GEORGIA DOT RESEARCH PROJECT 19-14

Final Report

EVALUATION OF GUARDRAIL PERFORMANCE IN HIGH-RISK ACCIDENT ZONES ON GEORGIA ROADWAYS AND IDENTIFICATION OF ALTERNATIVE BARRIERS

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In cooperation with
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November 2021

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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EXECUTIVE SUMMARY

The objective of this research project is to identify representative high-accident-rate (or "high-risk") zones of roadside barrier collisions in Georgia and to evaluate the types and the effectiveness of the barrier systems deployed in these areas. Based on this study, alternative barrier approaches will be considered for recommendation to reduce potential injury, crash severity, and repair costs in these high-risk zones.

Twenty-eight (28) freeway sections with frequent roadside-barrier collisions were identified in Georgia. Road design, traffic, and crash records pertaining to the selected road sections have been collected. Based on the collected information, a barrier crash-frequency model and a crash-severity model were developed through statistical regression. The regression models were used in the benefit–cost analysis to determine whether a concrete barrier is a more economical alternative to the guardrail. A simple chart was developed as a quick decision-making tool for future roadway design projects.

CONCLUSIONS

The following conclusions can be drawn from this research:

1. The frequency of roadside-barrier collisions is mostly affected by the traffic volume and the degree of horizontal curve of the road.
2. The existence of unreported crashes poses a challenge to the barrier safety research. It leads to a mismatch between the crash data and the maintenance record. The percentage of unreported crashes reduces nonlinearly with the posted speed of the

road. Concrete barrier shows a slightly lower percentage of unreported crashes than guardrail.

3. The severity of barrier collisions is mostly affected by the posted speed of the road and the barrier type. The crash severity in general increases exponentially with the posted speed of the road. When the posted speed of the road is less than 55 mph, concrete barriers produce more severe crashes than guardrail due to the rigidity of the barrier. When the posted speed of the road is more than 55 mph, guardrails produce more fatal and severe (K/A) crashes due to the increased odds of penetrating/ vaulting.
4. The BCA result showed that concrete barrier is more cost-effective for road sections with a posted speed of 55mph or higher. Guardrail barrier is more cost-effective for road sections with a posted speed of 35 mph or less for the range of of crash frequencies analyzed. For roads with a posted speed of 40 to 50 mph, concrete barrier should be considered for higher-risk road sections.
5. When the past crash record is unavailable, the cost-effective barrier type can also be determined based on an estimated barrier collision rate. In general, conditions that favor a concrete barrier over guardrail are straight (or slightly curved) road sections or sections with a one-way AADT of 40,000 or more.

RECOMMENDATIONS

1. The Roadside Safety Analysis Program (RSAP) developed from the National Cooperative Highway Research Program (NCHRP) Project 22-27 is the most sophisticated tool available for benefit–cost analysis of roadside safety features.

However, the RSAP baseline model often underestimates the actual crash frequency of "high-risk" barrier sections, especially for sharp horizontal curves (e.g., ramps). Although the program allows use of a modification factor to boost the predicted crash frequency, it still requires a judgment of the total number of crashes (including the unreported crashes) of the road. It is recommended that the Georgia Department of Transportation (GDOT) wait for the next updated version of the program.

2. The roadside barrier selection tools developed in this research can be used as a quick decision-making tool for barrier-upgrade projects. When a more accurate benefit–cost analysis is needed, the barrier crash-frequency model and the crash-severity model developed in this research can be applied in a spreadsheet or other computation program. Guardrail maintenance record should be used when available to determine the past average crash frequency of the road. When crash records are used, unreported crashes must be considered using the method presented in this study.
3. It is recommended GDOT build an inventory database for roadside barriers and use an asset management system for tracking the history and condition of roadside barriers.

