Developing Guidelines for Median Barrier Installation: Benefit–Cost Analysis with Texas Data

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PART 1

Roadside Safety Design

Developing Guidelines for Median Barrier Installation

Benefit–Cost Analysis with Texas Data

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Guidelines for the installation of median barriers presented in the AASHTO *Roadside Design Guide* have remained essentially unchanged for more than 30 years. In recent years, the need for improved guidance has prompted several states to reevaluate their guidelines and has also precipitated a nationwide research project administered by the Transportation Research Board. The objective of the study, on which this paper is based, was to develop improved guidelines for the use of median barriers on new and existing high-speed, multilane, divided highways in Texas. The purpose here is to present some modeling and benefit–cost analysis results from that study, with a focus on the results from a particular data set developed under a cross-sectional with–without study design. The highways of interest are those classified as Interstates, freeways, and expressways with four or more lanes and posted speed limits of 55 mph (88 km/h) or higher. The models employed to estimate median-related crash frequencies and severities, including the Poisson-gamma and ordered multinomial logit models as well as modeling results from a full Bayes estimation method, are presented. From the modeling results, a preliminary benefit–cost analysis is described, in conjunction with some sensitivity analyses, for developing the guidelines for concrete and high-tension-cable barriers. A discussion of the limitations of this study and potential future extensions is provided.

Cross-median crashes occur when a vehicle crosses the median area of a divided roadway, enters the opposing traffic lanes, and then collides with one or more vehicles on the opposing lanes. The vehicle that crosses the median can also cause vehicles on the opposing lanes to collide with each other or run off the road. Because the relative speed of vehicles at the time of collision is usually high, cross-median crashes are typically violent and result in multiple injuries and fatalities (*1, 2*).

One way to reduce cross-median crashes is to install median traffic barriers, which are protective devices placed between two opposing traffic streams with the intention of keeping errant vehicles from reaching the other side of the traffic lanes. Median barriers, however, do not prevent crashes. After all, they too are obstacles on the roadside, and vehicles striking barriers can cause occupant injury and vehicle damage. Generally speaking, installing a median barrier changes the characteristics of median-related crashes in two ways. On the one hand, it transforms cross-median crashes (had the barrier not been installed) into hit-median-barrier crashes. On the other hand, it prematurely forces some of the left-encroached vehicles that could have safely recovered (had the barrier not been installed) to hit the barrier.

In developing selection and installation guidelines for roadside safety features, it has long been recognized that the median barrier requires a different modeling approach than that for other, nonmedian safety features. One reason is that a cross-median crash involves not only the encroaching vehicles but also the traffic in the opposing direction of travel (*1*). The complexity of the cross-median event can be illustrated with the following plausible probabilistic description. As the traffic volume increases, which is usually accompanied by the presence of more traffic lanes (except for the vehicles on the innermost lane), the probability for an errant vehicle to be able to reach the edge of the median area on its side of travel is reduced (*a*) because of the need to traverse more physical distance on average and (*b*) because of the increased chance of hitting other vehicles in the same traveling direction before the errant vehicle reaches the median area. However, once the errant vehicle crosses the median and reaches the opposing traffic lane, the chance for that vehicle to result in a cross-median crash increases at higher traffic volumes since more vehicles are likely to be present in opposing lanes.

Within its performance limits, a median barrier is designed to contain and deflect an errant vehicle in a controlled manner with acceptable deceleration and low exit angle and is thus expected to result in less severe injury to the occupants or damage to the vehicle than the involved vehicle would otherwise experience in a cross-median crash. In determining whether it is cost-effective to install a barrier, this benefit of reducing the expected frequency and severity of an otherwise cross-median crash has to be compared with the cost of installing and maintaining the barrier and generating barrier crashes that would otherwise not have occurred. As pointed out by Hauer (*3*), ". . . the decision to install a median barrier is a balancing act."

Traditionally, the median barrier design process consists of first determining the need through a warrant analysis and then selecting an appropriate barrier type on the basis of the level of protection it offers, including its performance limits and its deflection and deceleration characteristics, installation and maintenance costs, and conditions at the site at which it is proposed to be installed, such as heavy-truck volume and horizontal curvature. Since the primary purpose of a median barrier is to prevent an errant vehicle from crossing a median on a divided highway and encountering oncoming traffic, the development of median barrier warrants has been based in part on some benefit–cost (B/C) analysis of the frequency and severity of cross-median crashes. Until recently, Texas Department of Transportation (TxDOT) median barrier standards consisted of only concrete barrier alternatives (*4*), which included the concrete traffic barrier, which

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is a Jersey-shaped safety barrier, and the single-slope concrete barrier. Both of these median barriers meet NCHRP Report 350 evaluation criteria for a Test Level 3 longitudinal barrier and are approved for general use on the National Highway System. TxDOT has recently begun to install and evaluate high-tension-cable median barriers. A variety of high-tension-cable barrier systems have been approved to meet NCHRP Report 350 performance criteria and are considered to be a cost-effective option for reducing cross-median crashes.

Guidelines for the installation need of median barriers presented in the AASHTO *Roadside Design Guide* (RDG) (*5*) have remained essentially unchanged for over 30 years. Access control, median width, and annual average daily traffic (AADT) volumes are the basic factors used in the RDG to determine need. In Texas, guidance for median barriers is differentiated on the basis of access control and median width (*4*). Median barriers are generally provided for controlled-access highways with medians of 30 ft (9 m) or less in width, which are similar to those recommended in the RDG. If justified through an operational or crash history analysis, barriers may be provided for medians with widths greater than 30 ft (9 m). In recent years, the need for improved guidance has prompted several states to reevaluate their guidelines, including California, North Carolina, Pennsylvania, and Washington (*6,* Chapter 7: Traffic Safety Systems; *7–9*). It has also precipitated a nationwide research project that is currently under way with NCHRP Project 17-14, Improved Guidelines for Median Safety. A brief review of some of these guidelines is provided in the next section.

The objective of the study on which this paper is based was to develop improved guidelines for the use of median barriers on new and existing high-speed, multilane, divided highways in Texas. The guidelines addressed when and where median barriers are justified and, if justified, how the installation should be priority ranked. The research approach taken by the study consisted of collecting roadway and median-related crash data to support the analysis under two study designs: cross-sectional with–without and before-and-after with reference groups. The former design aimed at estimating and comparing the crash frequency and severity for two groups of sites assembled from a cross section of highways in the same time period: sites with median barriers and sites without median barriers. The latter design was based on the evaluation of crash frequency and severity before and after the installation of median barriers for a selected number of sites, each of which was matched by a number of reference sites with similar before conditions in key traffic and design features. Typically, upstream and downstream sites of the same route or neighboring sites of the same class of routes were selected as reference sites. Only a small number of sites could be identified for use under the second study design and thus no formal analysis was carried out. It was noted that for many of these before-and-after sites, multiple design changes took place, including changes in the number of lanes and shoulder type and width and addition of safety features such as shoulder rumble strips. The purpose of this paper is to present the modeling and B/C analysis results from data developed for the cross-sectional with–without design. The highways of interest are those classified as Interstates, freeways, and expressways with four or more lanes and posted speed limits of 55 mph (88 km/h) or higher.

CURRENT GUIDELINES

For high-speed, controlled-access roadways with relatively flat, traversable medians, AASHTO's guidelines indicate that the designer should evaluate the need for a barrier on all medians up to 30 ft (10 m) in width when the AADT is 20,000 vehicles per day or greater. A barrier is optional for all medians between 30 ft (10 m) and 50 ft (15 m) wide or when the median width is less than 30 ft and the AADT is less than 20,000. In 1998 the North Carolina Department of Transportation (NCDOT) implemented a more stringent policy of installing median barriers for all new construction, reconstruction, and resurfacing projects with a median width of 70 ft (21 m) or less on freeways. NCDOT also instituted a traffic improvement program to install cable median barriers on approximately 1,000 mi of freeways over the 2000–2006 time period (*7*). Whereas in the last two decades or so median barriers have been either metal-beam guardrails (including W- and thrie beams) or concrete barriers (e.g., Jersey and constant-slope types), NCDOT has recently been one of the first state DOTs to use cable barriers (*10*).

In 1998 the California Department of Transportation (Caltrans) also adopted more stringent guidelines based on the AADT for freeways with medians less than 75 ft (23 m) wide (*6,* Chapter 7: Traffic Safety Systems). Concrete barriers are recommended for medians less than 20 ft (6.1 m) wide, concrete and thrie beam barriers can both be used for medians between 20 and 36 ft (6.1 m and 11 m) wide, and thrie beam barriers are recommended for medians 36 to 75 ft (11 m to 23 m) wide. A crash history warrant was also developed justifying further analysis to determine the advisability of a barrier when a site exceeds 0.5 cross-median crashes of any severity level per mile per year or 0.12 fatal cross-median crashes per mile per year. For new construction, median barriers are required whenever it is anticipated that they will be justified within 5 years after construction.

Glad et al. (*9*) report a B/C analysis conducted by the Washington State Department of Transportation (WSDOT) for cable, metal guardrail, and concrete barriers in which it was concluded that barriers placed in median sections up to 50 ft (15 m) wide are cost-effective for high-speed (posted speed limits >45 mph, or 72 km/h), high-volume, multilane, access-controlled, divided state highways. An in-service study was recently conducted on cable median barriers installed in the mid-1990s to analyze their initial installation cost, maintenance cost and experience, and crash history (*11*). It was noted that whereas the overall number of crashes increased noticeably, the number of severe crashes (with fatalities and disabling injuries) de-creased significantly. In addition, it was concluded that installation of the cable barriers had benefited society about $420,000 per mile annually.

The Florida Department of Transportation (FDOT) requires installation of median barriers on Interstates if the median width is less than 64 ft (20 m). Installation of median barriers is required on freeways with a design speed of 60 mph (96 km/h) or more and a median width of less than 60 ft (18 m) and on freeways with a design speed of less than 60 mph and a median width of less than 40 ft (12 m) (*12*). The FDOT guidelines also state that "a median barrier shall be provided . . . where reconstruction reduces the median width to less than the standard for the facility. No variations or exceptions to this criterion will be approved." Further, a cross-median crash history evaluation is required for any Interstate or expressway project. The evaluation has to be conducted in the area of interchanges 1 mi before the exit-ramp gore and 1 mi beyond the entrance-ramp gore. If there are three or more cross-median crashes in the most recent 5-year period within that segment, a median barrier must be provided and no B/C analysis is required. Depending on the length of the weaving section, this warrant is for about 0.35 to 0.4 cross-median crashes per mile per year, which is more stringent than the Caltrans crash-history warrant of 0.5 crashes per mile per year. For those segments that have fewer than three cross-median crashes, a B/C analysis must be conducted to determine the need for a barrier. In addition, for the remaining area of the project (outside of the gore area indicated), both a cross-median crash history and a B/C analysis need to be performed to justify the need.

ROAD INVENTORY AND CRASH DATA

The primary data sources utilized in this study include electronic traffic crash records and hard copies of police reports from the Texas Department of Public Safety (TxDPS) and the TxDOT general road inventory and Texas Reference Marker database. As indicated earlier, the highways of interest are those classified as Interstates, freeways, and expressways with four or more lanes and posted speed limits of 55 mph (88 km/h) or higher.

