Events That Produce Occupant Injury in Longitudinal Barrier Accidents

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ABSTRACT

Since the early days of highway safety research the design of longitudinal traffic barriers has been greatly influenced by two basic assumptions about the mechanism of occupant injuries. First, it has been assumed that the severity of occupant injury is directly related to the intensity of vehicle collision accelerations in the first barrier collision. It has been thought that the risk of occupant injury would be decreased by developing roadside features that would prevent high values of vehicle acceleration. The second assumption has been that occupants of vehicles involved in multiple-impact accidents would be subjected to the highest risk of injury in the first collision. Because vehicle speed and kinetic energy are generally greatest in the initial collision, it has been reasoned that the most severe occupant trauma occurs during the first collision event. Recent research at Southwest Research Institute has indicated that ensuring a smooth redirection is a more effective means of improving occupant safety than trying to limit vehicle lateral accelerations. It was found that occupants are rarely injured severely in a collision with a longitudinal barrier that smoothly redirects the vehicle. In the light of these recent findings, many of the typical assumptions made in designing and evaluating highway safety hardware may not be as appropriate as was once thought. Data from sled tests, accident data analysis, and full-scale crash tests indicate that the likelihood of an occupant sustaining serious injury in a collision with a longitudinal barrier is quite low if the vehicle remains upright and is smoothly redirected.

Since the early days of highway safety research, the design of longitudinal barriers such as guardrails, bridge rails, and median barriers has been greatly influenced by two basic assumptions about the causes of occupant injuries when vehicles collide with such devices. It has been assumed that occupants are subjected to the highest risk of injury during the vehicle's initial collision with a longitudinal barrier; subsequent collisions with the same or other roadside features have been presumed to be less hazardous because of lower vehicle speeds. Second, the probability of severe occupant injury has been assumed to be directly and primarily related to the intensity of vehicle collision accelerations. It has been thought that by designing roadside hardware to limit high values of vehicle accelerations the frequency and severity of occupant injuries would be diminished.

A recent study performed at Southwest Research Institute (SwRI) and sponsored by the FHWA produced findings that indicate that these traditional assumptions may not be completely accurate. The results of this study indicated that (a) even when subjected to what have generally been considered severe impact conditions, occupants are not severely injured and (b) vehicle trajectory and stability after the initial collision are major factors in the causation of occupant injuries.

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FLAIL SPACE MODEL

Traditionally, the dynamic performance evaluation of longitudinal barrier systems was accomplished by assessing vehicle kinematic and dynamic quantities derived from carefully controlled crash tests. In addition to requiring that the vehicle be smoothly redirected and remain upright, the peak 50-msec average lateral and longitudinal accelerations were acquired and evaluated on the assumption that the severity of occupant injury in a longitudinal barrier collision was primarily a function of the vehicle's collision dynamics. Chi (1) provides an informative historical evaluation of the many pre-NCHRP Report 230 injury evaluation criteria.

NCHRP Report 230 (2) advocated the use of the flail space concept and occupant risk criteria that linked vehicle kinematics to the occupant's risk of sustaining physical injuries. The occupant risk factor is the hypothetical impact velocity of the occupant with the vehicle interior: the greater the occupant impact velocity the more severe the resulting injuries. The occupant is assumed to behave as a free missile that continues to travel along the precollision trajectory and at the precollision velocity while the vehicle responds to the collision forces. In essence, the vehicle compartment moves toward the occupant, striking the occupant at a determinable velocity. This concept allows all of the previous occupant severity indices to be unified in a single value: the occupant risk factor.

At the time NCHRP Report 230 was written, there was little evidence to establish threshold values for the occupant-to-passenger compartment impact velocity required to prevent severe injuries. Some data were available for frontal occupant impacts into the windshield from crash cushion studies. No data were available, however, for occupant lateral impacts into the door during redirectional collisions. In addition, there were no comprehensive data available to establish appropriate flail space dimensions for calculating the occupant risk factor.

To better define the flail space envelope, a survey was made of typical 1978 to 1984 vehicle interior dimensions to determine the distribution of flail space distances. The following equation, which can be used to calculate the occupant's impact velocity with the vehicle interior when the vehicle is not yawing, illustrates the importance of the flail dimension (s).

$$\upsilon = 2As^{1/2} \quad (1)$$

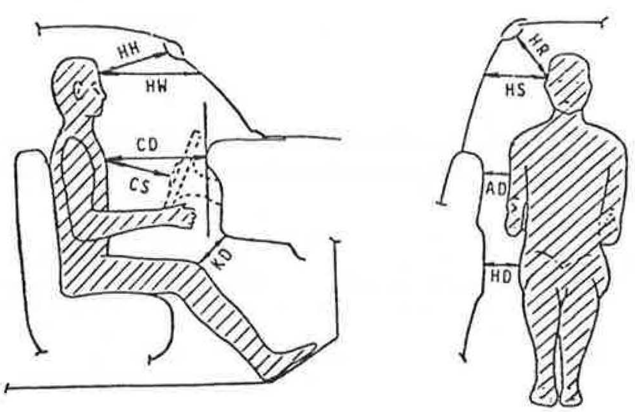
where

υ = occupant-compartment impact velocity (fps),
A = average vehicle accelerations (ft/sec^2), and
s = flail distance (ft).

For relatively long collision events, such as redirectional collisions, the occupant impact velocity increases as the square root of the appropriate flail space distance given the same average acceleration. This implies that occupants in "spacious" compartments where the flail space is maximized are more at risk. Table 1 gives a summary of the results of a passenger compartment survey that was performed using data from the New Car Assessment Program (NCAP) on 1978 to 1984 passenger sedans. To create a "worst case" scenario the passenger was assumed to be small (i.e., 5th percentile female) and seated in the right front passenger position with the seat in the rear-most position. The NCHRP Report 230 (2) value of 2 ft was found to be an appropriately conservative yet realistic value for the longitudinal flail distance compared with 22 in. shown in Table 1 for the dimension HW. For the lateral flail distance, values in Table 1 range from 7 to 13 in. for the dimension HS, and a 12-in. lateral flail distance, as suggested in NCHRP Report 230, was deemed appropriate. The data in Table 1, then, indicate that the NCHRP Report 230 suggestions of 1 ft in the lateral direction and 2 ft in the longitudinal direction are, indeed, representative of flail distances in the vehicle population.

TABLE 1 Typical Passenger Compartment Clearance Dimensions

Dimension[a]	Range[b]	Median[b] Distance	75th Percentile[b] Distance
HW	15-24	20	22
CD	19-24	21	22.5
CS	10-17	13	15
HS	7-13	9	10
AD	1-7	4.5	5.5
HD	5.5-9.5	6	8
HH	11-20	14	15
HR	4-10	6	7.5
KD	3-10.5	7	8



[a]Dimensions are for a 5th percentile female seated in the driver position with the seat in its rearmost position.
[b]The dimensions are, to a small degree, functions of vehicle weight. The values reported are for 1978 to 1984 passenger automobiles with core weights greater than 3,680 lb.

ANTHROPOMETRIC DUMMY SLED TESTS

To establish a link between the flail space model and occupant protection standards used by NHTSA, a series of sled tests was conducted in which unrestrained anthropometric dummies were observed during simulated small car frontal and side impacts. Three frontal tests were performed in which the passenger compartment underwent velocity changes of 25, 35, and 45 fps at acceleration rates of 4.7, 9.8, and 16.6 *g*'s, respectively. Four side impact tests were performed in which the passenger compartment experienced velocity changes of 20, 30, 35, and 45 fps at constant accelerations of 2.6, 9.4, 14.1, and 18.4 *g*'s, respectively.

A 1979 Honda Civic passenger compartment body buck with standard bucket seats and glass windows was used in these seven tests. A Part 572 5th percentile female dummy instrumented according to FMVSS 208 was positioned in a normal attitude with the seat in the rearmost position for the frontal tests. A 165-lb, 50th percentile male side impact dummy (SID) was used in the side impact tests. Figures 1 and 2 show sequential photographs from the test series and illustrate typical tajectories of the occupant in frontal and side impacts. A summary of the sled test findings is given in Table 2.

