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Real-World Impact Conditions for Run-Off-the-Road Accidents

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ABSTRACT

Information is presented on real-world impact conditions for accidents involving roadside objects and features based on in-depth accident data. Of particular interest are the distributions of impact speed and angle for various functional classes. Other considerations relating to impact conditions, such as vehicle orientation at impact, are also discussed. The potential applications of the information presented in this paper are illustrated with two examples, one involving the full-scale crash test matrix and the other involving benefit-cost procedures.

In the design of roadside safety appurtenances and features, it is desirable to have information on the real-world impact conditions to ensure that the appurtenances and features will be effective in serving the intended purpose of mitigating the consequences of impacts by errant vehicles. The impact conditions refer primarily to impact speed and angle, but there are also other considerations, such as the orientation of the vehicle at impact and the area of impact on the vehicle.

To obtain such detailed information, in-depth investigation and reconstruction of accidents are required. Police-level accident data do not provide sufficient detail for this purpose. Also, the accidents have to be either a census or a statistically representative sample in order to establish the distributions of impact conditions. Unfortunately, the costs associated with in-depth accident investigation and reconstruction are high and few programs of this nature have been undertaken.

Two such data sources (1,2) were identified and analyzed as part of a study conducted for the FHWA on severity measures for roadside objects and features (3). The first source provides data on a statistically representative sample of pole accidents collected over a 20-month period from two study areas: Bexar County (including the city of San Antonio), Texas, and a nine-county area around Lexington, Kentucky. The second source includes a census of accidents involving bridge rails, bridge or parapet ends, and approach guardrails in a 15-county area around San Antonio, Texas, over a 21-month period.

After screening for nonapplicable cases, 472 pole accident cases and 124 bridge accident cases were merged for use in the study. Note that the actual sample size available for analysis is slightly less than 596 because some of the cases have unknown impact speed or angle. Also, the pole accident cases

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are weighted in accordance with the statistical sampling scheme. The results of the analysis are summarized in this paper, followed by discussions of two example applications of the information under real-world accident conditions for roadside objects and features.

REAL-WORLD IMPACT CONDITIONS

For the purpose of this paper, the impact conditions are defined by impact speed for point objects (e.g., pole supports) and by both impact speed and angle for longitudinal objects (e.g., guardrails and median barriers). The emphasis of this paper is on the distributions of impact speed and impact angle. However, there are other considerations relating to impact conditions, such as the orientation of the vehicle at impact, the area of impact on the vehicle, and postimpact trajectory of the vehicle. Brief discussions of these other considerations will also be presented.

Impact Speed and Angle Distributions

Using the in-depth accident data from the two previously mentioned sources, the distributions of impact speed and angle are first determined individually (i.e., univariate distributions). A number of theoretical distributions, such as normal, exponential, and negative binomial, were fitted to the data and it was found that a gamma function provides the best fit for both univariate impact speed and impact angle distributions. Mathematically, the gamma distribution function is expressed as

$$c(x_i) = \int_0^{x_i} \{1/[\Gamma(\alpha)\ \beta^{\alpha}]\}\ t^{\alpha-1} E^{-t/\beta} dt$$

where

x_i = impact speed or angle,
$c(x_i)$ = cumulative probability of x,
t = dummy variable for integration, and
α, β = estimated coefficients.

Note that the gamma function is uniquely defined by the two coefficients, α and β. The cumulative gamma distribution functions for impact speed and angle for the combined data are graphically shown in Figures 1 and 2, respectively.

The process involved in determining these distributions is briefly described as follows. The empirical cumulative distribution function for impact speed or angle based on the observed data is first determined:

$c(x_i)$ = Number of accidents with $x \leq x_i$/Total number of accidents

where x_i is impact speed or angle and $c(x_i)$ is cumulative probability for x_i.

Different distribution functions are then fitted to the empirical distribution function using nonlinear least square regression. The gamma function is found to provide the best fit to the data and is therefore selected. The empirical cumulative percentages are also shown in Figures 1 and 2, and it is evident that a good fit is provided by the gamma distribution.

Because the impact conditions for longitudinal objects are defined by both impact speed and angle, it is necessary to determine the joint distribution for impact speed and angle. The actual data are arbitrarily divided into a 6 x 6 matrix and various known joint (bivariate) distributions are fitted to the data with little success. This is not surprising because the univariate impact speed and angle distributions are best estimated by gamma functions and there is no known means of mathematically expressing a joint gamma distribution.

The alternative is to assume that the impact speed and angle distributions are independent of each other so that the cell probability is simply the product of their marginal probabilities. The concern is of course with the validity of the independency assumption.

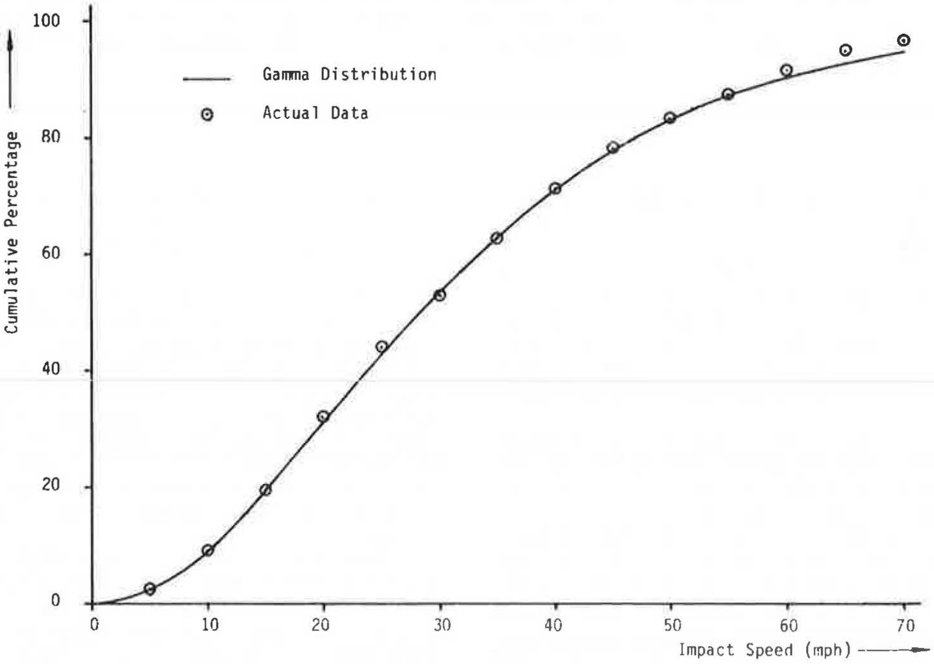

FIGURE 1 Impact speed distribution for combined data.

