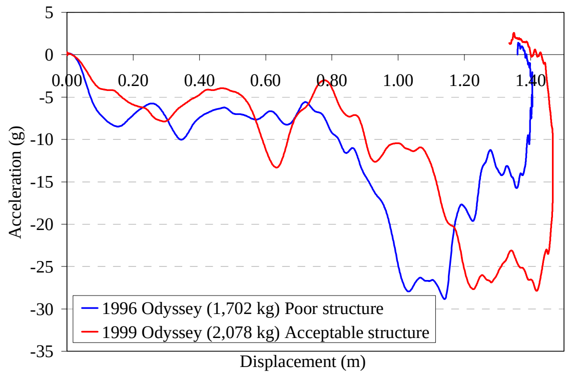

Figure 6. Acceleration vs. Displacement 1996 and 1999 Honda Odyssey

The Isuzu Rodeo (Figure 7) went from a poor structural rating for the 1996 model to a good rating for the 2000 model. The 2000 model has 6 cm additional front crush space and is slightly lighter. The accelerations recorded were similar until 75 cm of combined vehicle and barrier deformation had occurred. Peak accelerations were about the same, but the 2000 model peaked earlier than the 1996 model and had a second high peak at the end of the pulse. Maximum deformation was decreased by 8 cm, and intrusion into the toepan was reduced by 25 cm with the redesigned model. The reduction in intrusion was much greater than reduction in overall deformation.

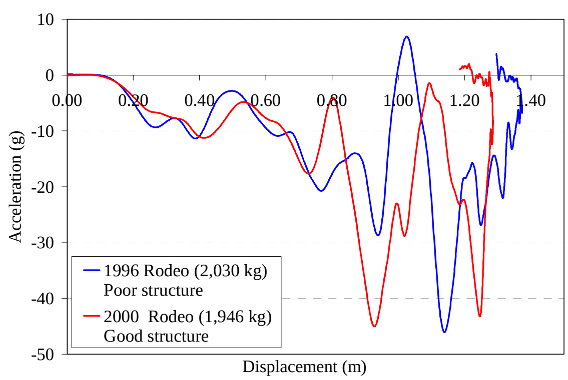

Figure 7. Acceleration vs. Displacement 1996 and 2000 Isuzu Rodeo

The Nissan Quest (Figure 8) went from an acceptable structural rating for the 1996 model to a poor rating for the 1999 model. This vehicle is the one example of a significant degradation in structural performance with a redesign. One major design difference between the two models is the addition of a left-side sliding door for the 1999 model. In the test of the redesigned model, the door structure buckled due to insufficient strength of the aperture. The stiffness calculated for both designs from the NCAP data were essentially the same. The accelerations recorded were similar until 70 cm of combined vehicle and barrier deformation had occurred. The 1996 model generally had higher accelerations than the 1999 model for the remainder of the crash. Maximum deformation was increased by 11 cm, and intrusion into the toepan was increased by 8 cm with the redesigned model.

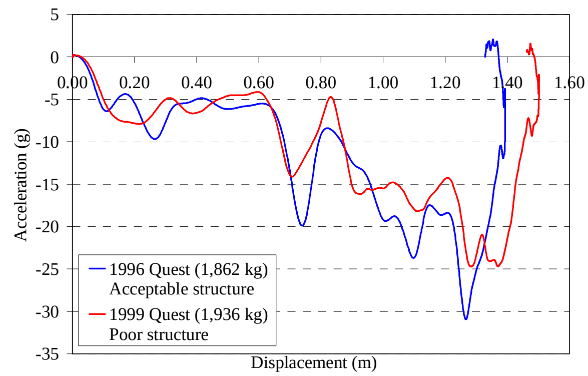

Figure 8. Acceleration vs. Displacement 1996 and 1999 Nissan Quest

The Saab 900 and Saab 9-3 (Figure 9) went from a poor structural rating for the 1995 900 model to an acceptable rating for the 1999 9-3 model. The accelerations recorded were similar until about 90 cm of combined vehicle and barrier deformation had occurred. Although both vehicles had the same maximum deformation, the 9-3 peak accelerations were higher and were sustained continuously as deformation neared the occupant compartment. The 900 acceleration fell off sharply between 120 and 130 cm of deformation, at which point collapse of the occupant compartment occurred. Maximum deformation was increased by 1 cm, and intrusion into the toepan was reduced by 8 cm with the redesigned model. The reduction in intrusion was much greater than reduction in overall deformation.