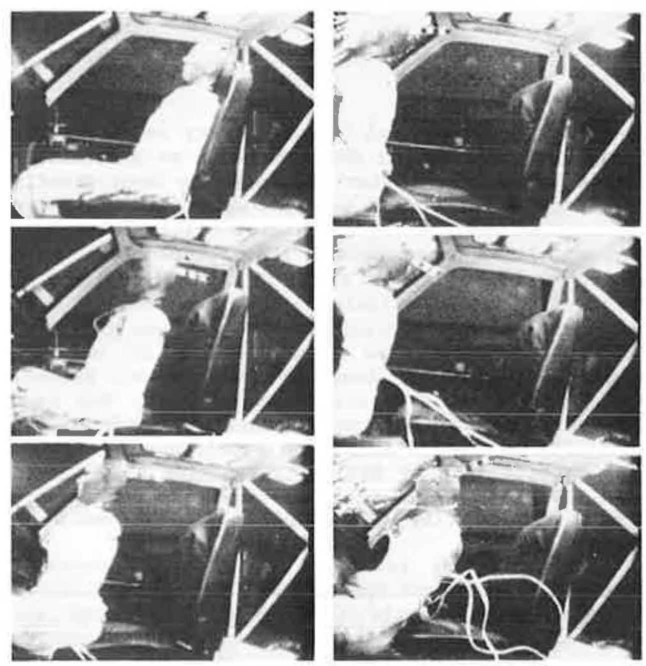


FIGURE 1 Typical frontal impact.

The findings given in Table 2 generally confirm the hypothesis that the simulated occupant behaves

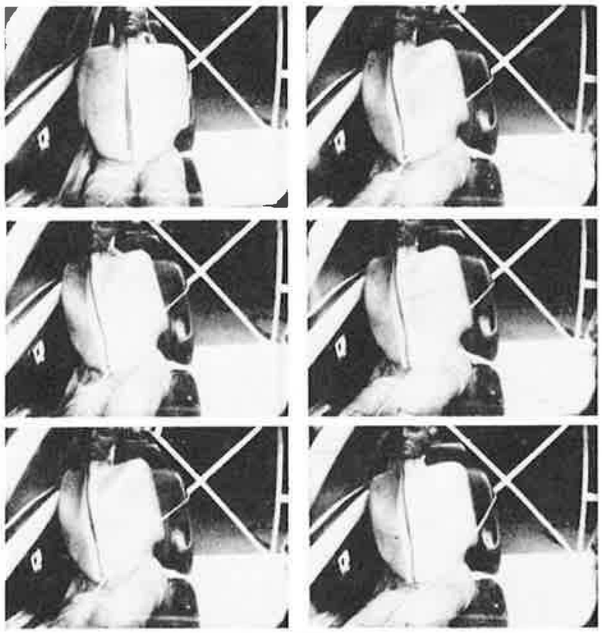


FIGURE 2 Typical side impact.

like a free missile. The occupant risk factor computed from the sled acceleration pulse using the free missile assumption compares favorably with test signals produced from the dummy accelerometers for both frontal and side impacts. The calculated occupant impact speed was reasonably close to the observed values given in Table 2 although the calculated values become more accurate as the accelerations increase and thus there is a tendency to overestimate the occupant risk factor at low accelerations.

For frontal impacts, the dummy responses tend to support the 30-fps occupant risk value suggested in NCHRP Report 230. A head injury criteria (HIC) score of 1345 occurred when the anthropometric dummy head struck the windshield at about 46 fps. By interpolating the data in Table 2 it was estimated that a head impact velocity of 40 fps would result in a HIC of 1000, the critical value established in FMVSS 208. In NCHRP Report 230 a safety factor of 1.33 was applied to the 40-fps limit to arrive at the 30-fps design limit. Chest accelerations also exceeded the FMVSS 208 60-g criterion for the 46-fps dummy impact condition. In redirectional tests, however, the longitudinal occupant risk is generally not a critical parameter because longitudinal accelerations are rarely sufficient to propel the occupant to the instrument panel. For this reason, the remainder of this paper will be primarily concerned with the lateral occupant risk factor.

For the side impact sled tests, the anthropometric dummy responses were surprisingly low. In NCHRP Report 153 (3) lateral vehicle accelerations of 5 g's were considered high. For Test 2540 in Table 2, the sled was accelerated laterally at 18.6 g's, and the resulting HIC was a mild 316, well below the FMVSS 208 threshold of 1000. The maximum occupant risk factor was calculated to be about 25 fps, which exceeds the design limit of 20 fps suggested in NCHRP Report 230. It should be noted that the actual lateral flail distance of 6.5 in. rather than the 12-in. value suggested in NCHRP Report 230 was used

TABLE 2 Sled Test Results

Left Side Impacts				
Test No.	2534	2533	2535	2540
Sled response[a,b]				
Change in velocity (fps)	20	30	35	40
Acceleration (g's)	-3.6	-8.0	-15.0	-18.4
Occupant risk data				
Time to head impact (sec)[c]	0.092	0.049	0.048	0.042
Average sled acceleration (g's)	-2.6	-9.4	-14.1	-18.4
Measured occupant impact velocity (fps)	7.7	14.8	21.8	24.9
Calculated occupant impact velocity (fps)	9.5	18.1	22.2	25.3
Head injury criteria data				
HIC	37	121	193	316
HIC duration (sec)	0.012	0.006	0.010	0.006
Head severity index	52	163	221	569
Thoracic trauma index data				
Sping g's–T12y	12.5	36.4	32.1	65.2
Upper rib g's–LUR_y	10.7	30.4	47.7	46.7
Assumed age (yr)	41	41	41	41
Weight (lb)	165	165	165	165
TTI	69	91	97	113
Probability of AIS ≥ 3 (%)	0	3	6	16
Frontal Impacts				
Test No.	2538	2537	2539	
Sled response[a,b]				
Change in velocity (fps)	25	35	45	
Acceleration (g's)	-5.6	-10.9	-16.8	
Occupant risk data				
Time to head impact[c]	0.140	0.105	0.085	
Average sled acceleration (g's)	-4.7	-9.8	-16.6	
Measured occupant impact velocity (fps)	21.1	33.2	45.6	
Calculated occupant impact velocity (fps)	23.5	34.4	45.8	
Head injury criteria data				
HIC	87	468	1345	
HIC duration (sec)	0.061	0.030	0.014	
Head severity index	30	55	94	
Peak chest acceleration (g's)	29.7	55.0	94.4	

[a] Buck was a 1979 Honda Civic passenger compartment.
[b] Side impact dummy was used in side impacts and Part 572 5th percentile female in frontal collisions.
[c] Flail distances were measured as 22.5 in. longitudinal and 6.5 in. lateral and used in velocity calculations.

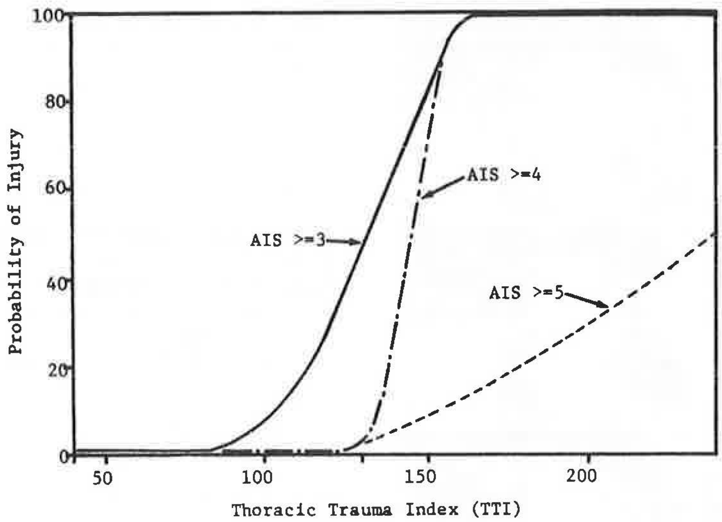


FIGURE 3 Probability of injury versus TTI.

in determining the occupant impact velocities given in Table 2.

