Comparative Performance of Barrier and End Treatment Types Using the Longitudinal Barrier Special Study File

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By using the Longitudinal Barrier Special Study file developed in the 1980s for FHWA as part of the National Highway Traffic Safety Administration's National Accident Sampling System data gathering, the performance of various types of guardrails, median barriers, and end treatments as well as the risk to the driver when striking a barrier length of need (LON) versus an end section are compared. Data elements describing the barriers and end treatments were much more detailed than is typically the case in police investigations. Multi-vehicle crashes were excluded, because of the difficulty in determining when driver injury occurs. Most of the analysis focuses on cases in which a vehicle strikes only a single barrier, though sometimes more than once. It was found that weak post barriers were less associated with driver injury than other barrier types. In regard to subsequent impact, rollover produced the highest rate of driver injury. Higher risks of serious driver injury were associated with blunt and turndown end treatments than with LON. End hits were more likely to result in serious driver injury than LON by being more likely to produce rollover and by producing more serious injuries when no rollovers occur.

For roadway and roadside design engineers and others interested in the performance of hardware, a persistent topic of interest has been the performance of various types of guardrails, median barriers, and end treatments, and the comparison of risk to the driver when striking a barrier length of need (LON) versus an end section. This topic was explored using the Longitudinal Barrier Special Study (LBSS) file developed in the 1980s for FHWA as part of the National Highway Traffic Safety Administration's (NHTSA) National Accident Sampling System (NASS) activity. Data were generated by NASS investigators working through various zone centers in the United States. For an eligible case, detail far beyond routine police crash investigation was obtained, with barrier descriptors including items such as post spacing, presence of block-out, end treatment type, angle of impact, yawing angle, and barrier performance (*1*).

From 1982 to 1986, about 1,200 crashes involving roadside barriers were input to the file for analysis. Almost half of the crash data was obtained in 1982 and 1983 (almost 300 cases each year). Within the file there are subsets of data pertaining to barrier, accident, vehicle, driver, occupant, and pedestrian variables. These variables can be linked to generate a vehicle-based contacts file (that is, to describe a vehicle's path through the crash, which could involve multiple barrier contacts and contacts with other vehicles or objects). A problem with building the file and conducting subsequent analysis was that the coding for the "object contacted" variable in the barrier subset was not uniform across the 5 years of data collection. Considerable recoding was required to develop the consistency necessary to ensure appropriate sample sizes for analysis.

REVIEW OF LITERATURE

The design of longitudinal traffic barriers has been influenced greatly by two basic assumptions: (a) occupants are subjected to the highest risk of injury during the vehicle's initial collision with a barrier, and (b) the probability of severe occupant injury is directly related to the intensity of vehicle collision accelerations (*2*). To assess these assumptions, Ray et al. (*2*) conducted sled tests and analyzed data from several accident files (including 1982 and 1983 LBSS data) and full-scale crash tests. They found that occupants rarely sustain serious injuries in collisions with longitudinal barriers if the vehicle remains upright and is redirected smoothly by the barriers. They concluded that the vehicle's post-impact trajectory is an important component of barrier performance and should be considered more carefully in future barrier development and testing.

A follow-up study by Ray et al. analyzed the risk of occupant injury in second collisions (*3*). Crash data from North Carolina and New York suggested that occupants were three times more likely to suffer severe injury in a second collision after the vehicle had been redirected successfully from a longitudinal barrier. Criteria for eligible cases included the following: (a) the longitudinal barrier was the first object struck, (b) the vehicle was a passenger vehicle, (c) the impact was in the midsection (LON) of the barrier, and (d) the impact angle was oblique. For the North Carolina data, nontracking vehicles were eliminated.

Bryden and Fortuniewicz analyzed data from completed field investigations at 3,302 traffic barrier accident sites in New York State to determine the effects of various parameters on barrier performance (*4*). Their research showed that collisions with traffic barriers resulted in low occupant injury rates than roadside accidents in general. Traffic barriers performed best for midsize passenger automobiles in terms of injury severity as well as vehicle containment and secondary collisions. They did not perform as well for vans and light trucks because of secondary rollovers. The severe injury rates of heavy trucks were comparable to those of automobiles, but

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heavy trucks often penetrated barriers and were involved in secondary collisions.

As part of a study on severity measures for roadside objects and features, Mak et al. analyzed two data sources containing information on real-world impact conditions for 472 pole accidents and 124 bridge accidents (*5*). They found that a gamma function provided the best fit for both univariate impact speed and impact angle distributions. Impact speed and angle probability distributions were developed for various functional classes of roadways. The authors cautioned that their results are limited only to reported accidents and that accidents involving poles and safety features at bridge sites are not necessarily representative of all run-off-road crashes.

Troxel et al. used the 1980-1985 Fatal Accident Reporting System and the 1982-1985 NASS data bases to extract the characteristics of side-impact accidents with fixed roadside objects (*6*). Such accidents involved tall, narrow objects such as trees and utility poles. Narrow-object collisions appeared to be twice as likely to result in fatalities as were broad-object collisions. Guardrail accidents accounted for 9 percent of all side-impact, fixed-object crashes and 4 percent of fatal side-impact, fixed-object crashes. All guardrail fatalities were caused by collisions with end sections and transitions. The authors suggested that the most effective countermeasures for guardrail collisions would involve improving the performance of terminals and transitions.

Pigman and Agent analyzed 110 accidents involving breakaway-cable-terminal (BCT) end treatments and 36 accidents involving median breakaway-cable-terminal (MBCT) end treatments as used in Kentucky (*7*). The BCT end treatment performed properly in 73 percent of accidents, with the wooden posts breaking away or the guardrail redirecting the vehicle. Proper performance ranged from 60 percent for end sections with no offset to 69 percent for a simple curve offset and 79 percent for a parabolic flare offset. The MBCT performed properly 63 percent of the time. The authors recommended that the MBCT end treatment design be modified or eliminated because of its stiffness and the problems associated with impacts at shallow angles.

Rollovers are an undesirable result of barrier crashes. To evaluate the performance of the concrete safety-shape barrier with the New Jersey profile, Perera and Ross used a modified version of the Highway-Vehicle-Object-Simulation Model (HVOSM) (*8*). They determined that overturns could be expected for small cars in nontracking or high-angle impacts with the concrete safety-shape barriers. The overturn problem could be mitigated by installing a barrier with a constant-slope face or a vertical wall. A retrofit design for the barrier consisting of a longitudinal member placed on the side of the barrier near the top also showed promise in reducing the problem.