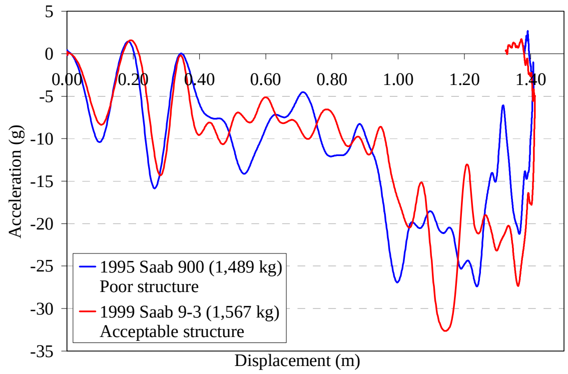

Figure 9. Acceleration vs. Displacement 1995 Saab 900 and 1999 Saab 9-3

The Toyota Avalon (Figure 10) went from a marginal structural rating for the 1996 model to an acceptable rating for the 1998 model and then to a good rating for the 2000 model. The 1996 model is 100 kg lighter than the 1998 and 2000 models, but they all have similar front crush space. Stiffness measures from the NCAP tests were available for the 1996 and 1998 models. These measures indicate the 1998 model is significantly stiffer, yet the data in Figure 10 would suggest the 1998 model is less stiff. The accelerations recorded were similar for all three models until 80 cm of combined vehicle and barrier deformation had occurred. Peak accelerations were about the same for all three models, with the best performer peaking first. The worst performer had the least mass and least total deformation. Maximum deformation was decreased by 8 cm, and intrusion into the toepan was reduced by 12 cm between the 1998 and 2000 models. The reduction in intrusion was somewhat greater than reduction in overall deformation.

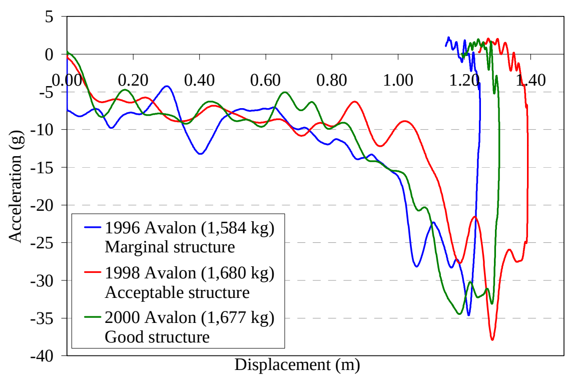

Figure 10. Acceleration vs. Displacement 1996, 1998, and 2000 Toyota Avalon

The Toyota Previa (Figure 11) went from a poor structural rating for the 1996 model to a good rating for the 1998 Sienna model. The Sienna is a completely new passenger van design that replaced the Previa, a snub-nosed mid-engine van. The Previa has only 89 cm of front crush space (one of the shortest, second only to the Ford Aerostar and Chevrolet Astro vans) compared with the Sienna's 120 cm. Despite similar dynamic deformation in the offset test, the Previa's occupant compartment failed catastrophically, whereas the Sienna had minimal occupant compartment intrusion. The stiffness calculated from the NCAP test indicated the Sienna is much less stiff than the Previa. The Sienna acceleration recorded was lower than that of the Previa until 120 cm of combined vehicle and barrier deformation had occurred. After this point, the Sienna acceleration increased rapidly to prevent intrusion into the occupant compartment. Maximum deformation was increased by 2 cm, and intrusion into the toepan was reduced by 19 cm with the redesigned model.

