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Analysis of Safety Benefits Expected Through Modifications in Drainage Structure Design

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The problem of providing improved design for roadway culverts is investigated through a twofold analysis: (a) examination of accidents on Texas highways and (b) presentation of a theoretical computation involving societal accident costs and a probability of impacts developed by the American Association of State Highway and Transportation Officials. The study findings indicate that culvert-related accidents are of minor significance in terms of overall accident occurrences. To achieve optimal accident reduction, it is essential that any enhancements to existing culvert designs be carefully considered. Recent research findings offer some insight into designs to mitigate the hazard potential of cross-drain and driveway culvert installations. The acceptance of any remedial measure must compare the cost associated with the recommended design with the cost involved in its required maintenance and the effect on performance due to terrain encountered in typical field installations. A list of proposed modifications to culvert design is provided to assist the designer in optimizing safety expenditures.

Safety on highways is a critical concern to the motorist as well as to state transportation departments. The design engineer must assess the abilities of the reasonable and prudent driver and provide a safe roadway environment while providing for the basic transportation needs of the community. In Texas, the discharge of these obligations is frequently obscured by the many facets involved in planning, constructing, and maintaining more than 72 000 miles of roadway on the Texas highway system. Budgetary limitations have caused severe shortages of funds for needed transportation improvements. All programs must therefore be judiciously compared and selected to achieve and maximize the overall betterment and safety of these highways.

Foody and Long (1) reported that in Ohio almost two-thirds of single-vehicle accidents on the rural, two-lane highway system did not involve a collision with a fixed object. In a comparison of injury-producing accidents, it was found that nonfixed objects were responsible for approximately the same percentage of injury-producing accidents as fixed objects. Terrain or the basic roadway design (or lack of it) represented the greatest hazard to a vehicle leaving the road on a rural, two-lane highway system. Furthermore, it was estimated that any fixed-object improvement program would affect less than 10 percent of the accidents. Therefore, it was concluded that, in Ohio, any major improvement program directed at roadside obstacles would not be economically feasible in comparison with a program in which primary emphasis was placed on improvements to the shoulder and/or roadways.

Similarly, a tabulation by the Texas Department of Public Safety (2) of accidents by type in Texas indicates that accidents involving nonfixed objects amounted to 76.1 and 77.1 percent of the fatalities occurring during 1977 and 1978, respectively. The largest single category of fatal accidents in Texas is the multiple-vehicle collisión. In 1977 and 1978, these accidents represented 38.6 and 38 percent, respectively, of all accidents. Although high speeds are frequently associated with this type of accident, since the opportunity exists for both drivers to exercise evasive action, pavement condition is an important factor that directly affects accident frequency and severity. Similarly, single-vehicle accidents that occur both on and off the roadway frequently also initially involve similar pavement conditions to which the driver has not successfully accommodated. Therefore, the importance of focusing primary effort on safe design and maintenance of the roadway is apparent.

Fixed objects off the roadway are another area of concern to the safety engineer. Optimization of design requires an intensive examination of each fixed object with respect to the overall safety of the facility. Basically, in order to select an optimum design, two questions should be answered in considering the treatment of fixed objects off the roadway:

1. Does a problem exist?
2. If a problem exists, what is the optimal method of treating the problem?

INVESTIGATION

Driveway culverts and crossroad culverts represent two types of the many fixed objects adjacent to the roadway. This paper attempts to examine this class of fixed objects to develop a procedure for a systematic evaluation of benefits to be derived from any proposed program for enhancement of these structures.

Four primary factors are involved in considering the relative hazard potential of any fixed object off the roadway: (a) distance of the object from the roadway, (b) frequency of occurrence of the object along the roadway, (c) obstacle size, and (d) traffic volume.

The distance of an obstacle from the roadway will affect the hazard potential of an impact in two ways: Not only is the probability of an impact greatly reduced by distance from the roadway, but also a markedly reduced severity of impact should be possible through driver corrective action in steering or vehicle braking and deceleration.

The frequency of occurrence of a hazard directly influences the probability of impact with that hazard, and probabilistic models have been developed to estimate this occurrence. When impacts with intermittently occurring obstacles are compared with those that occur continuously, however--such as guardfence, pavement edge drop-offs, or poor driving-surface friction resistance--the comparative exposure frequency is slight.

