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The Safety and Cost-Effectiveness of Approach Guardrail for Bridges on Low Volume Roads

By: Tim J. Gates, David A. Noyce, and Paul H. Stine

Tim J. Gates, P.E. (Corresponding Author)
Graduate Research Fellow
University of Wisconsin-Madison
Department of Civil and Environmental Engineering
1205 Engineering Hall
1415 Engineering Drive
Madison, WI 53706
tjgates@wisc.edu
Phone: 608-265-8583
Fax: 608-262-5199

David A. Noyce, Ph.D., P.E.
Assistant Professor
University of Wisconsin-Madison
Department of Civil and Environmental Engineering
1210 Engineering Hall
1415 Engineering Drive
Madison, WI 53706
noyce@engr.wisc.edu
Phone: (608) 265-1882
Fax: (608) 262-5199

Paul H. Stine, P.E.
State Aid Operations Engineer
Minnesota Department of Transportation
395 John Ireland Blvd, 4th Floor North
St. Paul, MN 55155-1899
paul.stine@dot.state.mn.us
Phone: (651) 296-9973

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ABSTRACT

Bridge approach guardrail is a commonly used safety feature designed to prevent collision with bridge components, such as the blunt end of the bridge rail, and other types of run-off-the-road crashes occurring on the bridge approach. The primary objective of this research was to determine the ADT threshold at which installation of bridge approach guardrail on low volume roads, such as county roads and secondary state highways, is cost-effective based on reductions in crash severity. A survey of U.S. state transportation agencies found that 26 of 35 responding agencies have policies or guidelines requiring placement of approach guardrail on all state-funded bridges, regardless of Average Daily Traffic (ADT) or roadway classification. Other states require bridge approach guardrail on state-funded local facilities only if a specified ADT threshold is exceeded. The authors used logistic regression and chi-square tests to analyze the characteristics of 96 run-off-the-road crashes that occurred on the approach or departure to 68 county state-aid highway bridges in 10 Minnesota counties over a 15-year period. Crashes that occurred at bridges with approach guardrail were found to be much less severe than crashes that occurred at bridges where no guardrail was present. None of the 33 crashes with approach guardrail resulted in fatalities or severe injuries, while roughly one-quarter of the 63 crashes with the roadside or bridge rail end resulted in fatalities or severe injuries. Crashes with the approach guardrail were much more likely to result in no injury compared to crashes with the roadside or bridge rail end. The subsequent benefit/cost analysis showed that overall, bridge approach guardrail has a benefit/cost ratio of 3.12 to 4.35 and is cost-effective (i.e., benefit/cost > 1) at ADTs greater than or equal to 400. Based on the benefit/cost analysis, the authors recommended that the ADT threshold for installation of bridge approach guardrail on low volume roads be set at 400, which is consistent with current AASHTO very low-volume local road guidelines for roadside clear zones.

Key words: guardrail, safety, cost-effectiveness, bridge rail, roadside

INTRODUCTION

Certain bridge components, including railings, piers, headwalls, and abutments are fixed-objects that are typically very close to the edge of the traveled way and their presence in the clear zone constitutes a roadside safety hazard. Roadside traffic barriers such as steel guardrail and other treatments are often connected to the ends of the bridge rail/parapet to keep vehicles from running-off-the-road (ROR) and striking the less-forgiving ends of the rail or other bridge components or roadside objects. Figure 1 shows a typical Minnesota county highway bridge with approach guardrail.

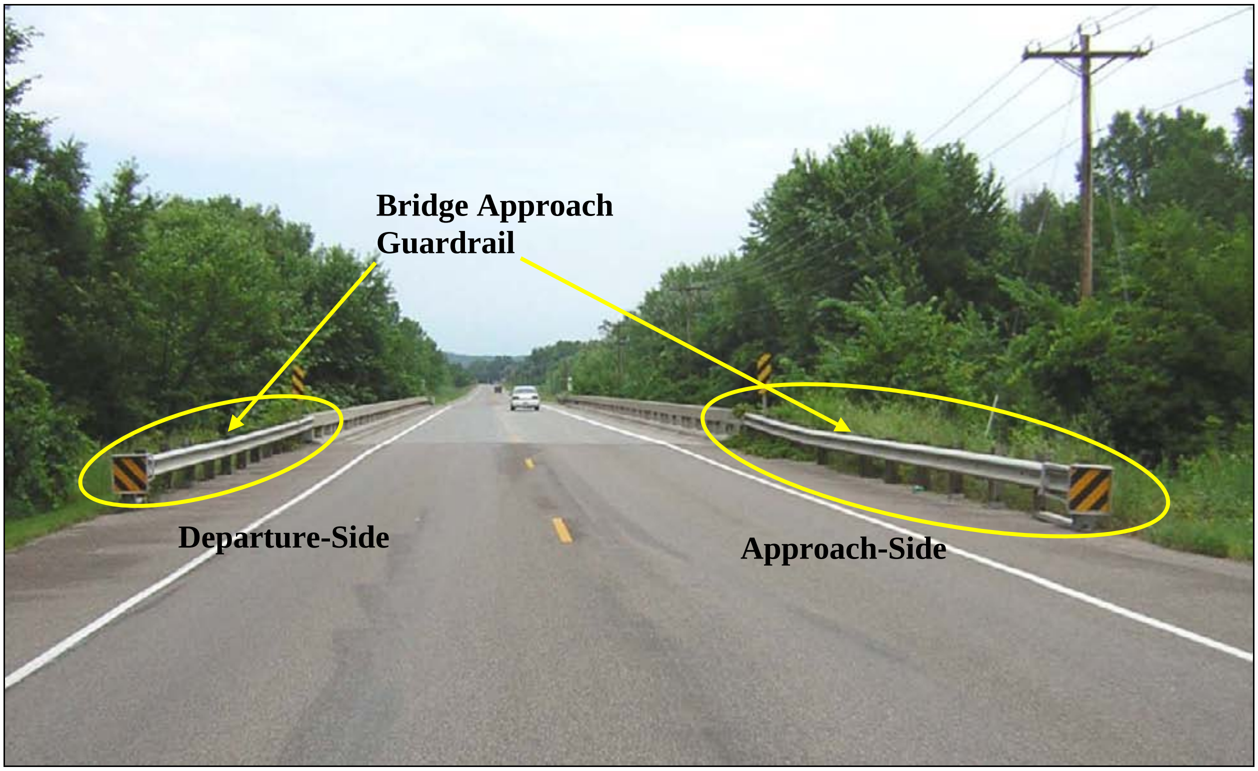


FIGURE 1 County highway bridge with approach guardrail (Minnesota).

The installation of guardrail on low volume roads can add costs and other safety and maintenance problems that may outweigh the proposed benefits. Guardrail itself is a fixed object near the roadway edge, potentially resulting in more crashes. Guardrail is also known to effectuate snow drifting during the winter months providing an additional maintenance and safety concern. Additionally, grass and weeds that grow near the guardrail cannot be cut by traditional lawn mowers thus requiring workers to use labor-intensive weed cutting devices around guardrail posts.

The FWHA requires bridge approach guardrail on the National Highway System (NHS), but states and local jurisdictions are given discretion to develop their own policies or guidelines for non-NHS roadways, such as county roads or secondary state highways. Thus, it is important to determine the appropriate criteria for placement of approach guardrail on non-NHS system bridges. This paper is based on research performed for the Minnesota Local Road Research Board (*1*).

Objectives and Tasks

The primary objectives of this research were to determine:

1.) State-of-the-practice for installation of bridge approach guardrail on low volume roads,
2.) Safety-effectiveness of bridge approach guardrail on low volume roads,
3.) Cost-effectiveness of bridge approach guardrail on low volume roads, and
4.) Average daily traffic (ADT) threshold for installation of bridge approach guardrail based on benefit/cost ratio >1.0.

Objective 1 was accomplished by a literature review and state DOT survey. Objectives 2, 3, and 4 were completed using bridge and crash data from Minnesota. Conclusions and recommendations were developed based on the research findings and are presented at the end of this paper.