Through statistical analyses of three accident data files and computer simulation using a modified version of HVOSM, Mak and Sicking also examined rollover accidents caused by concrete safety-shape barriers (*9*). Three impact conditions were identified as potential contributory factors to rollovers: (1) high impact angle and moderate to high impact speed; (2) high slip angle, low to moderate yaw rate, and moderate to high impact speed; and (3) high impact speed and low impact angle for vehicles in a tracking mode. The authors considered three alternative barrier shapes as countermeasures for reducing rollover rates. Of these, the F-shape offered little performance improvement and the vertical wall offered the greatest reduction in rollover potential, but with the greatest increase in lateral accelerations. The constant-sloped barrier was suggested as perhaps the best compromise solution.

CREATION OF THE ANALYSIS FILE

The LBSS data collected by field investigators were partitioned into accident, vehicle, occupant, driver, contacts, and impacts subfiles. The main file used for the analyses related to barrier and end types and risk in LON versus end crashes was a vehicle-oriented file built from these subfiles, with one record per vehicle. The analysis file was developed from an original accident-oriented file that contained information on all impacts by all vehicles involved in a crash and the object contacted for each impact. The file was first restricted to only single-vehicle accidents, with the reasoning being that the deletion of multiple-vehicle crashes would help ensure that the harm to the driver was related predominantly to the barrier impact rather than the impact with another vehicle, either before or after striking the barrier. Some 168 variables on the merged file were selected as candidates for analysis from the accident, vehicle, occupant, driver, contacts, and impacts subsets.

The analysis file also contained a "flag" variable that allowed it to be categorized into three types of analysis records, all of which involved single-vehicle crashes: (a) an "all hits" subfile, in which a vehicle may strike a barrier and then another barrier or object, (b) a "barrier hits only" subfile, in which a vehicle strikes no objects other than one or more longitudinal barriers, and (c) a "clean hits" subfile, in which a vehicle strikes only a single barrier, though sometimes more than once. Thus, using the clean hit file, the instances in which a vehicle struck a barrier, and nothing else, or the vehicle struck the same barrier several times could be examined.

The clean hits and barrier hits only subfiles are contained within the all hits file. The analyses used the clean hits and all hits data. Using the clean hits data is the most appropriate way to examine harm caused by a specific barrier type, in that any driver injury would be the result of striking the barrier. If a vehicle strikes another vehicle or object and then a barrier, determination of when the injury occurred is speculative at best. Thus, for most of the analyses, the clean hits file was used to verify the results from the larger all hits file. The clean hits file contained 665 vehicle records, and the all hits file contained 1,062 vehicle records.

CLEAN HITS FILE

Much of the analyses involved the clean hits subfile. Results from the all hits subfile were quite similar. From the clean hits data, 665 single vehicle impacts were available, 450 pertaining to LON and 215 to end-of-barrier crashes (with end hit defined as an impact occurring within the first 25 ft of the barrier). The percentages in the following data pertain to the total of 665 impacts.

- Guardrail types—23 percent G4 (1S) (blocked out W-beam with steel posts), 20 percent W-beam strong post.

- Median barrier types—58 percent concrete median barrier.
- Blocked-out presence—55 percent blocked out.
- End treatment type—41% blunt, 30 percent turndown, 10 percent breakaway cable.
- Location of end treatment in direction of vehicle travel—78 percent upstream (the first end a vehicle would encounter in normal direction of travel).
- Distance from end of barrier to initial point of impact—21 percent within first 3 m (10 ft).
- Length of longitudinal barrier section—87 percent longer than 30 m (100 ft).
- Location of barrier in direction of vehicle travel—61 percent off left side of road, 36 percent off right side. (When the item was coded, guardrail crashes split as 44 percent off of left side and 56 percent off of right side.)
- Curb presence—present 16 percent of time.
- Curb height—61 percent 25–127 m (1–5 in.), 39 percent 152–254 m (6–10 in.).
- Perpendicular distance from curb to barrier—62 percent 1 m (3 ft) or less.
- Total change in elevation—13 percent no change, 57 percent below edge of roadway, 30 percent above edge of roadway. (For LON, virtually the same percentages. For ends, 12 percent no change, 67 percent below edge of roadway, 21 percent above edge of roadway.)
- Longitudinal barrier height—32 percent 660–737 m (26–29 in.) in height, 30 percent 762–838 m (30–33 in.) in height. [For LON, 29 percent 660–737 m (26–29 in.) in height, 36 percent 762–838 m (30–33 in.) in height. For ends, 38 percent 660–737 m (26–29 in.) in height, 17 percent 762–838 m (30–33 in.) in height.]
- Total horizontal distance to barrier—3 percent barrier at edge of road, 22 percent 0.3–1.2 m (1–4 ft) from edge, 26 percent 1.5–2.4 m (5–8 ft) from edge, 29 percent 2.7–3.7 m (9–12 ft) from edge, and 20 percent 4 m (13 ft) and greater from edge.
- Length of direct contact with barrier—63 percent 0.3–6.1 m (1–20 ft) of contact, 27 percent 6.4–15.3 m (21–50 ft) of contact.
- Impact angle—1 percent at zero degrees, 21 percent at 1–8 degrees. (For LON, 1 percent at zero degrees and 15 percent at 1–8 degrees. For ends, 3 percent at zero degrees and 24 percent at 1–8 degrees).
- Yawing angle at impact—4 percent at zero degrees, 14 percent at 1–8 degrees, 32 percent greater than 27 degrees. (For LON, 3% at zero degrees, 11 percent at 1–8 degrees, 31 percent greater than 27 degrees. For ends, 5 percent at zero degrees, 22 percent at 1–8 degrees, 33 percent greater than 27 degrees).
- Impact speed—36 percent at 34–56 km/hr (21–35 mph), 30 percent at 58–72 km/hr (36–45 mph), 12 percent at 74–89 km/hr (46–55 mph), and 9 percent greater than 89 km/hr (55 mph). (For LON and ends separately, virtually the same percentages.)
- Separation angle—63 percent at 0–8 degrees. (For LON ends separately, virtually the same percentage.)
- Barrier performance—65 percent redirected, 11 percent snagged, 12 percent overrode. (For LON, 77 percent redirected, 9 percent snagged, 7 percent overrode; for ends, 38 percent redirected, 16 percent snagged, 22 percent overrode.)
- Postimpact trajectory—50 percent remained on roadside, 25 percent returned to roadway, 16 percent went on top of/over/through. (For LON, 52 percent remained on roadside, 28 percent returned to roadway, 11 percent went on top of/over/through. For ends, 47 percent remained on roadside, 18 percent returned to roadway, 25 percent went on top of/over/through.)
- Subsequent impact—10 percent rollover (9 percent for LON and 13 percent for ends).
- Driver age—0.3 percent less than 16 years; 22 percent 16–20 years; 20 percent 21–24 years; 31 percent 25–35 years; 20 percent 36–55 years; 5 percent 56–75 years; 1 percent 76 and over.
- Driver injury, MAIS scale—40 percent no injury, 45 percent minor injury, 9 percent MAIS 3 and above. (For LON, 42 percent no injury, 48 percent minor injury, 3 percent MAIS 3 and above. For ends, 40 percent no injury, 43 percent minor injury, 11.5 percent MAIS 3 and above.)
- Driver injury, KABCO scale—51 percent no injury, 12 percent possible or C injury, 24 percent non-incapacitating or B injury, 11 percent incapacitating or A injury, 0.8 percent killed. (For LON, 52% no injury, 12 percent C injury, 24 percent B injury, 10 percent A injury, and 0.7 percent killed. For ends, 48 percent no injury, 10 percent C injury, 23 percent B injury, 18 percent A injury, 1.4 percent killed.)
- Vehicle type—83 percent passenger cars, 15 percent light trucks and vans, and 3 percent heavy trucks.