Obstacle size influences both potential impact frequency and impact severity. Fewer and less severe impacts are expected with objects that offer a small, low "target" value.

Finally, traffic volume must be considered in comparing roadway appurtenances that need improvement. Higher-volume facilities, with their proportional increase in frequency of exposure to hazards, should receive priority in improvement scheduling over the comparable low-volume facility.

In this research, two approaches were used to investigate the problem: (a) Historical accident data were analyzed to determine the dimensions of the problem, and (b) a probabilistic model was used to estimate the frequency of impact in order to compute a benefit/cost (B/C) comparison for treated and untreated installations.

ACCIDENT STATISTICS

Statistics comparing culvert accidents with total accidents on Texas highways are given in Table 1 (3). A comparison with culvert accidents of all types indicates that culvert accidents represent only 0.7 percent of the total roadway accidents occurring on state-maintained roadways in Texas and only 1.5 percent of the fatalities, 1.4 percent of the injuries, and 0.4 percent of the property damage. Although any computed percentage will vary from year to year, it is apparent that culvert accidents represent a very low-frequency type of incident. To give an indication of the frequency at which vehicles departing the road collide with culverts, the Federal Highway Administration (FHWA) reports that impacts with culverts represent 3.1 percent of the most common impacts with roadside objects (4).

To evaluate the relative significance of the fixed-object collision, Table 2 gives a ranking of fixed objects based on societal costs. Since rates of fatalities, injuries, and property damage for collisions with a given fixture will vary, by weighting these rates with an estimate of the cost to society associated with each type of accident, a comparison between the severities of each type of fixed-object accident can be made. Societal costs reported by FHWA (5) were $287 175/fatality, $3185/

Table 1. Comparison between culvert accidents and total accidents on Texas highways in 1978.

Accident Category	Culvert Accidents	Total Accidents	Culvert Accidents as Percentage of All Accidents
Fatality			1.5
Accidents	37	2 538	
Fatalities	44	2 987	
Injury			1.4
Accidents	862	59 609	
Number injured	1217	94 545	
Property damage	570	140 135	0.4
All	1469	202 282	0.7

Table 2. Comparison of societal costs for 10 types of single-vehicle, fixed-object accidents on Texas highways in 1977.

Type of Fixed Object	Fatality No.	Fatality Cost ($000s)	Injury No.	Injury Cost ($000s)	Property Damage No.	Property Damage Cost ($000s)	Total Societal Costs ($000s)	Cost as Percentage of All Types of Accidents
Guardpost rail	102	29 292	3 339	10 635	6 490	3 375	43 302	3.8
Tree or shrub	95	27 282	1 067	3 398	1 559	811	31 491	2.7
Culvert headwall	62	17 805	1 018	3 242	1 339	696	21 743	1.9
End of bridge	72	20 677	194	618	371	193	21 488	1.9
Fence	43	12 349	1 278	4 070	2 757	1 434	17 853	1.5
Highway sign	42	12 061	1 099	3 500	3 560	1 851	17 412	1.5
Side of bridge	29	8 328	1 155	3 679	2 051	1 067	13 074	1.1
Utility pole	20	5 744	1 482	4 720	2 300	1 196	11 660	1.0
Pier or support	36	10 338	230	733	351	183	11 254	1.0
Luminaire pole	13	3 733	778	2 478	1 434	746	6 957	0.6
All accidents statewide	2 671	767 044	84 386	268 769	227 855	118 485	1 154 298	

injury, and $520 for property damage. When societal costs for the 10 most frequently struck fixed objects are compared with costs for single-vehicle accidents and total accidents, all culvert accidents represent only 1.9 percent of the cost of total accidents. Although these percentages cannot be used to infer the degree of hazard in relation to other fixed objects unless total numbers of fixed objects are known, they do reflect the low significance of total culvert accidents in relation to all accidents. In addition, since a culvert accident can be interpreted to include accidents involving large drainage structures (structures up to 20 ft long in Texas are classified as culverts) as well as small-diameter pipe culverts, these percentages are apt to be considerably overstated when only the typical smaller driveway and cross-drain culverts are considered.