Another injury measure better suited to side impacts is the thoracic trauma index (TTI). Eppinger et al. (4) developed a family of curves that relate the TTI to the probability of sustaining a given level of injury. This relationship is shown in Figure 3 and the TTI is defined by the following equation:

$$TTI = 1.4\ Age + 0.5\ (LUR_y + T12_y)\ [Weight\ (165\ lb)] \quad (2)$$

where

Age = occupant age (years),
LUR_y = left upper rib y acceleration (g's), and
$T12_y$ = Spinal y acceleration (g's).

Even at a vehicle lateral acceleration of 18.6 g's and an occupant impact velocity of 24.9 fps, the probability of a hypothetical 41-year-old, 165-lb occupant (TTI = 113) sustaining an AIS of 3 or greater is only 0.16, and the probability of sustaining an AIS of 4 or greater is nil as shown in Figure 3. The probability of severe injury (AIS $\geq$ 4) is quite remote for this occupant even under impact conditions that are generally considered to be severe.

The sled tests illustrated two important points. First, simulated occupants do behave like free missiles during collisions and their impact velocities can be calculated if the compartment geometry and the vehicle accelerations are known. Second, the lateral occupant risk design limit of 20 fps suggested in NCHRP Report 230 as well as vehicle acceleration values contained in NCHRP Report 153 may be unnecessarily conservative.

ACCIDENT ANALYSIS OF OCCUPANT INJURIES

To further investigate this apparent noncriticality of the lateral occupant risk factor during redirectional crash tests, a number of longitudinal barrier accident cases were examined in detail. Because 5 percent (5) of all fatal accidents, as the data in Table 3 indicate, can be attributed to an impact with a longitudinal barrier, the conclusions of the last section might reasonably be questioned.

TABLE 3 Distribution of Most Harmful Events Where the First Object Struck Is a Longitudinal Barrier (5)

	Longitudinal Barrier Is First Harmful Event	
Most Harmful Event	No.	Percentage
Overturn, noncollision	453	31
Other noncollision	116	8
Non-fixed objects	115	8
Longitudinal barrier[a]	442	31
Pier/abutment/parapet end	73	5
Other fixed objects	242	17
Total longitudinal barrier[b]	1,441	100
Total fatal accidents	27,516	

[a]Most harmful event may not necessarily be the first harmful event. It may include subsequent impact with same bridge rail or a bridge rail across the highway.
[b]Longitudinal barrier accidents represent 5.2 percent of the 27,516 fatal accidents.

To examine the importance of the lateral occupant impact velocity in real highway accidents, it was necessary to isolate those accident cases in which the lateral occupant impact velocity was the principal injury-producing mechanism. All cases in which some other aspect of vehicle dynamics or barrier performance could have caused the occupant injuries were screened from the data base leaving only those cases in which the

- Barrier was the first item struck by a passenger sedan;
- Vehicle was tracking before the first impact (i.e., heading angle and velocity vector were within 10 degrees);
- Vehicle was smoothly redirected after the first impact; there were no signs of vaulting, penetration, or severe post-wheel snagging in the first impact;
- First impact was not with a bridge pier, barrier terminal, or end treatment; and
- Vehicle did not roll over as a result of the first impact.

Using these criteria, 26 accident cases were selected from the narrow bridge study data base of 124 bridge-related accidents (6). Of the 124 narrow

TABLE 4 Characteristics of 81 Bridge Rail Accidents[a]

	No Second Impact	Result of Second Impact: Redirected or Spun Out to Rest	Redirected into Another Roadside Feature	Rollover	Vault/ Override	Total
Vehicle tracking at first impact						
Redirected or skidded to stop	7	9	8		2	26
Snagged	4	2	1			7
Penetrated			1			1
Vault/override	2	2	3	1		8
Rollover	2					2
Total	14	13	13	1	2	44
Vehicle not tracking at impact						
Redirected or skidded to stop	7	13				20
Snagged	3	5	1	1		10
Rollover	3					3
Vault/override	1	2	1			4
Total	15	20	2	1		37
Total	29	33	15	2	2	81

[a]Data from Calcote and Mak *(6)*.

bridge cases, 43 were eliminated because they involved a first collision with an end treatment or guardrail-bridge rail transition. Table 4 gives characteristics of the remaining 81 narrow bridge accidents that occurred along the midspan of the barrier system. The vehicle was not tracking in 46 percent of the cases, and, of the cases in which the vehicle was tracking, only about half met the performance criteria listed previously. Occupants suffered serious to critical injury in only 3 of the 26 eligible cases.

To supplement this small sample size, the Longitudinal Barrier Special Studies (LBSS) data base from the National Accident Sampling System (NASS) for the years 1982 and 1983 was surveyed and 139 cases out of a total of 555 were deemed eligible. The total number of eligible cases was therefore 165.

One of the most basic and widely used measures of occupant injury is the Abbreviated Injury Scale (AIS) (7):

AIS	Injury	
1	Minor	Non-life threatening
2	Moderate	
3	Serious	
4	Severe	Life threatening
5	Critical	
6	Unsurvivable	

Each individual injury is assigned an AIS score by the accident investigator. For example, minor cuts and scratches on the face may be scored as an AIS of 1 and a broken rib may be reported as an AIS of 3. A frequently used measure of the severity of all occupant trauma is the maximum AIS (MAIS). The MAIS is the highest AIS experienced by the occupant. Thus the MAIS of the occupant with facial cuts (AIS = 1) and broken ribs (AIS = 3) would be 3.

Injuries of AIS 4 or above are defined as life threatening. The intent of NCHRP Report 230 was to select an occupant risk design limit such that occupants would not sustain an injury of AIS 4 or greater.

Table 5 gives the distribution of the MAIS in each of the three data sources. Nearly 90 percent of the eligible cases in Table 5 (134 minor cases and 14 serious cases) exhibit injuries that are below the design injury limit of AIS 4. Only 2 percent of the eligible cases exhibit severe injury. It appears that the majority of vehicle occupants escapes severe injury when the vehicle is smoothly redirected and remains upright after a longitudinal barrier collision. Unfortunately the severity of occupant injury is unknown in almost 9 percent of the eligible cases (eight AIS-7 and six AIS-9 cases). There are two ways in which an NASS investigator can code an unknown injury. An AIS of 9 is used when the occupant cannot be located or departed the accident scene before any officials arrived. Generally an AIS of 9 indicates no injury or only minor injury because the occupant was capable of leaving the scene.

An AIS of 7 indicates that there was an injury but its severity is unknown. Unlike the AIS of 9, an AIS of 7 is often used by NASS investigators when

TABLE 5 Distribution of Injury in Three Data Bases

Source	Total Cases in Data Base	Eligible Cases[a] — Known Injury Severity: Minor, $0 \leq MAIS < 2$ No.	Percentage	Serious, $2 \leq MAIS < 4$ No.	Percentage	Severe, $4 \leq MAIS < 7$ No.	Percentage	Unknown Severity: MAIS = 7 No.	Percentage	MAIS = 9 No.	Percentage
1982 NASS LBSS	292	61	20.9	6	2.1	1	0.3	4	1.4	1	0.3
1983 NASS LBSS	263	50	19.0	7	2.7	0	0.0	4	1.5	5	1.9
Narrow bridge	124	23	18.5	1	0.8	2	1.6	0	0.0	0	0.0
Three data bases, combined	679	134	19.7	14	2.1	3		8	1.2	6	2.3

[a]Eligible cases are those in which (a) longitudinal barrier was struck by a passenger automobile; (b) vehicle was tracking before impact (i.e., heading angle and velocity vector are within 10 degrees); (c) vehicle was smoothly redirected after first impact; no vaulting, rollover, severe snagging or penetration; and (d) first impact was not with an end treatment or transition.

