AN UPDATE ON THE RELATIONSHIPS BETWEEN COMPUTED DELTA Vs AND IMPACT SPEEDS FOR OFFSET CRASH TESTS

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Paper Number 98-S6-O-07

ABSTRACT

The Insurance Institute for Highway Safety evaluates some aspects of new vehicle crashworthiness based on performance in a 40 percent frontal offset test into a deformable barrier. The impact speed of 64 km/h used in this program has been criticized as being too high and not representative of real-world crashes. At the 1996 Enhanced Safety of Vehicles conference, the estimated crash severities of a sample of real-world crashes from the National Automotive Sampling System (NASS) were compared with the Institute's 64 km/h offset crash tests of 16 midsize 1995-96 model four-door cars. Injury likelihood from the NASS sample was related to the test speed through delta V using the CRASH3 damage-only algorithm. Results from that study suggest that a 40 percent frontal offset test into a deformable barrier conducted at a speed less than 64 km/h would represent a crash severity that is lower than a large number of real-world car crashes with serious injuries. The present study expands on the previous work by providing one additional year of NASS data and results from 41 additional crash tests of 1995-98 model cars, passenger vans, and utility vehicles. Delta V and injury data were collected for real-world offset crashes from NASS for each of the three vehicle types and separated by restraint use. Results indicate that for cars, the Institute's 64 km/h frontal offset test represents a crash severity that encompasses about 80 percent of all real-world crashes with AIS 3 or greater injuries (i.e., the remainder occur at higher crash severities) but only about 33 percent of all fatal crashes.

INTRODUCTION

Crashworthiness evaluations have become increasingly common as a means of providing consumers with information on the relative crash protection offered by different vehicles. One such program is the National Highway Traffic Safety Administration's New Car Assessment Program (NCAP), in which vehicles are tested in a fully-engaged frontal crash at a speed of 56 km/h (35 mi/h) into a rigid barrier. NCAP has been very successful at differentiating the extremes of good and bad restraint system performance, all but eliminating the poorest of performers in recent years.[1]

In 1995, the Insurance Institute for Highway Safety began evaluating vehicles in another type of crash test called the "frontal offset test." This same test has been adopted by both the European and Australian NCAP programs.[2-3] In this test, only 40 percent of the vehicle's width strikes a deformable barrier attached to a rigid barrier at a speed of 64 km/h (40 mi/h). Unlike the NCAP test, only part of the front structure absorbs crush energy, resulting in large front-end deformations and potential occupant compartment intrusion.[4]

The value of comparative crashworthiness information derived from new vehicle crash testing depends on both the test configuration and the test speed. Frontal offset crashes represent a significant portion of real-world crashes that result in serious injuries to occupants.[5] However, the choice of an appropriate test speed can be more complex. If the test speed is low, it will be equivalent to a real-world crash severity at which crash injury risk also is low, and consequently the test results would not differentiate performance in injury-producing crashes. On the other hand, to encompass virtually all serious injuries in real-world crashes, the test speed would need to be so high that there likely would be no good performers and as a result no useful consumer information. The key to meaningful evaluations is to select a test speed that encompasses a significant number of real-world serious injuries while ensuring that the designs required to perform well in the test are reasonably attainable in the current fleet.

REAL-WORLD CRASH SEVERITY

The Institute's frontal offset crash test program has been criticized for testing vehicles at too high an impact speed. Some cite estimates of crash severity from real-world crash databases as evidence that the Institute's impact speed is too high. However, these conclusions are based on data that require closer examination because, despite a widespread misconception to the contrary, for the overwhelming bulk of crashes delta V is not the same as impact speed. In an Institute study presented at the 1996 Enhanced Safety of Vehicles conference, delta V estimates for 16 frontal offset crashes were compared with the distributions of delta V by injury severity from NASS.[6] That study found that about 50 percent of fatalities and 75 percent of serious injuries occurred in real-world crashes at severities below the severity of the Institute's test. This study updates that analysis with results from 41 additional crash tests and an additional year of NASS data.