PROBABILITY MODEL

A probability model was next used to establish a measure of the hazard potential of the individual culvert and to further complement the historical data. The American Association of State Highway and Transportation Officials (AASHTO) Guide for Selecting, Locating, and Designing Traffic Barriers (6) provides a procedure for estimating accidental departures from the roadway and expected impacts with a given fixed object, as well as a method for analysis with an improved design to achieve a B/C comparison.

Basically, the procedure used first estimates the expected frequency of accidental departure of a vehicle from the roadway based on the average daily traffic of the facility. Next, by using a nomograph (Figures 1 and 2) for a fixed object of known width, length, and distance from the roadway and an estimated departure frequency, the frequency of collision (C_F) with cross-drain and driveway culverts, respectively, is determined for various roadway densities.

A comparison of the benefits of an "improved" design is then made with the existing design to enable a B/C determination. By means of estimates of the expected severities associated with an impact with existing and improved designs and a computation of the societal cost of the accident, a dollar value can be assigned to each installation. The severity index used was based on a scale of 0-10. Figure 3 shows a graph that was revised from the AASHTO report to reflect the previously cited societal costs for fatalities, injuries, and property damage. Accident costs according to the severity-index scale can be summarized as follows:

Severity Index	Accident Cost ($)
0	520
1	920
2	1 320
3	1 719
4	4 959
5	16 585
6	36 731
7	88 116
8	173 579
9	227 537
10	272 975

Figure 1. Frequency of vehicle collisions with cross-drain culverts.