TABLE 6 Relationship Between an AIS of 7 and Police-Reported Accident Severity

Police-Reported Injury Severity	Probability of[a] AIS ≥ 2	Probability of[a] AIS ≥ 4	No. of Eligible[b] AIS-7 Cases	Probable No. Above AIS 2	Probable No. Above AIS 4
O–none	0.0050	0.0001	0	0.0	0.0
C–possible	0.0927	0.0016	1	0.0927	0.0016
B–nonincapacitating	0.1592	0.0057	3	0.4776	0.0171
A–incapacitating	0.4181	0.0438	3	1.2543	0.1314
K–fatality	0.6104	0.4416	0	0.0	0.0
U–unknown	0.2210	0.0166	1	0.2210	0.0166
Total			8	2.0456	0.1667
Figure used				2	0

[a]From 1984 NASS CSS data.
[b]These are the eight cases with AIS 7 from Table 5.

severe injury occurs but supporting documentation such as autopsy or hospital records cannot be obtained.

The NASS Continuous Sampling System (CSS) data for 1984 were used to calculate the probability of an AIS of 7 being coded when severe injury occurred. As the data in Table 6 indicate, the probability that any of the eight cases coded as AIS 7 included injuries greater than or equal to an AIS of 4 is quite low. All eight AIS-7 cases and all six AIS-9 cases can therefore be grouped with those below the AIS of 4 guideline. Thus the eight AIS-7 cases and the six AIS-9 cases can be grouped with the 134 minor injury cases and the 14 serious injury cases to show that 98 percent of the eligible cases indicate an acceptable level of occupant injury. Severe injuries were noted in only 2 percent of the eligible cases.

The 17 serious and severe injury cases in Table 5 were reconstructed in detail to determine exactly what feature of the accident caused these injuries. Each of the 17 cases studied with serious to unsurvivable injuries would have passed the two provisions of the NCHRP Report 230 criteria that require the vehicle (a) to be smoothly redirected and (b) to remain upright. With only three exceptions, all of the cases in Table 7 involved a subsequent collision with the same or another roadside feature. The reconstruction process therefore involved determining the speed and angle for two or three collisions. The vehicle deformation energy was calculated using the damage analysis portion of CRASH3 (8), barrier deformation energy was estimated using BARRIER VII (9), and energy dissipated by tire-ground friction along the trajectory was estimated by hand analysis methods. By proceeding from the last event to the first and summing all of the energies of vehicle and barrier deformation with the energies lost through tire-ground friction and braking, a reliable estimate of the impact speed can be produced.

Occupant injuries were assigned to particular impact events with, in most cases, a high degree of certainty. When there was uncertainty the injury was assigned to all phases equally. Figure 4 shows a typical diagram of vehicle trajectory, occupant injuries, and vehicle interior. Using these pieces of information, it is possible to match injuries with the events that caused them. For example, the dislocation of the occupant's left shoulder shown in Figure 4 can be assigned to the first collision. This is confirmed by the damage to the driver's side door shown in the interior sketch and the vehicle's position shown in the trajectory sketch. The lacerations on the right side of the head can be assigned, on the basis of the occupant contact points in the interior sketch, to the second collision. Because it is difficult to determine which phase of the accident caused the concussion it was attributed equally to both impacts. The occupant risk factor can be calculated from the impact conditions using a method

TABLE 7 Summary of Cases with Serious to Unsurvivable Injuries

Data Base	Case No.	Role[a]	Vehicle Weight (lb)	No. of Impacts	First Impact Speed (mph)	First Impact Angle (degrees)	First Impact MAIS	First Impact Occupant Risk (fps)	Second Impact Speed (mph)	Second Impact Angle (degrees)	Second Impact MAIS	Object Struck
NASS	83-53-010T	PUI	3,365	2	90	26	2	37	66	38	2	Bridge rail
NASS	82-81-078V	DUI	3,397	3	70	2	1	6	67	16	2	Guardrail
NASS	82-75-507V	DUI	1,813	2	46	15	0	15	?	90	4	Bridge pillar
NASS	83-32-532V	DUN	2,546	2	56	3	0	7	37	90	2	Utility pole
NASS	83-53-010T	DUN	3,365	2	90	26	1	37	66	38	2	Bridge rail
NASS	83-39-131V	DUN	3,161	2	69	5	0	12	37	45	3	Median barrier
NASS	82-52-083T	DRI	3,444	1	31	34	3	46				None
NASS	82-35-125V	DRI	3,541	2	?	2	0	?	?	9	2	Guardrail
NASS	82-78-511T	DRI	4,535	1	57	35	2	48				None
NASS	83-02-071T	DRI	2,338	2	49	17	0	16	28	90	3	Tree
NASS	82-55-293V	DRN	3,041	2	46	7	0	8	38	72	2	Ditch
NASS	82-06-513Z	DRN	3,981	1	34	10	3	8				None
NASS	83-30-516T	DRN	3,062	2	71	3	0	10	49	17	3	Median barrier
NASS	83-77-517T	DRN	2,811	2	23	2	1	2	9	45	2	Median barrier
NASS	83-02-523W	DRN	4,208	2	64	10	0	12	59	29	2	Median barrier
NBS	80-03-04-068	DUN	3,977	2	61	8	1	5	52	19	3	Bridge rail
NBS	80-03-22-071	DUN	3,980	4	48	10	0	12	33	90	5	Bridge pillar
NBS	79-12-03-049	DRN	4,318	3	52	8	0	4	20	90	4	Wingwall

[a]P = passenger, U = unrestrained, I = impact side, D = driver, R = restrained, and N = nonimpact side.