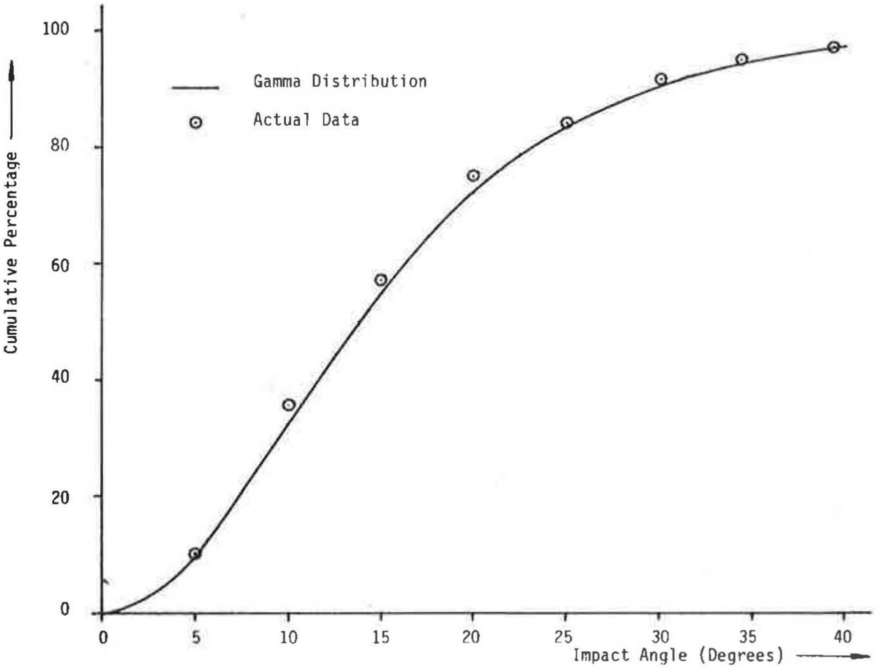

FIGURE 2 Impact angle distribution for combined data.

The data indicate that there is a weak negative correlation (-0.153) between impact speed and angle (i.e., higher impact speeds are associated with slightly lower impact angles). However, the correlation is so weak that any error introduced would likely be minor. A chi-square goodness-of-fit test was used to evaluate this hypothesis and the results indicate a reasonably good fit between the expected and the observed values, as indicated by the data in Table 1. In other words, it may be argued that the errors introduced by the independency assumption are fairly minor and acceptable for estimation purposes.

It should be pointed out that the goodness-of-fit test is very sensitive to the outlying cells (i.e., those cells with either very low or very high impact speeds or angles). Variations in the intervals of the matrix in these outlying areas could alter the results of the goodness-of-fit test. However, the probabilities associated with the outlying cells are very low and the errors introduced would therefore be relatively small.

It should be borne in mind that the impact speed and angle distributions are influenced by various roadway, roadside, and traffic characteristics. It

TABLE 1 Results of Goodness-of-Fit Test

Encroachment Angle (°) Encroachment Speed (mph)	≤ 5	6 - 10	11 - 15	16 - 20	21 - 30	> 30	Total
0 - 10.0	0.0088 (4.4) 0.004 (2)	0.0206 (10.03) 0.018 (9)	0.0204 (10.2) 0.022 (11)	0.0155 (7.8) 0.022 (11)	0.0168 (8.4) 0.014 (7)	0.0084 (4.2) 0.008 (4)	0.0905 (45.3) 0.008 (44)
10.1 -.20.0	0.0216 (10.8) 0.014 (7)	0.0505 (25.3) 0.048 (24)	0.0502 (25.1) 0.034 (17)	0.0381 (19.1) 0.040 (20)	0.0412 (20.6) 0.052 (26)	0.0206 (10.3) 0.032 (16)	0.2222 (111.1) 0.220 (110)
20.1 - 30.0	0.0219 (11.0) 0.020 (10)	0.0514 (25.7) 0.058 (29)	0.0511 (25.6) 0.052 (26)	0.0388 (19.4) 0.038 (19)	0.0419 (21.0) 0.022 (11)	0.0210 (10.5) 0.016 (8)	0.2261 (113.1) 0.206 (103)
30.1 - 40.0	0.0169 (8.5) 0.012 (6)	0.0396 (19.8) 0.054 (27)	0.0394 (19.7) 0.040 (20)	0.0299 (15.0) 0.026 (13)	0.0323 (16.2) 0.038 (19)	0.0162 (8.1) 0.014 (7)	0.1743 (87.2) 0.184 (92)
40.1 - 50.0	0.0114 (5.7) 0.016 (8)	0.0267 (13.4) 0.030 (15)	0.0265 (13.3) 0.038 (19)	0.0201 (10.1) 0.016 (8)	0.0218 (10.9) 0.018 (9)	0.0109 (5.5) 0.008 (4)	0.1174 (58.7) 0.126 (63)
> 50	0.0164 (8.2) 0.032 (16)	0.0386 (19.3) 0.052 (26)	0.0383 (19.2) 0.024 (12)	0.0291 (14.6) 0.032 (16)	0.0314 (15.7) 0.026 (13)	0.0157 (7.9) 0.010 (5)	0.1695 (84.8) 0.176 (88)
Total	0.0970 (48.5) 0.098 (49)	0.2274 (113.7) 0.260 (130)	0.2259 (113.0) 0.174 (87)	0.1715 (85.8) 0.174 (87)	0.1854 (92.7) 0.170 (85)	0.0928 (46.4) 0.088 (44)	1.0000 (500) 1.000 (500)

Legend:
Expected Percentage
(Expected Freq.)
Observed Percentage
(Observed Freq.)