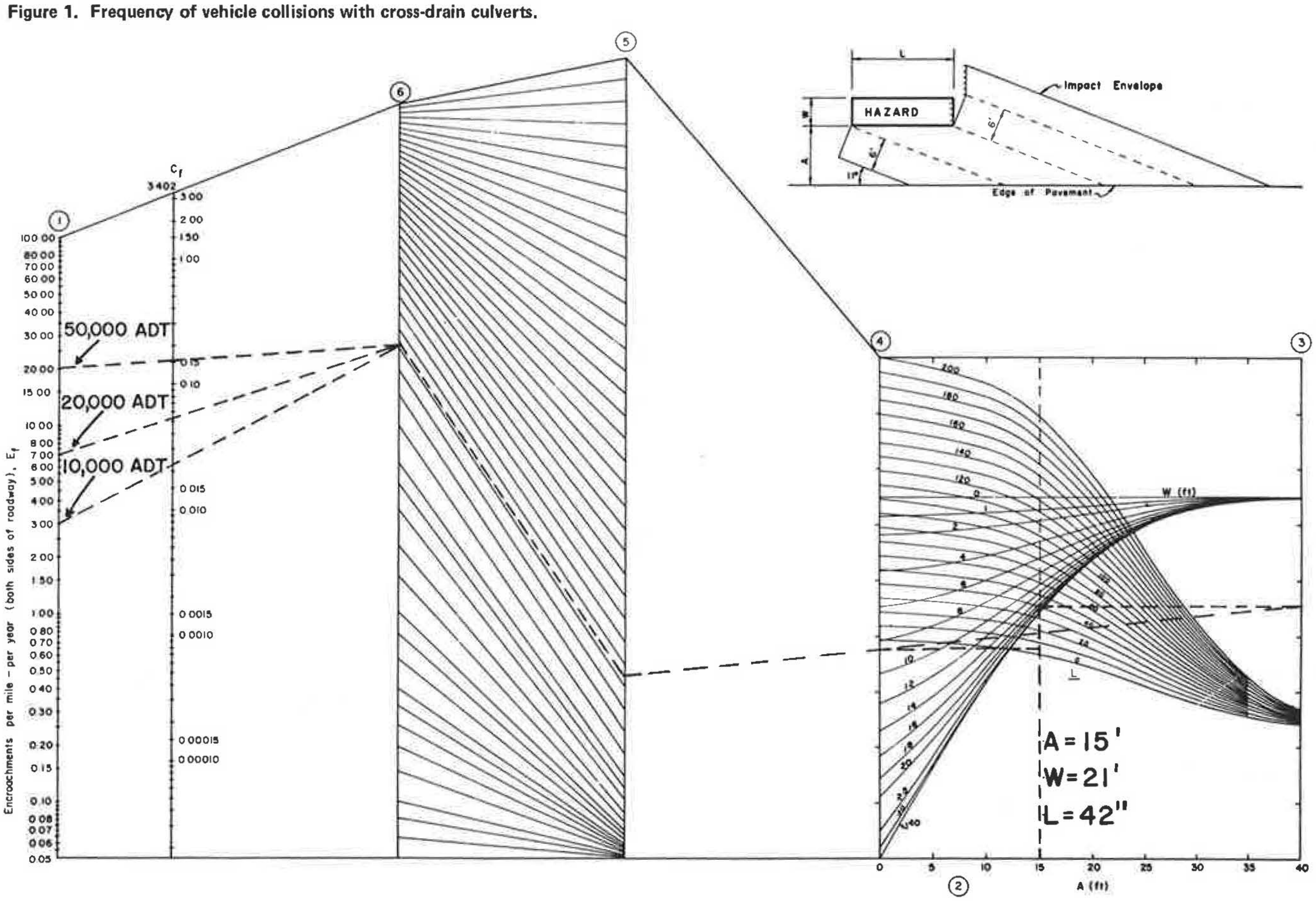


Figure 2. Frequency of vehicle collisions with driveway culverts.