STATE-OF-THE-PRACTICE

AASHTO Guidelines

Two AASHTO publications are widely regarded as the leading guidelines for clear-zone protection. The AASHTO *Roadside Design Guide (RDG)* (*2*) provides guidance for evaluating the need for shielding steep slopes and roadside objects, including bridge rail. Tables in the *RDG* provide minimum clear zone requirements based on design speed, ADT, and slope. For example, for a roadway with a design speed of 55 mph, ADT less than 750, and fore slopes flatter than 1:4, a minimum clear zone of 12-18 feet is required. However, the *RDG*, does not specifically address roadside design issues for very low-volume roads (i.e., ADT ≤ 400), which are of specific interest to the research described here.

Perhaps a better tool for addressing roadside design issues on very low-volume roads is the AASHTO *Guidelines for Geometric Design of Very Low-Volume Local Roads (ADT ≤ 400) (VLVRDG)* (*3*). These guidelines state that traffic barriers are not generally cost-effective on roads with very low traffic volumes because the probability of striking a fixed object on these types of roads is extremely low when compared to similar higher volume roadways. However, the AASHTO *VLVRDG* applies only to roads that are functionally classified as a local road and have a design ADT of 400 vpd or less because of the high level of driver familiarity that is associated with these types of roads.

Published Research

Several states have analyzed bridge approach guardrail through various research efforts, although most of the focus was typically placed on crashworthiness of the guardrail/bridge rail connections and end treatments. As a result, very few published literature sources were found to be directly related to the objectives of this research.

In a late 1970's study for the New Mexico DOT, Hall found that collisions with guardrail produced severity indices that were approximately 50 percent lower than that of collisions with bridge abutments, which had the highest severity index of all fixed object collisions that were examined (*4*). As a result, it was suggested that the addition of guardrail to protect an abutment or bridge would reduce the crash severity by 50 percent. Hall also found that bridges were the most common location for a guardrail crash to occur (28 percent of all reported guardrail crashes in New Mexico), likely due to the fact that bridges were the most common location for guardrail installation with 31 percent of all installations.

A study performed in Iowa in 1989 examined the application of bridge approach guardrail on primary roads (*5*). A benefit/cost analysis was completed using an early version of AASHTO's ROADSIDE software program, which generated linear relationships between the benefit/cost ratio and ADT at various lateral offsets for the guardrail. The Iowa study found the break-even benefit/cost ratio (i.e., benefit/cost = 1.0) for the application of bridge approach guardrail to apply to roadways with 1,400 ADT and a guardrail offset of 2 feet from the edge of pavement.

More recently, a study by Wolford and Sicking found little need for guardrail for protection of embankments and culverts when the ADT was less than approximately 500 vehicles per day, regardless of other variables (*6*).

Survey of Current Practice

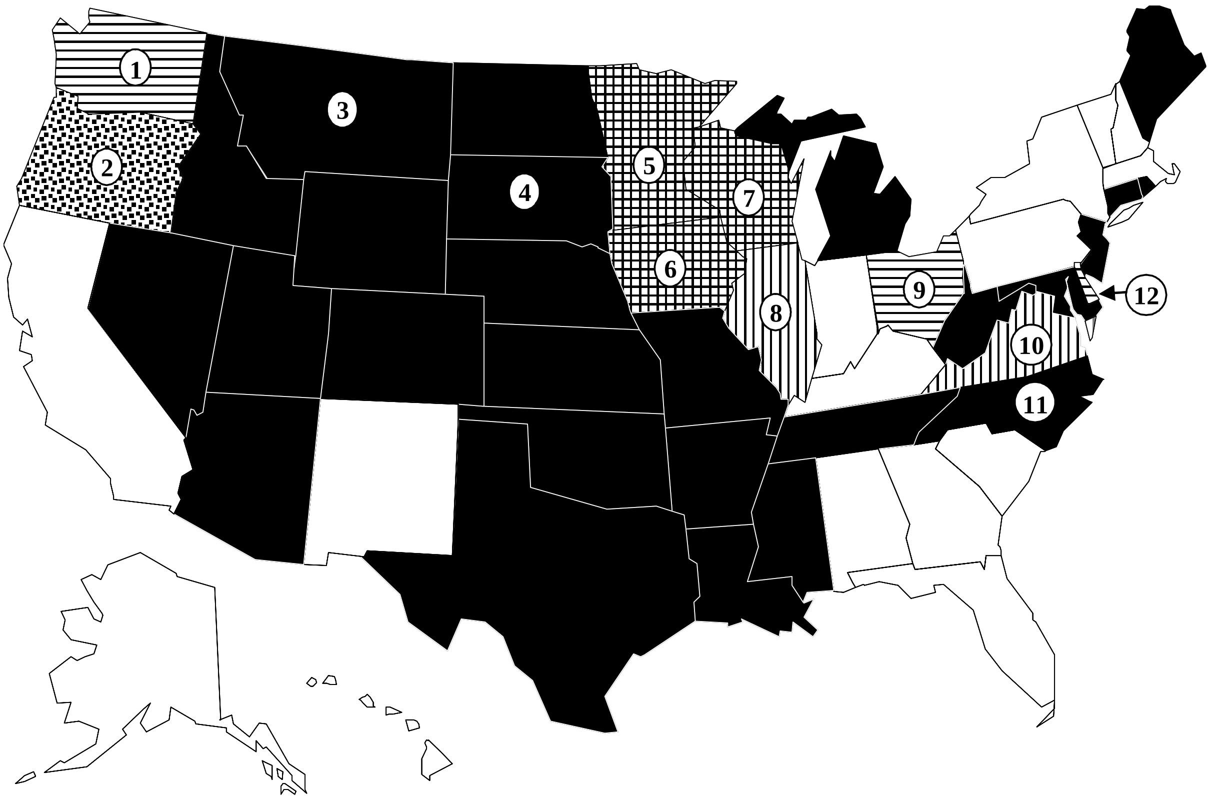
The authors conducted a survey of state transportation agencies to determine the state-of-the-practice for bridge approach guardrail installation on low volume highways, including those maintained by counties and other local jurisdictions. Please note that many bridges and roadways on the local system are built and/or maintained using state funds, and thus are typically required to conform to state standards and guidelines.

The survey, which consisted of seven questions, was administered via the Internet (with telephone follow-up) in January 2004 to relevant state DOT personnel from all 50 states. Thirty-five responses were received. A summary of the primary survey findings is shown in Figure 2.

Findings

As shown in Figure 2, 26 of the 35 responding state agencies (74 percent) have policies or guidelines requiring the placement of guardrail or attenuators on bridge approaches if the bridge was built using state funds, regardless of the roadway system. The general reasoning provided by these agencies was that the bridge rail or parapet ends are fixed-object hazards within the clear zone and therefore must be shielded. Many of these agencies cited the AASHTO *Roadside Design Guide* (*2*) as the basis for their policy or guideline. Furthermore, nearly every agency indicated that guardrail placement was dictated by agency policy rather than a guideline, although some agencies grant exceptions to their guardrail policy, as noted in Figure 2.

Four of the 35 responding state agencies (Minnesota, Wisconsin, Illinois, and Virginia) require bridge approach guardrail on state-funded local facilities only at locations where an ADT threshold is exceeded (Figure 2). Some noted that their respective ADT threshold values were based on the guidelines in the AASHTO *Guidelines for Geometric Design of Very Low-Volume Local Roads (ADT ≤ 400)*, which suggests that the use of guardrail for protection of fixed objects is generally not cost-effective for local roadways with ADT ≤ 400 (*3*). Six of the 35 responding states (Minnesota, Wisconsin, Iowa, Washington, Iowa, and Delaware) indicated that lower-speed facilities (i.e., speeds ≤ 45 mph) don't require approach guardrail.