Cross-median crashes are not explicitly indicated as such in TxDPS electronic records. However, the records contain key variables, including position of vehicles before and after impact and manner of collision, that allow potential cross-median crashes to be identified and then further verified with hard copy police reports. A rather inclusive set of screening criteria was adopted to identify potential cross-median crashes with the intent of minimizing the chance of missing any. From a 3-year (1997–1999) initial list of potential cross-median crashes identified from the electronic crash records, the study was narrowed down to 52 counties (of a total of 254 counties in Texas) for which hard copy police reports were requested and further modeling and analysis were done. These 52 counties covered about 90% of the potential cross-median crashes listed. In the end, hard copy police reports for 2 years (1998 and 1999) were obtained and manually reviewed to identify true cross-median crashes and get a sense of the nature of other median-related crashes and data quality. The police reports included all 791 identified potential cross-median crashes and a sample of over 1,000 median-related (nonpotential cross-median) crashes.

Of the 791 potential cross-median crashes reviewed, 443 cases were determined to be true cross-median crashes. In 136 of the 791 cases, parts of the vehicles, such as tires, hoods, and trailers, crossed the median and hit vehicles in the opposite lanes but the vehicle itself did not cross. The remaining 212 cases were not cross-median crashes, including some in which the involved vehicles drove on the wrong side of the highway and those in which vehicles made an illegal U-turn by driving across the grass median or using the median turnaround that is restricted to emergency and service vehicles. Inspection of the sampled median-related crashes generally indicated good data quality on key relevant variables.

Figure 1 shows the anatomy of median-related crashes with and without the presence of longitudinal median barriers. This diagram helps to conceptualize the kind of median-related crashes that need to be considered under the with–without study design. The types of median-related crashes can be broadly categorized as follows:

- Without median barriers: cross-median crashes, vehicle-part cross-median crashes, and other median-related (non-cross-median) crashes.
- With median barriers: barrier-breaching crashes, vehicle-part cross-median crashes, hit-median-barrier crashes, and other median-related crashes that did not hit median barriers.

Since median barriers are not intended to block vehicle parts from crossing the median, in the analysis performed under this study, those crashes were categorized as non-cross-median crashes.

Tables 1 through 3 provide a summary of the sample road sections and associated traffic crashes for 2 years (1998 and 1999) from the 52 Texas counties. It should be noted that a road section in two different years is treated as two separate sections. Table 1 presents the number of road sections with and without longitudinal barriers and their associated centerline miles, lane miles, and crash rates. Also, as noted in Table 1, only road sections with an AADT less than 150,001 vehicles per day, median width (including shoulder) between 15 and 150 ft, and number of lanes ≥4 are considered. As expected, road sections with longitudinal barriers have a higher overall median-related crash rate than those with no barriers: 0.108 crashes per million vehicle miles traveled (MVMT) versus 0.087 crashes (0.009 cross-median crashes plus 0.078 other median-related crashes) per MVMT. The overall cross-median crash rate of 0.009 per MVMT for sections with no barriers is higher than those reported for Pennsylvania (*8*), which were 0.004 and 0.007 crashes per MVMT, respectively, for Interstates and freeways in the 1994–1998 time period. It is also higher than the 0.007 crashes per MVMT reported in an earlier California study for freeways in the 1984–1988 time period (*13*). The Texas rate is considerably lower than the 0.021 crashes per MVMT reported for Washington State for sites at which median barriers were installed (*11*). Since these sites in Washington State were selected for installing median barriers, they can be expected to have higher cross-median crash histories and relatively narrower median widths than other sites that were not selected for barriers.

Table 2 shows the number and distribution of crashes by injury severity. By comparison, considerably higher proportions of cross-median crashes involved fatal (Type K) and incapacitating-injury (Type A) injury categories than did other types of median-related crashes:

- Cross-median crashes (no barrier): 21.1% Type K + 21.1% Type A = 42.2%.
- Other median-related crashes (no barrier): 2.3% Type K + 8.9% Type A = 11.2%.
- Median-related crashes (with barrier): 1.0% Type K + 5.2% Type A = 6.2%.

No barrier-breaching crashes were found among the 791 potential cross-median and 1,000 other median-related crashes reviewed. This lack is probably because concrete barriers are the predominant type of median barrier used in Texas. For want of better data, the economic analysis to be presented later in this paper assumes a 3% breaching rate (barrier-breaching crashes divided by reported barrier hits) for cable barriers as reported in the North Carolina study (*7*). For the Jersey concrete barrier, Martin and Quincy (*14*) reported a breaching rate (barrier-breaching crashes divided by all hit-barrier crashes) of 0.3% for high-speed roadways (with a posted speed limit of 80 mph, or 130 km/h) with narrow medians (10 to 16 ft, or 3 to 5 m), which was incurred mainly by large trucks. This low breaching rate for concrete barriers was used by this study for the economic analysis.

Table 3 gives summary statistics of the sample road sections, including number of crashes per road section by crash and median type, total vehicle miles incurred, AADT, number of lanes, and posted speed limit. The distribution of cross-median crashes by several median width categories is also provided. On average, road sections with no median barrier have lower AADTs, wider medians, fewer lanes, and higher posted speed limits than do those sections with median barriers. The most typical road sections with no median barrier have four lanes and a posted speed limit of 65 mph, whereas a typical barrier-separated section has six lanes and 55 mph as the posted speed. Despite this difference, it should be noted from Table 3 that there is still considerable overlap in the range of key variables for the two groups of road sections, including their median width, AADT,

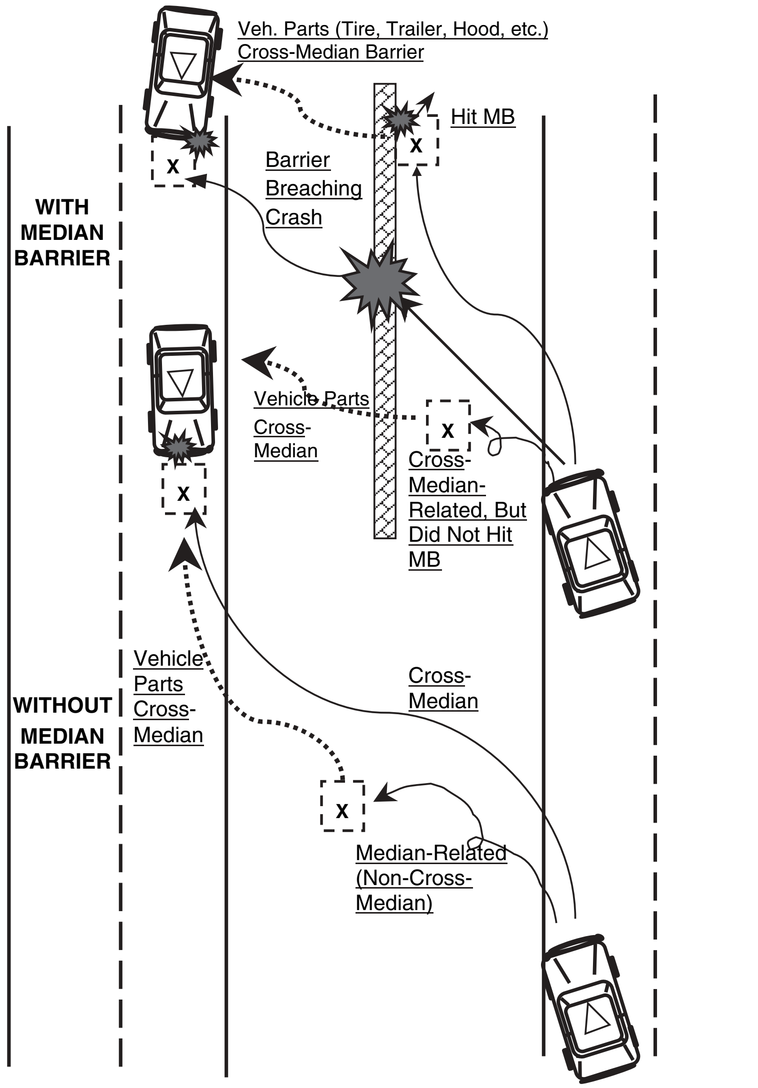


FIGURE 1 Anatomy of traffic crashes involving the median (not to scale) (MB = median barrier).

TABLE 1 Centerline Miles, Lane Miles, and Overall Crash Rates by Median Type and Crash Type, 1998–1999, for Interstates, Freeways, and Expressways in 52 Texas Counties

Median Type	Number of Road Section-Years*	Centerline Miles	Lane Miles	Vehicle Miles Traveled (millions)	Crash Type	Number of Crashes	Crash Rate (crashes/MVMT)
No longitudinal barrier	4,883	3,092	13,053	39,371	Cross-median crashes**	346	0.009
					Other median-related crashes (non-cross-medians)	3,064	0.078
With longitudinal barrier	2,386	1,161	6,707	34,088	Median-related crashes (including crashes that hit and did not hit barriers)	3,672	0.108
					Hit-median-barrier crashes***	2,714	0.080

Ranges of roadway data considered: AADT less than 150,001 vehicles per day; median width (including shoulder) between 15 and 150 ft; and number of lanes greater than or equal to 4.
*A road section in two different years is treated as two separate sections.
**Out of the 443 identified cross-median crashes, 97 of them were located at road sections either with AADT, median width, or number of lanes outside of the range of interest or with unknown median type or width.
***Hit-median-barrier crashes are a subset of the median-related crashes presented above. It is used to develop models for estimating the number of barrier hits per mile per year, which is used to estimate barrier repair costs.