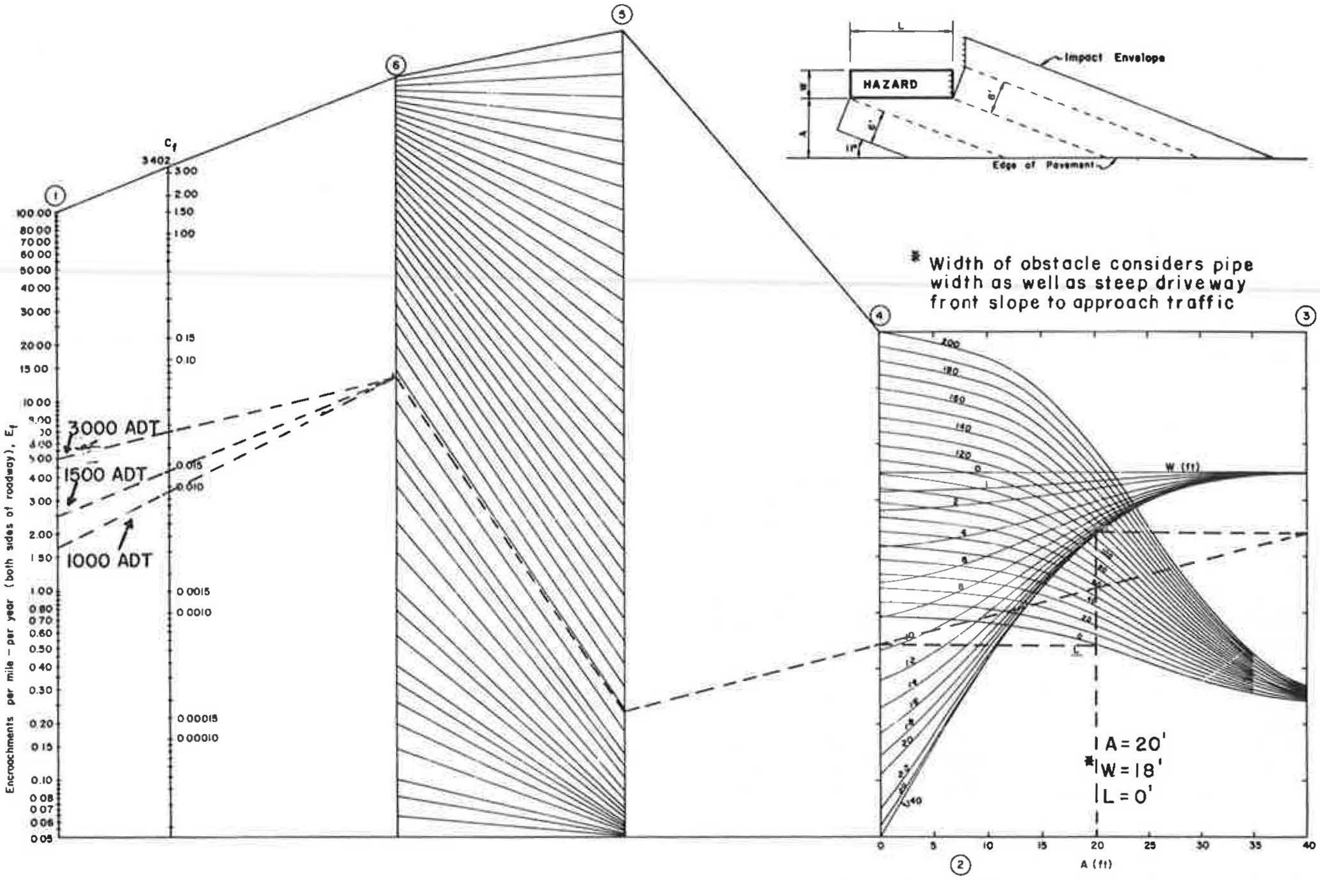


Figure 3. Dollar value of an accident.

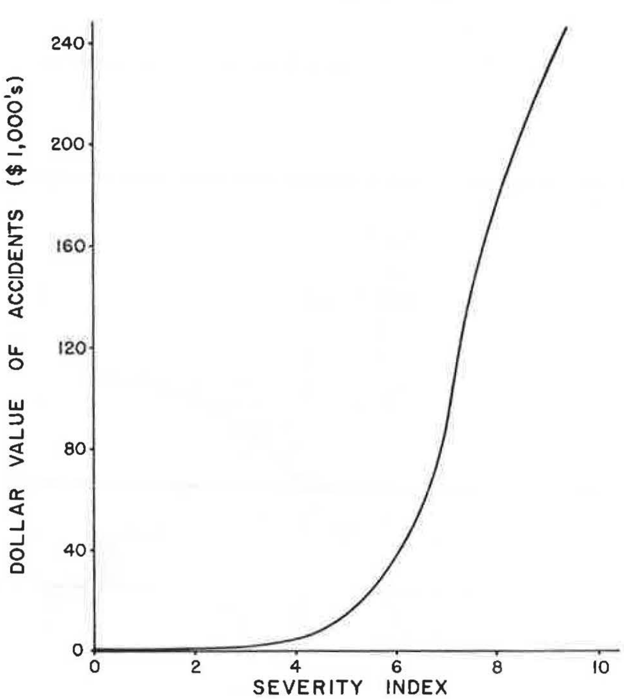


Figure 4. B/C value for cross-drain culverts versus ADT.

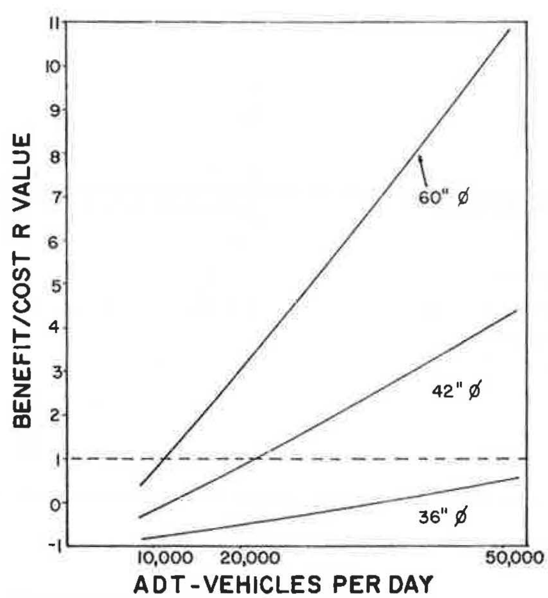
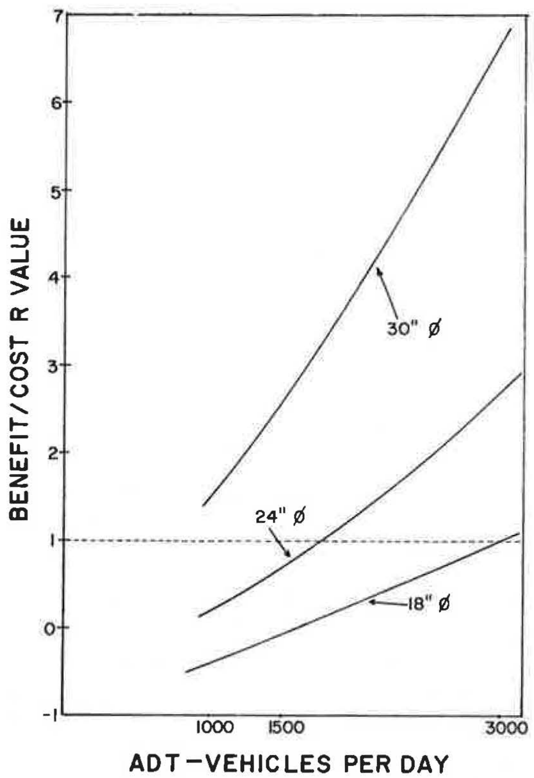