The first necessary step in selecting an evaluation test speed is to find a real-world measure of crash severity that can be compared with the chosen test speed. One of the most common measures used to assess the severity of real-world crashes is delta V, which is an estimate of the change in velocity of a vehicle during a crash. In the early days of crashworthiness research when belt use was extremely low, delta V was assumed to be an indicator of the impact speed with which unrestrained occupants impacted the interior structure in frontal crashes. However, delta V has continued to be used as an indicator of severity even as belt use has increased. For two-vehicle crashes, delta V can be used as a surrogate for vehicle acceleration. In a two-vehicle crash, the energy absorbed by both vehicles is combined and then apportioned to each vehicle in the form of delta V based on their mass ratio. This result is consistent with the underlying physics: The lighter vehicle will have a higher delta V and higher accelerations than the heavier collision partner. For single-vehicle crashes, delta V also can be used as a surrogate for vehicle acceleration to compare crashes provided the duration of the crashes is similar.

During the 1970s, a computer algorithm developed at Calspan for the U.S. Department of Transportation began to be widely used to compute delta V estimates. This program was capable of estimating both the impact velocity and change in velocity (delta V) of a vehicle in a crash based on information from the vehicle and the crash scene. The original algorithm was termed CRASH for Calspan Reconstruction of Accident Speeds on the Highway and contained two options that are included in today's version, damage-only and trajectory.

The resulting delta V computed from the damage-only algorithm represents the change in velocity of the vehicle's center of gravity at the time of maximum crush during the crash, and it does not include rebound velocity. The damage-only option computes delta V based on the conservation of momentum and the energy absorbed by the vehicle independent of any information from the crash scene. The energy absorbed during the crash is estimated by measuring the residual crush of the vehicle and applying an estimate of the stiffness to the measured crush area, which in the case of CRASH is done by selecting a stiffness category from a list. Each stiffness category contains stiffness coefficients that define a linear force-deflection curve for that vehicle category (mini cars, subcompact, compact, etc.). In an offset crash, the delta V calculated by the damage-only algorithm also is modified to account for rotation of the vehicle during the crash. Like the stiffness categories, CRASH contains generic size categories based on wheelbase whose coefficients are used to modify delta V in offset crashes.[7]

The second option for estimating delta V in the CRASH program is the trajectory option. This algorithm requires extensive information from the crash scene and multiple assumptions regarding the energy dissipated in tire-road friction, tripping forces, etc., to estimate post-crash energy dissipation. The laws of conservation of momentum are applied to the scene data to provide estimates of impact speed in addition to delta V. Because the damage-only estimate of delta V relies upon simple measures of vehicle damage, it has been used much more frequently than the trajectory option, which relies upon data collected at the crash scene that often is unavailable or questionable.

CRASH has been updated several time since its inception in the late 1970s. In the early 1980s, CRASH2 was changed to CRASH3 by updating the stiffness coefficients in the various categories used to calculate a vehicle's absorbed energy.[8] More recently, CRASH3 was changed to SMASH (Simulating Motor Vehicle Accident Speeds on the Highway), which includes another update in the stiffness coefficients and further allows the use of vehicle-specific stiffness coefficients in lieu of the pre-assigned stiffness categories used in CRASH3 to calculate absorbed energy.[9] SMASH also allows the user to input specific vehicle dimensions, such as overall length, wheelbase, etc., instead of relying upon generalized size categories. Prasad, who developed the SMASH program, cited significantly fewer errors when using vehicle-specific stiffness coefficients instead of the generalized stiffness categories in CRASH3.[9] Throughout these revisions, the basic equations used to calculate delta V have changed in form but not in substance.

NASS contains the largest sample of real-world crashes in the United States and frequently is used to relate crash severity to injuries in crashes. NASS is designed so that a sampling of crashes in various regions of the country can be scaled to represent the entire population. One data element in most NASS cases is an estimate of delta V for each vehicle involved in the crash as estimated by CRASH. (NASS has used various versions of CRASH over time and switched from CRASH3 to SMASH in January 1997). Approximately 90 percent of NASS cases that contain delta Vs from CRASH3 were calculated using the damage-only algorithm, and the remaining 10 percent used the trajectory model.[10] In this study, only results from the damage-only algorithm are used because the majority of NASS cases with computed delta Vs used this option.