TABLE 2 Number and Distribution of Crashes by Severity of Injury

Barrier and Crash Type	Total Number of Crashes	Severity Type: Fatal (K)	Incapacitating Injury (A)	Nonincapacitating Injury (B)	Possible Injury (C)	Property Damage Only (PDO)
No longitudinal barrier						
Cross-median crashes	346	73	73	82	58	60
	(100%)	(21.1%)	(21.1%)	(23.7%)	(16.8%)	(17.3%)
Other median-related crashes	3,064	71	272	639	734	1,348
	(100%)	(2.3%)	(8.9%)	(20.9%)	(23.9%)	(44.0%)
With longitudinal barrier						
All median-related crashes	3,672	36	190	681	1,098	1,667
(including hit-medians)	(100%)	(1.0%)	(5.2%)	(18.5%)	(29.9%)	(45.4%)
Hit-median-barrier crashes	2,714	13	128	490	835	1,248
	(100%)	(0.5%)	(4.7%)	(18.0%)	(30.8%)	(46.0%)

Same data set as in Table 1

TABLE 3 Summary Statistics of Sample Road Sections

	Sections with No Median Barrier (4,883 Section-Years)					Barrier-Separated Sections (2,386 Section-Years)				
	Mean	Standard Deviation	Min.	Max.	Distribution	Mean	Standard Deviation	Min.	Max.	Distribution
Number of crashes	—	—			—	—	—			—
No median barrier										
Cross-median			0	6				—	—	
Other median-related			0	19				—	—	
With median barrier			—	—				0	23	
All median-related			—	—				0	20	
Hit-barrier										
Exposure (in MVMT) (v = 365*AADT* segment length/ 1,000,000)	8.1	11.1	0.01	208.5	—	14.3	20.7	0.01	181.7	—
Year (1998 or 1999)	—	—	—	—	1998 = 49% 1999 = 51%	—	—	—	—	1998 = 40% 1999 = 60%
Median width (ft)	67.9	24.8	15.0	148.0		46.7	21.0	16.0	150.0	—
AADT (in 1,000s)	39.9	27.6	6.6	149.5		83.7	40.0	11.2	149.8	—
Number of lanes	—	—	—	—	**4 ln = 84.3%** 5 ln = 2.6% 6 ln = 10.1% 7 ln = 0.5% 8 ln = 1.5% 9 ln = 0.5% 10 ln = 0.3% >10 ln = 0.2 %	—	—	—	—	4 ln = 29.8% 5 ln = 3.4% **6 ln = 43.2%** 7 ln = 1.6% 8 ln = 20.1% 9 ln = 0.3% 10 ln = 1.6% > 10 ln = 0.1 %
Posted speed limit (mph)	—	—	—	—	55 mph = 31.8% 60 mph = 2.4% **65 mph = 40.9%** 70 mph = 24.9%	—	—	—	—	**55 mph = 54.0%** 60 mph = 13.5% 65 mph = 16.1% 70 mph = 16.4%
Cross-median crash frequency by median width (ft)					15–20 ft = 1 (0.3%) 21–30 ft = 11 (3.2%) 31–50 ft = 38 (11.0%) 51–74 ft = 234 (67.6%) ≥ 75 ft = 62 (17.9%) All width = 346 (100%)					

Same data set as in Tables 1 and 2

and posted speed limit. As for the cross-median crashes, the majority (234 crashes, or 67.6%) occurred on roads with a median width between 51 and 74 ft. In addition, 62 crashes (about 18%) occurred on roads with a median width of 75 ft or wider.

It should also be noted that

- The majority of the road sections have a rather flat median with side slopes of 6:1 (horizontal:vertical) or flatter and
- Only a small fraction of road sections (less than 2%) contain subsections with horizontal curves of 4 degrees (radius = 435 m) or higher.

Also, one limitation of the data for barrier-separated sections is that even though the median width is given, the exact placement (or offset) of the barrier from each side of the travel lane is not available from the database. This constraint kept the study from analyzing the data at the directional level.

Table 4 shows the estimates of crash costs for cross-median and other median-related crashes by median type (i.e., with and without median barriers). Data sources and examples of how estimates were derived are provided in the table's footnotes. By using the current system adopted by TxDOT in evaluating crash cost for safety-related projects, it is estimated that, on average, a cross-median fatal crash costs society about $1.5 million. This cost is about 24% higher than the value estimated for other median-related fatal crashes (with no barrier), which is about $1.16 million.

MODEL DEVELOPMENT

Four crash frequency models were developed:

- Cross-median crashes on sections with no barrier,
- Other median-related crashes on sections with no barrier,
- All median-related crashes on sections with a barrier, and
- Hit-median-barrier-only crashes on sections with a barrier.

Statistical relationships between traffic crashes and traffic flow and other geometric variables for road sections have been extensively modeled and evaluated in recent years. The Poisson-gamma model with the following functional and probabilistic structures is particularly favored (*15, 16*): the number of crashes at the ith section, Y_i, when conditional on its mean μ_i, is assumed to be Poisson distributed and independent over all sections:

$$Y_i|\mu_i \overset{\text{ind}}{\sim} \text{Po}(\mu_i) \tag{1}$$

where $i = 1, 2, \ldots, n$ and Po stands for Poisson.

The mean of the Poisson is structured as

$$\mu_i = v_i\tilde{\lambda}_i \exp(e_i) = v_i \exp\left(\beta_0 + \sum_{j=1}^{J} \beta_j x_{ij} + e_i\right) \tag{2}$$

where v_i is an offset term indicating total vehicle miles of travel incurred on section i, which basically quantifies the amount of vehicle exposure (or opportunity) for crash risk at the section, and other covariates as shown in Table 3 are indicated by vector x_{ij} for the jth covariate; β_0 is an unknown "fixed effect" intercept term; β_j's are unknown fixed-effect parameters; and e_i is an unstructured random effect independent of all covariates, which has a typical assumption that $\exp(e_i)$ is independent and gamma distributed with mean equal to 1 and variance $1/\Psi$ for all i (with $\Psi > 0$). This particular formulation provides flexible and attractive statistical properties. For example, conditional on μ_i and Ψ, Y_i can be shown to be distributed as a negative binomial random variable with mean and variance of $v_i\tilde{\lambda}_i$ and $v_i\tilde{\lambda}_i(1 + v_i\tilde{\lambda}_i/\Psi)$, respectively. Also, $\exp(e_i)$ can be viewed as unmodeled heterogeneities because of omitted exogenous variables and intrinsic randomness. The parameter Ψ is called the inverse dispersion parameter in that the Poisson model can be regarded as a limiting model of the negative binomial as Ψ approaches infinity. Key assumptions of this model, Bayesian interpretation of fixed and random effects, and specification of noninformative priors may be found elsewhere (*15–17*).

TABLE 4 Estimates of Crash Costs for Cross-Median and Other Median-Related Crashes by Median Type

		Number of Persons or Vehicles Involved with the Maximum Severity Incurred per Crash, 1998–99**				Adjusted Crash Costs (Year 2000 $)***		
			No Median Barrier		With Median Barrier	No Median Barrier		With Median Barrier
Crash Severity Type	Estimated Crash Cost for All State Highways (Yr 2000)*	All State Highways	Cross-Median Crashes	Other Median-Related Crashes	All Median-Related Crashes	Cross-Median Crashes	Other Median-Related Crashes	All Median-Related Crashes
Fatal (K)	1,191,887	1.15	1.43	1.12	1.17	1,482,086	1,160,794	1,212,615
Incapacitating (A)	69,199	1.31	1.57	1.32	1.21	82,933	69,727	63,917
Nonincapacitating (B)	25,218	1.39	1.79	1.26	1.21	32,475	22,859	21,952
Possible injury (C)	14,198	1.57	1.88	1.36	1.36	17,001	12,299	12,299
Property damage only (PDO)	1,969	1.78	2.18	1.10	1.13	2,411	1,217	1,250

*The cost was estimated by TxDOT Traffic Operations Division, based on the National Safety Council's estimate of societal cost (not the comprehensive cost), for crashes occurring on all state-maintained highways. The estimated crash costs will roughly triple if comprehensive costs are used.
**Obtained from Texas electronic traffic crash records. For example, on average, for fatal crashes, 1.15 persons were killed per crash in all state system fatal crashes; 1.43 persons were killed in a fatal cross-median crash. For PDO crashes, 1.78 vehicles were involved in each PDO crash for all state highways; while 1.1 vehicles were involved on average in a PDO median-related (non-cross-median) crash with no longitudinal barrier present.
***These adjusted costs were developed by the authors of this study. For example, the adjusted cost for a cross-median fatal crash is calculated as $1,191,887*(1.43/1.15) = $1,482,086 and as $69,199*(1.57/1.31) = $82,933 for cross-median incapacitating crashes.

In this study, a full Bayes approach was taken for model specification and estimation. The advantage of full Bayes treatment is that it takes into account the uncertainty associated with the estimates of the model parameters and can provide exact measures of uncertainty. The maximum likelihood and empirical Bayes methods, however, tend to overestimate precision because they typically ignore this uncertainty. Other potential advantages of taking the full Bayes approach include providing a direct and natural link between prediction and decision making and having an attractive hierarchical framework for complicated problem formulation. For all the models presented in this paper, the parameters and inferences were obtained using programs coded in the WinBUGS language (*18*), which provides the capability to model a variety of the so-called hierarchical models (*19*).

The results for the frequency models are presented in Table 5, which shows the posterior mean and standard error of the estimated parameters and some goodness-of-fit statistics (*15*). To illustrate what these models are estimating, Figure 2 shows the estimated number of cross-median crashes per mile per year on sections without a median barrier, including the 2.5th percentile, mean, and 97.5th percentile estimates. These estimates were developed for four-lane sections with a posted speed limit of 65 mph (104 km/h), which as indicated earlier was the most common lane-speed combination in the sample sections with no median barrier.

With an ordered multinomial logit model framework (the proportional-odds version), crash severity models were also developed for each of the four barrier-crash type combinations given earlier. All five crash severity types were considered in the model—K and A, as defined earlier; B, nonincapacitating injury; C, possible injury; and O, property damage only (see Table 2). Detailed statistical description of the models can be found elsewhere (*20,* Section 4.12). More-complicated nonparallel versions of the model framework were also tested but were not found to be warranted on the basis of some goodness-of-fit test criteria. Final modeling results are presented in Table 6. The models were formulated to ensure that larger and positive values of the β regression parameter and covariates led to an increased chance of belonging to the higher severity levels (*20*). To illustrate these estimated models, Figure 3 shows mean estimates of probabilities by AADT and median width for a median-related crash to result in a Type K, A, or B crash. It should be noted that none of the explanatory variables were found to be statistically significant in the severity model for cross-median crashes (most likely because of the small sample size), and the raw severity distribution as shown in Table 2 was adopted in the economic analysis.

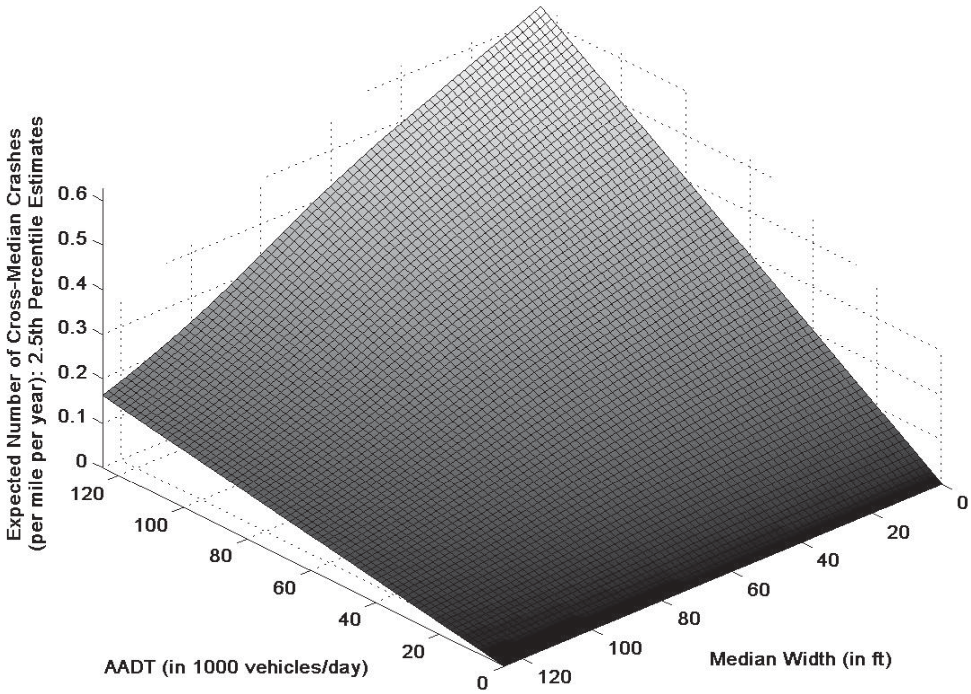
B/C AND SENSITIVITY ANALYSES

A B/C analysis is a systematic evaluation of the relevant benefits and costs of a set of investment alternatives. It addresses the relative benefit and cost of an incremental change, which is adding a median barrier to the existing or planned highways in this study. The B/C ratio