Legend:

- All state-aid bridges protected (n = 26)
- ADT and speed threshold (n = 3)
- ADT threshold (n = 2)
- Decision made on case-by-case basis (n = 1)
- Speed threshold (n = 3)
- No response (n = 15)

Notes:

1. Historic bridges or urban routes 35 mph or less may be exempted
2. ADT and operating speed are used to make bridge approach guardrail decisions for low-volume state and local roads.
3. Very low volume roads or low speed urban facilities may be exempted on a case-by-case basis, but rarely is this done.
4. ADT < 150 requires only turned down guardrail treatment connected directly to bridge
5. ADT < 750 doesn't require guardrail; design speed 40 mph or less may also be exempted
6. Guardrail not needed if speed limit is 35 mph or less; also exempted are bridges with ADT < 200, bridge wider than 24 ft, on tangent, and benefit/cost ratio < 0.8
7. ADT < 300 doesn't require guardrail; also exempted are curbed urban roads with design speeds 45 mph or less
8. ADT < 150 doesn't require guardrail (tangent alignment only); approach guardrail required for all bridges on curves
9. Speed limit 45 mph or less doesn't require guardrail
10. ADT < 400 doesn't require guardrail; factors such as speed, crashes, paving, cost, and bridge rail condition are also considered
11. Very low volume roads or low speed urban facilities may be exempted on case-by-case basis, but is generally not done
12. Design speeds 35 mph or less use a tapered-down parapet; guardrail must be applied if slope steeper than 3:1

FIGURE 2 Criteria for application of bridge approach guardrail on state-funded local roads.

CRASH ANALYSIS

Sample Bridges

The authors obtained data for 398 mostly rural county state-aid highway (CSAH) bridges from 10 Minnesota counties. Nearly all of the bridges were 2-lane structures over water. The 398 bridges were divided into two samples: those *with* approach guardrail (n = 155) and those *without* approach guardrail (n = 243). The presence of approach guardrail was confirmed by each county transportation department, while Mn/DOT's "Pontis" bridge database was queried to obtain other relevant bridge information. Figure 3 shows a map of the bridge locations by county and guardrail presence.

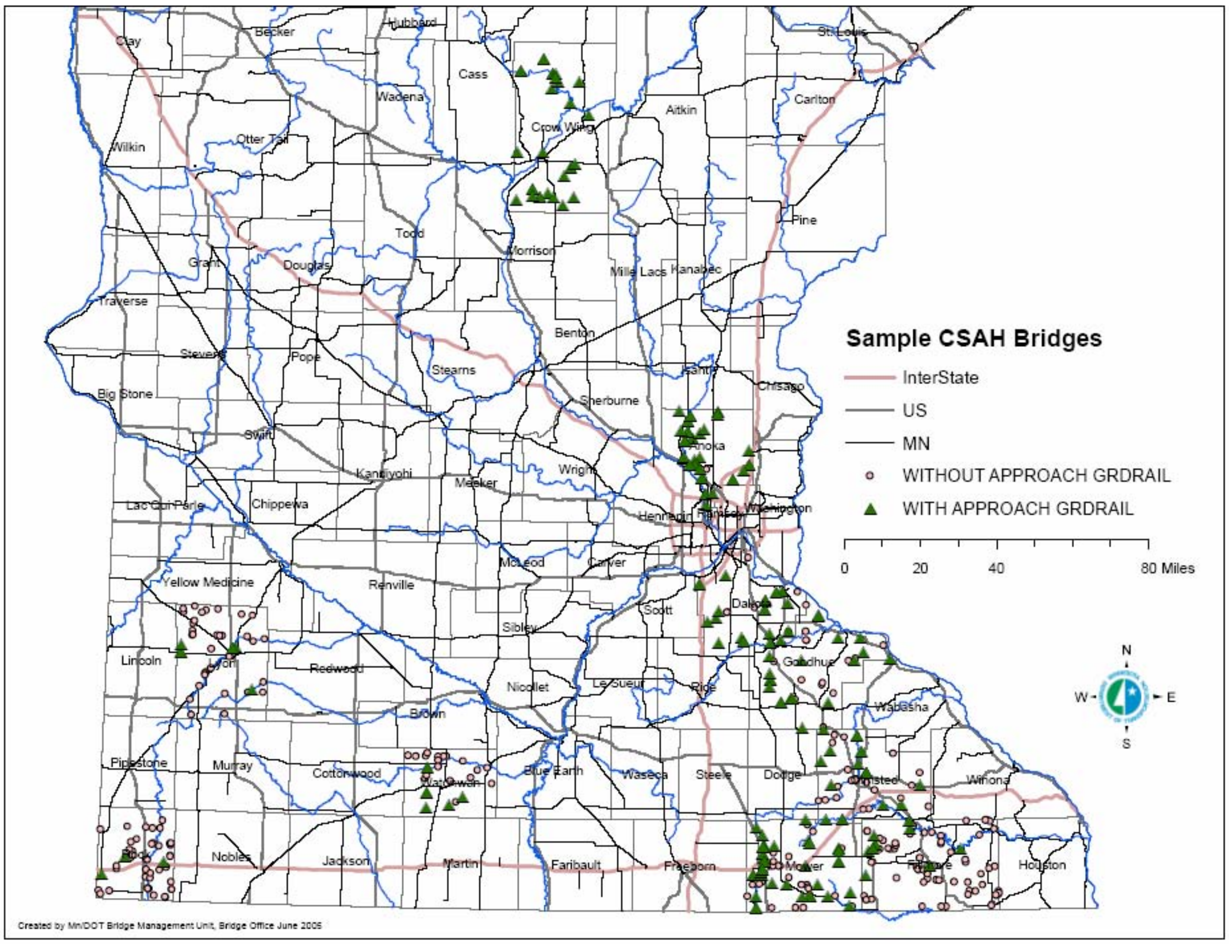


FIGURE 3 Map of Minnesota county state-aid highway bridges used in the analysis.

Most of the bridges without approach guardrail were located in the far southeast and southwest counties, while most of the bridges with approach guardrail were located farther north. As expected, the sample of bridges with approach guardrail was shifted towards the higher ADT ranges while the bridges without approach guardrail generally fell into the lower ADT ranges. The median ADT was 1,320 vehicles per day (vpd) with a range from 42 to 41,524 vpd for the 155 bridges with approach guardrail and 325 vpd with a range from 16 to 27,785 vpd for the 243 bridges without approach guardrail. The distribution of bridges by ADT range is shown later in Table 1. Note that all ADTs reported here are 2004 estimated values.

Crash Data

The Minnesota crash database was queried to obtain the information for crashes that occurred near the 398 bridges included in the sample. The database queries were filtered to include all single-vehicle fixed-object or ROR crashes that occurred from 1988 – 2002 within approximately 200-ft of the sample bridges. The resulting crash data set included a total of 263 crashes that met the aforementioned criteria, 156 of which occurred at bridges with approach guardrail and the remaining 107 crashes occurred at bridges without approach guardrail.

The authors obtained the police reports for nearly all of the 263 crashes to obtain detailed crash information that was not available from the crash database. The authors reviewed the diagram and description from each crash report to gather specific information about the crash, including:

- Initial object struck in the crash,
- Physical location of the crash with respect to the bridge (i.e., approach-side, departure-side, on the bridge), and
- Verification of the presence or absence of approach guardrail.

This information allowed the authors to determine which crashes should be included for further analysis based on whether or not the crash involved the approach guardrail or would likely have involved the approach guardrail had it existed. Specifically, a crash was included for further analyses if it: 1.) occurred on the approach or departure to one of the 398 sample bridges and 2.) involved collision with a bridge component (including approach guardrail), roadside fixed-object, or other roadside collision very near the bridge. Please note that crashes occurring on the bridge itself were excluded from the analysis because the presence or absence of approach guardrail would likely not affect the crash severity.

The crash report screening process resulted in 96 crashes which met the aforementioned criteria, 47 of which occurred at bridges *with* approach guardrail, while the remaining 49 crashes occurred at bridges *without* approach guardrail. Seventy-five percent of the 96 crashes occurred at locations with 55 mph speed limits, 14 percent had speed limits between 40 and 50 mph and 11 percent had speed limits between 30 and 35 mph. Eighty-four percent of the 96 crashes occurred on rural highways, while 16 percent occurred on urban/suburban highways. Only 68 of the 398 bridges (17 percent) experienced a run-off-road or fixed-object crash on the approach during the 15-year analysis period. Table 1 summarizes the crash frequencies by 2004 ADT category, severity, and guardrail presence.