CHAPTER 1. INTRODUCTION

BACKGROUND

Roadside barriers play an important role in highway traffic safety. The purpose for installing roadside barriers is to redirect and protect off-road vehicles from more harmful obstacles behind the barrier, such as a steep slope, a river, trees, or the opposing direction of traffic. W-beam guardrail systems are the predominant roadside safety barrier used on Georgia highways; other roadside barrier types in Georgia include thrie-beam (T-beam), concrete barrier, and cable barrier (figure 1). These systems are usually installed in accordance with guidelines for the Midwest Guardrail System (MGS)[1] and generally perform very well across the state. However, in certain areas of high traffic volume in Georgia, repetitive accident locations may benefit from the installation of alternative systems, rather than the traditional guardrail system. The most common alternative barrier system in Georgia is the single-slope concrete barrier system.

Figure 1. Photos. Standard roadside barriers deployed in Georgia in addition to the W-beam system.

OBJECTIVE

The objective of this research project is to identify representative high-accident-rate (or "high-risk") zones in Georgia and evaluate the type and effectiveness of the barrier system currently deployed in these areas. Based on this analysis, alternative barrier approaches will be considered for recommendation to reduce potential injury, crash severity, and repair costs in these high-risk accident zones.

SCOPE

This research focuses mainly on selection between two types of roadside barrier systems: the W-beam guardrail and the concrete barrier. The research goal is to: (1) determine whether concrete barrier is a more cost-effective alternative than guardrail on some of the high-risk sections in Georgia, and (2) develop simple selection criteria that are applicable to other high-risk road sections. The road and traffic characteristics considered in this research include roadway alignment, cross-section geometry, and traffic volume. Although the frequency and severity of barrier collisions can be affected by many other factors, such as weather and pavement surface conditions, these factors are not considered in this research. Also, all high-risk sections studied in this project are from either a simple freeway section or a freeway ramp; therefore, the research findings are not applicable to undivided highways or intersections.

LITERATURE REVIEW

The selection of barrier system is a comprehensive judgment based on many factors. The American Association of State Highway and Transportation Officials (AASHTO)

Roadside Design Guide (RDG)[2] provided a list of eight selection criteria for roadside barriers. These selection criteria include performance capacity, deflection, site conditions, compatibility, cost, maintenance, aesthetics, and field experience. The RDG also suggested that, at high-volume and high-collision-frequency sections, the repair cost may become the overriding consideration. A benefit–cost analysis (BCA) can be performed to compare the life-cycle cost and benefit of different barrier systems. A general guideline is provided by the U.S. Federal Highway Administration (FHWA) *Highway Safety Benefit–Cost Analysis Guide*.[3]

Elvik used meta-analysis to summarize evidence from 32 previous studies that evaluated the safety effects of median barriers, guardrails along the edge of the road, and crash cushions (i.e., impact attenuators).[4] Two hundred and thirty-two (232) estimates of safety effects were included in the meta-analysis. Based in part on this work, the Virginia DOT (VDOT) developed a risk-based management tool to use as a decision aid for allocation decisions for roadside safety hardware.[5] The decision tool comprises three parts: database, screening, and evaluation. A similar risk management study was performed by the Indiana Department of Transportation (INDOT).[6] The INDOT study examined the use of roadside guardrails on state roadways, conducted field visits to fatal crash sites, analyzed two-year crash data, and investigated the characteristics of crashes and main contribution factors. In addition, the study developed the probabilities for crash predictions and identified the costs associated with guardrail crash repairs and maintenance for guardrail benefit–cost analysis.