Chi Square = 38.2
Degree of Freedom = 31
pval = 0.175 (Reasonable Fit)
Correlation = -0.153

TABLE 2 Coefficients of Gamma Distribution Functions for Speed and Angle by Functional Class

Functional Class	Impact Speed α	Impact Speed β	Impact Angle α	Impact Angle β
Freeway	5.878	9.789	2.560	6.037
Urban arterial	3.293	7.687	2.241	6.992
Urban collector/local	2.940	7.061	3.319	4.973
Rural arterial	2.367	15.817	1.715	8.749
Rural collector/local	4.165	6.986	1.884	8.172
Combined (all data)	2.542	12.693	2.482	6.393

Note: Gamma distribution function $c(x_i) = \int_0^{x_i} \left\{1/[\Gamma(\alpha)\beta^{\alpha}]\right\} t^{\alpha-1} e^{-t/\beta} dt$

would not be possible to account for all of these factors, so highway type is used as a gross surrogate measure for all such characteristics.

The data are stratified by functional class and the impact speed and angle distributions are determined for each of the functional classes. The sample sizes for some of the functional classes are too small and thus these classes are grouped together for analysis purpose (e.g., major and minor arterials and collectors and local streets). Also, the sample size for rural freeways is too small for any meaningful analysis. It was therefore decided that the impact speed and angle distributions for rural freeways would be approximated by those of urban freeways and expressways. Thus only five functional classes are included in the analysis.

Functional Class	Sample Size
Freeway and expressway	191
Urban arterial	148
Urban collector or local	134
Rural arterial	65
Rural collector or local	58
Total	596

Given that the combined data (i.e., all functional classes combined) are best fitted by the gamma distribution, it is logical to assume that the gamma distribution would also apply to the individual functional classes. On the basis of this assumption, the impact speed and angle distributions for the individual functional classes are estimated. The fits for the individual functional classes are, as expected, not as good as that for the combined data because of the smaller sample sizes. This is the reason for making the assumption that the gamma distribution function applies to the individual functional classes.

Table 2 gives a summary of the coefficients of the univariate gamma distribution functions for impact speed and angle for the five functional classes and the combined data. The probabilities of various ranges of impact speed and angle for the five functional classes and the combined data are given in Tables 3 and 4, respectively.

Again, assuming that the independency assumption is valid for the individual functional classes as well as for the entire data set, the cell probabilities for each of the five functional classes can be computed easily (Tables 5-10).

Other Considerations

There are other considerations, in addition to impact speed and angle, that relate to real-world impact conditions. Even though the emphasis of this paper is on impact speed and angle, these other considerations should also be taken into account in defining the real-world impact conditions for accidents involving roadside objects and features. These other considerations are also addressed in the two studies (1,2) used for determining the impact speed and angle distributions, highlights of which are summarized next.

For pole impacts, the front of the vehicle is the most frequent area of impact (72.9 percent). Impacts with the back of the vehicle are extremely rare, accounting for only 1.9 percent of pole accidents. Side impacts are involved in approximately 25 percent of pole accidents (13 percent for the right side and 12.2 percent for the left side), and they result in much higher injury severity than frontal or rear impacts.

For impacts with longitudinal barriers, more than

TABLE 3 Impact Speed Probability Distribution by Functional Class

Impact Speed (mph)	Freeway	Urban Arterial	Urban Collector/ Local	Rural Arterial	Rural Collector/ Local	Combined
≤10	0.0020	0.1030	0.1810	0.0763	0.0468	0.0904
11-20	0.0507	0.3086	0.3718	0.1829	0.2439	0.2222
21-30	0.1548	0.2796	0.2529	0.1983	0.2989	0.2261
31-40	0.2208	0.1678	0.1203	0.1681	0.2115	0.1743
41-50	0.2100	0.0823	0.0481	0.1264	0.1136	0.1174
51-60	0.1560	0.0358	0.0174	0.0886	0.0518	0.0730
>60	0.2057	0.0229	0.0086	0.1594	0.0335	0.0965

TABLE 4 Impact Angle Probability Distribution by Functional Class

Impact Angle (degrees)	Freeway	Urban Arterial	Urban Collector/ Local	Rural Arterial	Rural Collector/ Local	Combined
≤5	0.0974	0.1155	0.0526	0.1723	0.1491	0.0970
6-10	0.2351	0.2313	0.2046	0.2354	0.2330	0.2274
11-15	0.2322	0.2169	0.2484	0.1936	0.2011	0.2258
16-20	0.1731	0.1623	0.2007	0.1397	0.1477	0.1716
21-25	0.1125	0.1089	0.1326	0.0946	0.1003	0.1145
26-30	0.0675	0.0685	0.0777	0.0618	0.0651	0.0708
>30	0.0822	0.0965	0.0833	0.1026	0.1037	0.0928

TABLE 5 **Impact Speed and Angle Distributions for Freeway**

Impact Speed (mph)	Impact Angle (degrees)							
	≤5	6-10	11-15	16-20	21-25	26-30	>30	Total
≤10	0.0002	0.0005	0.0005	0.0003	0.0002	0.0001	0.0002	0.0020
11-20	0.0049	0.0119	0.0118	0.0088	0.0057	0.0034	0.0042	0.0507
21-30	0.0151	0.0364	0.0359	0.0268	0.0174	0.0104	0.0127	0.1548
31-40	0.0215	0.0519	0.0513	0.0382	0.0248	0.0149	0.0181	0.2208
41-50	0.0205	0.0494	0.0488	0.0364	0.0236	0.0142	0.0173	0.2100
51-60	0.0152	0.0367	0.0362	0.0270	0.0176	0.0105	0.0128	0.1560
>60	0.0200	0.0484	0.0478	0.0356	0.0231	0.0139	0.0169	0.2057
Total	0.0974	0.2351	0.2322	0.1731	0.1125	0.0675	0.8222	1.0000

TABLE 6 **Impact Speed and Angle Distributions for Urban Arterial**

Impact Speed (mph)	Impact Angle (degrees)							
	≤5	6-10	11-15	16-20	21-25	26-30	>30	Total
≤10	0.0119	0.0238	0.0223	0.0167	0.0112	0.0071	0.0099	0.1030
11-20	0.0356	0.0714	0.0669	0.0501	0.0336	0.0211	0.0298	0.3086
21-30	0.0323	0.0647	0.0606	0.0454	0.0304	0.0192	0.0270	0.2796
31-40	0.0194	0.0388	0.0364	0.0272	0.0183	0.0115	0.0162	0.1678
41-50	0.0095	0.0190	0.0179	0.0134	0.0090	0.0056	0.0079	0.0823
51-60	0.0041	0.0083	0.0078	0.0058	0.0039	0.0025	0.0035	0.0358
>60	0.0026	0.0053	0.0050	0.0037	0.0025	0.0016	0.0022	0.0229
Total	0.1155	0.2313	0.2169	0.1623	0.1089	0.0685	0.0965	1.0000