REPRESENTATIVES OF THE LBSS FILE

Because of the nature of the questions that can be analyzed with the LBSS file, it is important to have some understanding of how "representative" the file is of barrier impacts in the United States. The LBSS file cannot be used for determining frequency or rate of barrier impacts, so questions concerning representativeness are related to the severity of the crash.

To examine the issue of representativeness, information was extracted from accident files from North Carolina, Michigan, Utah, Maine, and Illinois. The latter four states are part of the Highway Safety Information System, the FHWA data base used in many of their internal analyses. A number of tables were examined. In summary, fatal driver injuries occurred almost twice as often in the LBSS file as in all other files, and serious injury occurred slightly more often than in the North Carolina towaway file and significantly more often than in the Michigan towaway file or in the other states. Part of the difference in severity may be related to the selection of the LBSS sample of crashes for investigations. The emphasis on fatal crashes in some NASS procedures may have biased this file to a certain extent. In short, while much more like a towaway file than a total crash file, the LBSS file may indeed contain a slightly more severe set of guardrail impacts than is the case in the comparison groups of states. The analyses that follow are based exclusively on LBSS data and are comparative, so that representativeness is much less of a concern.

ANALYSIS AND RESULTS

The following section presents the methods and results of the analyses conducted. Again, the major questions being explored were (a) the comparative injury-related (injury severity to drivers) and vehicle trajectory-related (redirected, snagged, vaulted) performance of different types of barriers and different types of barrier end treatments, and (b) the comparison of performance for LON versus ends. Data pertaining to the exposure of vehicles to barriers and ends were unavailable for analysis, as were data pertaining to low severity impacts (driveways) where no crash data are reported to police or other investigating units. The analyses thus compare various barrier and end types.

LON Analysis

Comparisons of Barrier Types Within LON

Based on what was available in the file, nine types of guardrails (GR) and median barriers (MB) were grouped for analyses:

Barrier Type	*LBSS Description*
GR-1 (weak post)	G1, G2, G3
GR-2 (strong post)	G4 (1W), G4 (2W), G4 (1S), G4 (2S), G9
GR-3 (rigid)	Concrete safety shape
GR-4 (other)	Other guardrail type
GR-9 (W-beam strong post)	W-beam (strong post)
MB-5 (weak post)	MB1, MB2, MB3
MB-6 (strong post)	MB4W, MB4S, MB9
MB-7 (rigid)	Concrete median barrier (MB5)
MB-8 (other)	MB7, other median barrier type

(Note that GR-9, W-beam strong post, was examined as a separate category and not merged with the other types in GR-2. Much of the data referred to an older type of guardrail system likely to be located on lower-volume and lower-speed roadways, which is no longer installed.)

Distributions of severity of injuries to drivers involved in crashes into the LON of these barriers are shown in Tables 1 and 2 in terms of the KABCO and MAIS injury severity scales, respectively. These tables are based on all barrier hits, not just clean hits. The right-most column of Table 1 also gives the percentage of A or K injuries for each barrier type, and at the bottom of this column are results of a significance test comparing these A or K percentages. In Table 2 the last three columns show percentages having MAIS ≥ 1, MAIS ≥ 2, and MAIS ≥ 3, respectively (representing any injury, moderate to severe injury, and fairly severe injury), with significance test results given at the bottom of the columns. Note that no X^2 is shown for MAIS ≥ 3 because the data were too sparse for the test to be valid. The severe (A or K) KABCO injury differences across barrier types were marginally significant (p = .055), but the MAIS ≥ 3 injury differences were based on too few data to make valid comparisons. Because there were relatively few injuries at MAIS level 2, differences in the percentage with MAIS ≥ 2 were also only marginally significant (p = .10). On the other hand, the MAIS ≥ 1 differences were highly significant (p = .000).

Although the KABCO results look a bit worse, Tables 1 and 2 show that relatively few serious (or fatal) injuries resulted from hits into the LON for any of the barrier types. Thus, if differences in injury severity distributions between barrier types exist, they appear to be occurring primarily at the lower end of the severity scale. This is confirmed by the statistical tests associated with the MAIS data in the last three columns of Table 2.

Results were similar when the data were limited to clean hits into the barriers. Again, the significance tests showed significant differences across the barrier types with respect to driver injury versus no injury, but nonsignificant differences for MAIS ≥ 2. Both the all hits and the clean hits data suggest higher injury rates associated with barrier types GR-3 (rigid guardrail), MB-6 (strong post median barrier), and MB-7 (concrete median barrier).