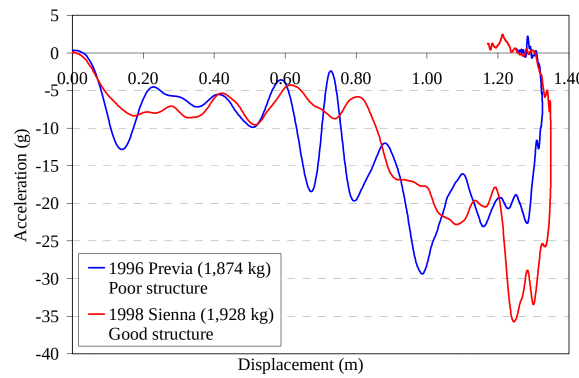

Figure 11. Acceleration vs. Displacement 1996 Toyota Previa and 1998 Toyota Sienna

The Volkswagen Passat (Figure 12) went from a poor structural rating for the 1995 model to an acceptable rating for the 1998 model. Both models have similar mass and available crush space. The NCAP test stiffness was slightly higher for the 1998 model using the first stiffness measurement method and slightly lower using the second method. The accelerations recorded generally were similar throughout the crash. Maximum deformation was increased by 6 cm, yet despite this, intrusion into the toepan was reduced by 20 cm with the redesigned model.

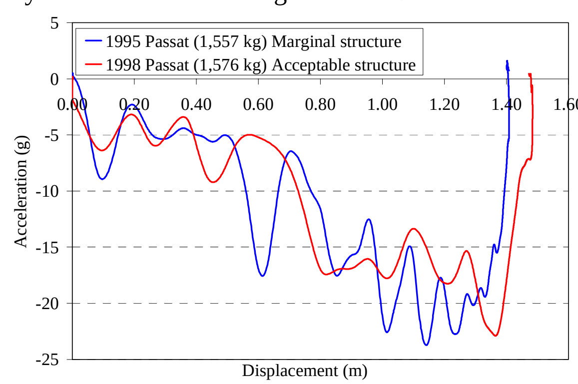

Figure 12. Acceleration vs. Displacement 1995 and 1998 Volkswagen Passat

DISCUSSION

Neither of the stiffness parameters calculated from NCAP test data correlated well with the IIHS structural evaluation in the offset test. No correlation was found even after controlling for mass, front-end length, and vehicle type. A general trend was observed between greater front-end length and better structural performance.

One possible reason for the lack of correlation is that the measures of stiffness are inappropriate. The extent of deformation that occurs in the NCAP test may be too low to adequately characterize what may occur in the offset test. In NCAP, the crash forces are distributed across the entire vehicle front end, and the occupant compartment is not challenged, resulting in little assessment of the occupant compartment strength relative to the crush zone strength. Neptune (1999) has compared the stiffness calculated from the NCAP test and the offset test and reported significant differences between the two for some vehicles.

Analysis of the eight models in this study indicates that those vehicles that exhibit signs of increased stiffness do so only late in the crash event, as deformation nears the occupant compartment (the 'bulkhead concept'). A good example of this is the Toyota Sienna shown in Figure 11; accelerations increase sharply after 120 cm of total deformation.

Seven out of eight vehicles tested before and after a redesign had improved structural performance after redesign. Four of these vehicles allowed more total occupant compartment movement during the crash than their predecessors while reducing intrusion dramatically. This suggests that these vehicles were designed to minimize occupant compartment intrusion, not by a simple increase in stiffness, but rather by careful placement of front structural elements and the matching of front-end stiffness to occupant compartment stiffness. The three other vehicles whose structural performance improved after a redesign allowed less total occupant compartment movement during the crash than their predecessors. These vehicles reduced occupant compartment intrusion by amounts greater than the overall reduction in occupant compartment movement, again suggesting careful front-end design is necessary for good test performance.

The Nissan Quest was the only vehicle to have significantly worse structural performance in the offset test after a redesign. The stiffness calculated from the NCAP test was essentially the same for both vehicles, and both have the same front-end length. The 1999 model had insufficient stiffness in the occupant compartment to sustain the front-end crash forces, resulting in excessive deformation in the occupant compartment without full use of the front energy-absorption capacity. Front-end stiffness must be well matched to occupant compartment stiffness, otherwise compartment failure will occur before complete energy absorption of the front structure is realized. This same phenomenon is apparent when comparing the IIHS tests of the 1995 Ford Taurus and 1995 Ford Contour. The Taurus front crush zone is used completely, and minimal intrusion into the occupant compartment occurred. In contrast, some of the energy-absorption capacity of the Contour remained unused, but the occupant compartment yielded, resulting in excessive intrusion into the occupant footwell by the engine cradle.