TABLE 7 **Impact Speed and Angle Distributions for Urban Collector/Local**

Impact Speed (mph)	Impact Angle (degrees)							
	≤5	6-10	11-15	16-20	21-25	26-30	>30	Total
≤10	0.0095	0.0370	0.0450	0.0363	0.0240	0.0141	0.0151	0.1810
11-20	0.0196	0.0761	0.0924	0.0746	0.0493	0.0289	0.0310	0.3718
21-30	0.0133	0.0517	0.0628	0.0508	0.0335	0.0197	0.0211	0.2529
31-40	0.0063	0.0246	0.0299	0.0241	0.0160	0.0093	0.0100	0.1203
41-50	0.0025	0.0098	0.0119	0.0097	0.0064	0.0037	0.0040	0.0481
51-60	0.0009	0.0036	0.0043	0.0035	0.0023	0.0014	0.0014	0.0174
>60	0.0005	0.0018	0.0021	0.0017	0.0011	0.0007	0.0007	0.0086
Total	0.0526	0.2046	0.2484	0.2007	0.1326	0.0777	0.0833	1.0001

TABLE 8 **Impact Speed and Angle Distributions for Rural Arterial**

Impact Speed (mph)	Impact Angle (degrees)							
	≤5	6-10	11-15	16-20	21-25	26-30	>30	Total
≤10	0.0131	0.0180	0.0148	0.0107	0.0072	0.0047	0.0078	0.0763
11-20	0.0315	0.0431	0.0354	0.0256	0.0173	0.0113	0.0188	0.1829
21-30	0.0342	0.0467	0.0384	0.0277	0.0188	0.0123	0.0203	0.1983
31-40	0.0290	0.0396	0.0325	0.0235	0.0159	0.0104	0.0172	0.1681
41-50	0.0218	0.0298	0.0245	0.0177	0.0120	0.0078	0.0130	0.1264
51-60	0.0153	0.0209	0.0172	0.0124	0.0084	0.0055	0.0091	0.0886
>60	0.0275	0.0375	0.0309	0.0223	0.0151	0.0099	0.0164	0.1594
Total	0.1723	0.2354	0.1936	0.1397	0.0946	0.0618	0.1026	1.0000

TABLE 9 **Impact Speed and Angle Distributions for Rural Collector/Local**

Impact Speed (mph)	Impact Angle (degrees)							
	≤5	6-10	11-15	16-20	21-25	26-30	>30	Total
≤10	0.0070	0.0109	0.0094	0.0069	0.0047	0.0030	0.0049	0.0468
11-20	0.0364	0.0568	0.0490	0.0360	0.0245	0.0159	0.0253	0.2439
21-30	0.0446	0.0696	0.0601	0.0441	0.0300	0.0195	0.0310	0.2989
31-40	0.0315	0.0493	0.0425	0.0312	0.0212	0.0138	0.0219	0.2115
41-50	0.0169	0.0265	0.0228	0.0168	0.0114	0.0074	0.0118	0.1136
51-60	0.0077	0.0121	0.0104	0.0077	0.0052	0.0034	0.0054	0.0518
>60	0.0050	0.0078	0.0067	0.0049	0.0034	0.0022	0.0035	0.0335
Total	0.1491	0.2330	0.2011	0.1477	0.1003	0.0651	0.1037	1.0000

TABLE 10 Impact Speed and Angle Distributions for Combined Data

Impact Speed (mph)	Impact Angle (degrees)							
	≤5	6-10	11-15	16-20	21-25	26-30	>30	Total
≤10	0.0088	0.0206	0.0204	0.0155	0.0104	0.0064	0.0084	0.0904
11-20	0.0216	0.0505	0.0502	0.0381	0.0254	0.0157	0.0206	0.2222
21-30	0.0219	0.0514	0.0511	0.0388	0.0259	0.0160	0.0210	0.2261
31-40	0.0169	0.0396	0.0394	0.0299	0.0200	0.0123	0.0162	0.1743
41-50	0.0114	0.0267	0.0265	0.0201	0.0134	0.0083	0.0109	0.1174
51-60	0.0071	0.0166	0.0165	0.0125	0.0084	0.0052	0.0068	0.0730
>60	0.0085	0.0200	0.0198	0.0151	0.0101	0.0062	0.0082	0.0879
Total	0.0970	0.2274	0.2258	0.1716	0.1145	0.0708	0.0928	0.9913

three-quarters (77.4 percent) of accidents involve more than one impact, and half of these accidents involve three or more impacts. The injury severity of the accidents increases with the number of impacts. This clearly illustrates the importance of the postimpact trajectory of the vehicles.

For the first barrier impact, only slightly more than half (51.2 percent) of the vehicles are tracking at impact whereas more than one-quarter (26.0 percent) of the vehicles are yawing at more than 30 degrees at impact. For subsequent barrier impacts, the impact speeds are lower, but the impact angles are higher than for first barrier impacts. The percentage of vehicles yawing at greater than 30 degrees increases from 26 percent for the first barrier impact to more than 40 percent for subsequent barrier impacts. Similarly, the percentage of side and back impacts doubles from less than 25 percent to more than 50 percent. This indicates that, for subsequent impacts, the vehicle trajectories are more abrupt although the impact speeds are lower.

Discussion

Caution should be exercised in using the results presented in this paper. It should be recognized that there are limitations associated with the data sources and the analyses. The results presented should be viewed only as an intermediate step in the effort to better define the distributions of impact conditions based on the best data currently available. As new and better data become available, the distributions should be updated and improved as appropriate. A brief discussion of some of the limitations associated with the two data sources used in the study follows.