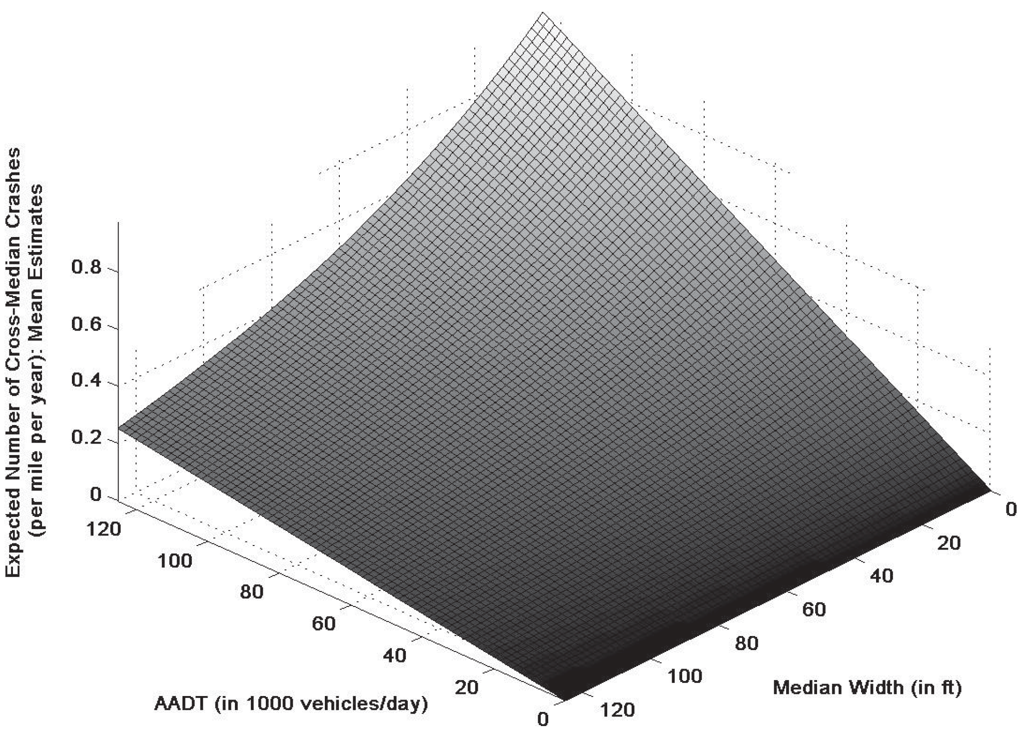
TABLE 5 Posterior Mean and Standard Error of Estimated Parameters of Crash Frequency Models and Some Goodness-of-Fit Statistics

	Crash Frequency Model			
	No Barrier		With Barrier	
Covariate (Coefficient)	Cross-Median Crashes	Other Median-Related Crashes	All Median-Related Crashes	Hit-Median-Barrier Crashes
Offset = exposure (in MVMT) = v_i (=365*AADT*Segment Length/1,000,000)	—*	—	—	—
Intercept term				
Overall intercept (β_0)	−3.779 (±0.48)	−2.239 (±0.07)	−1.771 (±0.07)	−1.740 (±0.09)
Dummy variable for 1999: 1 if 1999 and 0 if 1998 (β_1)	1.163 (±0.14)	−0.068 (±0.05)	−0.031 (±0.05)	−0.018 (±0.06)
Median width (in ft) (β_2)	−0.011 (±0.003)	−0.002 (±0.001)	−0.006 (±0.001)	−0.013 (±0.002)
Log(AADT) (β_3) (AADT in 1,000s)	—	—	—	—
Number of lanes (= β_4)	−0.293 (±0.09)	—	—	—
Posted speed limit (mph)				
Dummy variable for 60 mph (=1 if 60 mph; =0 otherwise) (β_5)	−0.139 (±0.54)	−0.342 (±0.17)	−0.575 (±0.08)	−0.663 (±0.10)
Dummy variable for 65 mph (=1 if 65 mph; =0 otherwise) (β_6)	0.500 (±0.16)	−0.126 (±0.06)	−0.075 (±0.07)	−0.188 (±0.09)
Dummy variable for 70 mph (=1 if 70 mph; =0 otherwise) (β_7)	0.284 (±0.18)	−0.079 (±0.07)	−0.007 (±0.07)	0.004 (±0.09)
Inverse dispersion parameter				
Inverse dispersion parameter for this model (ψ)	0.727 (±0.17)	1.388 (±0.12)	1.956 (±0.16)	1.464 (±0.13)
Inverse dispersion parameter for worst possible model of crash frequency (ψ_0^{freq})	0.158 (±0.02)	0.429 (±0.02)	0.466 (±0.02)	0.367 (±0.02)
Goodness-of-fit measures				
Deviance information criterion/sample size (DIC/n)	0.39	1.71	2.54	2.14
$R^2_{\psi,freq} = 1 - (1/\psi)/(1/\psi_0^{freq})$	0.78	0.69	0.76	0.75

NOTE: All models were structured using the full Bayes framework with noninformative priors (or hyperpriors). Parameters (β and ψ) were estimated by using Markov chain Monte Carlo techniques. and the values shown in the table are their posterior means. Values in parentheses are the estimated 1 standard error of parameters to their left based on the posterior density of the parameter.
*—indicates not statistically significant at a 10% significance level.



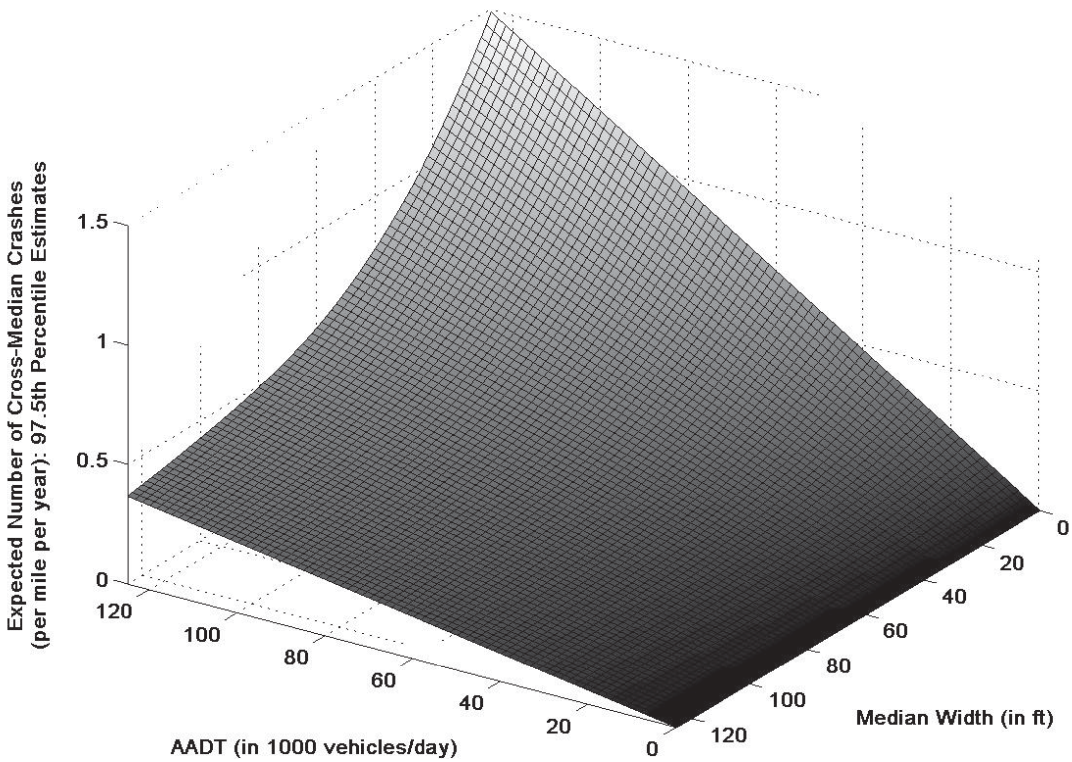
(a)



(b)

FIGURE 2 Estimated number of cross-median crashes on sections with no median barrier: (*a*) 2.5th percentile estimates, (*b*) mean estimates.

(continued)



(c)

FIGURE 2 *(continued)* **Estimated number of cross-median crashes on sections with no median barrier: (*c*) 97.5th percentile estimates [intended for four-lane highway section with posted speed limit of 65 mph (104 km/h)].**

is the ratio of the expected benefits accrued from crash or severity reduction, or both, to expected costs of implementing, operating, and maintaining the project. The relation of either present worth of benefits to costs or equivalent uniform annual benefits to costs can be used to determine the ratio (*21, 22*). The latter ratio was adopted in this study.

On the basis of the estimates from the frequency and severity models presented earlier and the crash costs in Table 4, B/C ratios for installing median barriers were computed for various AADT and median-width combinations for four-lane sections with a posted speed limit of 65 mph (104 km/h). Main assumptions employed in calculating the mean and low estimates of B/C ratios, including project life, interest rate, site preparation and grading cost, barrier installation cost, barrier repair cost, annual traffic growth rate, barrier-breaching crash rate, and salvage value of barriers at the end of project life, are presented in Table 7. Site preparation and grading costs were estimated in this study using limited field data for medians with mild slopes of 6:1 or flatter. Barrier installation costs, both high and low estimates, were taken from multiple sources, including recent winning-bid contracts in Texas, literature on the TxDOT website, manufacturers, and some of the reports and papers cited here.

Under these assumptions and valuations, the mean B/C ratios for installing concrete barriers are presented in Table 8 for AADT between 0 and 125,000 vehicles per day and median width between 0 and 125 ft (38 m). The mean B/C ratios range from 0 to about 16 and are greater than 1 when AADT is greater than about 10,000 vehicles per day (for a median width less than 60 ft, or 18 m). In general, the mean B/C ratio increases as AADT increases but decreases as the median width increases. Marginal changes in mean B/C ratios as the median width increases by 1 ft are diminishing as the median width increases (data not shown). Roughly, it was noted that for all AADT levels, this rate of decrease in B/C ratios drops to about half of the initial rate as the median width increases to about 70 ft (21 m).

Given the stochastic nature of traffic crashes, the uncertainty associated with the main assumptions above, and individual site differences (e.g., site preparation costs), a mean B/C ratio greater than 1 does not necessarily lead to a net benefit for a specific project. Thus, sensitivity analyses to gauge the variations of B/C ratios when some assumptions are off or when the mean prediction is not realized are important for guideline development. With limited resources, it also seems advisable to select a mean B/C ratio at a break point, where there is no great likelihood that any error in the assumptions or deviation from the predictions made in developing the guidelines will result in inefficient or even wasteful expenditures. Following this advice, the greater the uncertainties about the data, models, and assumptions, the higher the B/C ratios needed to select as break points to ensure that net benefits will be realized with high probability when the guidelines are implemented.