All subsequent comparisons of barrier type were based on driver injury (MAIS ≥ 1) versus no injury (MAIS = 0) using MAIS. This is because the MAIS data were obtained from medical records and are considered more reliable than the police codes. A limitation is that the MAIS data are not as complete. Rows 1 to 5 (guardrails) and rows 6 to 9 (median barriers) of Table 2 were also analyzed separately as subtables relative to MAIS ≥ 1. For all hits the respective X^2 statistics and p-values were $X_4^2 = 6.762$ (p = .149) for guardrails and $X_3^2 = 14.874$ (p = .002) for median barriers; for clean hits these quantities were $X_4^2 = 9.975$ (p = .041), and $X_3^2 = 10.298$ (p = .016). Thus, when considered separately the differences in injury rates across the different types of median barriers were statistically significant. The injury rate differences across guardrail types were only marginally significant. Because injury rates for guardrails and median barriers were relatively similar, it seemed most efficient to analyze guardrails and barriers together instead of splitting a moderate-sized data set into two rather small subsets.

To further investigate differences in barrier type while taking into account the effects of certain covariates, logistic models of the form

$$\log \frac{p}{1-p} = \beta_o + \sum_{j=1}^{J} \beta_j X_j \qquad (1)$$

were fit to the data using SAS PROC LOGISTIC (*10*). The quantity $R = (p/1 - p)$ in Equation 1 can be thought of as the risk of injury. Taking exponentials of both sides of Equation 1 shows that injury risk (R) can be expressed as the product of factors

$$R = (e^{\beta_o})(e^{\beta_1 X_1})(e^{\beta_2 X_2}) \cdots (e^{\beta_j X_j})$$

A model of this type formulated to make comparisons among the five guardrail and four median barrier types contained eight dummy or indicator variables to flag the various guardrail and barrier types:

$X_1 = 1$ if GR-2, 0 otherwise.

$X_2 = 1$ if GR-3, 0 otherwise.

$\vdots$

$X_8 = 1$ if MB-8, 0 otherwise.

The model also contained three covariates: impact speed, vehicle curb weight, and impact angle. Thus, the estimated

TABLE 1 Driver Injury Severity (KABCO) by Barrier Type: All Hits into LON

	KABCO Injury Severity						
Type	0	C	B	A	K	Total	Percent A or K
GR-1	35	8	10	0	0	53	
	(66.0)	(15.1)	(18.9)	(0.0)	(0.0)		0.00
GR-2	72	13	36	20	3	144	
	(50.0)	(9.0)	(25.0)	(13.9)	(2.1)		16.0
GR-3	4	1	8	1	0	14	
	(28.6)	(7.1)	(57.1)	(7.1)	(0.0)		7.14
GR-4	49	10	15	6	0	80	
	(61.3)	(12.5)	(18.8)	(7.5)	(0.0)		7.5
GR-9	25	6	10	6	1	48	
	(52.1)	(12.5)	(20.8)	(12.5)	(2.1)		14.6
MB-5	23	3	5	3	0	34	
	(67.7)	(8.8)	(14.7)	(8.8)	(0.0)		8.8
MB-6	16	6	11	6	1	40	
	(40.0)	(15.0)	(27.5)	(15.0)	(2.5)		17.5
MB-7	55	17	47	20	3	142	
	(38.7)	(11.9)	(33.1)	(14.8)	(2.1)		16.2
MB-8	12	4	7	3	0	26	
	(46.2)	(15.4)	(26.9)	(11.5)	(0.0)		11.5
						580	$X^2_8 = 15.2$ p = .055

Key:

Barrier Type

GR-1 (weak post)
GR-2 (strong post)
GR-3 (rigid)
GR-4 (other)
GR-9 (W-beam strong post)
MB-5 (weak post)
MB-6 (strong post)
MB-7 (rigid)
MB-8 (other)

model coefficients provide estimates of the relative injury risk associated with the different barrier types while taking into account that the different types of barriers may have been struck by vehicles of different sizes with different speeds and impact angles. Ranges of the variation in these factors are given in the introductory section.

Other variables tested as covariates but found not to make a statistically significant improvement in the model were yaw angle, effective barrier height, separation angle, horizontal distance to barrier, length of barrier, and driver age. For a vehicle striking guardrail type GR-1, all of the variables $X_1 = X_2 = \cdots = X_8 = 0$, so the estimated injury risk has the form

$$R_1 = (e^{\beta_o}) \text{ (covariate effects)}$$

For a vehicle striking guardrail type GR-2, the dummy variable $X_1 = 1$ and all other dummy variables are zero, so the injury risk has the form

$$R_2 = (e^{\beta_o})(e^{\beta_1}) \text{ (covariate effects)}$$

For fixed values of the covariates then

$$R_2 = (e^{\beta_1})\, R_1$$

Thus, the estimated model coefficients $\beta_1, \ldots, \beta_8$ gives multiplication factors for injury risks of GR-2, . . . , MB-8 relative to GR-1. Table 3 gives the estimated values of these coefficients when the model was fit to the all hits data. The table also gives standard errors and p-values for the estimated pa-

TABLE 2 Driver Injury Severity (MAIS) by Barrier Type: All Hits into LON

	MAIS Injury Severity								Percent Injured		
Type	0	1	2	3	4	5	6	Total	MAIS ≥ 1	MAIS ≥ 2	MAIS ≥ 3
GR-1	27	4	2	1	0	0	0	54			
	(50.0)	(44.4)	(3.7)	(1.9)	(0.0)	(0.0)	(0.0)		50.0	5.6	1.9
GR-2	50	62	13	4	0	1	2	132			
	(37.8)	(47.0)	(9.9)	(3.0)	(0.0)	(0.8)	(1.5)		62.1	15.2	5.3
GR-3	3	8	3	0	0	0	0	14			
	(21.4)	(57.1)	(21.4)	(0.0)	(0.0)	(0.0)	(0.0)		78.6	21.4	0.0
GR-4	40	33	5	3	0	0	0	81			
	(49.4)	(40.7)	(6.2)	(3.7)	(0.0)	(0.0)	(0.0)		50.6	9.9	3.7
GR-9	22	18	3	2	0	0	1	46			
	(47.8)	(39.1)	(6.5)	(4.4)	(0.0)	(0.0)	(2.2)		52.2	13.0	6.5
MB-5	21	12	0	1	0	0	0	34			
	(61.8)	(35.3)	(0.0)	(2.9)	(0.0)	(0.0)	(0.0)		38.2	2.9	2.9
MB-6	10	21	5	2	0	0	1	39			
	(25.6)	(53.9)	(12.8)	(5.1)	(0.0)	(0.0)	(2.6)		74.4	20.5	7.7
MB-7	36	80	16	4	1	0	2	139			
	(25.9)	(57.6)	(11.5)	(2.9)	(0.7)	(0.0)	(1.4)		74.1	16.6	5.4
MB-8	9	16	1	0	0	0	0	26			
	(34.6)	(61.5)	(3.9)	(0.0)	(0.0)	(0.0)	(0.0)		65.4	3.9	0.0
								559	$X^2_8=30.5$ $p = .000$	$X^2_8=13.3$ $p = .102$	