METHOD

Using the NASS measurement protocol, delta Vs were calculated using the CRASH3 damage-only algorithm for the 57 vehicles subjected to the Institute's 64 km/h frontal offset test. The energy absorbed by the deformable barrier was determined using estimates of the deformed volume and the static crush strength of the barrier material. This estimate of energy absorbed by the deformable barrier was included in the delta V estimate for each vehicle. The average crash test delta V was tabulated for all tested vehicles within each vehicle type.

In addition to the delta Vs calculated by CRASH3, delta Vs also were computed using SMASH. All delta Vs calculated by SMASH were based on vehicle-specific size and stiffness properties. As much information as possible regarding size, overall length, wheelbase, and weight was entered into the program. The vehicle-specific stiffness coefficients were determined using the method developed by Prasad, which requires at least two points to define the slope and intercept of the $\sqrt{N}$ versus average crush line.[9] In this study, slopes were determined using NCAP or Federal Motor Vehicle Safety Standard (FMVSS) 208 test results for the vehicles along with a 12 km/h no-measurable-damage assumption. For some completely new models, SMASH delta Vs were not calculated due to lack of necessary NCAP or FMVSS 208 crash test data. Crash test data from previous model years were used to estimate stiffness coefficients for some redesigned vehicles considered not to have changed dramatically in structure. The energy absorbed by the deformable barrier was included in the delta V estimates.

Delta Vs from real-world crashes were extracted from the 1990-95 NASS data files for crashes that matched the conditions of the Institute's offset crash test. Cases were selected based on Collision Deformation Classification (CDC) coding, which includes impact angle, impact location, and amount of direct engagement. For this study, single- or multiple-vehicle towaway crashes coded as frontal, with one-third to two-thirds direct damage to the front-end and 11 to 1 o'clock principal direction of force, were selected. These data were reduced further by selecting only those cases where delta Vs were calculated using the CRASH3 damage-only algorithm (no trajectory cases or OLDMISS cases). The 1990-95 NASS data contain a total of 14,608 vehicles in frontal crashes (all clock directions, CDC code "Frontal"), of which 7,005 (48 percent) meet the Institute's offset conditions. Of the 7,005 vehicles, only 3,255 (46 percent) have computed delta Vs from the CRASH3 damage-only algorithm. These 3,255 vehicles were used in this study to relate CRASH3 delta V to injury levels.

RESULTS

Tables 1-6 list the delta Vs (including the deformable barrier energy) calculated by CRASH3 and SMASH for the Institute's frontal offset tests. CRASH3 delta Vs consistently are lower than actual impact speeds; the average CRASH3 delta Vs are 33 percent lower for cars, 22 percent lower for utility vehicles, and 10 percent lower for passenger vans. Overall, SMASH (using vehicle-specific stiffness properties) increases delta V, but SMASH delta Vs still are 3-12 percent lower than impact speeds.

The fact that delta Vs are lower than impact speeds should not be surprising. In a frontal offset test, the vehicle's center of gravity does not stop at the time of maximum crush because the vehicle rotates about the barrier during the crash. This rotation means that the computed delta V should be lower than impact speed. The large differences between delta Vs calculated using CRASH3 and SMASH result solely from the difference between the preassigned size and stiffness properties used in CRASH3 and the vehicle-specific properties used in SMASH. However, high-speed film analysis of the Institute's offset tests indicate actual delta Vs should be 2-3 km/h lower than impact speeds due to the effects of rotation, suggesting that CRASH3 is substantially underestimating delta Vs in offset crashes for most vehicle types.

Table 1.
Delta Vs Computed for Midsize Four-Door Cars in 64 km/h 40 Percent Offset Crashes, Including Deformable Barrier Energy