As part of the sensitivity analyses, Table 9 shows low estimates of B/C ratios, which are based on the 2.5th percentile estimates of cross-median crash frequency, a 1% annual traffic growth rate, and other assumptions presented earlier, in Table 7. Choosing a B/C ratio of 1 as a break point from Table 9 would (in the authors' judgment) ensure that even under an unexpected future condition, the benefit would most likely outweigh the cost if the guidelines are followed. This analysis helps to establish a median width–AADT combination zone (Zone 4 in Table 10), in which installing concrete median barriers may not be beneficial. It may be noted that this zone corresponds

TABLE 6 Posterior Mean and Standard Error of the Estimated Parameters of Crash Severity Models and Some Goodness-of-Fit Statistics: Final Modeling Results

	Crash Severity Model			
	No Barrier		With Barrier	
Covariate (Coefficient)	Cross-Median Crashes	Other Median-Related Crashes	All Median-Related Crashes	Hit-Median-Barrier Crashes
Cutpoints (to represent 5 levels of crash severities)	—*			
θ_1		0.139 (±0.11)	0.070 (±0.37)	0.608 (±0.34)
θ_2		1.138 (±0.11)	1.381 (±0.37)	1.979 (±0.34)
θ_3		2.464 (±0.12)	2.998 (±0.38)	3.697 (±0.35)
θ_4		4.144 (±0.16)	4.926 (±0.16)	6.169 (±0.45)
Dummy variable for 1999: 1 if 1999 and 0 if 1998 (β_1)	—	0.1085 (±0.07)	0.038 (±0.07)	0.016 (±0.07)
Median width (in ft) (β_2)	—	0.0032 (±0.001)	−0.0032 (±0.002)	−0.0031 (±0.002)
Log(AADT) (β_3) (AADT in 1,000s)	—	—	0.1626 (±0.08)	0.293 (±0.08)
Number of lanes (= β_4)	—	—	−0.060 (±0.026)	−0.066 (±0.03)
Posted speed limit (mph)				
Dummy variable for 60 mph (=1 if 60 mph; =0 otherwise) (β_5)	—	0.377 (±0.22)	0.298 (±0.10)	0.257 (±0.12)
Dummy variable for 65 mph (=1 if 65 mph; =0 otherwise) (β_6)	—	0.159 (±0.08)	−0.243 (±0.10)	−0.423 (±0.12)
Dummy variable for 70 mph (=1 if 70 mph; =0 otherwise) (β_7)	—	0.183 (±0.09)	−0.025 (±0.09)	0.007 (±0.09)
Goodness-of-fit measures				
Deviance information criterion/sample size (DIC/n)	—	8,180/3,064	8,773/3,672	6,504/3,672
Worst possible DIC value/n		9,834/3,064	11,438/3,672	10,118/3,672

NOTE: All models were structured using the full Bayes framework with noninformative priors (or hyperpriors). Parameters (β and ψ) were estimated by using Markov chain Monte Carlo techniques. and the values shown in the table are their posterior means. Values in parentheses are the estimated 1 standard error of parameters to their left based on the posterior density of the parameter.
*—indicates not statistically significant at a 10% significance level.

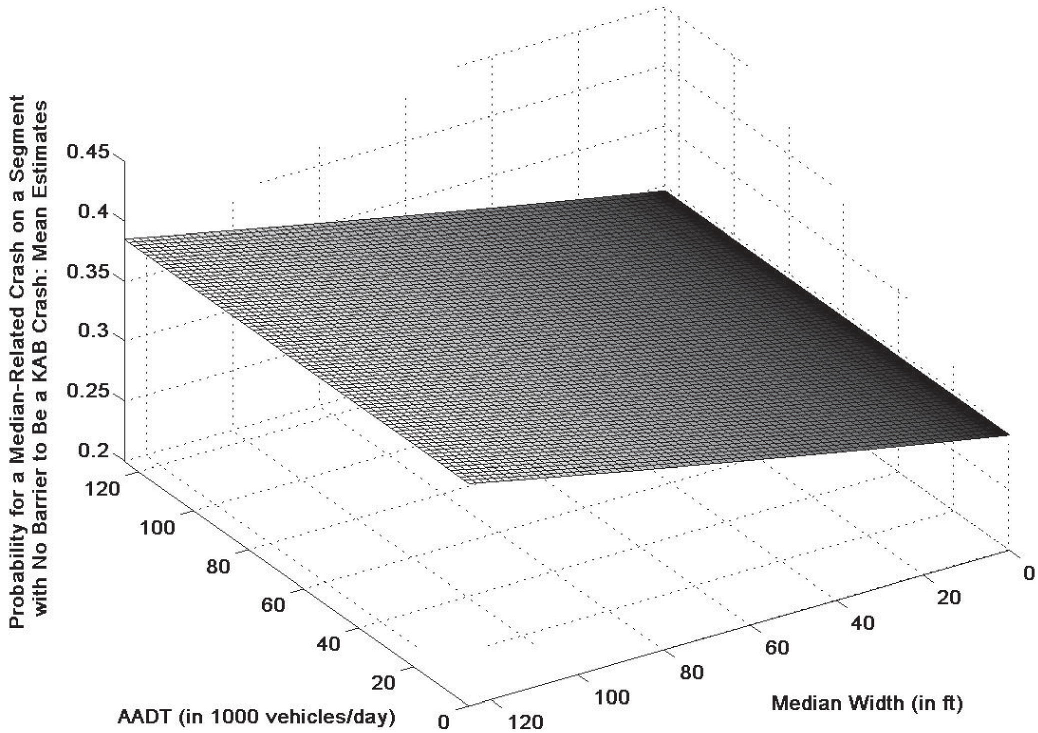
quite well to a zone selected from the mean B/C ratios (in Table 10) using 2.0 as the break point.

From the analyses presented earlier and the developed cross-median crash frequency model (and other sensitivity analyses not presented here), one possible and rather simple option developed for installing concrete median barriers is presented in Table 10. It is noted that many other alternative guidelines are possible. Under this option, the table of mean B/C ratios is divided into four priority zones: mean B/C ratio greater than 10, between 6 and 10, between 2 and 6, and below 2. Road sections in Zone 1, which have mean B/C ratios greater than 10, should be given the highest priority in consideration of the installation of concrete median barriers; Zone 2 should be given the second-highest priority; and so on.

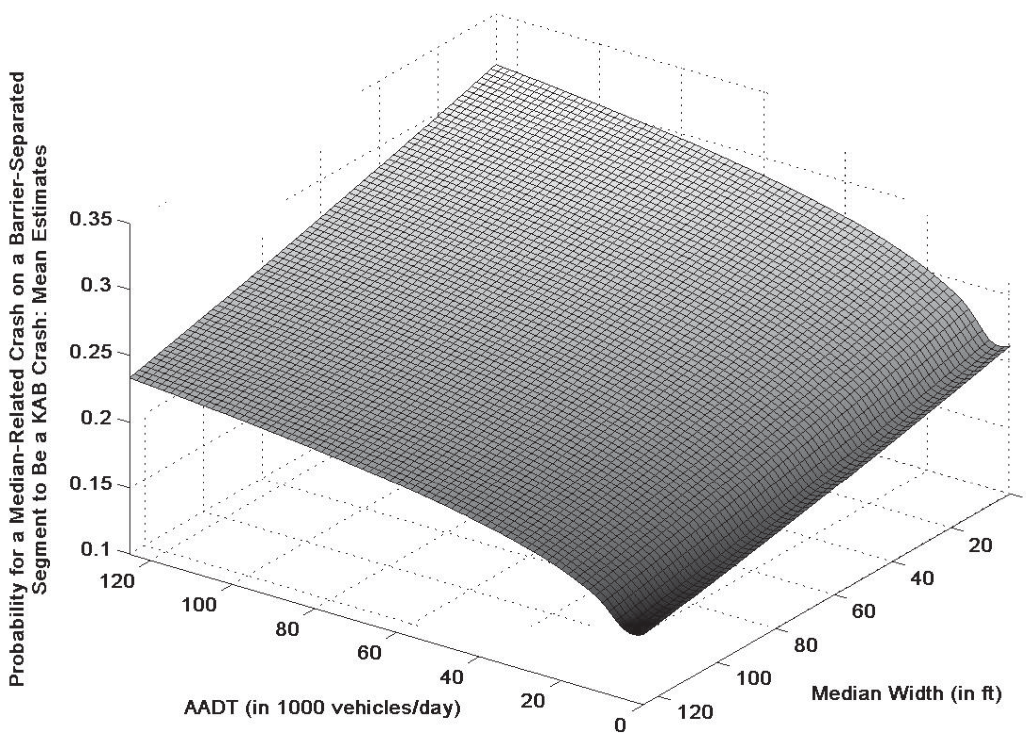
On the basis of the developed cross-median crash frequency model, the mean expected number of cross-median crashes for all the cells that fall in each priority zone is also provided in Table 10: 0.7, 0.4, and 0.2 cross-median crashes per mile per year for Zones 1, 2, and 3, respectively. These values could potentially be used in cross-median crash history guidelines. For example, for any existing road section, if its cross-median crashes exceed 0.7, 0.4, and 0.2 crashes per mile per year in a 5-year time period, it could be reprioritized to Zone 1, 2, or 3, respectively, if it does not already belong to that zone on the basis of AADT and median width.

As indicated earlier, TxDOT has recently begun to install and evaluate high-tension-cable median barriers. So far, only a handful of other states have tried the system, including Oklahoma, Iowa, Colorado, and Utah. Some articles and reports have presented the potential advantages of this system relative to concrete barriers and provide some promising (though limited) field examples (*23–25*). In-service performance evaluation data for this system are still rather limited, especially on barrier-breaching rates and injury severity distributions, when compared with those for concrete and other median barriers. Several issues regarding this type of cable barrier that need more research include placement of the barrier on mild side slopes and sharp horizontal curves, truck volume at which the system should not be installed, and need for a concrete (or other type of) mow strip. All these issues can potentially have significant safety and cost implications and can change the B/C analysis as more data and research results become available.