TABLE 1 Run-off-Road and Fixed-Object Crash Frequency by ADT, KABCO Severity, and Guardrail Presence, 1988-2002

	Bridge Count		Crash Frequency											
			PDO		C-injury		B-injury		A-injury		Fatal		TOTAL	
2004 ADT	No GR	GR	No GR	GR	No GR	GR	No GR	GR	No GR	GR	No GR	GR	No GR	GR
<150	63	6	3	0	0	0	1	0	0	0	0	0	4	0
150-399	72	21	4	3	1	0	1	0	3	2	1	0	10	5
400-749	51	25	4	1	1	0	5	3	2	0	1	0	13	4
750-999	12	15	1	0	1	1	1	1	1	0	2	0	6	2
1,000-1,499	17	21	4	5	3	4	0	3	1	0	1	0	9	12
1,500-4,999	16	29	0	5	0	1	0	0	0	0	1	0	1	6
5,000-9,999	5	20	1	3	1	1	1	3	1	0	0	1	4	8
10,000<	7	18	1	5	0	2	1	3	0	0	0	0	2	10
All	243	155	18	22	7	9	10	13	8	2	6	1	49	47

Note: GR = bridges with approach guardrail
No GR = bridges without approach guardrail

Hypotheses and Statistical Procedures

A major objective of the research was to determine if the presence of approach guardrail had an effect on the severity of crashes that occurred on the approach or departure to bridges on low volume roads. In particular, the authors hypothesized that for crashes occurring near these bridges, the presence of approach guardrail would result in a greater proportion of guardrail crashes contrasted with a lower proportion of crashes with bridge components (i.e., bridge rail ends) and crashes with the roadside (i.e., ditches, trees, rollovers, etc.). Consequently, it was also hypothesized that approach guardrail presence would result in a lower proportion of fatal and A-injury crashes and a higher proportion of less-severe crashes.

Numerous analyses were performed to test these hypotheses. The authors first used logistic regression to determine if crash severity was affected by various roadway, bridge, and crash characteristics, including: object struck, pavement surface condition, ADT, speed limit, deck width, and deck width minus approach width. The authors also used two-way Pearson chi-square tests to determine if guardrail presence had an effect on both crash type and severity. The chi-square analyses included: crash severity versus object struck, object struck versus guardrail presence, crash severity versus guardrail presence. The authors also assessed the safety effects of installing departure-side guardrail in addition to approach-side guardrail.

To avoid sparse categories in the analyses, the reported crash severities were clustered to form three discrete categories based on the KABCO scale: property damage only (PDO), B-injuries/C-injuries, and fatalities/A-injuries. Similarly, the object types were clustered into three discrete categories: guardrail, bridge rail, and roadside. Crashes occurring at the bridge rail/guardrail connection were included in the guardrail category.

Logistic Regression Model for Crash Severity

Logistic regression was used to predict crash severity as a function of various roadway, bridge, and crash factors for the sample of 96 crashes. Logistic regression is a useful technique for predicting the probability of an outcome based on values of a set of predictor variables. Logistic regression is similar to linear regression except that the response variable is categorical rather than a numeric value. Specifically, ordinal logistic regression was used here because the response for the dependent variable (severity) is ordered, but the distances are non-numeric (i.e., A-injury is more severe than B-injury). The ordinal logistic regression model for binary response has the form:

$$\ln\left[\frac{p_i}{(1-p_i)}\right] = \alpha + \beta' X_i \tag{1}$$

Where: p_i = Probability($y_i = y_1 \mid X_i$) is the response probability to be modeled (i.e., crash severity given that a crash has occurred), and y_1 is the first ordered level of y

α = Intercept parameter

β' = Vector of slope parameters

X_i = Vector of predictor variables

A stepwise ordinal logistic regression model was developed to predict crash severity versus object struck, surface condition, 2004 ADT, speed limit, deck width, and deck width minus approach width. These predictor variables were chosen because they are often associated with crash frequency or crash severity. The analysis was run in SAS using the LOGISTIC procedure. The results are displayed in Table 2 with discussion to follow.

TABLE 2 Results of Ordinal Logistic Regression Analysis for Crash Severity

Summary of Stepwise Selection

Step	Entered	Deg. of Freedom	Num. In	Score Chi-Square	P-Value
1	OBJECT	2	1	7.8278	0.0200

Alpha for entry = 0.1

No additional predictors met the 0.1 significance level necessary for entry into the model

Predictors not entered: SURFACE COND., ADT, SPEED LIMIT, DECK WIDTH, DECK WIDTH-APP. WIDTH

Score Test for the Proportional Odds Assumption

Chi-Square	Deg. of Freedom	P-Value (Chi-Square)
5.3263	2	0.0697

Analysis of Maximum Likelihood Estimates

Parameter	DF	Estimate	Std. Error	Chi-Square	P-Value
Intercept (K/A)	1	-2.3331	0.4229	30.4366	<.0001 Sig.
Intercept (K/A + B/C)	1	-0.3460	0.3470	0.9942	0.3187 Insig.
OBJECT Roadside	1	1.0233	0.5134	3.9719	0.0463 Sig.
OBJECT Bridge Rail	1	1.1973	0.4674	6.5610	0.0104 Sig.

Odds Ratio Estimates

Effect	Point Estimate	95% Confidence Limits	
OBJECT Roadside vs. Guardrail	2.782	1.017	7.611
OBJECT Bridge Rail vs. Guardrail	3.311	1.325	8.276

Table 2 shows that the stepwise logistic regression analysis found object struck (OBJECT) to be the only predictor variable with a significant effect on crash severity. Surface condition, ADT, speed limit, deck width, and deck width minus approach width did not have statistically significant effects on crash severity for the data observed here. Interpretation of the score test verifies that the proportional odds model is adequately valid for fitting the data (p-value = 0.0697) meaning that the parameter estimates could then be used to determine the probability of a certain crash severity based on the object struck in the collision. Because the ordinal logistic regression equation is a binary function, two equations were necessary to represent the three severity levels (K/A, B/C, PDO):

$$\ln\left[\frac{\pi_{K/A}}{(\pi_{B/C}+\pi_{PDO})}\right] = -2.3331 + 1.0233x_{roadside} + 1.1973x_{bridgerail} \quad (2)$$

$$\ln\left[\frac{(\pi_{K/A}+\pi_{B/C})}{\pi_{PDO}}\right] = -0.3460 + 1.0233x_{roadside} + 1.1973x_{bridgerail} \quad (3)$$

Where: $\pi_{K/A}$ = Probability of Fatal or A-injury (given a crash has occurred)
$\pi_{B/C}$ = Probability of B- or C-injury (given a crash has occurred)
π_{PDO} = Probability of Property Damage Only (given a crash has occurred)
$x_{roadside}$ = Roadside crash indicator (1 if yes, 0 otherwise)
$x_{bridgerail}$ = Bridge rail crash indicator (1 if yes, 0 otherwise)
Note: Guardrail crash is indicated by 0's for both $x_{roadside}$ and $x_{bridgerail}$

Accordingly, based on the preceding equations, the predicted probabilities for each crash severity versus object struck were calculated in the following way:

$$\pi_{K/A} = \frac{e^{equation(2)}}{1+e^{equation(2)}} \quad (4)$$

$$\pi_{B/C} = \frac{e^{equation(3)}}{1+e^{equation(3)}} - \frac{e^{equation(2)}}{1+e^{equation(2)}}, \left(\pi_{K/A}+\pi_{B/C} = \frac{e^{equation(3)}}{1+e^{equation(3)}}\right) \quad (5)$$

$$\pi_{PDO} = 1-(\pi_{K/A}+\pi_{B/C}) \quad (6)$$

Equations 4, 5, and 6 were used to compute the probabilities of a crash being of K/A, B/C, and PDO severity levels given that a crash with the roadside, bridge rail, or guardrail had occurred. These probabilities are shown in Table 3. Note, that crashes occurring at the bridge rail/guardrail connection were included with guardrail crashes.