Make/Model	Actual Impact Speed (km/h)	Delta V (km/h)	
		CRASH3	SMASH
Subaru Legacy	64	39	53
Volvo 850	65	44	58
Mazda Millenia	64	41	55
Toyota Camry (95)	64	48	58
Mitsubishi Galant	64	47	65
Honda Accord	64	40	49
Ford Contour	64	38	57
Chevrolet Lumina	64	42	56
Nissan Maxima	64	43	59
Ford Taurus (95)	64	44	68
Chevrolet Cavalier	64	37	45
Chrysler Cirrus	65	48	76
Volkswagen Passat (95)	64	43	52
Saab 900	64	46	60
Ford Taurus (96)	64	43	64
Toyota Avalon	64	44	54
Hyundai Sonata	64	48	56
Pontiac Grand Prix	64	42	61
Toyota Camry (97)	64	45	57
Toyota Avalon (98)	65	42	n/a
Nissan Maxima (98)	65	47	n/a
Honda Accord (98)	64	58	n/a
Volkswagen Passat (98)	65	37	n/a
	Average:	44	58

Table 2.
Delta Vs Computed for Small Four-Door Cars in 64 km/h 40 Percent Offset Crashes, Including Deformable Barrier Energy

	Actual Impact	Delta V (km/h)	
Make/Model	Speed (km/h)	CRASH3	SMASH
Honda Civic	64	44	60
Mitsubishi Mirage	64	46	51
Kia Sephia	64	40	52
Saturn SL2	64	45	49
Ford Escort	64	39	51
Mazda Protégé	64	40	53
Volkswagen Jetta	64	43	53
Dodge Neon	64	48	59
Hyundai Elantra	65	38	46
Nissan Sentra	64	45	55
Toyota Corolla	64	40	n/a
	Average:	43	53

Table 3.
Delta Vs Computed for Luxury Cars in 64 km/h 40 Percent Offset Crashes, Including Deformable Barrier Energy

	Actual Impact	Delta V (km/h)	
Make/Model	Speed (km/h)	CRASH3	SMASH
BMW 540i	64	41	n/a
Lexus LS 400	64	37	n/a
Cadillac Seville	64	44	n/a
Mercedes-Benz E420	64	40	n/a
Lincoln Continental	64	47	n/a
Infiniti Q45	64	37	n/a
	Average:	41	n/a

Table 4.
Delta Vs Computed for Passenger Vans in 64 km/h 40 Percent Offset Crashes, Including Deformable Barrier Energy

	Actual Impact	Delta V (km/h)	
Make/Model	Speed (km/h)	CRASH3	SMASH
Chevrolet Astro	64	59	56
Nissan Quest	64	58	57
Honda Odyssey	64	42	59
Ford Aerostar	64	65	60
Dodge Grand Caravan	64	59	63
Toyota Previa	64	49	63
Pontiac Trans Sport	64	69	64
Mazda MPV	64	74	69
Ford Windstar	66	63	71
Toyota Sienna	65	46	n/a
	Average:	58	62

Table 5.
Delta Vs Computed for Utility Vehicles in 64 km/h 40 Percent Offset Crashes, Including Deformable Barrier Energy

	Actual Impact	Delta V (km/h)	
Make/Model	Speed (km/h)	CRASH3	SMASH
Jeep Grand Cherokee	64	49	44
Toyota 4Runner	64	45	52
Ford Explorer	63	49	58
Land Rover Discovery	64	52	60
Mitsubishi Montero	65	45	61
Nissan Pathfinder	65	52	65
Chevrolet Blazer	64	64	66
Isuzu Rodeo	63	46	72
	Average:	50	60

Table 6.
Summary of CRASH3 and SMASH Delta Vs by Vehicle Type in 64 km/h 40 Percent Offset Crashes, Including Deformable Barrier Energy

	CRASH3		SMASH	
Vehicle Type	Delta V (km/h)	N	Delta V (km/h)	N
Cars	43	39	56	29
Passenger vans	58	10	62	9
Utility vehicles	50	8	60	8

Table 7 reports the differences between the coefficients contained within the CRASH3 pre-assigned stiffness categories (1-9) and the vehicle-specific stiffness coefficients calculated for the vehicles tested by the Institute. Values duplicated in the far-right column indicate that vehicles in the same Institute test category were assigned different stiffness categories according to NASS protocol.