First, the impact conditions refer only to reported accidents. It is well known that some accidents are not brought to the attention of law enforcement agencies or are not reported by the police for a variety of reasons. The impact conditions of these unreported accidents could be significantly different from those of reported accidents. For example, the majority of these unreported accidents might be at low impact speeds and angles, which would drastically alter the distributions. Unfortunately, the extent of such unreported accidents is not known and it is not possible to estimate the effects of such unreported accidents on the distributions of impact conditions as presented in this paper.

Second, accidents involving pole supports and appurtenances at bridge sites are not necessarily representative of all run-off-the-road accidents. For example, pole supports and appurtenances at bridge sites are likely to be placed relatively close to the roadway. This reduced extent of lateral offset may have some, albeit unknown, effect on the distributions of impact conditions. Similarly, the sites where the data were collected in the two studies are not necessarily geographically representative.

Third, functional class is used as a gross surrogate measure for the various roadway, roadside, and traffic characteristics that could influence the distributions of the impact conditions. Some examples of such influencing characteristics are lane and shoulder width, horizontal and vertical alignment, lateral offset, roadside slope, and traffic volume and speed. It would be desirable to evaluate the effect of each characteristic individually, but the sample size is too small for such detailed analysis.

EXAMPLE APPLICATIONS

Information on real-world impact conditions can be helpful in the design and evaluation of roadside safety appurtenances and features. Two example applications are illustrated. The first example is a comparison of the full-scale crash test matrix currently in use and real-world impact conditions. The second example involves the use of the information in a benefit-cost model for evaluating highway safety improvements.

Full-Scale Crash Test Matrix

The full-scale crash test matrix for performance evaluation of roadside safety appurtenances has evolved over the years (4-7) with little consideration given to real-world impact conditions. It would be interesting to see how the full-scale crash test matrix currently in use would compare with real-world impact conditions.

Tables 11 and 12 are reproduced from Tables 3 and 4 of NCHRP Report 230 (4) and give the current recommended minimum and supplemental full-scale crash test matrix for roadside safety appurtenances, respectively. Tests that involve large vehicles are excluded from this comparison because the accident data pertain only to passenger vehicles.

The comparisons are divided into two parts: those for point objects, such as breakaway or yielding supports, crash cushions, and barrier ends, in which only impact speed is considered; and those for longitudinal barriers in which both impact speed and impact angle are included.

For point objects, the crash test speeds are either 20 or 60 mph except for one supplemental test at 40 mph for yielding or base-bending supports. Table 13 gives a summary of the percentage of impacting vehicles with speeds of up to 20 mph, greater than 40 mph, and greater than 60 mph for various highway types. It is evident from the table that there are major differences in speed distributions among the various highway types.

As may be expected, freeways have the highest impact speed distribution, followed by rural ar-

TABLE 11 Crash Test Conditions for Minimum Matrix (4)

Appurtenance	Test Designation	Vehicle Type(d)	Impact Speed (mph)	Impact Angle(e) (deg)	Target Impact Severity(f) (ft-kips)	Impact Point(g)	Evaluation Criteria(h)
Longitudinal Barrier(a) Length-of-Need	10	4500S	60	25(i)	$97^{-9, +17}$	For post and beam systems, midway between posts in span contianing railing splice	A,D,E,H,I
	11	2250S	60	15(i)	$18^{-2, +3}$	For post and beam systems, vehicle should contact railing splice	A,D,E,F,(G),H,I
	12	1800S	60	15(i)	$14^{-2, +2}$	For post and beam system, vehicle should contact railing splice	A,D,E,F,(G),H,I
Transition	30	4500S	60	25(i)	$97^{-9, +17}$	15 ft upstream from second system	A,D,E,H,I
Terminal	40	4500S	60	25(i)	$97^{-9, +17}$	At beginning of lenth-of-need	A,D,E,H,I
	41	4500S	60	0(i)	$541^{-53, +94}$	Center nose of device	C,D,E,F,(G),H,J
	42	2250S	60	15(i)	$18^{-2, +3}$	Midway between nose and lenth-of-need	C,D,E,F,(G),H,I,J
	43	2250S	60(o)	0(i)	$270^{-26, +47}$	Offset 1.25 ft from center nose of device	C,D,E,F,(G),H,J
	44	1800S	60	15(i)	$14^{-2, +2}$	Midway between nose and length-of-need	C,D,E,F,(G),H,I,J
	45	1800S	60(o)	0(i)	$216^{-21, +37}$	Offset 1.25 ft from center nose of device	C,D,E,F,(G),H,J
Crash Cushion(b)	50	4500S	60	0(j)	$541^{-53, +94}$	Center nose of device	C,D,E,F,(G),H,J
	51	2250S	60(o)	0(j)	$270^{-26, +47}$	Center nose of device	C,D,E,F,(G),H,J
	52	1800S	60(o)	0(j)	$216^{-21, +37}$	Center nose of device	C,D,E,F,(G),H,J
	53(l)	4500S	60	20(j)	$63^{-6, +11}$	Alongside, midlength	C,D,E,H,I,J
	54	4500S	60	10-15(j)	$541^{-53, +94}$	0-3 ft offset from center of nose of device	C,D,E,F,(G),H,J
Breakaway or Yielding Support(c)	60	2250S	20	(k)	$30^{-4, +4}$	Center of bumper(m,n)	B,D,E, F,(G),H,J
	61	2250S	60	(k)	$270^{-26, +47}$	At quarter point of bumper(n)	B,D,E,F,(G),H,J
	62	1800S	20	(k)	$24^{-3, +3}$	Center of bumper(m,n)	B,D,E,F,(G),H,J
	63	1800S	60	(k)	$216^{-21, +37}$	At quarter point of bumper(n)	B,D,E,F,(G),H,J