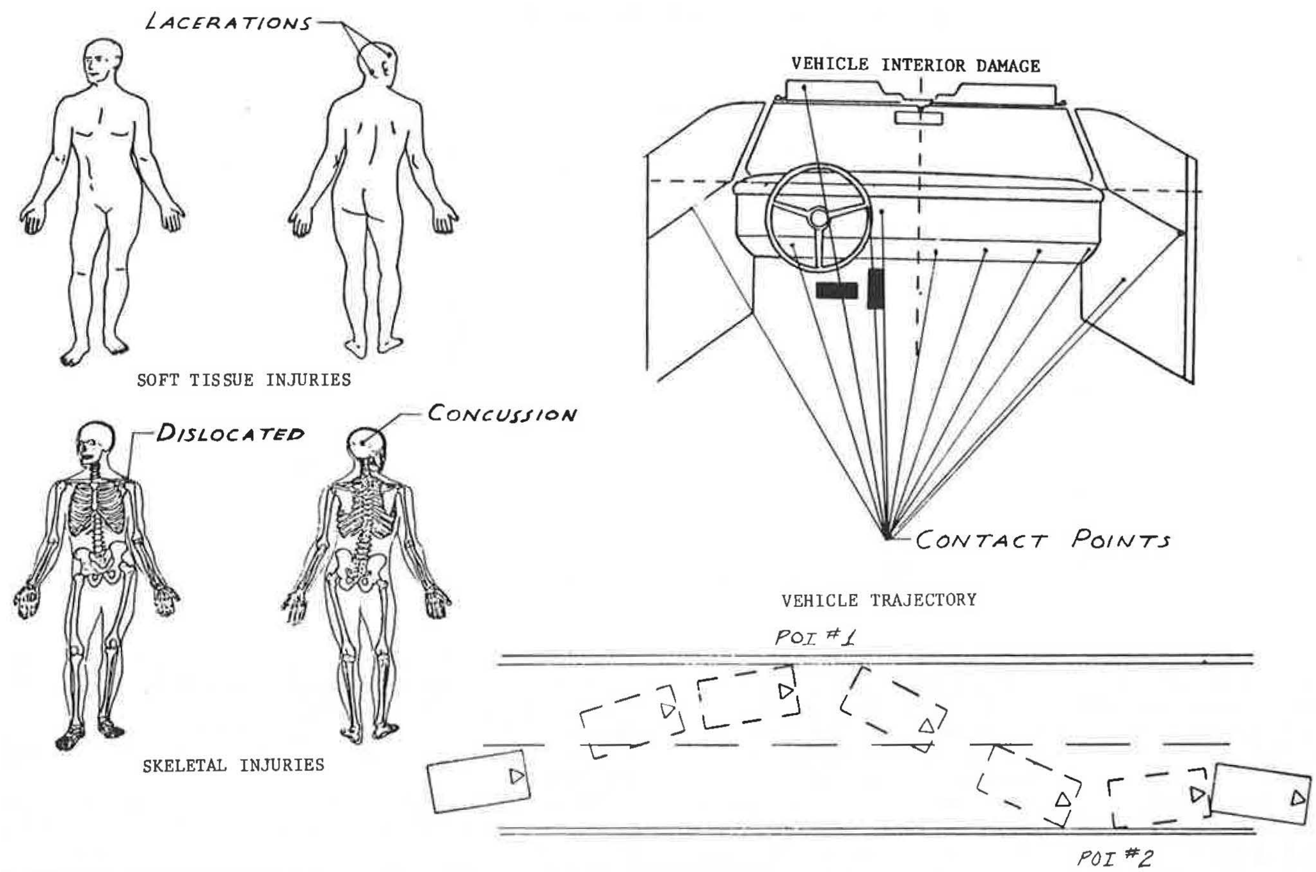


FIGURE 4 Typical accident reconstruction summary sheet, Case NASS 82-02-078V.

developed in another phase of this project and then compared with the actual level of injury experienced in each phase of the accident.

A summary of the 17 cases studied in detail is given in Table 7. When the MAIS for each of the multiple impacts is examined, it becomes apparent that none of the occupants suffered severe injury in the first impact. Recalling that these 17 cases are those 2 percent of eligible cases in which severe or serious injury occurred, it appears that the first impact in all 165 eligible cases in Table 5 resulted in injuries less than the design limit of AIS 4. Indeed, 96 percent of all eligible cases resulted in only minor injuries: 134 minor injury cases from Table 5, 13 of the 17 cases summarized in Table 7, 6 of the 8 AIS-7 accident cases, and all AIS-9 cases.

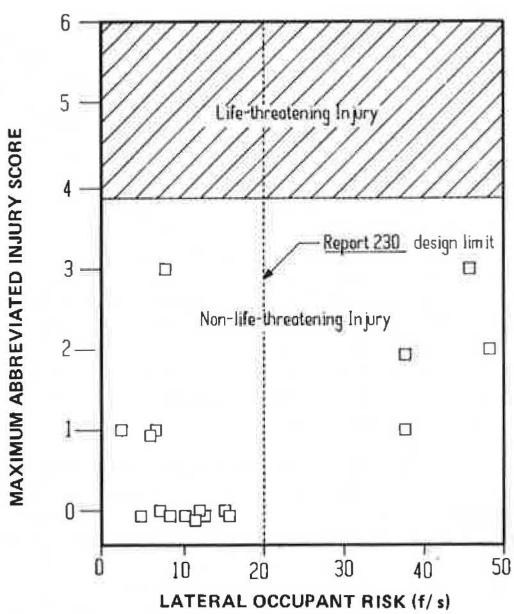


FIGURE 5 Occupant injury versus lateral occupant risk factor.

The original intent of this research was to discover some relationship between the occupant risk factor and the actual level of injury sustained in real highway accidents. The data proved to be surprising. Figure 5 shows a plot of the occupant risk factor versus the MAIS for the first impact of each of the serious and severe injury cases in Table 7. None of the 17 accident cases resulted in a life-threatening injury after the first impact. Figure 5 illustrates the apparent relationship between the occupant risk factor and the MAIS. Injuries greater than or equal to an AIS of 4 do not appear likely until the occupant risk factor is in excess of 40 fps, twice the design limit suggested in NCHRP Report 230.

TYPICAL VALUES IN FULL-SCALE CRASH TESTS

The sled test data indicated that serious injuries were not likely to occur under what have generally been considered to be severe impact conditions. How useful, then, is the occupant risk factor for evaluating longitudinal barriers?

Since NCHRP Report 230 was published in 1981, nearly 300 full-scale crash tests have been performed at SwRI. Rarely has a test device been disqualified

TABLE 8 Occupant Risk Values for 15 Bridge Rail Crash Tests (10)

Test No.	Impact Conditions[a] Speed (mph)	Angle (degrees)	Occupant Risk Frontal (fps)	Side[b] (fps)	50-msec Avg[b] Vehicle Acceleration Front (g's)	Side (g's)	Comments
NBR-1	60.7	19.3	7.2	21.8	-5.8	12.6	Smooth redirection
NBR-2	61.4	24.9	3.0	21.6	-6.3	8.4	Smooth redirection
NBBR-1	61.4	20.0	5.3	20.7	-4.9	13.5	Smooth redirection
NBBR-2	58.4	24.3	-[c]	9.9	-5.9	8.2	Smooth redirection
NCBR-1	59.7	18.8	14.0	22.7	-8.1	12.9	Smooth redirection
NCBR-2	60.0	25.0	16.6	31.2	-6.9	17.9	Smooth redirection
OBR-1	58.6	18.8	0.8	19.9	-3.3	10.2	Smooth redirection
OBR-2	60.8	24.3	20.9	26.0	-5.2	13.7	Snagged hood
OBR-3	60.0	25.0	0.9	28.2	-5.2	15.9	Smooth redirection
KBR-1	61.9	20.3	11.5	20.4	-7.5	11.2	Smooth redirection
KBR-2	60.5	24.0	30.0	23.3	-8.3	13.4	Severe snagging
OHBR-1	60.6	19.6	7.3	20.6	-5.6	11.4	Smooth redirection
OHBR-2	60.0	25.0	7.0	25.1	-6.1	12.1	Smooth redirection
LABR-1	60.4	18.8	-[c]	23.6	-4.4	12.8	Smooth redirection
LABR-2	59.7	19.1	14.0	22.8	-5.3	10.8	Smooth redirection

[a]20-degree tests utilized Honda Civics and 25-degree tests utilized Plymouth Furys.
[b]From transducer data.
[c]Hypothetical occupant did not displace the required 24 in.

because of the occupant risk criteria alone. Table 8 gives a brief summary of the impact conditions, occupant risk measurements, and 50-msec average accelerations from a research project (10) that involved a number of crash tests of operational bridge rails. Bridge rails are generally rigid barrier systems and therefore provide minimal energy dissipation during collisions; the highest values of the occupant risk factor should be observed during bridge rail tests. The data in Table 8 indicate that even in rigid barrier collisions the occupant risk factors are generally in the same range that was shown to be noncritical for the sled tests in Table 2. The probability of an occupant sustaining injuries of AIS 4 or greater is remote for these 15 typical rigid barrier installations.

Clearly there are two problems with using the occupant risk criteria for evaluating longitudinal barrier crash tests. First, as the sled test and accident data imply, serious injury does not appear likely at the current NCHRP Report 230 design limit of 20 fps or even at a more liberal value of 30 fps. The accident data imply that severe occupant injury is not likely until occupant lateral impact velocities of at least 40 fps occur. Second, the occupant risk is nearly always below 30 fps even in rigid barrier tests. Hence, although the flail space concept is both accurate and simple to use, it does not provide a measure that is meaningful in assessing longitudinal barrier crash tests.