Key:

Barrier Type
GR-1 (weak post)
GR-2 (strong post)
GR-3 (rigid)
GR-4 (other)
GR-9 (W-beam strong post)
MB-5 (weak post)
MB-6 (strong post)
MB-7 (rigid)
MB-8 (other)

rameters. Because barrier types 2 to 9 are compared in this model with barrier type 1, the statistical significance of the estimates $B_1, \ldots, B_8$ is a function of the variability in injury severity associated with hits into barrier type 1, and with each of the other types in turn. Thus, the variability (or inversely the stability) of the behavior of barrier type 1 is a factor relative to the statistical significance of each of the other barrier effect estimates. The estimate of β_1 is statistically significant and has the value $\beta_1 = .84$. Thus, for equal speed, curb weight, and impact angle, the injury risk for a crash into guardrail type GR-2 is estimated to be $(e^{.84}) = 2.32$ times the injury risk of a crash into a guardrail of type GR-1.

Guardrail type 1, weak post systems, served as a reference group or baseline for the model of Table 3. Thus, each barrier type is compared with weak post systems, a design that provides a more forgiving impact by allowing large deflection. These systems should be limited to locations where such large deflections are permissible. A disadvantage of these systems is that barrier damage in a crash is generally extensive. That all of the estimates are positive indicates that the estimated injury risk was higher for each of the other barrier types than for weak post systems. However, the standard error and *p*-values show some of these differences to be not statistically significant (GR-4, "other" guardrail; GR-9, W-beam strong post guardrail; and MB-5, weak post median barrier).

To further examine differences in barrier types, some grouping of similar barriers was done. This resulted in six groups of barriers:

Group 1—GR-1, MB-5 (Weak post guardrail and median barrier).
Group 2—GR-2 (Strong post guardrail).
Group 3—MB-6 (Strong post median barrier).
Group 4—GR-3 (Rigid guardrail).
Group 5—MB-7 (Rigid median barrier).
Group 6—GR-4, MB-8, GR-9 (Other guardrail and median barrier).

Table 4 gives results from a logistic model similar to that of Table 3, but based on the six groups of barriers. From the *p*-values shown in the top portion of the table, it can be seen that groups 2, 3, and 5 all differ significantly from group 1;

TABLE 3 Logistic Model Results Comparing Nine Barrier Types: All Hits into LON

Variable	Parameter Estimate	Standard Error	P-value
GR-2	.84	.40	.03
GR-3	1.53	.88	.08
GR-4	.57	.44	.19
GR-9	.35	.50	.48
MB-5	.19	.54	.72
MB-6	1.25	.53	.018
MB-7	1.76	.46	.0002
MB-8	.92	.61	.127
Speed	.05	.01	.0001
Curb Weight	-.05	.01	.0013
Impact Angle	.02	.007	.001

Key:

Barrier Type

GR-1 (weak post)
GR-2 (strong post)
GR-3 (rigid)
GR-4 (other)
GR-9 (W-beam strong post)
MB-5 (weak post)
MB-6 (strong post)
MB-7 (rigid)
MB-8 (other)

group 6 does not differ significantly from group 1; the significance of group 4 is marginal. The positive signs of the coefficients indicate that groups 2 to 6 are estimated to be associated with injury risks greater than that of group 1. By estimating other models with groups 2 to 6 omitted one at a time, the table of pairwise comparisons shown in the middle portion of Table 4 was generated. This table shows, for example, that group 2 differs significantly from groups 1 and 5 but not from groups 3, 4, and 6. The bottom portion of the table lists the relative risks of injury for each significant difference. Fitting models to the clean hits data file produced similar results.

Barrier Performance in Terms of Vehicle-Barrier Interaction and Postimpact Trajectory

Although the analysis so far has involved performance in terms of harm to the driver, additional analyses were conducted to examine differences in vehicle-barrier interaction and vehicle trajectory following impact. All the analyses in this section are limited to vehicle hits into barrier LON only. In many cases separate analyses are carried out for all barrier hits and clean hits only. Table 5 gives a tabulation of barrier performance by barrier type. This table shows that 75 percent of the case vehicles were redirected by the barrier, 8.5 percent snagged, 9 percent overrode the barrier, and 3 percent or less each vaulted, penetrated, or had some other involvement with the barrier. Guardrail type GR-1, weak post systems, had the highest percentage of snags (23 percent), but some snagging is expected for this more forgiving design. Type GR-4 also had a high snag percentage (18 percent) and the highest percentage of overrides (21 percent). Type GR-9, W-beam strong post, had a high percentage of overrides (16 percent) and the highest percentage vaulting the barrier (12 percent).

A tabulation of barrier performance by driver injury (injured versus not injured based on MAIS) is shown in Table 6. Injury rates vary relatively little across the performance categories as confirmed by the nonsignificant X^2-statistic. Logistic models were run to further investigate relationships between barrier performance and driver injury while taking into account impact speed, curb weight, and impact angle. In these analyses, the injury risk to drivers of vehicles that were snagged, overrode the barrier, or fell into any of the remaining three performance categories were compared with the injury risk to drivers of vehicles that were redirected by the barrier. Results from one such analysis—a model fit to data from all barrier hits—are shown in Table 7. None of the barrier performance indicator variables was statistically significant (compared with redirected), nor were there statistically significant differences between the performance estimates, as can be seen from an examination of their standard errors. In other words, for any driver injury versus no injury, categories such as snagging and overriding were not statistically different from redirection. Because of small sample sizes, the categories of vaulted, penetrated, and other were combined for the modeling. The results were similar for the clean hit data.