(a) Includes guardrail, bridgerail, median and construction barriers.
(b) Includes devices such as water cells, sand containers, steel drums, etc.
(c) Includes sign, luminaire, and signal box supports.
(d) See Table 2 for description.
(e) + 2 degrees
(f) $IS = 1/2\, m\, (v \sin \theta)^2$ where m is vehicle test inertial mass, slugs; v is impact speed, fps; and θ is impact angle for redirectional impacts or 90 deg for frontal impacts, deg.
(g) Point on appurtenance where initial vehicle contact is made.
(h) See Table 6 for performance evaluation factors; ( ) denotes supplementary status.
(i) From centerline of highway.
(j) From line of symmetry of device.
(k) Test article shall be oriented with respect to the vehicle approach path to a position that will theoretically produce the maximum vehicle velocity change; the orientation shall be consistent with reasonably expected traffic situations.
(l) See Commentary, Chapter 4 Test Conditions for devices which are not intended to redirect vehicle when impacted on the side of the device.
(m) For base bending devices, the impact point should be at the quarter point of the bumper.
(n) For multiple supports, align vehicle so that the maximum number of supports are contacted assuming the vehicle departs from the highway with an angle from 0 to 30 deg.
(o) For devices that produce fairly constant or slowly varying vehicle accelerations; an additional test at 20 mph (32 kph) is recommended for staged devices, those devices that produce a sequence of individual vehicle deceleration pulses (i.e. "lumpy" device) and/or those devices comprised of massive components that are displaced during dynamic performance (see commentary).

terials, and urban collectors and local streets have the lowest. The percentage of impacting vehicles with speeds of up to 20 mph ranges from a low of 5 percent for freeways to a high of 30.9 percent for urban arterials and 37.2 percent for urban collectors and local streets. Freeways and rural arterials have substantial percentages of accidents with impact speeds above 60 mph (20.6 and 15.9 percent, respectively), and those for the other highway types are quite low, ranging from 0.9 to 3.4 percent. The percentages of impact speeds above 40 mph are again highest for freeways (57.2 percent) and lowest for urban collectors and local streets (7.4 percent).

For longitudinal barriers, the two major test conditions are at impact speeds of 60 mph with impact angles at 15 or 25 degrees. Table 14 gives a summary of the percentages of accidents with impact conditions that exceed one or both of these criteria. It is interesting to note that, unlike those of impact speed, the distributions of impact angles vary little among the various highway types. This supports the assumption of independency between impact speed and angle. The 15-degree impact angle is slightly above the median (55th percentile) and the 25-degree impact angle represents roughly the 85th percentile.

When both impact speed and angle criteria are taken into consideration, the percentage of accidents that exceed both criteria is actually quite small. For instance, even for freeways, only 3 percent of the accidents have impact speeds of more than 60 mph and impact angles greater than 25 degrees, and 9 percent of the accidents have impact speeds of more than 60 mph and impact angles greater that 15 degrees. This suggests that the current full-scale crash test conditions for longitudinal barriers are actually rather stringent.

The results of the comparison of the crash test matrix and real-world impact conditions point to the desirability of the multiple service level concept (8). Currently, appurtenances are designed under one set of test conditions regardless of the application. As a result, appurtenances may be underde-

TABLE 12 Typical Supolementary Crash Test Conditions (4)

Appurtenance	Test Designation	Vehicle Type[d]	Impact Speed (mph)	Impact Angle[e] (deg)	Target Impact Severity[f] (ft-kips)	Impact Point[g]	Evaluation Criteria[h]
Longitudinal Barrier[a] Length-of-Need	S13	1800S	60	20[i]	$25^{-2,+4}$	For post and beam system, at mid span.	A,D,E,H,I
	S14[p]	4500S	60	15[i]	$36^{-4,+6}$	For post and beam system, vehicle should contact railing splice.	A,D,E,H,I
	S15[q]	40,000P	60	15[i]	$237^{-23,+41}$	For post and beam system, vehicle should contact railing splice.	A,D,E
	S16[r]	20,000P	45	7[i]	$14^{-2,+3}$	For post and beam system, vehicle should contact railing splice.	A,D,E
	S17[r]	20,000P	50	15[i]	$77^{-9,+16}$	For post and beam system, vehicle should contact railing splice.	A,D,E
	S18[r]	20,000P	60	15[i]	$111^{-11,+19}$	For post and beam system, vehicle should contact railing splice.	A,D,E
	S19	32,000P	60	15[i]	$97^{-9,+17}$	For post and beam system, vehicle should contact railing splice.	A,D,E
	S20[s]	80,000A	50	15[i]	[t]	For post and beam sytem, vehicle should contact railing splice.	A,D[s]
	S21[s]	80,000F	50	15[i]	[t]	For post and beam system, vehicle should contact railing splice.	A,D[s]
Transition	S31[p]	4500S	60	15[i]	$36^{-4,+6}$	15 ft upstream from second system	A,D,E,H
	S32[q]	40,000P	60	15[i]	$237^{-23,+41}$	15 ft upstream from second system	A,D,E
Terminals	S46[p]	4500S	60	15[i]	$36^{-4,+6}$	At beginning of length-of-need	A,D,E,H
	S47[q]	40,000P	60	15[i]	$237^{-27,+41}$	At beginning of length-of-need	A,D,E
Crash Cushion[b]	(NONE)						
Breakaway or Yielding Support[c]	S64	1800S	40	[k]	$96^{-14,+15}$	Center of bumper[m,n]	B,D,E,F,(G),H,J

For notes (a) through (o), see Table 3.

(p) Multiple Service Level 1 structural adequacy test; see Commentary, Chapter 4.

(q) Multiple Service Level 3 structural adequacy test; see Commentary, Chapter 4.

(r) Utility bus stability test; S16 for Multiple Service Level 1 appurtenance; S17 for Multiple Service Level 2 appurtenance; S18 specified for Multiple Service Level 3 appurtenance.

(s) Cargo/debris containment test; vehicle, cargo, and debris shall be contained on traffic side of barrier.

(t) Not appropriate for articulated vehicles.

TABLE 13 Percentage of Accidents by Impact Speed and Highway Type for Point Objects

Highway Type	Percentage at ≤20 mph	Percentage at >40 mph	Percentage at >60 mph
Freeway	5.1	57.2	20.6
Urban arterial	30.9	14.1	2.3
Urban collector/local	37.2	7.4	0.9
Rural arterial	18.3	37.4	15.9
Rural collector/local	24.4	19.9	3.4
Combined	22.2	28.7	9.7

signed for certain conditions and overdesigned for others. It may be desirable to establish different performance standards or guidelines for use with different applications.