Figure 5. B/C value for driveway culverts versus ADT.



The following equations were used to compute the R, or B/C value, of the existing installation:

$$C_{TU} = C_I + C_D (C_F)(K_T) + C_M (K_T) + C_{OVD} (C_F)(K_T) - C_S (K_F) \quad (1)$$

$$C_{TP} = C_I + C_D (C_F)(K_T) + C_M (K_T) + C_{OVD} (C_F)(K_T) - C_S (K_F) \quad (2)$$

$$C_{TD} = C_I + C_D (C_F)(K_T) + C_M (K_T) - C_S (K_F) \quad (3)$$

$$R = (C_{TU} - C_{TP})/C_{TD} \quad (4)$$

where

C_{TU} = cost of unprotected fixed object,
C_{TP} = cost of protected fixed object,
C_{TD} = cost of installation of protected fixed object,
R = B/C ratio,
C_I = initial cost of fixed object,
C_D = cost of damage through use,
C_F = collision frequency,
C_M = cost of maintenance through use,
C_{OVD} = cost of accidents,
C_S = salvage value (cost), and
K_T, K_F = interest rates based on 20-year life at 8 percent.

FINDINGS

Cross-Drain Culverts

Figure 4 shows B/C values calculated for culvert sizes as large as 60 in in diameter for average daily traffic (ADT) through 50 000 vehicles/day. An interpretation of the B/C ratio is that a negative value and values less than 1 imply that no benefit is expected for the proposed enhancement. It is only when a B/C ratio of 1 is attained or exceeded that a net benefit is realized. For this analysis, unprotected culvert installations assumed cross-drain culverts without headwalls that are sloped to coincide with the side slope of the roadway. The protected culvert design assumed the same culvert with the addition of a bar grate.

B/C ratios for cross-drain culverts indicated that, for culvert sizes through 42 in in diameter on roads with traffic densities of $\leq$20 000 vehicles/day, no benefit is expected for a culvert protected by grates.

Driveway Culverts

Figure 5 shows B/C values calculated for 18-, 24-, and 30-in-diameter driveway culverts for roadways with ADT between 1000 and 3000 vehicles/day. Unprotected culverts were considered to be circular corrugated metal pipes that do not have headwalls and have no special end treatments. Protected culverts were assumed to have a pipe with a 6:1 tapered end that has been stabilized with concrete riprap. Neither corrugated arch pipe nor concrete pipe was considered in this analysis because of their higher cost of modification compared with the circular pipe.

B/C ratios for the designs considered indicate that, for an 18-in-diameter pipe culvert, a modified design is not cost effective for traffic densities up to 3000 vehicles/day. Similarly, a modified 24-in culvert is cost effective for traffic densities greater than 1800 vehicles/day. A 30-in culvert shows a B/C ratio of greater than 1 for all traffic densities.

Table 3 illustrates a table of safety benefit countermeasures as an example of some B/C ratios for roadway and roadside improvements on actual construction projects (5). It is noted with interest that many of the highest B/C ratio items are concerned with treatment of the driving surface or adjacent areas. It should also be emphasized that, when improvements are being considered, a B/C ratio is one of the several tools available to the designer to establish a priority of needed improvements to a facility. Other crucial elements that must also be considered in any proposed improvement program are (a) available funds to achieve the needed program without curtailing essential roadway improvements elsewhere and (b) the effect that such improvements will produce with respect to increased maintenance of a facility.