Taking these limitations into consideration, Table 11 presents the mean B/C ratios between the high-tension-cable barrier and the concrete barrier. As noted, on the basis of deflection characteristics upon impact, cable barriers are generally not recommended for use when the median width is less than 25 ft (8 m). In Table 11, a ratio of 1 indicates that concrete and high-tension-cable barriers have the same mean B/C ratio. Higher ratios suggest increased the favorability of installing the high-tension-cable barrier over the concrete barrier, in terms of their mean B/C ratios. Thus, this ratio is called the favorability ratio of installing a high-tension-cable barrier over a concrete barrier. As shown in Table 11, this favorability ratio ranges from 1 to about 4 from the upper right corner to the lower left corner, indicating that (*a*) when the deflection distance is available, the



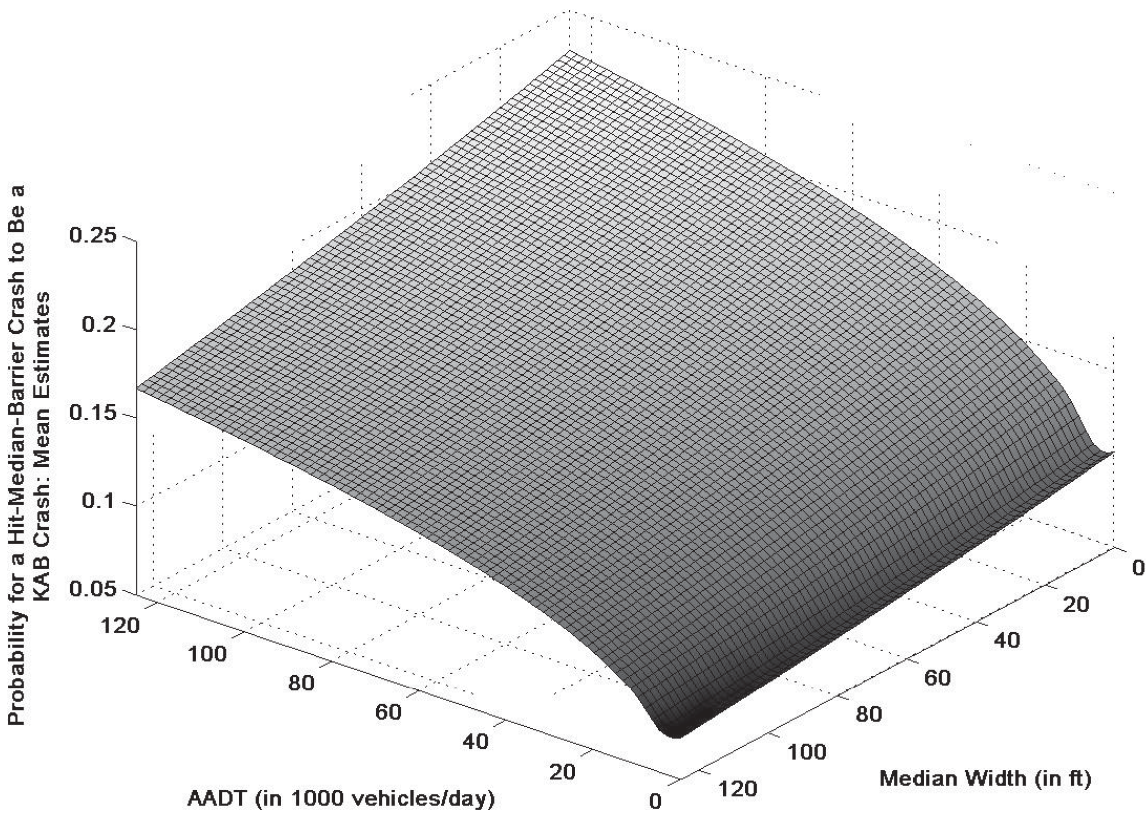
(a)



(b)

FIGURE 3 Mean estimated probability for median-related crash to be KAB crash: (*a*) median-related crashes (non-cross-median), sections with no barrier; (*b*) all median-related crashes, sections with barriers.

(continued)



(c)

FIGURE 3 *(continued)* Mean estimated probability for median-related crash to be KAB crash:*(c)* hit-median-barrier crashes, sections with barriers [intended for four-lane highway section with posted speed limit of 65 mph (104 km/h)].

TABLE 7 Main Assumptions Employed in Sensitivity Analysis of B/C Ratios

	Mean B/C Estimate		Low B/C Estimate	
	Concrete Barrier	Cable Barrier (High-Tension)	Concrete Barrier	Cable Barrier (High-Tension)
Project life (yrs)—do not consider future widening plan	20	20	20	20
Interest rate (%)	5	5	5	5
AADT annual growth rate (%)	3	3	1	1
Estimate of cross-median Crash frequency	Mean	Mean	2.5th percentile	2.5th percentile
Installation cost per mile* ($1,000)	(190+370)/2	(65+100)/2	370	100
Site preparation and grading cost* ($1,000)	(Median width in ft-20)*100/80	0	(Median width in ft-20)*100/80	0
Barrier breaching crash rate as a percent of estimated barrier-hits** or crashes	0.3% (of estimated number of reported crashes)	3% (of estimated number of barrier-hits)**	0.3% (of estimated number of reported crashes)	3% (of estimated number of barrier-hits)
Repair cost per hit** ($1,000)	0	(0.35+0.70)/2	0	0.70
Salvage value at end of project life ($1,000)	0	0	0	0

*It is assumed that barriers are placed near the center of the median. Installation costs include material, labor, and equipment costs. The site preparation cost for concrete barriers is assumed to be a linear function of median width (excluding existing shoulder width of 20 ft), with an estimate of $100,000 at median width of 100 ft. This assumes a relatively mild slope of 6:1 or flatter without a lot of earthwork to flatten the slope to a 10:1. These costs do not include user costs due, e.g., to travel delay, and traffic control and engineering costs during constructions.

**To estimate the number of hits on cable barriers that require repair, the estimated number of hit-barrier crashes from the model is multiplied by a factor of 2 to account for unreported crashes and crashes that do not meet the reporting and coding threshold. Since July 1, 1995, TxDPS stopped coding those PDO crashes for which vehicles did not have to be towed away.

TABLE 8 B/C Ratios for Installing Concrete Barriers: Mean Estimates

Median	AADT (in 1,000s)																									
Width (ft)	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125
0	0	0.8	1.6	2.3	3.0	3.7	4.4	5.0	5.7	6.3	7.0	7.6	8.2	8.8	9.5	10.1	10.7	11.3	12.0	12.6	13.2	13.9	14.5	15.2	15.8	16.5
5	0	0.8	1.5	2.2	2.9	3.6	4.2	4.9	5.5	6.1	6.7	7.3	8.0	8.6	9.1	9.7	10.3	11.0	11.6	12.2	12.8	13.4	14.1	14.7	15.3	16.0
10	0	0.8	1.5	2.1	2.8	3.4	4.1	4.7	5.3	5.9	6.5	7.1	7.7	8.3	8.9	9.4	10.0	10.6	11.2	11.8	12.4	13.0	13.6	14.2	14.8	15.4
15	0	0.7	1.4	2.1	2.7	3.3	4.0	4.6	5.2	5.7	6.3	6.9	7.5	8.0	8.6	9.2	9.7	10.3	10.9	11.4	12.0	12.6	13.2	13.8	14.4	15.0
20	0	0.7	1.4	2.0	2.6	3.2	3.8	4.4	5.0	5.6	6.2	6.7	7.3	7.8	8.4	8.9	9.5	10.0	10.6	11.1	11.7	12.3	12.8	13.4	14.0	14.6
25	0	0.7	1.3	1.9	2.5	3.1	3.7	4.2	4.8	5.3	5.8	6.4	6.9	7.4	8.0	8.5	9.0	9.5	10.1	10.6	11.2	11.7	12.2	12.8	13.3	13.9
30	0	0.6	1.2	1.8	2.4	2.9	3.5	4.0	4.5	5.1	5.6	6.1	6.6	7.1	7.6	8.1	8.6	9.1	9.6	10.1	10.6	11.1	11.6	12.2	12.7	13.2
35	0	0.6	1.2	1.7	2.3	2.8	3.3	3.8	4.3	4.8	5.3	5.8	6.3	6.8	7.2	7.7	8.2	8.7	9.2	9.7	10.1	10.6	11.1	11.6	12.1	12.6
40	0	0.6	1.1	1.7	2.2	2.7	3.2	3.7	4.2	4.6	5.1	5.6	6.0	6.5	6.9	7.4	7.9	8.3	8.8	9.3	9.7	10.2	10.7	11.2	11.6	12.1
45	0	0.6	1.1	1.6	2.1	2.6	3.0	3.5	4.0	4.4	4.9	5.3	5.8	6.2	6.6	7.1	7.5	8.0	8.4	8.9	9.3	9.8	10.2	10.7	11.2	11.6
50	0	0.5	1.0	1.5	2.0	2.5	2.9	3.4	3.8	4.3	4.7	5.1	5.5	6.0	6.4	6.8	7.2	7.7	8.1	8.5	9.0	9.4	9.9	10.3	10.7	11.2
55	0	0.5	1.0	1.5	1.9	2.4	2.8	3.2	3.7	4.1	4.5	4.9	5.3	5.7	6.2	6.6	7.0	7.4	7.8	8.2	8.6	9.1	9.5	9.9	10.4	10.8
60	0	0.5	1.0	1.4	1.8	2.3	2.7	3.1	3.5	3.9	4.3	4.7	5.1	5.5	5.9	6.3	6.7	7.1	7.5	7.9	8.3	8.7	9.1	9.5	9.9	10.4
65	0	0.5	0.9	1.4	1.8	2.2	2.6	3.0	3.4	3.8	4.2	4.6	5.0	5.3	5.7	6.1	6.5	6.9	7.3	7.6	8.0	8.4	8.8	9.2	9.6	10.0
70	0	0.5	0.9	1.3	1.7	2.1	2.5	2.9	3.3	3.7	4.1	4.4	4.8	5.2	5.5	5.9	6.3	6.6	7.0	7.4	7.8	8.2	8.5	8.9	9.3	9.7
75	0	0.4	0.9	1.3	1.7	2.1	2.4	2.8	3.2	3.6	3.9	4.3	4.6	5.0	5.4	5.7	6.1	6.4	6.8	7.2	7.5	7.9	8.3	8.6	9.0	9.4
80	0	0.4	0.8	1.2	1.6	2.0	2.4	2.7	3.1	3.4	3.8	4.2	4.5	4.8	5.2	5.5	5.9	6.2	6.6	7.0	7.3	7.7	8.0	8.4	8.8	9.1
85	0	0.4	0.8	1.2	1.6	1.9	2.3	2.6	3.0	3.3	3.7	4.0	4.4	4.7	5.1	5.4	5.7	6.1	6.4	6.8	7.1	7.5	7.8	8.2	8.5	8.9
90	0	0.4	0.8	1.2	1.5	1.9	2.2	2.6	2.9	3.3	3.6	3.9	4.3	4.6	4.9	5.2	5.6	5.9	6.2	6.6	6.9	7.3	7.6	7.9	8.3	8.6
95	0	0.4	0.8	1.1	1.5	1.8	2.2	2.5	2.8	3.2	3.5	3.8	4.1	4.5	4.8	5.1	5.4	5.7	6.1	6.4	6.7	7.1	7.4	7.7	8.1	8.4
100	0	0.4	0.7	1.1	1.4	1.8	2.1	2.4	2.8	3.1	3.4	3.7	4.0	4.3	4.7	5.0	5.3	5.6	5.9	6.2	6.6	6.9	7.2	7.5	7.9	8.2
105	0	0.4	0.7	1.1	1.4	1.7	2.0	2.4	2.7	3.0	3.3	3.6	3.9	4.2	4.5	4.9	5.2	5.5	5.8	6.1	6.4	6.7	7.0	7.4	7.7	8.0
110	0	0.4	0.7	1.0	1.4	1.7	2.0	2.3	2.6	2.9	3.2	3.5	3.8	4.2	4.4	4.7	5.1	5.4	5.7	6.0	6.3	6.6	6.9	7.2	7.5	7.8
115	0	0.4	0.7	1.0	1.3	1.6	2.0	2.3	2.6	2.9	3.2	3.5	3.8	4.1	4.3	4.6	4.9	5.2	5.5	5.8	6.1	6.4	6.7	7.0	7.4	7.7
120	0	0.3	0.7	1.0	1.3	1.6	1.9	2.2	2.5	2.8	3.1	3.4	3.7	4.0	4.3	4.5	4.8	5.1	5.4	5.7	6.0	6.3	6.6	6.9	7.2	7.5
125	0	0.3	0.7	1.0	1.3	1.6	1.9	2.2	2.5	2.7	3.0	3.3	3.6	3.9	4.2	4.5	4.7	5.0	5.3	5.6	5.9	6.2	6.5	6.8	7.1	7.4