One possible approach is to select the test conditions at a given percentile of real-world impact conditions. Table 15 gives impact speeds, rounded off to the nearest 5 mph, for the various highway types at different percentiles. It is evident from the data in the table that, for a given percentile, the impact speed varies greatly among the various highway types. For example, the current test speed of 60 mph corresponds to the 90th percentile impact speed for all highway types. However, the 90th percentile impact speeds for individual highway types range from a low of 40 mph for urban collectors and local streets to a high of 70 mph for freeways and rural arterials.

TABLE 14 Percentage of Accidents by Impact Speed, Angle, and Highway Type for Longitudinal Barriers

Highway Type	>60 mph	>15°	>25°	>60 mph and >15°	>60 mph and >25°
Freeway	20.6	43.5	15.0	8.95	3.08
Urban arterial	2.3	43.6	16.5	1.00	0.39
Urban collector/local	0.9	49.4	16.1	0.42	0.14
Rural arterial	15.9	39.9	16.4	6.36	2.62
Rural collector/local	3.4	41.7	16.9	1.40	0.35
Combined	9.7	45.0	16.4	4.34	1.58

TABLE 15 Percentile Impact Speed by Highway Type

Highway Type	Percentile Impact Speed (mph) 85th	90th	95th
Freeway	65	70	80
Urban arterial	40	45	50
Urban collector/local	35	40	45
Rural arterial	60	70	80
Rural collector/local	45	50	60
Combined	50	60	70

An appurtenance designed for freeway use could be overdesigned for applications on urban streets and vice versa. It appears logical and perhaps more cost-effective to have different performance standards or guidelines for testing appurtenances intended for different applications. For example, a lower test speed of 45 mph may be sufficient for guardrails designed for use on urban streets, which might allow for reduced post sizes or increased post spacing. This in turn could result in lower costs for the appurtenances and still allow a reasonable level of performance to be maintained.

Information other than impact speed and angle may also be useful in assessing the crash test matrix. For example, side impacts account for nearly 25 percent of point object accidents with much higher resultant injury severity. It is also known that the breakaway mechanism for pole supports may not function properly in some side impacts. An additional side impact test in the current test matrix may be desirable.

The postimpact trajectory of impacting vehicles and subsequent impacts are other areas of concern about impacts with longitudinal barriers. The potential hazard with postimpact trajectory is recognized in the current testing procedures, and evaluation criteria based on exit speed and angle and redirection into the traffic lanes have been established. Nevertheless, a closer examination of the postimpact trajectory of the vehicle may be desirable.

Little attention has been given to vehicle yawing at impact, and its effect on the performance of appurtenances is virtually unknown except that it increases the probability of nonfrontal impacts. Given the high proportion of nontracking vehicles at impact for reported accidents, it may be desirable to study the effect of vehicle yawing on the performance of appurtenances.

Benefit-Cost Model

Benefit-cost (B-C) procedures are used to determine if the benefits from a safety improvement justify the associated costs and to rank improvements in priority order so as to maximize the benefits for a given funding level. Inputs to the B-C model include the angles at which vehicles depart from the travelway for the determination of the number of expected accidents at a given site, and impact speeds and angles for the estimation of the severity of the accidents, the costs for repairing roadside facilities, and the performance of safety devices.

Accident prediction algorithms are frequently based on an encroachment probability model. The model assumes that inadvertent encroachments are randomly distributed along the roadway and that these errant vehicles travel along a relatively straight path after leaving the travelway. The path of an encroaching vehicle and the probability of an accident are therefore directly related to the angle of encroachment. However, only limited data on the distribution of encroachment angles are available from a few encroachment and special accident studies (9-12) that do not distinguish among encroachment characteristics on different classes of highways.

The severity of accidents involving roadside objects and features is strongly related to the impact speed and, for longitudinal objects, also the angle of impact. Repair costs for roadside appurtenances and the performance of safety devices have been shown to be related to the kinetic energy and lateral momentum of impacting vehicles (4,9,13). The performance of safety devices is especially important when trying to determine the appropriate performance level at a specific site.

Joint impact speed and angle distributions have not been available directly from accident data. A point-mass cornering model has therefore been used to relate impact speed distributions to impact angle distributions. Furthermore, the impact speed data are based on estimates by police officers (11,12), which are highly unreliable.

The impact speed and angle distributions described herein have been incorporated into revised B-C procedures (see paper by Sicking and Ross in this Record) in an effort to improve the accuracy of encroachment probability B-C algorithms. This in turn could provide better estimates of the probability of an accident occurring, the severity of an accident when it does occur, the likelihood that an appurtenance would perform satisfactorily, and the repair cost for the appurtenance. All of the aforementioned probabilities and costs are important to the overall B-C analysis.

Other information related to impact conditions may also contribute to the B-C analysis even though it is not incorporated in the current procedures. For example, vehicle orientation at impact, such as side impacts into pole supports, may have a significant influence on accident severity. These potential effects have not been evaluated, in part because of the lack of information on impact conditions. Some of the information presented in this paper may be suitable for incorporation into the B-C procedures in the future.

SUMMARY

In this paper is presented information on the real-world impact conditions of accidents involving roadside objects and features based on in-depth accident data. Of particular interest are the distributions of impact speed and angle for various functional classes. The potential applications of the information presented herein are illustrated with two examples, one involving the full-scale crash test matrix and the other involving B-C procedures.

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Discussion

J. D. Michie*

The authors address an important topic and attempt to develop impact angles and speeds for vehicles in roadside collisions. Although the authors caution the readers about the limitations of the data, their presentation of findings to four significant figures (i.e., Tables 2-10) suggests that the results are extremely precise. I not only question the inferred precision of the angle and speed models, I also question the representativeness for all roadside collisions of the accident data. The last point is most important because it bears directly on basis assumptions for cost-benefit analyses of roadside safety.

The paper is based on police-reported accident cases that were subsequently investigated and reconstructed. Police-reported accidents represent only about one-third of the 18 million highway accidents that are annually reported to all sources (National Safety Council, 1980-1982 data). Moreover, it has been determined by Galati (1) and by Bryden (NYDOT Proposal for Project 180-1, June 1983) that as few as 10 percent of longitudinal barrier collisions may be reported. For obsolete longitudinal barriers located on older, lower traffic volume roads, the percentage of unreported driveaway collisions is believed to decrease to approximately 60 percent. Thus the data base used by the authors reflects only a part (i.e., 10 to 40 percent) of roadside collisions. This would not be a problem if the reported accident data base were representative of all roadside collisions. Indeed, the authors recognized that the less severe collisions are underrepresented, especially the low-speed and low-angle impacts with longitudinal barriers. Obviously, the models are thus skewed to the more severe impacts. Although I question the validity of the impact speed model, my greatest concern is with the impact angle model. Although a gamma function certainly provides the best fit for the reported accident data set, it is opined that an exponential function (which differs greatly from the gamma function) would have resulted if a more representative sample had been available.