CONCLUSIONS

There was no significant correlation between stiffness (using either method) and the offset structural performance when looking at all vehicles or cars alone. Stiffness was analyzed after controlling for mass and front-end length in multiple regressions, but still no strong correlation to test performance was found.

Vehicles whose structural performance improved after a redesign do not show any evidence of increased stiffness for the first half-meter of vehicle deformation. All vehicles that improved after redesign had significant reductions in occupant compartment intrusion. These reductions typically were found to be much greater than reductions in overall movement of the occupant compartment during the crash. This suggests that careful design and placement of the front structural elements plus good matching of front-end stiffness to occupant compartment is required to improve offset test performance.

ACKNOWLEDGMENT

This work was supported by the Insurance Institute for Highway Safety.

REFERENCES

Insurance Institute for Highway Safety. 2000a. Crashworthiness evaluation offset barrier crash test protocol, ver. 8. Arlington, VA.

Insurance Institute for Highway Safety. 2000b. Crashworthiness evaluation guidelines for rating structural performance. Arlington, VA.

Lund, A.K.; Zuby, D.S.; and Nolan, J.M. 1995. Deformable barriers and occupant protection in offset frontal car-to-car crashes. SAE Technical Paper Series 950496. Warrendale, PA: Society of Automotive Engineers.

Meyerson, S.L. and Nolan, J.M. 2001. Effects of geometry and stiffness on the frontal compatibility of utility vehicles. *Proceedings of the 17th International Technical Conference on the Enhanced Safety of Vehicles* (CD ROM). Washington, DC: National Highway Traffic Safety Administration.

Nash, C. 1987. CRASH 3 – current status. SAE Technical Paper Series 870040. Warrendale, PA: Society of Automotive Engineers.

National Highway Traffic Safety Administration. 1981 (rev. 1982). *CRASH3 User's Guide and Technical Manual*. Washington, DC: U.S. Department of Transportation.

National Highway Traffic Safety Administration. 1999. *NASS/CDS Data Collection, Coding, and Editing Manual*. Washington, DC: U.S. Department of Transportation.

Neptune, J. 1999. A comparison of crush stiffness characteristics for partial-overlap and full-overlap frontal crash tests. SAE Technical Paper Series 1999-01-0105. Warrendale, PA: Society of Automotive Engineers.

Nolan, J.M.; Powell, M.R.; Preuss, C.A.; and Lund, A.K. 1999. Factors contributing to front-side compatibility: a comparison of crash test results (SAE 99SC02). *Proceedings of the 43rd Stapp Car Crash Conference* (P-350), 13-24. Warrendale, PA: Society of Automotive Engineers.

Nolan, J.M.; Preuss, C.A.; Jones, S.L.; and O'Neill, B. 1998. An update on the relationships between computed delta Vs and impact speeds for offset crash tests. *Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles*, 2:1234-41. Washington, DC: National Highway Traffic Safety Administration

O'Neill, B.; Preuss, C.A.; and Nolan, J.M. 1996. Relationships between computed delta V and impact speeds for offset crash tests. *Proceedings of the 15th International Technical Conference on the Enhanced Safety of Vehicles*, 1433-40. Washington, DC: National Highway Traffic Safety Administration.

Park, B., Hackney, J. et al. 1999. The New Car Assessment Program: Has it led to stiffer light trucks and vans over the years? SAE Technical Paper Series. 1999-01-0064. Warrendale, PA: Society of Automotive Engineers.

Prasad, A. 1990a. Energy dissipated in vehicle crush: a study using the repeated test technique. SAE Technical Paper Series 900412. Warrendale, PA: Society of Automotive Engineers.

Prasad, A. 1990b. CRASH3 damage algorithm reformulation for front and rear collisions. SAE Technical Paper Series 900098. Warrendale, PA: Society of Automotive Engineers.

Zobel, R. 1999. Accident analysis and measures to establish compatibility. SAE Technical Paper Series 1999-01-0065. Warrendale, PA: Society of Automotive Engineers.