For CRASH3, small and midsize cars are assigned stiffness category 2, 3, or 9; passenger vans are assigned category 7 or 4; and utility vehicles are assigned category 7 or 8. Note the difference in stiffness coefficients (slope)* for CRASH3 category 4 and the passenger van average vehicle-specific stiffness coefficients. Both the Honda Odyssey and Toyota Previa are assigned a category 4 stiffness and have CRASH3 delta Vs much lower than the other vans. The four utility vehicles assigned a category 8 stiffness have the four lowest delta Vs for those vehicles. Except for category 7 (vans and four-wheel drive vehicles), the pre-assigned stiffness coefficients are much lower than the vehicle-specific stiffness coefficients calculated for those vehicles. The lower stiffness coefficients result in lower estimates of energy absorbed by vehicle deformation and consequently yield lower delta Vs.

* The intercept is nearly the same for all vehicles.

Table 7.
Comparison of CRASH3 Pre-Assigned Categories and Vehicle-Specific Coefficients used in SMASH

Stiffness Category	CRASH3 Stiffness Category Description	CRASH3 Category Stiffness Coefficient Sqrt(N)/cm	Average Vehicle-Specific Coefficients Calculated for SMASH Sqrt(N)/cm
1	Mini-cars	5.7	
2	Subcompact	5.4	7.4 & 8.5 (small and midsize cars)
3	Compact	6.2	7.4 & 8.5 (small and midsize cars)
4	Intermediate	4.8	8.8 (passenger vans)
5	Full size	5.1	
6	Luxury	5.1	
7	Vans and four-wheel drive	9.3	8.8 & 9.2 (passenger vans and utility vehicles)
8	Pickup trucks	5.9	9.2 (utility vehicles)
9	Front-wheel drive	5.1	7.4 & 8.5 (small and midsize cars)

Table 8.
Median Delta-V (km/h) by Injury Level from NASS 1990-95, Weighted

	All Towaways		MAIS 2+		MAIS 3+		Fatalities	
	Delta-V	Raw N	Delta-V	Raw N	Delta-V	Raw N	Delta-V	Raw N
All passenger vehicles*	20	3,255	27	1,112	31	512	48	136
All passenger vehicles – belted	18	1,720	25	429	24	177	55	30
All passenger vehicles – unbelted	23	1,316	30	644	34	319	47	99
Cars and passenger vans	20	2,615	27	923	29	423	50	117
Cars and passenger vans – belted	19	1,381	25	352	24	144	55	23
Cars and passenger vans – unbelted	23	1,047	29	536	32	264	47	87
Pickups and utilities	21	571	32	169	40	81	40	18
Pickups and utilities – belted	18	306	30	68	32	31	43	7
Pickups and utilities – unbelted	24	235	34	97	48	49	40	11

*Passenger vehicles include cars, pickup trucks, utility vehicles, and passenger vans.

Table 8 shows the median delta Vs by vehicle type, restraint use, and maximum injury severity from the 1990-95 NASS data files. Injury severity measures presented are the maximum abbreviated injury scale (MAIS) code for either of the front-seat occupants of the vehicle. The delta Vs from NASS are weighted according to NASS guidelines. For reference, the raw (unweighted) number of samples are shown for each vehicle/restraint type. There were an insufficient number of cases with airbag deployments that met the selection criteria, and consequently airbag-equipped cars are not put in a separate category.

Figure 1 shows the cumulative distribution of delta Vs from NASS 1990-95 by MAIS level for passenger vehicles (cars, passenger vans, pickups, and utility vehicles) whose occupants were estimated by NASS to have been restrained during the crash.

Figure 2 shows the cumulative distribution of delta Vs from NASS 1990-95 by MAIS level for cars (cars and passenger vans) whose occupants were estimated by NASS to have been restrained during the crash. The average CRASH3 delta V for the Institute's tests (cars only) is 43 km/h. About 33 percent of fatalities and 80 percent of MAIS 3+ injuries in cars occur below delta Vs of 43 km/h.

Figure 3 shows the cumulative distribution of delta Vs from NASS 1990-95 by MAIS level for pickup trucks and utility vehicles. The average CRASH3 delta V for the Institute's utility vehicle tests is 50 km/h. About 80 percent of fatalities and 75 percent of MAIS 3+ injuries in pickup trucks and utility vehicles occur below delta Vs of 50 km/h. Note, however, that the sample includes both restrained and unrestrained occupants and that the sample size was limited for this vehicle category, with only 18 fatal crashes and 81 MAIS 3+ injury crashes.