CURRENT RESEARCH

Research into the reduction of the relative degree of hazard of typical highway culvert designs has been initiated by the Texas State Department of Highways and Public Transportation (TSDHPT). A cooperative research study (7) was directed at producing guidance on some of the fundamental questions concerning cross-drain and driveway culvert installations. A full-scale vehicle test program was conducted to investigate the maximum spacing of bars on culvert grates to provide for a safe vehicle traversal with a minimum hydraulic disruption to the system. Also tested was a comparison of high-speed impacts with driveway-culvert slopes. The culmination of this research activity has provided the engineer with a comparative measure of performance constraints that may be used as a guide in the design of future culvert installations.

SUMMARY AND CONCLUSIONS

In any consideration of roadside design safety, primary emphasis must be placed on the driving surface itself. Roadways should be constructed so

Table 3. Benefits of roadway and roadside safety countermeasures.

Rank	Code	Improvement	Service Life (years)	No. of Projects	Avg Annual Accident Experience: Before: Accidents	Before: Injuries	Before: Fatalities	After: Accidents	After: Injuries	After: Fatalities	Annual Accident Reduction Expected (%): Accidents	Injuries	Fatalities	Benefit ($)	Cost per Project ($)	B/C Ratio
1	23	Shoulder widening or improvement	20	46	1917	585	35	1353	465	21	29	20	41	4 754 088	35 200	28.83
2	64	Installation of striping and/or delineators	4	2000	5849	3351	113	5060	2599	60	13	20	46	17 493 150	1 094	26.49
3	25	Skid treatment (grooving)	20	96	1117	395	27	580	275	7	48	30	74	6 372 399	32 385	20.12
4	60	Installation or upgrading of traffic signs	4	775	3727	1538	80	2879	1030	23	23	33	27	8 031 275	2 278	15.03
5	57	Signing and/or marking	10	3046	191	142	34	192	82	22	0	42	35	3 638 462	536	14.94
6	63	Installation or improvement of median barrier	10	23	962	479	48	994	449	4	-3	6	91	12 712 361	270 070	13.73
7	65	Installation of roadway lighting	10	115	1119	546	20	1022	499	6	9	9	73	4 393 559	19 363	13.24
8	62	Installation or improvement of road-edge guardrail	10	1651	2077	844	69	1716	719	29	13	15	59	12 273 743	4 546	10.97
9	50	Replacement of signs only with flashing lights (railroad crossing)	10	56	36	17	7	2	1	0.06	94	93	99	2 014 682	25 655	9.41
10	60,64	Sign-striping combination	4	465	5858	2844	90	4464	2108	65	24	26	27	9 982 024	8 270	8.60
11	61	Breakaway signs or lighting supports	4	527	195	41	2	127	23	0	35	44	100	656 538	569	7.25
12	11	Installation or improvement of traffic signals	10	699	9408	4181	87	7698	2840	43	18	32	49	17 688 205	26 650	6.36
13	26	Skid treatment (overlay)	20	126	3071	1627	37	2552	1194	26	17	27	30	4 747 692	60 796	6.09
14	55	Replacement of signs (only) with automatic gates	10	101	43	17	11	0.2	0.03	0.2	99	99	100	3 100 704	37 872	5.44
15	10	Channelization including left-turn bays	10	612	5815	2618	83	4481	1860	30	23	29	65	17 982 781	50 091	3.94
16	20	Pavement widening, no lanes added	20	241	951	489	26	715	301	4	25	33	87	7 238 042	80 188	3.68
17	13	Improvement of sight distance	10	142	338	205	6	234	127	4	31	38	36	859 826	13 696	2.97
18	12	Combination of codes 10 and 11	10	36	887	333	1	609	215	0.5	31	35	50	620 449	64 846	1.78
19	56	Replacement of active devices with automatic gates	10	166	28	11	3	5	3	0.1	81	75	96	948 528	33 921	1.13
20	42	Combination of codes 40 and 41[a]	20	69	423	219	6	332	150	2	21	32	69	1 350 900	211 055	0.91
21	31	Replacement of bridge or other major structures	30	163	113	84	5	63	33	0	44	60	47	1 548 658	118 475	0.90
22	21	Addition of lanes without new median	20	96	1482	595	7	1224	531	5	17	11	31	900 544	114 987	0.80
23	30	Widening of existing bridge or other major structures	20	354	565	291	3	198	76	2	65	74	33	1 103 632	75 440	0.41

[a]Specified in the complete table contained in the FHWA report (4).

that motorists can achieve their transportation needs in safety and with confidence. Off-roadway fixtures must assume a decidedly subordinate importance to those on-roadway features that confront every motorist. The greater the distance the fixed object is from the traveled way, the less frequent its occurrence, and the smaller its size, the less of a hazard that object becomes.