These injury results are not what would normally be expected. In particular, vaulting and penetrating a barrier are considered barrier failures and more likely to produce injury than redirection. Table 6 showed vaulting to produce injury 86 percent of the time, but penetration produced injury only 42 percent of the time. Thus, the combination of these two outcomes with the category of "other" may partially account for the modelling results, which indicate no difference in these failure modes and redirection.

Further exploration through three-way cross-tabulations showed a few possible coding errors by investigators, in that eight of the vehicles indicated to have either overrode, vaulted, or penetrated a barrier also were coded to have returned to the roadway or crossed to the other side. Injury to drivers of vehicles that overrode, vaulted, or penetrated was present more than 80 percent of the time when the vehicle either struck another object or rolled over.

Examination of a number of variables for each case of vaulting and penetrating a barrier also helped in understanding some of the injury results. For the vaulting cases, almost all involved W-beam barriers, with about half being the older W-beam strong post design. Many of the barrier heights were less than 711 mm (28 in.) high, and several had curbs. Almost half of the impact angles exceeded 28 degrees. Only one case had an impact speed in the 74–89 km/hr (46–55 mph) range, but four others were not coded, perhaps implying high speeds. Six of the cases involved rollover. Most of the crashes occurred on Interstate routes, with only two on county routes.

For the penetrating cases, about half involved cable guardrail, which is a forgiving system that allows large deflections. Most of the barrier heights were less than 711 mm (28 in.), and only a few curbs were present. About half of the impact

TABLE 4 Logistic Model Comparing Six Groups of Barrier Types: All Hits into LON

Variable	Estimate	Standard Error	P-Value
Group 2 (strong post GR)	.77	.34	.022
Group 3 (strong post MB)	1.18	.49	.016
Group 4 (rigid GR)	1.46	.85	.087
Group 5 (rigid (MB)	1.69	.42	.001
Group 6 (other GR and MB)	.49	.33	.138
Speed	.05	.01	.001
Curb Weight	-.05	.01	.001
Impact Angle	.02	.007	.001

Pairwise comparisons: p-values

Group	2	3	4	5	6
1	.02	.02	.09	.001	ns
2		ns	ns	.02	ns
3			ns	ns	ns
4				ns	ns
5					.002

Relative risks for significant differences:

$R_2/R_1 = 2.17$
$R_3/R_1 = 3.27$
$R_4/R_1 = 4.31$
$R_5/R_1 = 5.40$

$R_5/R_2 = 2.49$
$R_5/R_6 = 3.30$

angles exceeded 28 degrees. Two of the impact speeds exceeded 97 km/hr (60 mph) and eight more were not coded, perhaps implying high speeds. Most of the cases involved no subsequent impacts, and there was only one rollover. About half of the crashes occurred on local or county routes, and only three involved large trucks.

Subsequent Impact Following First Barrier Impact

Frequencies of subsequent impacts with certain other objects are shown in Table 8 by barrier type. The data used for these analyses were the all hits data because in clean hits subsequent impacts were restricted to the same longitudinal barrier. Note that no subsequent impacts with other vehicles are shown in Table 8; these cases have been excluded from all the data files for this analysis. Approximately 9 percent of the vehicles rolled over after striking the barriers. The rollover rate for barrier type MB-7, the concrete median barrier, is nearly double this overall rate. (The rollover rate for GR-3 was also quite large, 20 percent, but was based on only 15 cases.)

Injury distributions associated with subsequent impacts are shown in Table 9, which shows rollover to have the highest rate of driver injury. However, in a logistic model that compared the injury risk of rollover with that for all other subsequent impacts (including none), the estimated rollover effect was not statistically significant ($p = .119$).

End Treatment Analyses

Tables 10 and 11 give the maximum data in the file on type of end treatment cross-classified by driver injury severity. In these tables, end treatment type and LON are determined by the barrier subset variable called "end treatment type" for the first impact. The data are not restricted to clean hits. Following some initial analyses comparing injured and uninjured drivers, it appeared that differences between types of barrier ends and ends versus LON were more pronounced in the more serious injuries than in the "any injury" versus "no injury" comparison. This can be seen in the last columns of the tables, which show percentages with A or K injuries and

TABLE 5 Vehicle-Barrier Interaction by Barrier Type: All Hits into LON

Barrier Type	Performance						
	Redirected	Snagged	Overrode	Vaulted	Penetrated	Other	Total
GR-1	34 (60.7)	13 (23.2)	4 (7.1)	0 (0.0)	2 (3.6)	3 (5.4)	56
GR-2	112 (75.7)	10 (6.8)	10 (6.8)	6 (4.1)	7 (4.7)	3 (2.0)	148
GR-3	13 (86.7)	0 (0.0)	2 (13.3)	0 (0.0)	0 (0.0)	0 (0.0)	15
GR-4	43 (50.6)	15 (17.7)	18 (21.2)	0 (0.0)	4 (4.7)	5 (5.9)	85
GR-9	29 (59.2)	5 (10.2)	8 (16.3)	6 (12.2)	1 (2.0)	0 (0.0)	49
MB-5	28 (82.4)	4 (11.8)	1 (2.9)	0 (0.0)	0 (0.0)	1 (2.9)	34
MB-6	36 (87.8)	2 (4.9)	1 (2.4)	1 (2.4)	0 (0.0)	1 (2.4)	41
MB-7	135 (91.2)	0 (0.0)	8 (5.4)	0 (0.0)	0 (0.0)	5 (3.4)	148
MB-8	21 (77.8)	2 (7.4)	2 (7.4)	1 (3.7)	1 (3.7)	0 (0.0)	27
Total	451 (74.9)	51 (8.5)	54 (9.0)	13 (2.2)	15 (2.5)	18 (3.0)	603

Key:

Barrier Type

GR-1 (weak post)
GR-2 (strong post)
GR-3 (rigid)
GR-4 (other)
GR-9 (W-beam strong post)
MB-5 (weak post)
MB-6 (strong post)
MB-7 (rigid)
MB-8 (other)