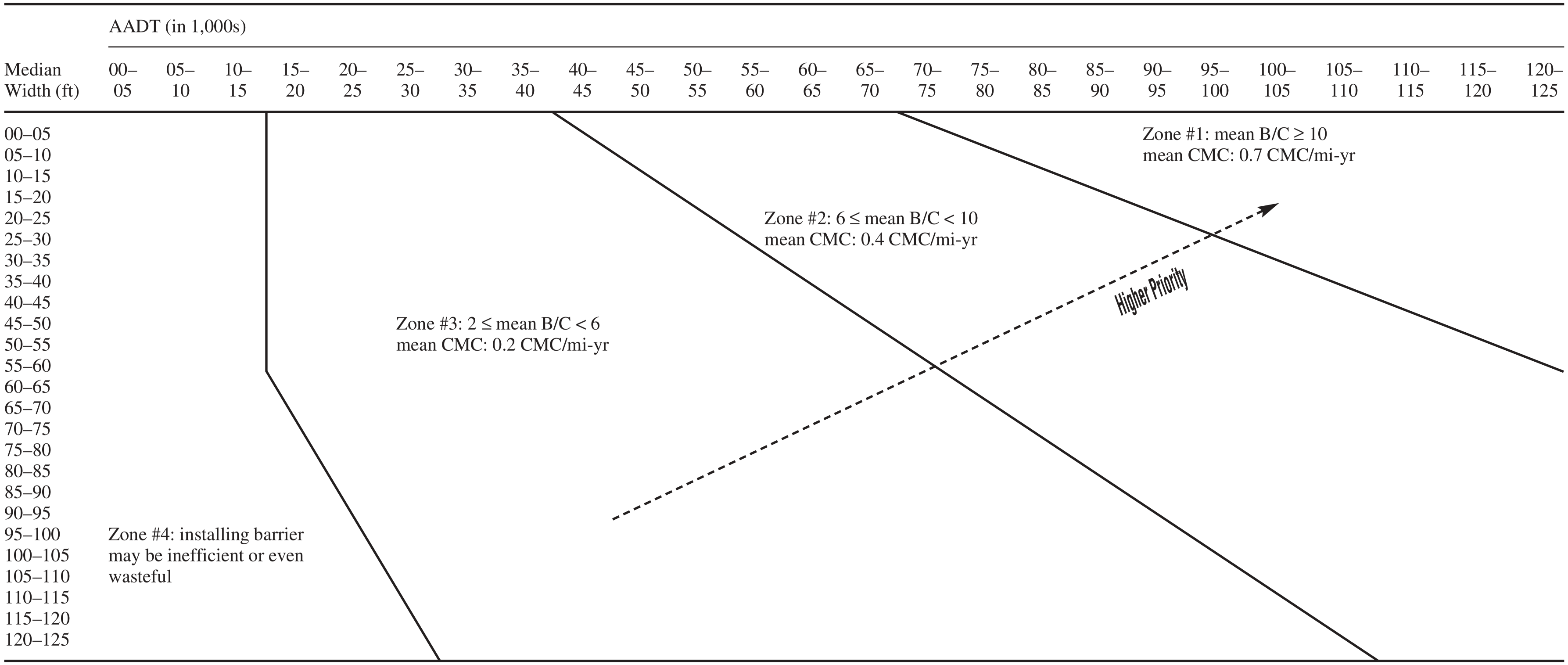
NOTE: Based on a 4-lane highway with a posted speed limit of 65 mph (104 km/hr) scenario

TABLE 9 B/C Ratios for Installing Concrete Barriers: Low Estimates

Median Width (ft)	AADT (in 1,000s) 0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125
0	0	0.3	0.6	0.9	1.1	1.4	1.6	1.9	2.1	2.3	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.4	4.6	4.8	5.0	5.2	5.4	5.6
5	0	0.3	0.6	0.9	1.2	1.4	1.7	1.9	2.1	2.4	2.6	2.8	3.0	3.3	3.5	3.7	3.9	4.1	4.3	4.5	4.7	4.9	5.1	5.3	5.5	5.7
10	0	0.3	0.6	0.9	1.2	1.4	1.7	1.9	2.2	2.4	2.6	2.9	3.1	3.3	3.5	3.7	4.0	4.2	4.4	4.6	4.8	5.0	5.2	5.4	5.6	5.9
15	0	0.3	0.6	0.9	1.2	1.4	1.7	1.9	2.2	2.4	2.7	2.9	3.1	3.4	3.6	3.8	4.0	4.2	4.4	4.7	4.9	5.1	5.3	5.5	5.7	6.0
20	0	0.3	0.6	0.9	1.2	1.5	1.7	2.0	2.2	2.5	2.7	2.9	3.2	3.4	3.6	3.9	4.1	4.3	4.5	4.7	5.0	5.2	5.4	5.6	5.8	6.1
25	0	0.3	0.6	0.9	1.2	1.4	1.7	1.9	2.2	2.4	2.7	2.9	3.1	3.4	3.6	3.8	4.1	4.3	4.5	4.7	4.9	5.2	5.4	5.6	5.8	6.1
30	0	0.3	0.6	0.9	1.2	1.4	1.7	1.9	2.2	2.4	2.6	2.9	3.1	3.3	3.6	3.8	4.0	4.2	4.5	4.7	4.9	5.1	5.3	5.5	5.8	6.0
35	0	0.3	0.6	0.9	1.1	1.4	1.7	1.9	2.1	2.4	2.6	2.9	3.1	3.3	3.5	3.8	4.0	4.2	4.4	4.7	4.9	5.1	5.3	5.5	5.8	6.0
40	0	0.3	0.6	0.9	1.1	1.4	1.6	1.9	2.1	2.4	2.6	2.8	3.1	3.3	3.5	3.7	4.0	4.2	4.4	4.6	4.8	5.0	5.3	5.5	5.7	5.9
45	0	0.3	0.6	0.8	1.1	1.4	1.6	1.8	2.1	2.3	2.6	2.8	3.0	3.2	3.5	3.7	3.9	4.1	4.3	4.6	4.8	5.0	5.2	5.4	5.7	5.9
50	0	0.3	0.6	0.8	1.1	1.3	1.6	1.8	2.0	2.3	2.5	2.7	3.0	3.2	3.4	3.6	3.8	4.1	4.3	4.5	4.7	4.9	5.1	5.4	5.6	5.8
55	0	0.3	0.6	0.8	1.1	1.3	1.5	1.8	2.0	2.2	2.5	2.7	2.9	3.1	3.3	3.6	3.8	4.0	4.2	4.4	4.6	4.8	5.0	5.3	5.5	5.7
60	0	0.3	0.5	0.8	1.0	1.3	1.5	1.7	2.0	2.2	2.4	2.6	2.8	3.1	3.3	3.5	3.7	3.9	4.1	4.3	4.5	4.7	4.9	5.1	5.4	5.6
65	0	0.3	0.5	0.8	1.0	1.2	1.5	1.7	1.9	2.1	2.3	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.4	4.6	4.8	5.0	5.2	5.5
70	0	0.3	0.5	0.7	1.0	1.2	1.4	1.6	1.9	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.5	3.7	3.9	4.1	4.3	4.5	4.7	4.9	5.1	5.3
75	0	0.3	0.5	0.7	0.9	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.4	4.6	4.8	5.0	5.2
80	0	0.2	0.5	0.7	0.9	1.1	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.5	3.7	3.9	4.0	4.2	4.4	4.6	4.8	5.0
85	0	0.2	0.5	0.7	0.9	1.1	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.6	2.8	3.0	3.2	3.4	3.6	3.7	3.9	4.1	4.3	4.5	4.7	4.9
90	0	0.2	0.4	0.6	0.9	1.1	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.7	2.9	3.1	3.3	3.5	3.6	3.8	4.0	4.2	4.3	4.5	4.7
95	0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	1.9	2.1	2.3	2.5	2.7	2.8	3.0	3.2	3.3	3.5	3.7	3.9	4.0	4.2	4.4	4.6
100	0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.5	1.7	1.9	2.1	2.2	2.4	2.6	2.7	2.9	3.1	3.2	3.4	3.6	3.7	3.9	4.1	4.3	4.4
105	0	0.2	0.4	0.6	0.8	1.0	1.1	1.3	1.5	1.7	1.8	2.0	2.2	2.3	2.5	2.7	2.8	3.0	3.2	3.3	3.5	3.6	3.8	4.0	4.2	4.3
110	0	0.2	0.4	0.6	0.8	0.9	1.1	1.3	1.5	1.6	1.8	2.0	2.1	2.3	2.4	2.6	2.8	2.9	3.1	3.2	3.4	3.6	3.7	3.9	4.1	4.2
115	0	0.2	0.4	0.6	0.7	0.9	1.1	1.2	1.4	1.6	1.7	1.9	2.1	2.2	2.4	2.5	2.7	2.9	3.0	3.2	3.3	3.5	3.6	3.8	4.0	4.1
120	0	0.2	0.4	0.5	0.7	0.9	1.1	1.2	1.4	1.5	1.7	1.9	2.0	2.2	2.3	2.5	2.6	2.8	3.0	3.1	3.3	3.4	3.6	3.7	3.9	4.0
125	0	0.2	0.4	0.5	0.7	0.9	1.0	1.2	1.4	1.5	1.7	1.8	2.0	2.1	2.3	2.4	2.6	2.7	2.9	3.0	3.2	3.3	3.5	3.6	3.8	4.0

NOTE: Based on a 4-lane highway with a posted speed limit of 65 mph (104 km/hr) scenario

TABLE 10 Potential Guideline for Installing Concrete Median Barriers Based on Priority-Zone Concept and Cross-Median Crash History (5-Year Period)



NOTE: Based on a 4-lane highway with a posted speed limit of 65 mph (104 km/h) scenario
CMC = cross-median crash

TABLE 11 Mean B/C Ratios for Installing High-Tension Cable Barriers over Mean Ratios for Concrete Barriers: Favorability Ratios