TABLE 3 Probability of Crash Severity versus Object Struck from Logistic Regression

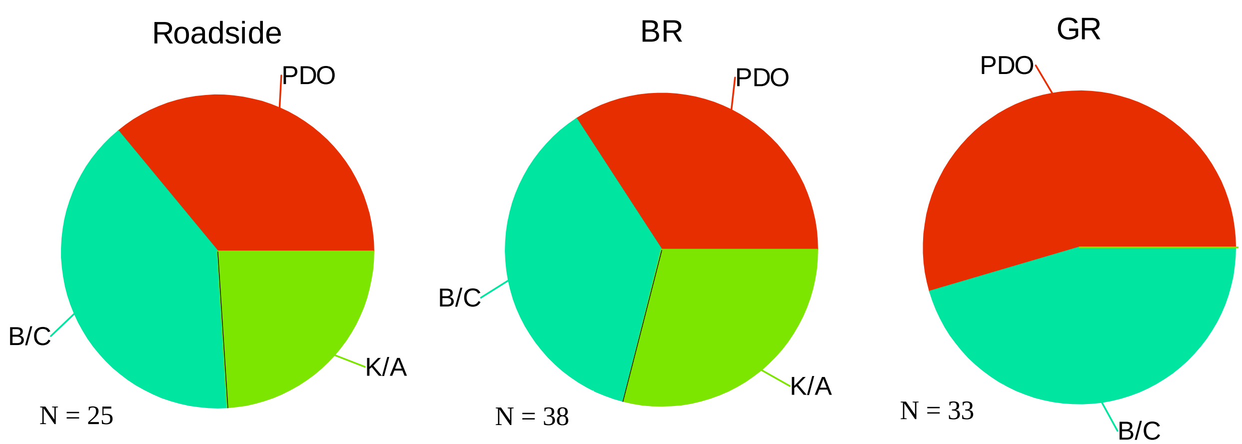
	Probability of a Given Crash Severity Based on the Object Struck		
Severity	Roadside	Bridge Rail	Guardrail
PDO	0.337	0.299	0.586
B/C	0.451	0.458	0.326
K/A	0.213	0.243	0.088

Based on the logistic probabilities shown in Table 3, collisions with the roadside or bridge rail end are approximately 2.5 times more likely to result in fatalities or A-injuries versus collisions with approach guardrail. Guardrail crashes are roughly twice as likely to result in no injuries versus roadside or bridge rail crashes. The most severe collisions are those with the bridge rail, although roadside collisions are nearly as severe.

Chi-Square Analyses

Crash Severity vs. Object Struck

The results of the logistic regression probabilities for crash severity versus object struck were verified by a two-way Pearson chi-square test. The two-way Pearson chi-square test measures the independence (or level of association) between the rows and columns of a crosstabulation table; for example, testing the null hypothesis (H_o) that initial object struck (rows) is independent of the presence of approach guardrail (columns). The findings are shown in Figure 4.



Note: Roadside = roadside collisions
BR = bridge rail collisions
GR = guardrail collisions (includes bridge rail/guardrail connection)

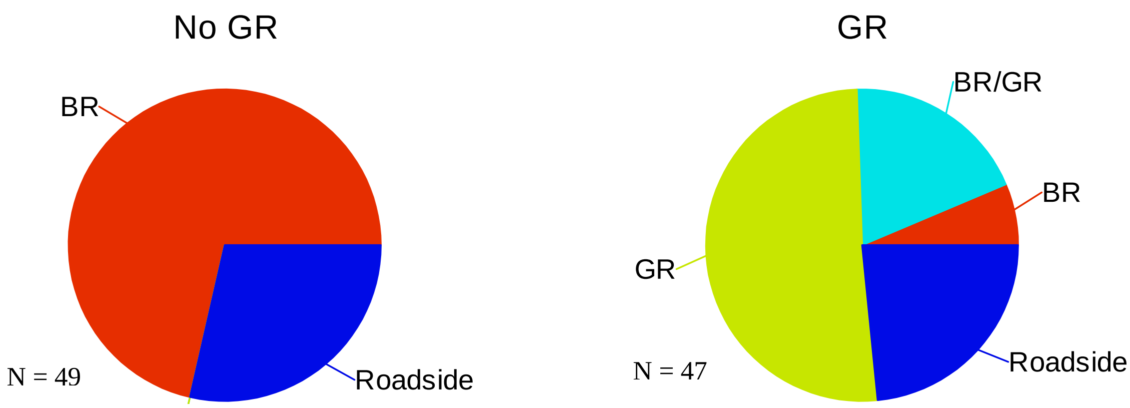
	Value	Degrees of Freedom	Probability	Significant Differences?
Pearson chi-square	11.452	4.000	0.022	Yes

FIGURE 4 Crash severity vs. object struck.

Comparison of Table 3 with Figure 4 shows that the crash severities predicted by logistic regression modeling correlate closely with the actual crash data shown in the pie charts. Perhaps the most significant finding shown in Figure 4 is that zero of the 33 crashes with approach guardrail resulted in fatalities or A-injuries, while roughly one-quarter of the 63 roadside and bridge rail crashes resulted in fatalities or A-injuries. Crashes with the approach guardrail were much more likely to result in no injury versus roadside or bridge rail crashes. The type of object struck had little effect on the proportion of B/C injuries.

Object Struck vs. Guardrail Presence

The previous analysis showed that crash severity is significantly affected by the type of object struck in the collision. Thus, it was important to verify whether or not the presence of approach guardrail had an effect on the types of objects struck. The authors hypothesized that presence of approach guardrail would result in a greater proportion of guardrail crashes and a lesser proportion of crashes with other bridge components and roadside crashes when compared to bridges without approach guardrail. The hypothesis was tested using a two-way Pearson chi-square test for independence at a 95 percent level of confidence. Figure 5 displays the chi-square test results.



Note: No GR (chart title) = bridges without approach guardrail
GR (chart title) = bridges with approach guardrail
Roadside (response category) = roadside collisions
GR (response category) = guardrail collisions
BR (response category) = bridge rail collisions
BR/GR (response category) = collisions with bridge rail/guardrail

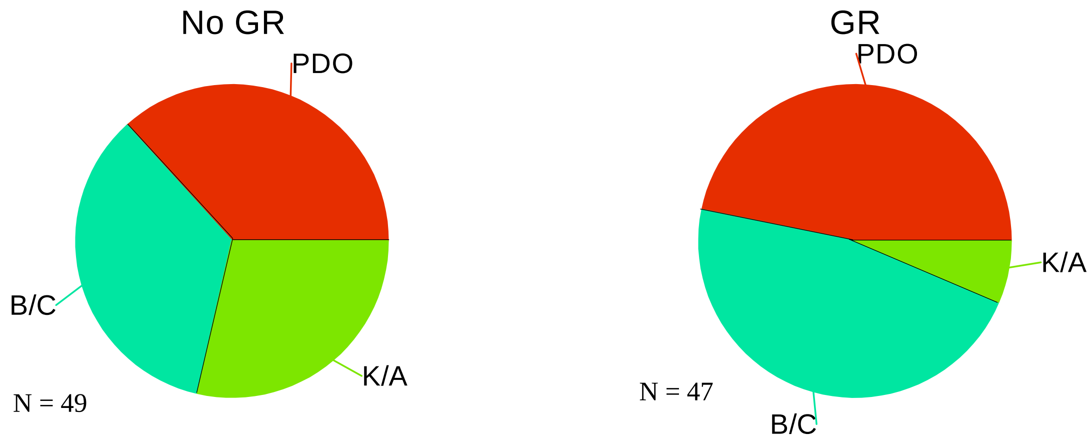
	Value	Degrees of Freedom	Probability	Significant Differences?
Pearson chi-square	60.292	3.000	0.000	Yes

FIGURE 5 Initial object struck vs. guardrail presence.