DISCUSSION

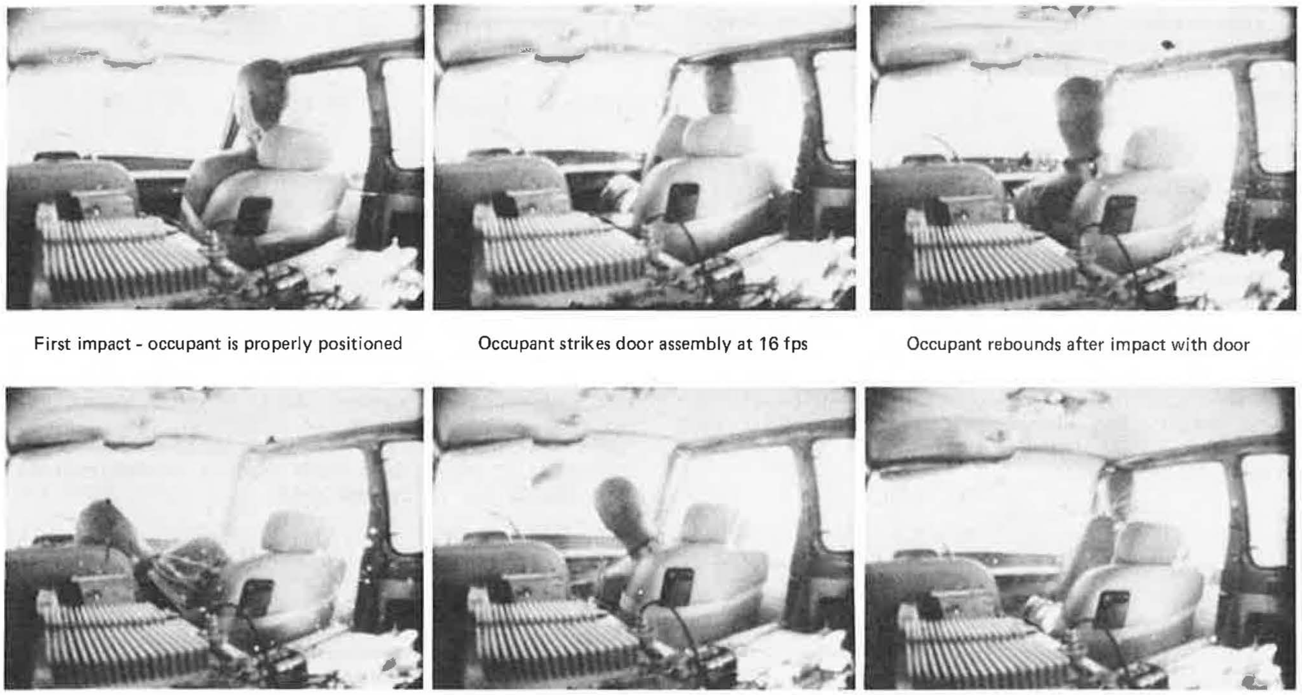
How then are occupants being injured and killed in the nearly 1,500 fatal longitudinal barrier accidents that occur each year (5)? Some clues may have been suggested earlier in this paper.

In more than 80 percent of the cases summarized in Table 7, the vehicle struck another roadside object after being successfully redirected from the first collision. For all of the vehicle occupants that experienced secondary impacts, the MAIS was greater in the second impact than the first, sometimes by a large margin. For example, after the first barrier impact in NASS Case 83-02-071T the occupant had sustained no injuries. After the vehicle was redirected, however, it collided with a tree; the MAIS for the second collision was 3. Often, in the cases summarized in Table 6, the occupant sustained no injuries during the first redirection only to become involved in another, much more serious, subsequent collision. Clearly, redirection into other roadside features poses a serious hazard to vehicle occupants.

There are several possible reasons for this increase in injury rate for occupants of vehicles that are redirected from a longitudinal barrier and subsequently strike other roadside features. Although the impact speed is nearly always less in second collisions, the angle frequently increases. In Table 7, the second impact angle was larger than the first in all of the multiple-impact cases. Frontal impacts may be more injurious than side impacts because of the greater amount of flail space in which the occupant may accelerate as discussed earlier in this paper. Therefore, as the impact angle becomes larger, the impact will become more frontal. Because occupants have larger flail distances available in frontal collisions they may be at greater risk of sustaining injury.

Another important feature of the secondary collision is the occupant's position in the passenger compartment. At the time of the initial collision the occupant is usually positioned correctly in the seat. During the first redirectional collision the occupant will strike the door surface and rebound beyond his preimpact position. Thus, if a second collision occurs, a larger flail space is available in which to accelerate to a higher velocity. Figure 6 shows a set of sequential photographs of an anthropometric dummy taken during a longitudinal crash test in which the vehicle unintentionally struck two barriers. The dummy struck the door in the first collision, rebounded beyond its original seating position, and then struck the door again at a higher velocity during the second collision. The dummy's flail distance was more than two times greater in the second collision.

Although considerable attention and effort have been devoted to defining and measuring vehicle accelerations during longitudinal barrier crash tests, little effort has been directed to affecting the after-collision trajectory of the vehicle. This lack of attention to the postimpact trajectory can be attributed to both the unrecognized importance of this phase of the test by the technical community and the unpredictability and frequently erratic be-



First impact - occupant is properly positioned

Occupant strikes door assembly at 16 fps

Occupant rebounds after impact with door

Second impact - occupant out of position at second impact

Occupant accelerates toward door

Occupant strikes door assembly at 35 fps

FIGURE 6 Effect of occupant position on occupant risk factor.

havior of the vehicle caused by wheel and frame damage as well as imprecise braking controls. Even with improved braking controls, the authors are not confident that the after-collision vehicle trajectory would be a good crash test assessment criterion.

On the other hand, by changing the emphasis of barrier design from reducing vehicle accelerations during a collision to effecting more predictable vehicle trajectories, longitudinal barrier developers may be able to improve the vehicle's postimpact trajectory and greatly increase the safety of the vehicle occupants.

Although a number of possible reasons have been suggested for the causes of occupant injuries after the initial collision with a longitudinal barrier, the data are not sufficient to suggest the magnitude of the redirection problem. Cumulatively, however, postimpact vehicle trajectory and stability appear to be crucial to providing protection to vehicle occupants.

The ultimate objective of longitudinal barrier designers is to protect occupants by shielding vehicles from more hazardous roadside objects and to shield pedestrians from traffic. It is often a difficult task to determine what specific aspects of a design will work best toward these goals. For many years longitudinal barrier designers have attempted to find a balance between the often conflicting goals of barrier flexibility for vehicle occupant protection and barrier strength for vehicle containment.

The discussions in previous sections have suggested that these goals need not conflict. A longitudinal barrier system that performs correctly, smoothly redirecting the vehicle without serious snagging, vaulting, penetration, or rollover, will not subject the occupant to lateral collision forces of a magnitude great enough to cause severe injury. Thus, if designers ensure that longitudinal barriers perform "correctly," vehicle occupants will generally be well protected in redirectional collisions.

Although the foregoing discussion indicates that the occupant risk factor may not be the critical evaluation factor in longitudinal barrier tests, the authors recommend that these measurements continue to be taken especially because they are easily calculated from vehicle dynamics. Moreover, the vehicle kinematics and occupant risk determinations are critical for other roadside hardware evaluation tests such as those of crash cushions and breakaway supports.

CONCLUSIONS

There are two principal conclusions to this study. First, when a tracking vehicle strikes a longitudinal barrier and is smoothly redirected and remains upright, the risk of severe occupant injury in that collision is quite small. Although the flail space model and the occupant risk criteria are useful and simple tools for estimating the behavior of occupants in a collision environment, they do not appear to be a discerning assessment factor for redirectional tests. In the absence of snagging, barrier penetration, or rollover, it is not likely that high values of occupant-interior impact velocity will be observed. Because NCHRP Report 230 already requires smooth redirection and an upright vehicle, the occupant risk factor is a redundant evaluation criteria.