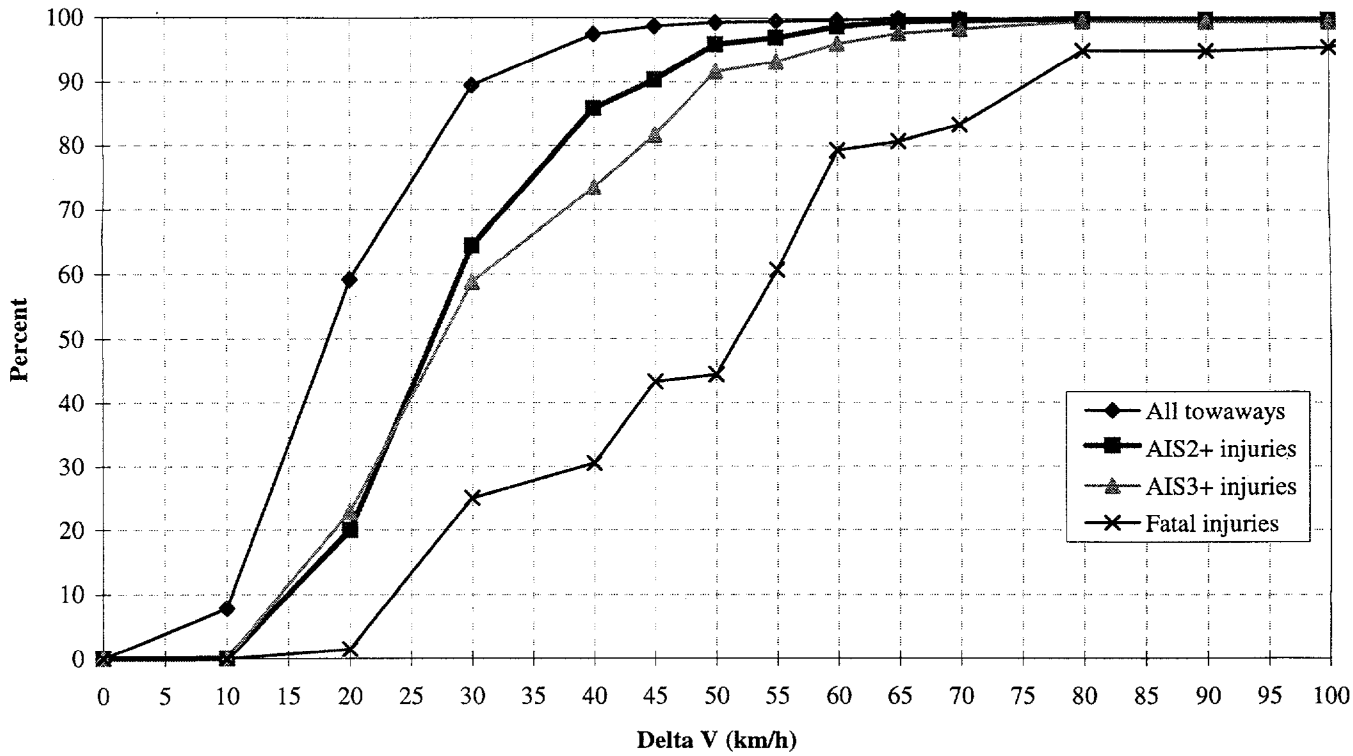

Figure 1. Cumulative Distribution of Delta Vs in Offset Crashes — Passenger Vehicles by Injury Severity, Belted Front-Seat Occupants.