Figure 5 shows that approximately 70 percent of the crashes occurring on the approach or departure to bridges without approach guardrail were collisions with the bridge rail and approximately 30 percent were collisions with a roadside fixed object or rollover. As expected, the results were much different for bridges with approach guardrail. Seventy percent of the crashes at bridges with approach guardrail involved collision with either the guardrail or the bridge rail/guardrail connection. Six percent of the crashes at bridges with approach guardrail were collisions with the bridge rail, while roadside collisions comprised 23 percent. Further analysis showed that most of the roadside collisions and all of the bridge rail collisions occurring at bridges with approach guardrail occurred on the departure-side of bridges where guardrail either did not exist or was too short to prevent the vehicle from running off the road. More discussion of departure-side crashes has been provided later in this paper.

Crash Severity vs. Guardrail Presence

The previous analyses have shown that: 1.) guardrail crashes resulted in significantly lower severity versus bridge rail and roadside collisions and 2.) collisions with guardrail accounted for nearly all of the crashes at bridges with approach guardrail. Thus, the authors hypothesized that bridges with approach guardrail would have a lesser proportion of severe injury/fatal crashes and greater proportion of PDO crashes versus bridges without approach guardrail. The hypothesis was tested using a two-way Pearson chi-square test for independence at a 95 percent level of confidence. Figure 6 shows the observed crash severities for bridges with and without approach guardrail and the associated chi-square test results.



Note: No GR (chart title) = bridges without approach guardrail
GR (chart title) = bridges with approach guardrail

	Value	Degrees of Freedom	Probability	Significant Differences?
Pearson chi-square	8.121	2.000	0.017	Yes

FIGURE 6 Crash severity vs. guardrail presence.

Figure 6 confirms that crashes at bridges with approach guardrail were significantly less severe than crashes at bridges without approach guardrail. While approach guardrail did not appear to have a large effect on the proportion of B- and C-injury crashes, K and A-injury crashes accounted for a much smaller proportion of the crashes for bridges with approach guardrail. Only three of the 47 crashes (6.4 percent) at bridges with approach guardrail were K or A-injuries, while 14 of the 49 crashes (28.5 percent) at bridges without approach guardrail were K or A-injuries – a rate that is 4.5 times greater than at bridges with approach guardrail.

Departure-Side vs. Approach-Side Crashes Closer analysis of the three K and A-injury crashes at bridges with approach guardrail showed that each crash occurred on the departure-side of a bridge where guardrail either did not exist or was too short to be effective, thus resulting in a more severe collision with the bridge rail end or roadside. Guardrail installed on the departure-side in addition to the approach-side of a bridge is designed to provide additional protection for departure-side events, such as where the vehicle runs-off-the-road to the right after crossing the bridge or crosses the centerline ahead of the bridge and runs-off-the-road to the left, potentially striking the bridge rail end (see Figure 1 for more details). The authors found that installation of departure-side guardrail in Minnesota was a practice that varied from county to county, although most of the recent installations included guardrail on both the approach- and departure-sides of the bridge.

The authors performed further analysis of the severities of approach-side versus departure-side crashes. The rate of occurrence for departure-side crashes (34 percent of all crashes) was slightly more than half the rate of approach-side crashes (62 percent). Of the 47 crashes at bridges with approach guardrail, 17 were departure-side crashes and 29 were approach-side crashes (one crash could not be determined). Departure-side guardrail either did not exist or was too short to be effective for 11 of the 17 departure-side crashes resulting in collision with either the roadside or bridge rail end. Alarmingly, nine of these 11 crashes resulted in either an injury or fatality (one fatality, two A-injuries, two B-injuries, and four C-injuries). Guardrail collisions accounted for the remaining six departure-side crashes, four of which resulted in property-damage only, while the other two resulted in minor injuries. Approach-side crashes (where guardrail existed in all cases) resulted in 25 guardrail collisions and four roadside collisions. The four roadside collisions occurred at locations where the approach-side guardrail was of inadequate length. The approach-side crashes were much less severe than departure-side crashes as slightly more than half were property-damage only, while the rest were B- or C-injuries. Most importantly, none of the approach-side crashes were fatalities or A-injuries. Thus, although the sample sizes are relatively small, these findings suggest that substantial reductions in crash severity will occur if departure-side guardrail is installed in addition to approach-side guardrail.

BENEFIT/COST ANALYSIS

The primary objective of this research was to determine the cost-effectiveness of bridge approach guardrail and recommend a threshold ADT for installation on low volume highways based on a benefit/cost ratio > 1.0.

Installation, Maintenance, and Repair Costs for Bridge Approach Guardrail

The first step in the benefit/cost analysis was to determine the approximate life-cycle cost (in 2004 dollars) for a typical section of approach guardrail. Costs for bridge approach guardrail include those for:

- Installation
    - Standard guardrail,
    - Transition guardrail,
    - End treatment,
    - Supplementary signs and/or delineators, and
    - Labor;
- Maintenance
    - Vegetation removal,
    - Snow removal; and
- Repair.

An approximate life-cycle cost for a typical installation of approach guardrail was developed based on the following assumptions:

- 30-year design life for guardrail,
- Guardrail is applied at all four bridge corners (i.e., approach and departure sides),
- Each guardrail section is approximately 75 ft in length (including transition section) and includes proper end treatment,
- One guardrail section will need to be replaced every 5-years due to vehicular or other type of damage,
- Guardrail adds an additional annual maintenance cost of $100 per bridge for additional weed removal and snow removal,
- Guardrail has no salvage value at the end of its useful life, and
- 3.6 percent annual discount rate (i.e., interest rate minus inflation) (*7*).

Based on these assumptions, the 2004 life-cycle cost for bridge approach guardrail was estimated at $27,100 - $45,000 per bridge, with approximately $14,400 - $20,000 (roughly 40 – 60 percent) of that being the cost of materials and labor for installation. Because the crash analysis period was 15 years in length (i.e., ½ of the 30-year guardrail life-cycle), the approach guardrail life-cycle costs were halved for use in the benefit/cost calculations.

Predicted Crash Savings Due to Approach Guardrail Installation

The primary "benefit" for installing approach guardrail is a reduction in the severity and subsequent cost of run-off-the-road and fixed object crashes occurring on bridge approaches. Based on the results of the crash analysis, installation of bridge approach guardrail is expected to greatly reduce the occurrence of all types of roadside collisions and collisions with bridge components – especially the blunt ends of the bridge rail. These crashes would typically be replaced by a collision with the approach guardrail. Collisions with approach guardrail were shown in the logistic regression analysis to be significantly less severe when compared to collisions with the bridge rail end or the roadside. Thus, the expected reductions in crash severity from installing approach guardrail will consequently result in net crash cost savings. Mn/DOT's estimated 2004 costs per crash for each KABCO severity level were used in the analysis described here (*7*):

- Property Damage - $4,300,
- C-Injury - $29,000,
- B-Injury - $59,000,
- A-Injury - $270,000, and
- Fatal - $3,500,000.

Analysis and Findings

The benefit/cost analysis was performed using the sample of 49 crashes that occurred at bridges without approach guardrail. As stated earlier, each of these 49 crashes was either a collision with the end of the bridge rail or collision with the roadside. To compute the crash benefit provided by approach guardrail, the authors assumed that each of the 49 bridge rail and roadside collisions would have resulted in collision with the approach guardrail had an adequate section of approach guardrail been in place at the time of the crash. The expected crash severities assuming guardrail had been in place were computed using the logistic probabilities shown in Table 3 for collisions with approach guardrail. Thus, the severities reported for each of the 49 collisions with the bridge rail or roadside were replaced by severities of 0.586 PDO, 0.326 B/C injury, and 0.088 K/A injury predicted for each crash with the approach guardrail.