TABLE 6 Barrier Performance by Driver Injury (MAIS): All Hits into LON

Performance	Injured (MAIS $\geq$ 1)	Not Injured	Total
Redirected	258 (61.4)	162 (38.6)	420
Snagged	30 (61.2)	19 (38.8)	49
Overrode	31 (59.6)	21 (40.4)	52
Vaulted	12 (85.7)	2 (14.3)	14
Penetrated	5 (41.7)	7 (58.3)	12
Other	11 (61.1)	7 (38.9)	18
Total	347 (61.4)	218 (38.9)	565

X^2_4 df = 5.536 p = .354

TABLE 7 Logistic Model Results for Injury Risk as Function of Barrier Performance: All Hits into LON

Variable	Estimate	S.E.	P-Value
Snagged	.34	.37	.36
Overrode	.02	.40	.95
Vaulted, penetrated, other	-.55	.46	.24
Speed	.05	.009	.0001
Curb Weight	-.05	.01	.0005
Impact Angle	.02	.007	.0017

TABLE 8 Subsequent Impact Following First Barrier Impact by Barrier Type: All Hits into LON

Barrier Type	Subsequent Impact None	Other Roadside Object	Same Barrier	Other Barrier	Rollover	Total
GR-1	35 (67.3)	8 (15.4)	6 (11.5)	3 (5.8)	0 (0.00)	52
GR-2	67 (48.2)	26 (18.7)	20 (14.4)	14 (10.1)	12 (8.6)	139
GR-3	6 (40.00)	1 (6.67)	5 (33.33)	0 (0.00)	3 (20.00)	15
GR-4	47 (55.3)	20 (23.5)	8 (9.4)	6 (7.1)	4 (4.7)	85
GR-9	25 (55.6)	9 (20.0)	4 (8.9)	3 (6.7)	4 (8.9)	45
MB-5	22 (64.7)	2 (5.9)	7 (20.6)	2 (5.9)	1 (2.9)	34
MB-6	25 (62.5)	4 (10.0)	6 (15.0)	2 (5.0)	3 (7.5)	40
MB-7	72 (49.7)	2 (1.4)	45 (31.0)	3 (2.1)	23 (15.9)	145
MB-8	16 (61.5)	2 (7.7)	6 (23.1)	1 (3.9)	1 (3.9)	26
Total	315 (54.2)	74 (12.2)	107 (18.4)	34 (5.9)	51 (8.8)	581

Key:

Barrier Type

GR-1 (weak post)
GR-2 (strong post)
GR-3 (rigid)
GR-4 (other)
GR-9 (W-beam strong post)
MB-5 (weak post)
MB-6 (strong post)
MB-7 (rigid)
MB-8 (other)

TABLE 9 Subsequent Impact by Driver Injury: All Hits

Subsequent Impact	Injured (MAIS ≥ 1)	Not Injured	Total
None	164 (55.4)	132 (44.6)	296
Other roadside object	47 (68.1)	22 (31.9)	69
Same barrier	58 (58.6)	41 (41.4)	99
Another barrier	20 (64.5)	11 (35.5)	31
Rollover	43 (87.8)	6 (12.2)	49
Total	328	215	544

$X^2_4 = 20.51$ $p = .001$

TABLE 10 End Treatment by Driver Injury (KABCO): All Barrier Hits

	Injury Severity						
End Treatment Type	No Injury	C	B	A	K	Total	Percent A or K
Length of Need	294 (50.4)	68 (11.7)	149 (25.6)	64 (11.0)	8 (1.37)	583	12.4
Blunt	60 (44.8)	18 (13.4)	31 (23.1)	22 (16.4)	3 (2.2)	134	18.7
Non-Breakaway Cable	10 (41.7)	2 (8.3)	6 (25.0)	6 (25.0)	0 (0.0)	24	25.0
Turndown	51 (47.2)	10 (9.3)	26 (24.1)	16 (14.8)	5 (4.6)	108	19.4
Breakaway Cable	14 (41.2)	2 (5.9)	10 (29.4)	8 (23.5)	0 (0.0)	34	23.5
Anchoring to Backslope	6 (46.15)	3 (23.08)	3 (23.08)	1 (7.69)	0 (0.00)	13	7.7
Attached to Parapet	5 (22.73)	3 (13.64)	9 (40.91)	5 (22.73)	0 (0.00)	22	22.7
Other	3 (37.50)	0 (0.00)	1 (12.50)	4 (50.00)	0 (0.00)	8	50.0
Total	443 (47.8)	106 (11.5)	235 (25.4)	126 (13.6)	16 (2.2)	926	15.3

TABLE 11 End Treatment Type by Driver Injury (MAIS): All Barrier Hits

End Treatment Type	Driver Injury Severity (MAIS)								
	0	1	2	3	4	5	6	Total	Percent MAIS≥3
Length of Need	221 (38.8)	274 (48.1)	48 (8.4)	18 (3.2)	1 (0.18)	1 (0.18)	6 (1.1)	569	4.7
Blunt	52 (40.9)	51 (40.2)	11 (8.7)	5 (3.9)	3 (2.4)	4 (3.2)	1 (0.8)	127	10.3
Non-Breakaway Cable	9 (40.9)	8 (36.4)	2 (9.1)	2 (9.1)	1 (4.6)	0 (0.0)	0 (0.0	22	13.6
Turndown	37 (36.6)	43 (42.6)	11 (10.9)	5 (5.0)	0 (0.0)	0 (0.0)	5 (5.0)	101	10.0
Breakaway Cable	9 (27.3)	15 (45.5)	5 (15.2)	3 (9.1)	1 (3.0)	0 (0.0)	0 (0.0)	33	12.1
Anchoring to Backslope	6 (46.15)	5 (38.46)	1 (7.69)	1 (7.69)	0 (0.0)	0 (0.0)	0 (0.0)	13	7.7
Attached to Parapet	5 (26.32)	10 (52.63)	4 (21.05)	0 (0.00)	0 (0.0)	0 (0.0)	0 (0.0)	19	0.0
Other	2 (25.00)	3 (37.50)	1 (12.50)	1 (12.50)	1 (12.50)	0 (0.0)	0 (0.0)	8	25.0
Total	341 (38.2)	409 (45.9)	83 (9.3)	35 (3.9)	7 (0.8)	5 (0.6)	12 (1.4)	892	6.7

percentages with MAIS ≥ 3, respectively. It can also be seen from the tables that blunt and turndown end treatments predominated. In most of the analyses that follow all the remaining end treatment types were combined into a single "other" category. This collapsing appears reasonably justified in terms of the serious injury percentages given in Tables 10 and 11.