Second, the postimpact trajectory of the vehicle, though difficult to predict or control, is an important feature of barrier performance and should be more carefully considered in future longitudinal barrier development and testing. Although it is doubtful that postimpact trajectory can be explicitly used as a test evaluation criteria, it is a feature of motor vehicle collisions that should receive more attention from the highway safety community. The authors are confident that this aspect of vehicle and appurtenance interaction can be used to develop even more creative and innovative methods of providing an even higher level of safety on our nation's highways.

ACKNOWLEDGMENTS

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Discussion

John G. Viner*

The authors' first conclusion states that, in tracking vehicle impacts with longitudinal barriers in which the outcome is a smooth redirection with no overturn, "the risk of severe occupant injury in that collision in quite small," and high values of occupant-interior impact velocity are "not likely." Thus the authors state that the occupant risk factor is a redundant evaluation criterion in redirection crash tests conducted according to NCHRP Report 230 procedures. The relevant data in this paper (four side-on dummy tests and 165 accidents) do not support this conclusion. When viewed from the broader perspective of other data from NASS, a somewhat inverse hypothesis may be supportable.

DUMMY DATA

The calibration procedures recommended by the NHTSA were not followed in the dummy tests. The data in Table 2 indicate that measured values of spine and upper rib acceleration (used in calculating TTI, which in turn is used to estimate the probability of AIS $\geq$ 3) do not consistently increase with increasing test ΔV. The values of TTI for the 40-fps test are in the area of the AIS $\geq$ 3 versus TTI curve (Figure 3), where small changes in TTI produce relatively large changes in this estimate. The 20- and 30-fps tests are close to this region of the curve. These side-on tests were made with a flail space distance of 6.5 in.; yet, as noted by the authors, the measured flail space values from the 1978-1984 NCAP tests ranged from 7 to 13 in. and the NCHRP Report 230 procedure uses 12 in.

The apparent inconsistency in the dummy data suggests that the failure to follow the recommended calibration procedures has affected the validity of the data. If a 12-in. flail space had been used, as recommended by NCHRP Report 230 (and the authors), the dummy accelerations would have been larger. Because the estimate of probability of injury (AIS $\geq$ 3) is quite sensitive to increases in dummy accelerations, a repeat of these tests using a 12-in. flail space is likely to result in significantly larger estimates of injury probability.

ACCIDENT DATA

The authors' conclusion that the risk of severe injury (AIS $\geq$ 4) is "quite small" in tracking vehicle impacts with longitudinal barriers, if the vehicle is smoothly redirected without overturning, is

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debatable. The 2 percent (3 of 165) of the eligible longitudinal barrier cases with AIS $\geq$ 4 is comparable to the national estimate from NASS 1984 data that 1.5 percent of all run-off-road accidents (trees, rollovers, ditches, guardrails, etc.) result in AIS $\geq$ 4 injuries. The NASS estimate is calculated from 4,911 investigated accidents in which the first harmful event occurred outside the shoulder of the road.

A similar comparison can be made with the AIS $\geq$ 2 cases in this paper. The 17 AIS $\geq$ 2 cases represent 11 percent of the eligible accidents. From the 1984 NASS data on accidents in which the first harmful event occurred outside the shoulder, 12 percent had AIS $\geq$ 2. Thus, at both the AIS $\geq$ 2 and the AIS $\geq$ 4 levels, the eligible longitudinal barrier cases (tracking vehicles that strike in the length of need and that are redirected by the barrier and remain upright) were found to be comparable with roadside accidents in general.

End impacts, overturns, penetrations, and vaulting accidents with longitudinal barriers, which were excluded from the eligible longitudinal barrier accident cases in this study, are more severe than impacts that result in smooth redirection. This suggests that tracking vehicle impacts with longitudinal barriers are more likely to result in AIS $\geq$ 2 and AIS $\geq$ 4 injuries than are run-off-road accidents in general.

Although the intent of longitudinal barriers is to protect the traveling public from the more serious roadside hazards, the finding in this study that under favorable conditions (no end impacts, rollovers, etc.) the severity of injury to occupants of tracking vehicles in longitudinal barrier impacts was the same as that of roadside accidents in general deserves further attention. The authors' observation that the 300 tests examined by NCHRP Report 230 criteria have rarely resulted in occupant risk criteria alone disqualifying a device thus suggests further study to see if lowering or revising the occupant risk criteria should be considered.

LATERAL OCCUPANT RISK DESIGN LIMIT

The measure of effectiveness used by the authors for the accident analysis, likelihood of AIS $\geq$ 4, was selected because "The intent of NCHRP Report 230 was to select an occupant risk design limit such that occupants would not sustain an injury of AIS 4 or greater." This is not the case. As stated on page 30 of NCHRP Report 230, "Accident statistics from France (22) indicate that injuries of AIS 3 or greater were sustained in 50 percent of side impact cases for a ΔV of at least 30 fps (9.4 m/s). Where the compartment space is not intruded, an upper lateral occupant impact velocity of 30 fps (9.1 m/s) appears to be a reasonable limit. . . ." NCHRP Report 230 recommends that a factor of safety of 1.5 be used with this limit value giving a 20-fps design limit to lateral ΔV in the appropriate crash tests.

This interpretation of AIS 4 as a design limit rather than a 50 percent chance of AIS $\geq$ 3 makes a difference because the AIS scale is not a linear scale of injury outcome. For example, from the 1984 NASS estimates of accidents with first harmful events outside the shoulder, accidents with a maximum AIS of 3 result in fatalities in 5.4 percent of the cases whereas, with an AIS of 4, fatalities result in 15.6 percent of these cases. For comparison, 1.2 percent of all such accidents are estimated to result in fatalities.

In Figure 5, the authors compare the calculated ΔV from the 17 reconstructed accidents (in which AIS $\geq$ 2) with the actual injuries sustained in the first impact in these cases. The authors state that the original purpose of this research was to discover some relationship between lateral ΔV and likelihood of injury. Looking at the data from the point of view of the quote from NCHRP Report 230 (see Figure 5), only four cases had a calculated ΔV of at least 30 fps. One case was AIS 3 and two were AIS 2. This is consistent with the 50 percent chance of AIS $\geq$ 3 in this selected limit.

CONCLUSIONS

1. The dummy data used to support the authors' first conclusion are questionable because (a) recommended calibration procedures were not followed, (b) the data showed apparent contradictions, (c) the flail space used in these tests was less than either that found from vehicle measurements or NCHRP Report 230 recommendations, and (d) the calculated likelihood of AIS $\geq$ 3 injuries is quite sensitive to the dummy data values.

2. The accident data do not support the authors' assertion that the risk of severe occupant injuries in the selected longitudinal barrier cases is small. Rather, from NASS 1984 data, the outcome of these longitudinal barrier collisions (under the favorable conditions of excluding end impacts, rollovers, vaulting, snagging, and underride) was found to be comparable to that of roadside accidents in general.

3. The authors found that the current occupant risk criteria are rarely a discerning assessment factor in redirection tests. Yet, a set of longitudinal barrier accidents with characteristics associated with successful crash test outcomes (no vaulting, no overturn, redirected vehicle, etc.) was found to have severities identical to roadside collisions in general.

4. In summary, the data in this paper, when supplemented by a comparison with roadside accidents in general, do not support the authors' conclusion that the occupant risk factor in redirectional crash tests is redundant. Rather, the data indicate that either the allowable lateral limit of ΔV should be lowered from the current value of 20 fps or the severity of the impact conditions (test speed-angle combinations) should be increased.

The link between measurements made on the crash test pad in redirectional-type crash tests and probability of injury has been recognized as a research need by specialists in this area for a number of years. The authors' use of the relatively new side impact dummies and reconstructions of accidents that have been investigated in depth is indeed valuable in increasing our current tenuous understanding in this area. Further study to see if the lateral ΔV limit of 20 fps should be lowered or test severity increased should be considered. The NASS and National Crash Severity Study data bases can be used to help interpret the results of such studies.