The expected costs for each guardrail crash were computed by using $4,300 for each PDO, $59,000 for each B/C injury, and $270,000 for each K/A injury. The authors deemed it appropriate to use Mn/DOT's A-injury cost of $270,000 to represent the cost of a K/A severity crash due to the fact that none of the 33 guardrail collisions observed in this study resulted in a fatality. Thus, based on the logistic probabilities for crash severity, the predicted average cost of each approach guardrail crash was approximately $45,000 – significantly lower than the estimated average cost of $490,000 per crash based on the reported severities of the 49 crashes.

Prior to performing the benefit/cost computations, the 49 crashes were separated into categories based on the 2004 ADT. This was to allow for determination of a threshold ADT for approach guardrail installation. Many of the ADT categories were based on Mn/DOT roadway and/or bridge classification thresholds. Table 4 displays the actual reported crash severities and estimated costs along with the predicted crash severities and costs assuming guardrail had been in place at the time of the crash.

TABLE 4 Actual and Predicted Crash Severities and Crash Costs for Bridges without Approach Guardrail

		PDO		B/C injury		K/A injury		TOTAL	
	2004 ADT	Actual	Predicted if GR had been in place[a]	Actual	Predicted if GR had been in place[a]	Actual	Predicted if GR had been in place[a]	Actual	Predicted if GR had been in place[a]
CRASH FREQUENCIES	<150	3	2.34	1	1.30	0	0.35	4	4
	150- 399	4	5.86	2	3.26	4	0.88	10	10
	400- 749	4	7.62	6	4.24	3	1.14	13	13
	750- 999	1	3.52	2	1.96	3	0.53	6	6
	1000-1499	4	5.27	3	2.93	2	0.79	9	9
	1500-4999	0	0.59	0	0.33	1	0.09	1	1
	5000-9999	1	2.34	2	1.30	1	0.35	4	4
	10,000<	1	1.17	1	0.65	0	0.18	2	2
	All	18	28.71	17	15.97	14	4.31	49	49
CRASH COSTS[b]	<150	$12.9	$10.1	$59	$76.9	$0	$95.0	$71.9	$182.1
	150- 399	$17.2	$25.2	$88	$192.3	$4,310	$237.6	$4,415.2	$455.1
	400- 749	$17.2	$32.8	$324	$250.0	$4,040	$308.9	$4,381.2	$591.7
	750- 999	$4.3	$15.1	$88	$115.4	$7,270	$142.6	$7,362.3	$273.1
	1000-1499	$17.2	$22.7	$87	$173.1	$3,770	$213.8	$3,874.2	$409.6
	1500-4999	$0	$2.5	$0	$19.2	$3,500	$23.7	$3,500.0	$45.5
	5000-9999	$4.3	$10.1	$88	$76.9	$270	$95.0	$362.3	$182.1
	10,000<	$4.3	$5.0	$59	$38.5	$0	$47.5	$63.3	$91.0
	All	$77.4	$123.5	$793	$942.5	$23,160	$1,164.2	$24,030.4	$2,230.2

Note: [a] Based on logistic probabilities of an approach guardrail crash resulting in the specific severity category.
[b] In 2004 dollars (thousands) based on Mn/DOT's costs per crash of a given severity (*7*).

Table 4 shows that for nearly all ADT categories, the total crash costs were predicted to be greatly reduced if approach guardrail had been in place when the crashes occurred. This was due to the expectation that many K/A injury crashes would be replaced by crashes of a lower severity. When all crashes were considered, the overall crash cost was nearly 11 times greater for the actual crashes that occurred than would have been expected had guardrail been in place. The estimated crash savings for the 49 bridge rail/roadside collisions, assuming approach guardrail had been in place for each of the crashes, was approximately \$445,000 per crash and \$90,000 per bridge. Figure 7 shows the predicted crash cost savings per bridge (2004 dollars) expected if approach guardrail had been in place at the time of the collision. Also shown in Figure 7 are the estimated approach guardrail installation and maintenance costs for the 15-year analysis period (i.e., ½ of the 30-year life-cycle cost).

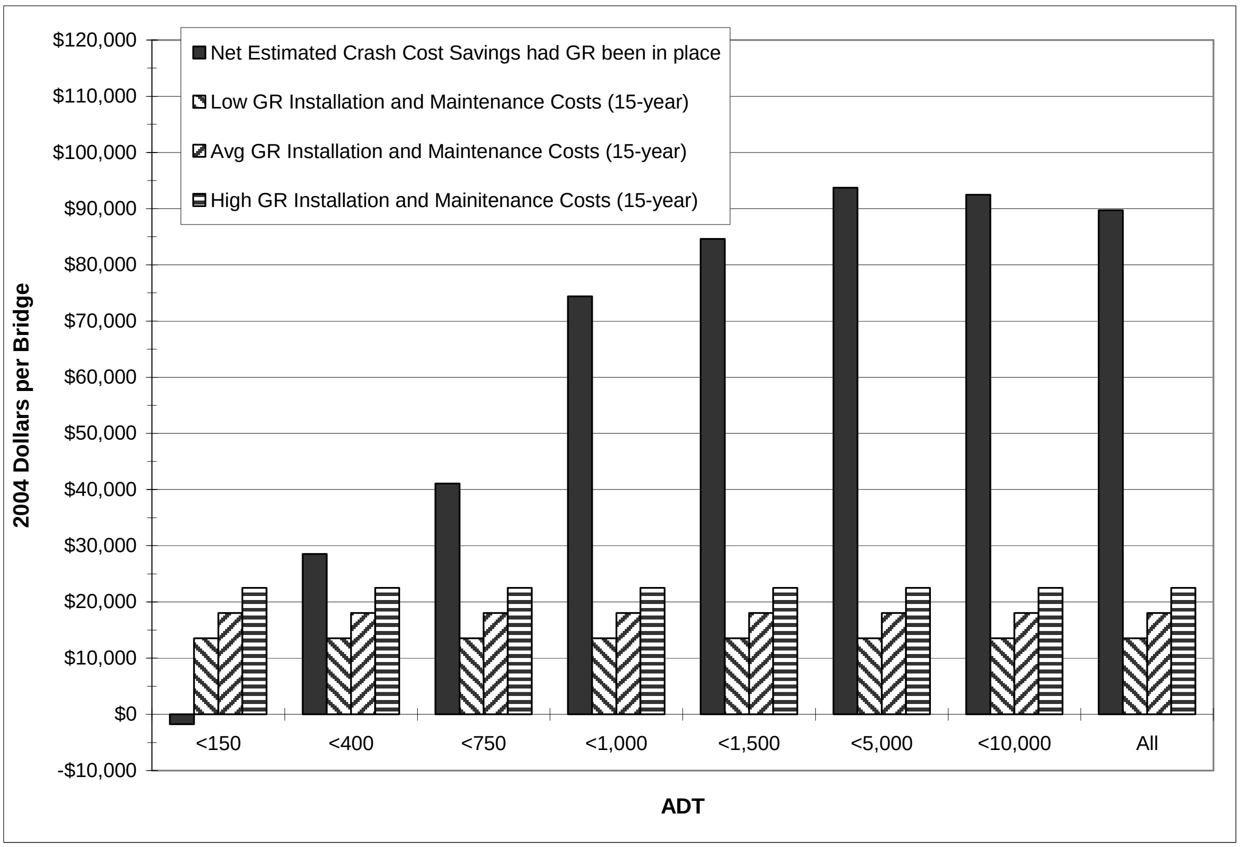


FIGURE 7 Predicted crash savings and costs per bridge if approach guardrail is installed.