A problem that arose in the analysis of end treatment types was that, although impact speed has been shown to be a significant factor relative to driver injury, estimated impact speed was available for only about 27 percent of the end hit cases. Neither curb weight nor impact angle was found to have a significant effect.

Table 12 shows results from a logistic model for comparing three types of end hits with hits into LON, using impact speed as a covariate. This model shows estimated risk of serious injury (MAIS ≥ 3) to be significantly greater for blunt ends and turndown ends than for LON. Estimated injury risks for the combined other end types are not significantly greater than that for LON; however, the standard errors shown in Table 12 suggest that the injury risks do not differ significantly across the three end types either.

Comparisons of the three end types are further explored in Tables 13 and 14, which show injury severity classified by the three end types for two more-restrictive types of end hits. In Table 13 only upstream, end-on hits (from the all hits file) are considered. Upstream hits within 25 ft of the end are tabulated in Table 14. In neither case are there significant differences between end types.

Further Analysis of Rollovers

Vehicle rollovers associated with barrier impacts were studied further by examining associations between rollovers and driver injury severity and between rollovers and barrier end hits versus LON. In particular, these analyses address the question of whether the higher injury risk associated with end hits is primarily a result of more rollovers associated with end hits. The analyses that follow were based on clean hits data. Table

TABLE 12 Logistic Model Results for Comparing Three End Types Versus LON Relative to Risk of Injury at MAIS ≥ 3: All Hits

Variable	Estimate	Standard Error	p-value
Blunt ends	1.78	.71	.012
Turndown ends	1.42	.70	.041
Other end types	.96	.71	.174
Speed	.03	.02	.027

TABLE 13 Comparison of End Types for Upstream Hits, End On

End Type	MAIS ≥3	<3	Total
Blunt	7	52	59
	(11.9)	(88.1)	
Turndown	4	25	29
	(13.8)	(86.2)	
All other	5	25	30
	(16.7)	(83.3)	
Total	16	102	118

$X_2^2 = .393$ $p = .822$

TABLE 14 Comparison of End Types for Upstream Hits, End On to 25 ft

End Type	MAIS ≥3	<3	Total
Blunt	9	72	81
	(11.1)	(88.9)	
Turndown	7	59	66
	(10.6)	(89.4)	
All other	7	45	52
	(13.5)	(86.5)	
Total	23	176	199

$X_2^2 = .259$ $p = .879$

TABLE 15 Rollover Versus Driver Injury: Clean Hits Only

	Percent Injured		
Rollover Status	MAIS ≥ 1	MAIS ≥ 3	A+K
No Rollover	59.4%	5.8%	13.5%
Rollover	84.7%	15.2%	30.2%
X^2_1d.f.	20.9	11.2	18.6
p-value	.000	.001	.000

TABLE 16 Three-Way Table of Rollover by End Versus LON by MAIS Injury Severity

		Injury Severity		
Rollover	End/LON	MAIS < 3	(MAIS ≥ 3)	Total
Yes	LON	42	7	49
		(85.7)	(14.3)	
	End	30	6	36
		(83.3)	(16.7)	
	Total	72	13	85
		$\chi^2_1 = .051$	p = .763	
No	LON	498	18	516
		(96.5)	(3.5)	
	End	254	27	281
		(90.4)	(9.6)	
	Total	752	45	797
		$\chi^2_1 = 12.791$	p = .000	

*In this table any hit in which an end type was coded was considered an end hit; length-of-need was "no" end hit.

15 shows results from contingency tables of rollover versus the three characterizations of driver injury used in previous analyses. All three characterizations show significantly higher injury or serious injury rates associated with rollovers.

Comparisons of rollover rates for hits into LON with rollover rates for end hits yielded the following rates:

- 8.46 for LON,
- 13.62 for all end hits,
- 17.16 for upstream, end-on hits, and
- 17.43 for upstream hits within 25 ft of barrier end.

All three end rates differed significantly from the LON rate with $p < .02$ in each comparison. Tables 16 and 17 show three-way breakdowns of rollover by end and LON by injury severity (MAIS and KABCO, respectively), in which end hits refer to any end hit. These tables show no significant differences in injury rates between ends and LON when rollovers

TABLE 17 Three-Way Table of Rollover by End Versus LON by KABCO Injury Severity

Rollover	End/LON	Injury Severity O,C,B	Injury Severity A,K	Total
Yes	LON	34 (68.0)	16 (32.0)	50
	End	33 (71.7)	13 (28.3)	46
	Total	67	29	96
		$\chi^2_1 = .159$	$p = .690$	
No	LON	474 (89.3)	57 (10.7)	531
	End	235 (81.3)	54 (18.7)	289
	Total	709	111	820
		$\chi^2_1 = 10.107$	$p = .001$	

occurred, but when no rollovers occurred significantly higher injury rates were associated with end hits. Similar tables were analyzed for comparing LON hits with upstream end-on hits and upstream hits within 25 ft of barrier end. The results were the same; no significant differences when rollovers occurred, and higher injury rates associated with end hits when rollovers did not occur. Thus, it seems that end hits are more likely to result in serious injury than LON hits by being more likely to produce rollover and by producing more serious injuries when no rollovers occur.

SUMMARY

The following is a brief summary of these analyses:

- Weak post barriers were less associated with driver injury (MAIS $\geq$ 1) than other barrier types.
- In regard to subsequent impact, rollover produced the highest rate of driver injury (MAIS $\geq$ 1).
- Higher risks of serious driver injury (A + K, MAIS $\geq$ 3) were associated with blunt and turndown end treatments than with LON.
- Rollover was associated with both higher driver injury (MAIS $\geq$ 1) and serious injury (A + K) rates.
- End hits are more likely to result in serious driver injury than LON by being more likely to produce rollover and by producing more serious injuries when no rollovers occur.

These descriptive statistical analyses and modeling results have produced a wealth of information. Some of the findings are provocative and in need of further clinical exploration. It is recommended that this be done in subsequent research, primarily because design engineers could learn a great deal from seeing the outcomes of various kinds of real-world barrier impacts. Although the LBSS file is certainly not free of error, it remains a comprehensive information source.

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