This investigation into the enhancement of culvert designs has first considered historical accident data on culvert accidents of all types. In a survey of six states and more than 8000 accidents, accidents involving culverts are reported to represent 3.1 percent of the most commonly occurring roadside fixed-object accidents. In Texas, culvert accidents of all types for 1978 represented 0.7 percent of total roadway accidents, 1.5 percent of fatalities, 1.4 percent of injuries, and 0.4 percent of property damage. Historical accident data, therefore, have indicated that culvert-related accidents of all types occur at a low frequency.

Next, a societal cost comparison that weights each accident by the cost involved with fatalities, injuries, and property damage has indicated that for 1977 culvert accidents represent 1.9 percent of the cost of all accidents occurring on Texas highways. This theoretical computation also indicates that culvert accidents of all types are a low-cost item compared with all types of accidents.

Finally, B/C comparisons were computed for protected and unprotected cross-drain and driveway culvert installations to generate some measure that could assist the designer in an evaluation of alternative safety expenditures. Because of the shortage of funds available for needed construction and maintenance, an arbitrary program to slope the ends of driveway culverts and to require grates on many cross-drain culverts does not appear to be in the best interest of the traveling public. Instead, the following recommendations are offered to optimize the overall safety of the highway system:

1. The involvement of cross-drain culverts in fixed-object accidents represents a low-frequency occurrence where full shoulders and flat side slopes are present. Culvert ends do not require special safety treatments for the following sizes and traffic densities based on preliminary B/C computations:

Pipe Diameter (in)	Traffic Density (vehicles/day)
36	50 000
42	20 000
60	10 000

2. For driveway culverts, there is a higher potential for injury to vehicle occupants if the culvert end is untreated than if the design provides a 6:1 sloped end. However, preliminary B/C computation involving impact frequency indicates that treatment of driveway culvert ends need not be provided where full shoulders are present for the following pipe sizes and traffic densities:

Pipe Diameter (in)	Traffic Density (vehicles/day)
18	3000
24	1600
≥30	Treatment warranted if inside clear zone

3. A high priority for safety expenditures should be assigned to on-roadway factors that directly involve the safety of all motorists. A list compiled by FHWA indicates that the top five safety B/C

countermeasures to be applied to the highway system are (a) shoulder widening or improvement, (b) installation of striping and/or delineators, (c) skid treatment and grooving, (d) installation or upgrading of traffic signs, and (e) signing and/or marking.

4. Additional improvements to culvert installations that should be considered are (a) locating driveway and cross-drain culverts as far from the travel way as possible, (b) minimizing cover of driveway culverts to reduce overall height of the obstacle, (c) using ditchline driveways without pipes wherever possible, and (d) deleting concrete headwalls and shaping fill adjacent to pipe ends on driveway culverts to minimize the opportunity for abrupt vehicle decelerations on possible impacts.

5. Since the cost and hazard potential of culverts dictate the use of the minimum pipe sizes able to accommodate expected hydraulic flow conditions, the use of grates to improve chance impact performance should be considered with extreme caution. The reduction in culvert capacity caused by the addition of a grate necessitates larger culvert sizes (and fill heights). This can greatly increase the hazard potential of the installation as the height of the force that results more nearly approaches the vehicle center of mass.

The B/C computations presented in this paper have only considered routine maintenance costs. They have not addressed the potential for extensive damage to the facility and adjacent property or the hazard to the motorist when water overflows onto the highway because of a blockage caused by a reduction in hydraulic capacity during high-intensity rainfalls. The costs associated with these problems are very real and need to be carefully assessed by highway designers whenever a culvert upgrading program is initiated and alternative safety expenditures are considered.

ACKNOWLEDGMENT

The contents of this paper reflect our views, and we are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of FHWA or TSDHPT. This paper does not constitute a standard, specification, or regulation.

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