The data in Table 4 and Figure 7 were used to compute a benefit/cost ratio for each ADT category using Equation 7 with the results displayed in Table 5 and Figure 8:

$$\frac{\text{Benefit}}{\text{Cost}} = \frac{\text{Cost of Crashes Based on Reported Severities}}{\text{Cost of Crashes Assuming GR Installed} + \text{GR Install. and Maint. Costs}} \qquad (7)$$

TABLE 5 Benefit/Cost Calculations for Bridge Approach Guardrail (15-year analysis period)

		Benefits[a]	Costs[a]				Benefit/Cost		
ADT	Bridges Without GR	Estimated Cost of Crashes that Occurred at Bridges Without GR	Predicted Cost of Crashes if GR had been In Place[b]	Min. GR Installation and Maintenance Costs	Avg. GR Installation and Maintenance Costs	Max. GR Installation and Maintenance Costs	**Max**	**Avg**	**Min**
<150	63	$1,141	$2,890	$13,550	$18,025	$22,500	**0.07**	**0.05**	**0.04**
<400	135	$33,238	$4,720	$13,550	$18,025	$22,500	**1.82**	**1.46**	**1.22**
<750	186	$47,679	$6,607	$13,550	$18,025	$22,500	**2.37**	**1.94**	**1.64**
<1,000	198	$81,973	$7,586	$13,550	$18,025	$22,500	**3.88**	**3.20**	**2.72**
<1,500	215	$93,511	$8,891	$13,550	$18,025	$22,500	**4.17**	**3.47**	**2.98**
<5,000	231	$102,185	$8,472	$13,550	$18,025	$22,500	**4.64**	**3.86**	**3.30**
<10,000	236	$101,556	$9,064	$13,550	$18,025	$22,500	**4.49**	**3.75**	**3.22**
All	243	$98,891	$9,178	$13,550	$18,025	$22,500	**4.35**	**3.64**	**3.12**
All >400	108	$180,956	$14,750	$13,550	$18,025	$22,500	**6.39**	**5.52**	**4.86**

Notes: [a] In 2004 dollars per bridge
[b] Based on severity probabilities generated by logistic regression assuming collision with approach guardrail.

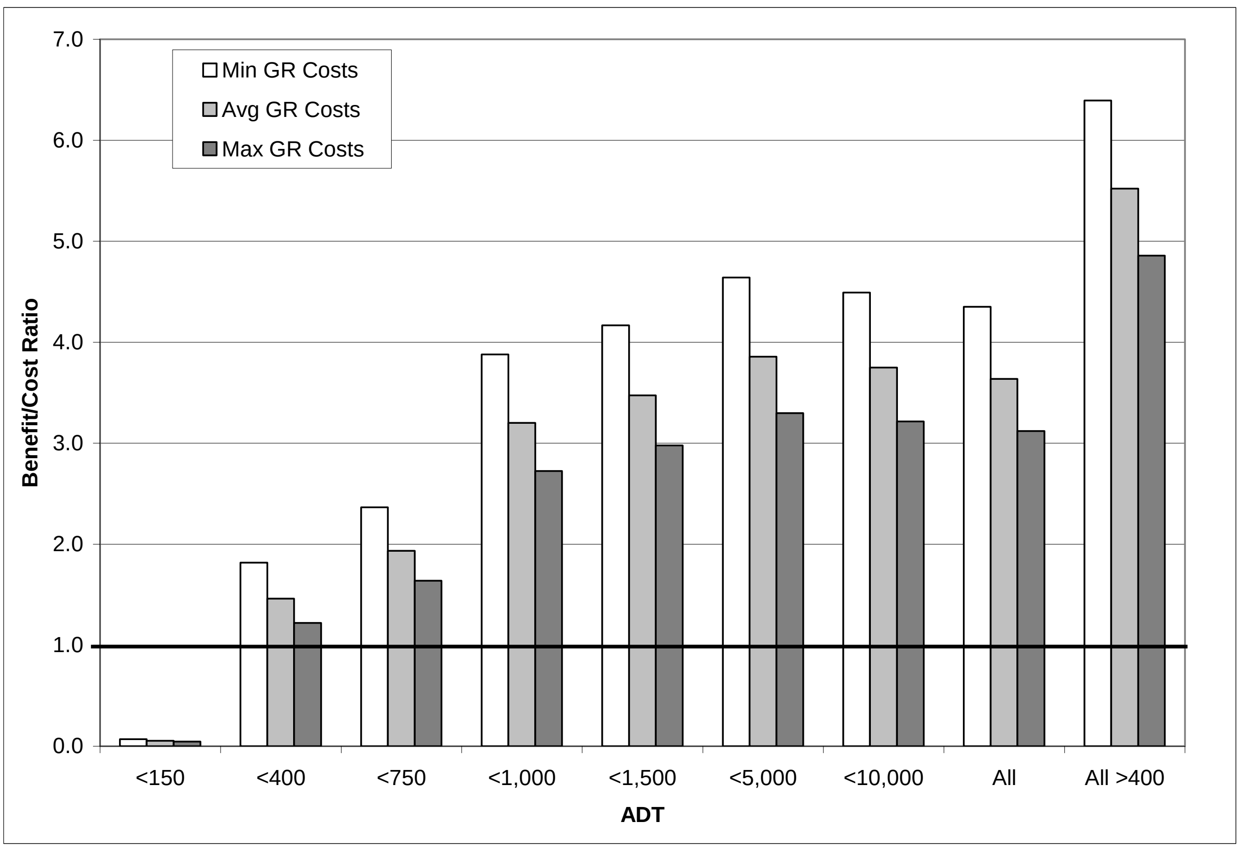


FIGURE 8 Benefit/Cost ratios for bridge approach guardrail based on cumulative ADT and guardrail installation and maintenance costs.

Table 5 and Figure 8 show that for bridges with ADT less than 150, the benefit/cost ratio for bridge approach guardrail was very small (i.e., < 0.10) due to an extreme infrequency of crashes at these bridges. The benefit/cost ratio became greater than 1.0 at an ADT threshold of 400. Closer analysis of crashes for ADTs less than 400 revealed that the benefit/cost ratio became equal to 1.0 at an ADT of slightly less than 400, although a threshold of 400 was deemed appropriate for recommendations presented here (*3*). The benefit/cost ratio for approach guardrail increased steadily as the ADT threshold increased above 400. If all bridges were considered, the overall benefit/cost ratio ranged between 3.12 and 4.35 depending on guardrail installation and maintenance costs. If only bridges with ADT greater than 400 wereconsidered, the overall benefit/cost ratio ranged between 4.86 and 6.39.

RECOMMENED CRITERIA FOR INSTALLATION OF BRIDGE APPROACH GUARDRAIL ON LOW VOLUME ROADS

The primary task of this research was to determine the appropriate ADT threshold at which installation of bridge approach guardrail on low volume roads is cost-effective. Although the analyses were based on data from county state-aid highways, the authors believe it is appropriate to extend these findings and recommendations to other non-NHS routes with similar characteristics, such as secondary state highways.

The chi-square analysis of 96 Minnesota crashes showed significantly lower rates of severe crashes (i.e., fatalities and A-injuries) at bridges where approach guardrail existed for all bridges except those with very low ADTs, where crashes were extremely infrequent. The subsequent benefit/cost analysis showed that approach guardrail is cost-effective (i.e., benefit/cost > 1) at all bridges except those with ADTs less than 400 and becomes increasingly more cost-effective with increasing ADT. Overall, approach guardrail has a benefit/cost ratio ranging from 3.12 to 4.35 depending on guardrail installation/maintenance costs.

The authors recommend that the ADT threshold for bridge approach guardrail installation on low volume roads be set at 400. In other words, all highway bridges with ADT greater than or equal to 400 should have guardrail connected to both the approach and departure sides of the bridge. A threshold ADT of 400 is consistent with current AASHTO very low-volume local road guidelines for roadside clear zones (*3*). The forecasted future ADT should be used for determining the need for approach guardrail on newly constructed or reconstructed bridges.

Installation of approach guardrail on bridges with ADT greater than 400 was predicted to have a benefit/cost ratio between 4.86 and 6.39. It is recommended that bridges with ADT between 150 and 400, especially those between 300 and 400, be reviewed on a case-by-case basis for guardrail need. For example, bridges located on horizontal curves and with bridge deck widths equal to or less than the approach roadway may warrant guardrail at ADT between 150 and 400. Placement of approach guardrail at bridges with ADT less than 150 is probably not cost-effective in most cases due to the extremely infrequent rate of crashes at these bridges.

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