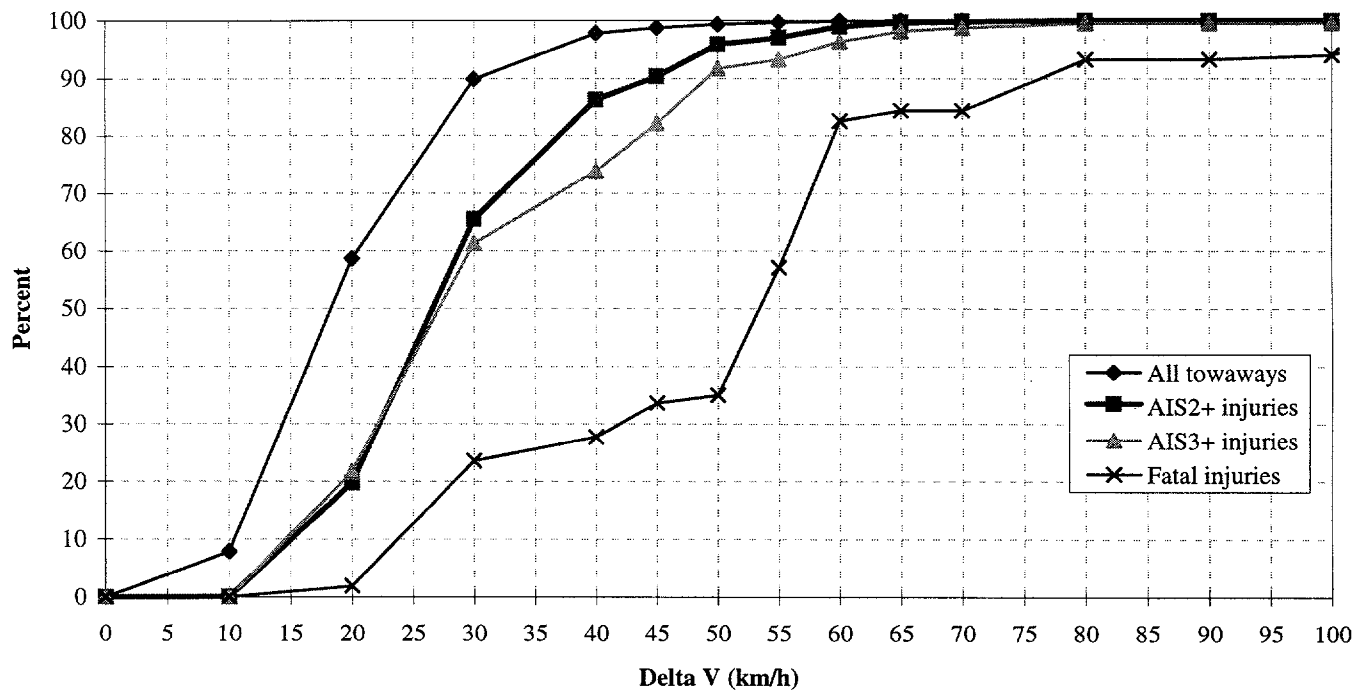

Figure 2. Cumulative Distribution of Delta Vs in Offset Crashes — Cars (Cars and Passenger Vans) by Injury Severity, Belted Front-Seat Occupants.