Median Width (ft)	AADT (in 1,000s) 5**	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125
25*	2.3	2.1	2.0	1.9	1.8	1.8	1.7	1.6	1.6	1.5	1.5	1.4	1.4	1.3	1.3	1.3	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.0	1.0
30	2.3	2.2	2.1	2.0	1.9	1.9	1.8	1.7	1.7	1.6	1.6	1.5	1.5	1.4	1.4	1.4	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.1	1.1
35	2.4	2.3	2.2	2.1	2.1	2.0	1.9	1.8	1.8	1.7	1.7	1.6	1.6	1.5	1.5	1.5	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.2	1.2
40	2.6	2.4	2.3	2.2	2.2	2.1	2.0	2.0	1.9	1.8	1.8	1.7	1.7	1.7	1.6	1.6	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.3	1.3
45	2.7	2.5	2.4	2.4	2.3	2.2	2.1	2.1	2.0	2.0	1.9	1.9	1.8	1.8	1.7	1.7	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.4	1.4
50	2.8	2.6	2.5	2.5	2.4	2.3	2.2	2.2	2.1	2.1	2.0	2.0	1.9	1.9	1.8	1.8	1.8	1.7	1.7	1.7	1.6	1.6	1.6	1.5	1.5
55	2.9	2.7	2.7	2.6	2.5	2.4	2.4	2.3	2.2	2.2	2.1	2.1	2.0	2.0	1.9	1.9	1.9	1.8	1.8	1.8	1.7	1.7	1.7	1.6	1.6
60	3.0	2.9	2.8	2.7	2.6	2.5	2.5	2.4	2.4	2.3	2.2	2.2	2.2	2.1	2.1	2.0	2.0	1.9	1.9	1.9	1.8	1.8	1.8	1.8	1.7
65	3.1	3.0	2.9	2.8	2.7	2.7	2.6	2.5	2.5	2.4	2.4	2.3	2.3	2.2	2.2	2.1	2.1	2.1	2.0	2.0	2.0	1.9	1.9	1.9	1.8
70	3.2	3.1	3.0	2.9	2.8	2.8	2.7	2.7	2.6	2.5	2.5	2.4	2.4	2.3	2.3	2.3	2.2	2.2	2.2	2.1	2.1	2.1	2.0	2.0	2.0
75	3.3	3.2	3.1	3.0	3.0	2.9	2.8	2.8	2.7	2.7	2.6	2.6	2.5	2.5	2.4	2.4	2.3	2.3	2.3	2.2	2.2	2.2	2.1	2.1	2.1
80	3.4	3.3	3.2	3.1	3.1	3.0	3.0	2.9	2.8	2.8	2.7	2.7	2.6	2.6	2.6	2.5	2.5	2.4	2.4	2.4	2.3	2.3	2.3	2.2	2.2
85	3.5	3.4	3.3	3.3	3.2	3.1	3.1	3.0	3.0	2.9	2.9	2.8	2.8	2.7	2.7	2.6	2.6	2.6	2.5	2.5	2.5	2.4	2.4	2.4	2.3
90	3.6	3.5	3.4	3.4	3.3	3.3	3.2	3.1	3.1	3.0	3.0	2.9	2.9	2.8	2.8	2.8	2.7	2.7	2.7	2.6	2.6	2.6	2.5	2.5	2.5
95	3.7	3.6	3.6	3.5	3.4	3.4	3.3	3.3	3.2	3.2	3.1	3.1	3.0	3.0	2.9	2.9	2.9	2.8	2.8	2.7	2.7	2.7	2.6	2.6	2.6
100	3.8	3.7	3.7	3.6	3.5	3.5	3.4	3.4	3.3	3.3	3.2	3.2	3.1	3.1	3.1	3.0	3.0	2.9	2.9	2.9	2.8	2.8	2.8	2.7	2.7
105	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.4	3.3	3.3	3.2	3.2	3.2	3.1	3.1	3.0	3.0	3.0	2.9	2.9	2.9	2.8
110	4.0	4.0	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.4	3.4	3.3	3.3	3.2	3.2	3.2	3.1	3.1	3.1	3.0	3.0	3.0
115	4.1	4.1	4.0	3.9	3.9	3.8	3.8	3.7	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.4	3.4	3.3	3.3	3.3	3.2	3.2	3.2	3.1	3.1
120	4.2	4.2	4.1	4.1	4.0	4.0	3.9	3.9	3.8	3.8	3.7	3.7	3.7	3.6	3.6	3.5	3.5	3.5	3.4	3.4	3.4	3.3	3.3	3.3	3.2
125	4.3	4.3	4.2	4.2	4.1	4.1	4.0	4.0	3.9	3.9	3.9	3.8	3.8	3.7	3.7	3.7	3.6	3.6	3.6	3.5	3.5	3.5	3.4	3.4	3.4

Based on a 4-lane highway with a posted speed limit of 65 mph (104 km/hr) scenario.
*Due to the deflection characteristic of cable barriers upon impact, installing on medians with a width less than 25 ft is usually not recommended.
**Low estimates of the B/C ratios for high-tension cable barriers are less than 1 when AADT is less than 5,000.

cable barrier is more favorable than the concrete barrier at the same AADT and median width and (*b*) the favorability increases as AADT decreases and as median width increases. Given the limitations of the data indicated earlier, one possible recommendation at this time is to consider using high-tension-cable barriers (instead of concrete barriers) only when the favorability ratio in Table 11 exceeds 2, as shown in the shaded are of the table.

DISCUSSION OF RESULTS

In the analysis just presented, the concept of discounting the present worth of future lives saved and injuries and property damages averted, as discussed in U.S. Department of Transportation memorandums (*26*), was not implemented. A separate sensitivity analysis suggested that the B/C ratios as presented in Tables 8 and 9 would be reduced by about 40% if a 5% discount rate were employed. In addition, if the comprehensive crash cost (instead of the calculable economic cost) and the 5% discount rate for future lives saved were used, the B/C ratios in these tables would increase by a factor of about 2.

There are many directions in which this study could be extended. Some promising extensions are as follows:

- No explanatory variable was found to be statistically significant in development of the severity model for cross-median crashes, most likely because of the small sample size. Obtaining another 2 to 3 years' worth of cross-median crash data would be helpful.
- As indicated, one limitation of the data used in this study for barrier-separated sections was that even though the median width was given, the exact placement (or offset) of the barrier from each side of the travel lane was not available from the database. These data could potentially be field collected to develop more-robust frequency and severity models at the travel-direction level.
- A before-and-after with reference group design was planned for this study. However, only a small number of sites could be identified for use under this study design and thus no formal analysis was carried out. As more median barriers are installed in Texas, this study design could become a viable approach in the near future.
- As pointed out in the previous section, in-service performance evaluation data for the high-tension-cable barrier system are rather limited at this time, especially on barrier-breaching rates and injury severity distributions. Other issues that need more research for the high-tension-cable barrier include placement of the barrier on mild side slopes and sharp horizontal curves, truck volume at which the system should not be installed, and need for a concrete (or other type of) mow strip.

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REFERENCES

1. Mak, K. *Cross-Median Accident Prediction Model.* Working Paper, NCHRP Project 22-12: Guidelines for the Selection, Installation, and Maintenance of Highway Safety Features. Texas Transportation Institute, College Station, 1998.
2. Donnell, E. T., and J. M. Mason, Jr. Predicting the Severity of Median-Related Crashes in Pennsylvania by Using Logistic Regression. In

Transportation Research Record: Journal of the Transportation Research Board, No. 1897, Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 55–63.
3. Hauer, E. *The Median and Safety.* Unpublished manuscript, University of Toronto, Ontario, Canada, March 24, 2000.
4. *Roadway Design Manual.* Texas Department of Transportation, Austin, Feb. 2001.
5. *Roadside Design Guide.* American Association of State Highway and Transportation Officials, Washington, D.C., 2002.
6. *Traffic Manual.* California Department of Transportation, Sacramento, May 1998.
7. Lacy, J. K. Median Guardrails in North Carolina: Benefits and Concerns. Presented at North Carolina Incident Management Conference, High Point, N.C., May 7, 2003.
8. Mason, J. M., Jr., E. T. Donnell, D. W. Harwood, K. M. Bauer, J. M. Sada, and M. T. Pietrucha. *Median Safety Study (Interstates and Expressways).* Final Report FHWA-PA-2001-009-97-04. Pennsylvania Transportation Institute, Pennsylvania State University, June 2001.
9. Glad, R. W., R. B. Albin, D. M. McIntoch, and D. K. Olson. *Median Treatment Study on Washington State Highways.* Research Report WA-RD 516.1. Washington State Department of Transportation, Olympia, March 2002.
10. Hunter, W. W., J. R. Stewart, K. A. Eccles, H. F. Huang, F. M. Council, and D. L. Harkey. Three-Strand Cable Median Barrier in North Carolina: In-Service Evaluation. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1743,* TRB, National Research Council, Washington, D.C., 2001, pp. 97–103.
11. McClanahan, D., R. B. Albin, and J. C. Milton. Washington State Cable Median Barrier In-Service Study. Presented at the 83rd Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 2004.
12. *Plans Preparation Manual.* Vol. 1, *Design Criteria and Process,* rev. ed. Roadway Design Office, Florida Department of Transportation, Tallahassee, Jan. 1, 2004.
13. Seamons, L. L., and R. N. Smith. *Past and Current Median Barrier Practice in California.* Report Caltrans-TE-90-2. Division of Traffic Operations, California Department of Transportation, Sacramento, June 1991.
14. Martin, J.-L., and R. Quincy. Crossover Crashes at Median Strips Equipped with Barriers on a French Motorway Network. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1758,* TRB, National Research Council, Washington, D.C., 2001, pp. 6–12.
15. Miaou, S-P., J. J. Song, and B. K. Mallick. Roadway Traffic-Crash Mapping: A Space-Time Modeling Approach. *Journal of Transportation and Statistics,* Vol. 6, No. 1, Nov. 2003, pp. 33–57.
16. Miaou, S-P., and D. Lord. Modeling Traffic Crash-Flow Relationships for Intersections: Dispersion Parameter, Functional Form, and Bayes Versus Empirical Bayes Methods. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1840,* Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 31–40.
17. Gelman, A., J. B. Carlin, H. S. Stern, and D. B. Rubin. *Bayesian Data Analysis.* Chapman & Hall/CRC Press, London, 1995.
18. Spiegelhalter, D. J., A. Thomas, N. G. Best, and D. Lunn. *WinBUGS Version 1.4 User Manual.* MRC Biostatistics Unit, Cambridge University, England, 2003.
19. Carlin, B. P., and T. A. Louis. *Bayes and Empirical Bayes Methods for Data Analysis.* Chapman & Hall/CRC Press, London, 1996.
20. Congdon, P. *Bayesian Statistical Modeling.* Wiley, New York, 2001.
21. *Highway Safety Evaluation: Procedural Guide.* Report FHWA-TS-81-219. FHWA, U.S. Department of Transportation, Nov. 1981.
22. *Benefit/Cost Analysis for Transportation Projects.* Office of Investment Management, Minnesota Department of Transportation, St. Paul, 2002.
23. Center for Transportation Research and Education, Iowa State University. New Guardrail System Should Save Lives. *Technology News,* March–May, 2004.
24. Outcalt, W. *Cable Guardrail.* Interim Report CDOT-DTD-R-2004-10. Colorado Department of Transportation, Denver, June 2004.
25. Sharp, B., and R. Stewart. *Annual Experimental Features Report: High-Tension Cable Median Barrier (Brifen, Trinity) at UDOT.* Report UT-04.03. Utah Department of Transportation, Salt Lake City, June 2004.
26. *Treatment of Value of Life and Injuries in Preparing Economic Evaluations.* Office of the Secretary of Transportation, U.S. Department of Transportation, Jan. 29, 2002, and Jan. 8, 1993.

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