A secondary concern is the generalization of model application from only bridge rail data to longitudinal barriers in general. Bridge rails are peculiar to the longitudinal barriers set in that they are (a) generally located closer to the traveled way and (b) generally more rigid. Barrier offset distance affects the maximum potential angle at which a vehicle can turn into a barrier and attendantly affects the spectrum of impact angles. Barrier rigidness may affect vehicle damage and the number of unreported driveaway collisions. To illustrate the difference between bridge rail and longitudinal barriers, the authors report that 77.4 percent of impacts resulted in one or more subsequent impacts; because bridge rails are rigid and located near the traveled way, they readily redirect the errant vehicles across the highway and often into another bridge rail or fixed object. In contrast, Bryden and Fortuniewicz (see their paper in this Record) showed that multiple impacts occur in only 26 percent of the reported cases. Clearly, bridge rail accident data are not representative of longitudinal barrier collisions, at least with regard to the propensity for secondary impacts.

The data sets used by the authors represent the most complete description of a group of roadside collisions, but the data suffer from (a) lack of exposure information such as traffic volume, operating speed distribution, vehicle types and distribution, and density of roadside features and (b) measurement or estimate of unreported accidents from continuous monitoring techniques (very expensive) to highway damage repair records or periodic photologging of scuff marks on barriers. The approach suggested by Cirillo (2) appears to address these limitations.

The authors are to be commended for addressing a most important aspect of roadside safety. Having accurate speed and angle impact models is crucial to effecting a more rational crash test matrix and providing more realistic cost-benefit analysis programs.

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Authors' Closure

The authors would like to thank J.D. Michie for his thoughtful comments on the paper. We agree with the comments in general but would differ on some of the specific points. First, some cell probabilities, especially those for joint impact speed and angle distributions, are very small and require four decimal places to provide one significant figure. For example, the cell probabilities for impact speed of

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10 mph and less on freeways are on the order of 0.0001 to 0.0005 for the various impact angle ranges (see Table 4 of the paper). The use of four decimal places is maintained throughout all the tables for uniformity and does not imply extreme precision.

Second, the authors recognize the importance of exposure and attempt to control for exposure by using highway functional class as a surrogate measure. The sample size is not large enough for more detailed breakdown, as suggested by Michie, to include exposure measures such as traffic volume, operating speed, and vehicle type.

The authors recognize and agree in principle with Michie on the limitations of the accident data used in developing the impact angle and speed distributions. There is no question that a certain percentage of accidents involving roadside objects is not reported to the law enforcement agencies for a variety of reasons. A number of studies, some of which are cited by Michie, attempted to determine the extent of unreported barrier accidents by comparing the number of scuff marks, scrapes, and dents on barriers with reported barrier accidents (first harmful event only). The results vary greatly among the studies, and there is no consistent trend.

The authors have some doubts as to how meaningful and accurate these estimates of unreported accidents are. It is the opinion of the authors that many of these barrier scuff marks, scrapes, and dents are caused by vehicles, such as large trucks, and maintenance and farm equipment that are on the shoulder intentionally and are thus not unreported accidents. Also, damage to barriers can be caused by secondary impacts that would not be identified when only first harmful events are considered.

For instance, in an ongoing study conducted by the Texas Transportation Institute (TTI) for the FHWA, all accident reports for 1982 were manually reviewed for two sections of freeways in San Antonio, Texas, in an effort to identify concrete median barrier (CMB) accidents. It was found that 40 percent of the CMB impacts were not the first harmful event but were subsequent to vehicle-to-vehicle impacts. Also, multiple impacts with the barrier were noted in many of the accidents. A simple comparison of scuff marks, scrapes, and dents on barriers and reported barrier impacts as first harmful events would have incorrectly identified these subsequent impacts as unreported accidents.

This discussion does not imply that there are no unreported barrier accidents but simply that we have pitifully little information about these "unreported accidents." This brings us to a more fundamental concern: whether and how we should account for these unreported accidents in the design and performance evaluation of roadside appurtenances. There is no available information on these unreported accidents and it is unlikely that such data will become available in the foreseeable future. Assumptions and conjectures could be made about the characteristics of these unreported accidents, such as an exponential distribution for impact angles, mentioned by Michie. However, the fact remains that we simply do not know. The authors would argue that it is better and more practical to use available data from reported accidents than to depend on unsubstantiated assumptions and conjectures about unreported accidents. Furthermore, it can be argued that it is better to err on the side of overstating the impact severity because this will generally result in greater use of improved safety features.

The discussions presented in the paper on impact conditions other than speed and angle, such as areas of impact on the vehicle, vehicle yawing at impact, and subsequent impacts, are direct excerpts from the two referenced studies and are included in the paper for information purposes. It is certainly not the authors' intention to suggest that bridge rail accidents are representative of other longitudinal barrier collisions. However, the authors believe that the issues raised with the bridge rail accidents would also apply to other longitudinal barrier accidents, though the magnitude of the problems may be different. For example, subsequent impacts may be more frequent for bridge rail accidents than for other longitudinal barriers as pointed out by Michie, but this should not negate the concern for subsequent impacts.

Another point raised by Michie is the effect of barrier offset distance on the impact angle at which a vehicle strikes an object. The authors agree that the potential for higher impact angles increases as offset distance increases. However, the potential for reduced impact angle (or no contact at all) also increases with greater offset distance because drivers, if in control of steering or braking, or both, will typically try to steer back to the roadway or stop, or both, before striking the object. Indeed, the data reported in the paper suggest that impact angle is somewhat independent of offset distance.

In summary, though the authors differ with Michie's comments on specific points, the comments are well founded and reflect the general lack of available information in this area. The authors recognize the limitations of the materials presented in the paper but hope that the information will be of some utility to researchers in the roadside safety area.