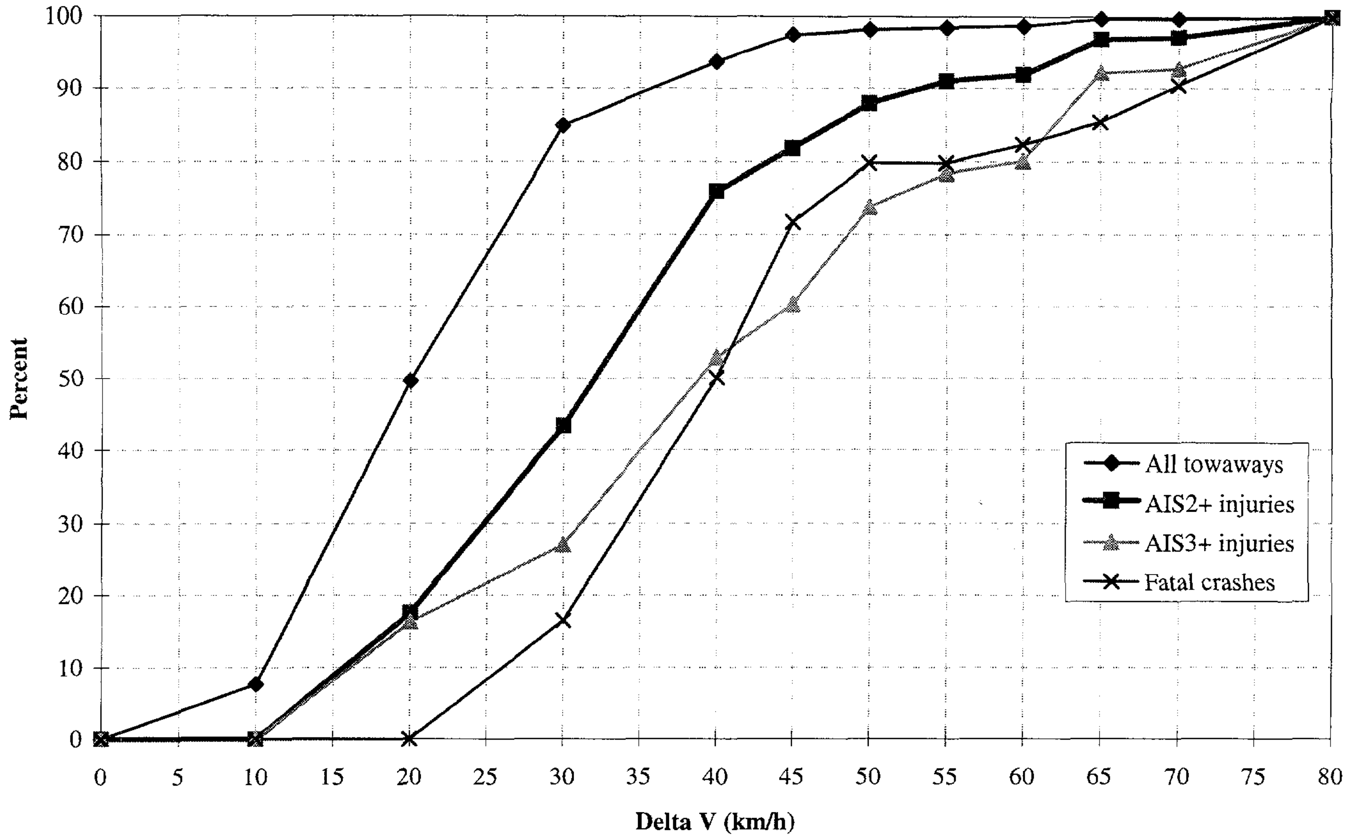

Figure 3. Cumulative Distribution of Delta Vs in Offset Crashes — Pickup Trucks and Utility Vehicles by Injury Severity, Belted and Unbelted Front-Seat Occupants.

DISCUSSION

Only in the special case of a full-width crash into a rigid barrier is delta V equal to impact speed. For a frontal offset crash, the delta V should be lower than the impact speed due to rotation of the vehicle. Even though delta Vs for offset crashes should be lower than the impact speeds, the estimates from CRASH3 are lower than the true delta Vs. Among new vehicles tested by the Institute, average CRASH3 delta Vs are 33 percent lower than impact speeds for cars, 22 percent lower for utility vehicles, and 10 percent lower for passenger vans. The delta V estimates obtained from SMASH, using vehicle-specific stiffness and size properties, are higher than the CRASH3 estimates, ranging 3-12 percent lower than impact speeds. The results from the SMASH program indicate that CRASH3 underestimates delta V because of poor preassigned stiffness and size category coefficients.

As offset crash testing becomes more common, it is imperative that investigators studying the relationship between such tests and real-world crashes be aware of the CRASH3 bias. For cars, about 80 percent of the significant injuries in real-world frontal offset crashes occur in crashes with severities at or below that represented by the Institute's frontal offset crash test. However, only about one-third of the occupant deaths in cars involved in frontal offset crashes occur with severities at or below that represented by the Institute's offset crash test speed. This latter estimate is lower than in the 1996 study (about 50 percent),[6] which may be due to the previous study's smaller sample size as well as the fact that the present study considered only NASS cases in which occupants were believed to be belted. These findings reinforce the conclusion that offset testing at a speed below 64 km/h would mean that new vehicle crashworthiness performance would be assessed at too low a severity level, and in effect would be a performance goal that would not address many of the serious injuries that occur in real-world crashes.

ACKNOWLEDGMENT

This work was supported by the Insurance Institute for Highway Safety

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