Authors' Closure

In the preceding discussion by a member of Committee A2A04, the discussant correctly states in his final summary that "the link between measurements made on the crash test pad in redirection-type crash tests and [the] probability of injury has been recognized as a research need by specialists in this area for a number of years." There have indeed been few investigations into the relationship between measurements made during full-scale vehicle crash tests and the risk of injury to vehicle occupants in real-world accidents. The data discussed in the paper represent a first step in an area that demands much more attention from the research community. The discussant has raised a number of topics and has helped to focus critical and creative thinking on these important issues. The authors are indebted to the discussant's diligence and insight and for this opportunity to further clarify our findings.

There are a number of specific questions in the discussion, but nearly all of them hinge ultimately on one of two issues: (a) the value and validity of data taken in the anthropometric dummy sled tests and (b) the acceptable level of injury specified in NCHRP Report 230 (1).

SLED TEST DATA

Figure 7 shows a plot of the dummy response data for the side impact sled tests given in Table 2 of the paper. The discussant states that because the spinal and lower rib accelerations vary slightly the data are flawed. Figure 7 shows that all of the data are within normal experimental tolerances. Furthermore, data for frontal impacts, also given in Table 2 of the paper, confirm that an occupant head impact velocity of 40 fps into a late-model vehicle windshield will produce an HIC of about 1000. This is also shown graphically in Figure 7. Thus the data are within the range of expected values, and the abbreviated test procedures used in this exploratory research appear to be both adequate and appropriate.

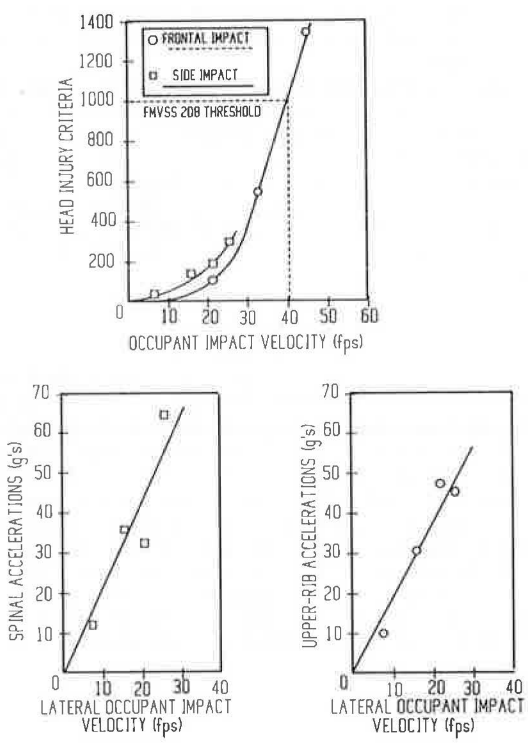

FIGURE 7 Sled test dummy responses.

The discussant apparently misunderstands the purpose of these sled tests: to examine the actual dummy response at various levels of occupant impact velocity. A flail distance of 6.5 in. was used in the sled tests because that was the actual distance measured between the head of the 50th percentile male side-impact dummy and the driver's-side door window. One of the basic assumptions of the flail space model is that human response to a collision is best quantified as a function of the occupant impact velocity. If two physiologically similar occupants experience identical occupant impact velocities, their responses should be similar regardless of the interior geometry or acceleration history of the vehicle. The NCHRP Report 230 lateral flail distance of 12 in. is used in evaluating full-scale crash tests to provide the worst case impact velocity given a particular acceleration history. In contrast, the purpose of these sled tests was to measure actual dummy responses at the occupant impact velocities actually experienced.

ACCEPTANCE INJURY THRESHOLD

Another key point of contention appears to be the question, "What should the upper bound for occupant injury severity be: AIS 2, 3, or 4?" Michie (12), in the original formulation of the flail space and occupant risk concept, suggested that:

> In line with current Federal Motor Vehicle Safety Standard (FMVSS) 208, an upper design limit for occupant protection falls between Codes 3 and 4.

This approach was restated in NCHRP Report 230 (1, p.30):

> An attempt has been made to set threshold values at a level equivalent to the American Association of Automotive Medicine Abbreviated Injury Scale (AIS) of 3 or less (3). AIS-3 classifies the resulting injury as severe but not life threatening.

Contrary to the discussant's understanding that NCHRP Report 230 specifies that the occupant has a 0.50 probability of receiving AIS-3 injuries, that report states in the passage quoted that all injuries of AIS 3 or less are acceptable though hardware developers should always strive to minimize occupant injury. Hence, the intention of NCHRP Report 230 is primarily to eliminate life-threatening injuries, that is, injuries of AIS 4 or greater.

When the acceptable injury range of AIS of 3 or less had been established, appropriate occupant impact velocities corresponding to the AIS-3 severity level were set based on the limited accident and research studies available to the author of NCHRP Report 230. A nominal 40-fps velocity was selected for occupants striking the windshield or instrument panel, and 30-fps velocity was selected for occupants striking the door. The 40-fps velocity threshold was well supported by research experience, in contrast to quite limited knowledge of human tolerance to side impacts. It was assumed in NCHRP Report 230 that occupant injury severity is a function of occupant impact velocity and that this injury severity would be lessened by reducing these impact velocities. Accordingly, reduction factors were applied to the 40- and 30-fps threshold velocities to arrive at design values of 30 and 20 fps for longitudinal and lateral impacts, respectively.

One of the objectives of this research program was to explore the relationship assumed in NCHRP Report 230 between lateral occupant impact velocity and injury in real-world accidents. As shown graphically in Figure 5, there were no occupant injuries during the first vehicle impact that were greater than AIS 3 even for occupant risk values of nearly 50 fps. From these data points, it appears to the authors that the lateral impact threshold limit of 30 fps may be too conservative and could be increased to 35 or 38 fps without adversely affecting occupant injury level. Simply stated, the design value of 20 fps may be unnecessarily restrictive, especially for more rigid longitudinal barrier systems, and could be relaxed to a design value of 25 or 30 fps.

CONCLUSION

The development of roadside safety hardware has been an active field of research for more than 25 years. Many of the attitudes and assumptions of the earlier years have become solidly cast into our present thinking about occupant protection with little regard to the validity of those assumptions today. The taxonomist Steven J. Gould has said that "Good science is self-correcting" (4); good engineering should also be self-correcting.

This study has suggested that the current 20-fps design limit for the lateral occupant impact velocity is not as crucial in mitigating injuries in redirectional collisions as was once believed. The effort spent by hardware developers in meeting this overly restrictive measure might better be spent in effecting improvements in other phases of the collision, namely the postimpact trajectory.

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Low-Maintenance End Treatment for Concrete Barriers

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ABSTRACT

The development of a low-maintenance crash cushion end treatment for concrete barriers is described. Features of the cushion include (a) no sacrificial energy-absorbing elements, (b) sufficient strength to withstand most impacts without damage to any components, (c) width approximately the same as that of the standard concrete safety shaped barrier, and (d) compliance with NCHRP Report 230 safety standards after only minor modifications. Results of six full-scale crash tests on the cushion are described.

Maintenance activities on heavily traveled urban freeways have become a major problem for most transportation agencies. Metal beam barriers on these freeways are frequently struck and must be repaired after most accidents. In recognition of these problems, highway engineers have begun to replace metal beam barriers with the almost maintenance-free concrete safety shaped barrier. However, the ends of these rigid concrete barriers pose both safety and maintenance problems. When left exposed or sloped to the ground, the rigid barrier end is a severe hazard. Efforts to mitigate this hazard include the use of crash cushion end treatments, flared ends, ends buried in earth berms or back slopes, and transition to a W-beam that is then terminated with a guardrail terminal. All of these safety treatments present some safety or maintenance problems, or both.

The crash cushion is probably the safest concrete barrier end treatment in use. However, crash cushion maintenance can be costly. All existing crash cushions use expendable energy-absorbing elements to attenuate head-on impacts, which destroy one or more of these energy-absorbing elements. Replacement of the damaged elements is costly, and for those end

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