Fewer studies, however, specifically investigate the relative effectiveness of highway safety hardware alternatives, particularly in high-crash zones. Zou et al. investigated the safety performance of road barriers in Indiana in reducing the risk of injury.[7] The authors compared the risk of injury among different hazardous events faced by an occupant in a single-vehicle crash. The hazardous events included rolling over, striking three types of barriers (i.e., guardrails, concrete barrier walls, and cable barriers) with different barrier offsets to the edge of the traveled way, and striking various roadside objects. A total of 2,124 single-vehicle crashes (3,257 occupants) that occurred between the years 2008 and 2012 on 517 pair-matched homogeneous barrier and nonbarrier segments were analyzed. A binary logistic regression model with mixed effects was estimated for vehicle occupants. The modeling results revealed that hitting a barrier was associated with lower risk of injury than a high-hazard event (e.g., hitting a pole, rollover, etc.). This study found that the odds of injury were 43 percent lower when striking a guardrail instead of a median concrete barrier that was offset 15–18 ft, and 65 percent lower when striking a median concrete barrier offset 7–14 ft. The odds of injury when striking a near-side median cable barrier were 57 percent lower than the odds for a guardrail face. This reduction for a far-side median cable barrier was 37 percent. Thus, the authors concluded that a guardrail should be preferred over a concrete wall, and a cable barrier should be preferred over a guardrail where the road and traffic conditions allow.

Zou and Tarko studied the probabilities of various types of crash events possible under various road and barrier scenarios.[8] Seven barrier-relevant crash events possible after a vehicle departs the road were identified based on existing crash data, and their probabilities were estimated given the presence and location of three types of barriers: median concrete barriers, median and roadside W-beam steel guardrails, and high-tension median cable barriers. A multinomial logit model with variable outcomes was estimated based on 2,049 barrier-relevant crashes occurring between 2003 and 2012 on 1,258 unidirectional traveled ways in Indiana. The results of this study indicated that road departures lead to less frequent crossings of unprotected (no barriers) medians 50–80 ft wide than for narrower medians 30–50 ft wide.

More recently, Russo and Savolainen investigated barrier performance using an analysis of crash frequency and severity data from freeway segments where high-tension cable, thrie-beam, and concrete median barriers were installed.[9] They conducted a manual review of crash reports to identify crashes in which a vehicle left the roadway and encroached into the median. This review also involved an examination of crash outcomes when a barrier strike occurred, which included vehicle containment, penetration, or re-direction onto the travel lanes. Statistical models were developed to identify factors that affect the frequency, severity, and outcomes of median-related crashes, with particular emphasis on differences between segments with varying median barrier types. Several roadway-, traffic-, and environmental-related characteristics were found to affect these metrics, with results varying across the different barrier types.

The Florida DOT (FDOT) designates three factors to assess when considering barrier upgrades: (1) nature and extent of barrier deficiencies, (2) past crash history, and (3) cost-effectiveness of the recommended improvement.[10] However, limited specific information on the use of these assessment factors is presented.

CHAPTER 2. HIGH-RISK ROADSIDE BARRIER SECTIONS IN GEORGIA

Road sections with more frequent barrier collisions were identified in this research. Two sources of information were considered during the process: crash report data and maintenance data.

CRASH REPORT DATA

Crash report data are available in the Georgia Electronic Accident Reporting System (GEARS). In this database, crashes involving roadside-barrier collisions can be identified by filtering the “first hazardous event” with keywords of “guard rail face,” “guard rail end,” “median barrier,” and “cable barrier.” In this study, the crash data from 2017 to 2020 were used. Earlier crash data were excluded because of the potential change of the road characteristics. In the four-year period, a total of 18,108 crashes were reported where a single vehicle first struck on the roadside barrier. As shown in figure 2, most of these roadside-barrier collisions occurred in the Atlanta metropolitan area or on the high-volume national highway.

The crash-severity data in GEARS showed that, overall, 70 percent of the single-vehicle roadside-barrier collisions are rated as property damage only (PDO), and about one percent are fatal (figure 3). In general, the crash severity increases with the posted speed of the road up to 60–65 mph. Interestingly, the crashes that occurred on roads with a posted speed of 70 mph (interstate routes) showed less crash severity (figure 4). This trend indicated that there may be other factors affecting the severity of roadside-barrier collisions.

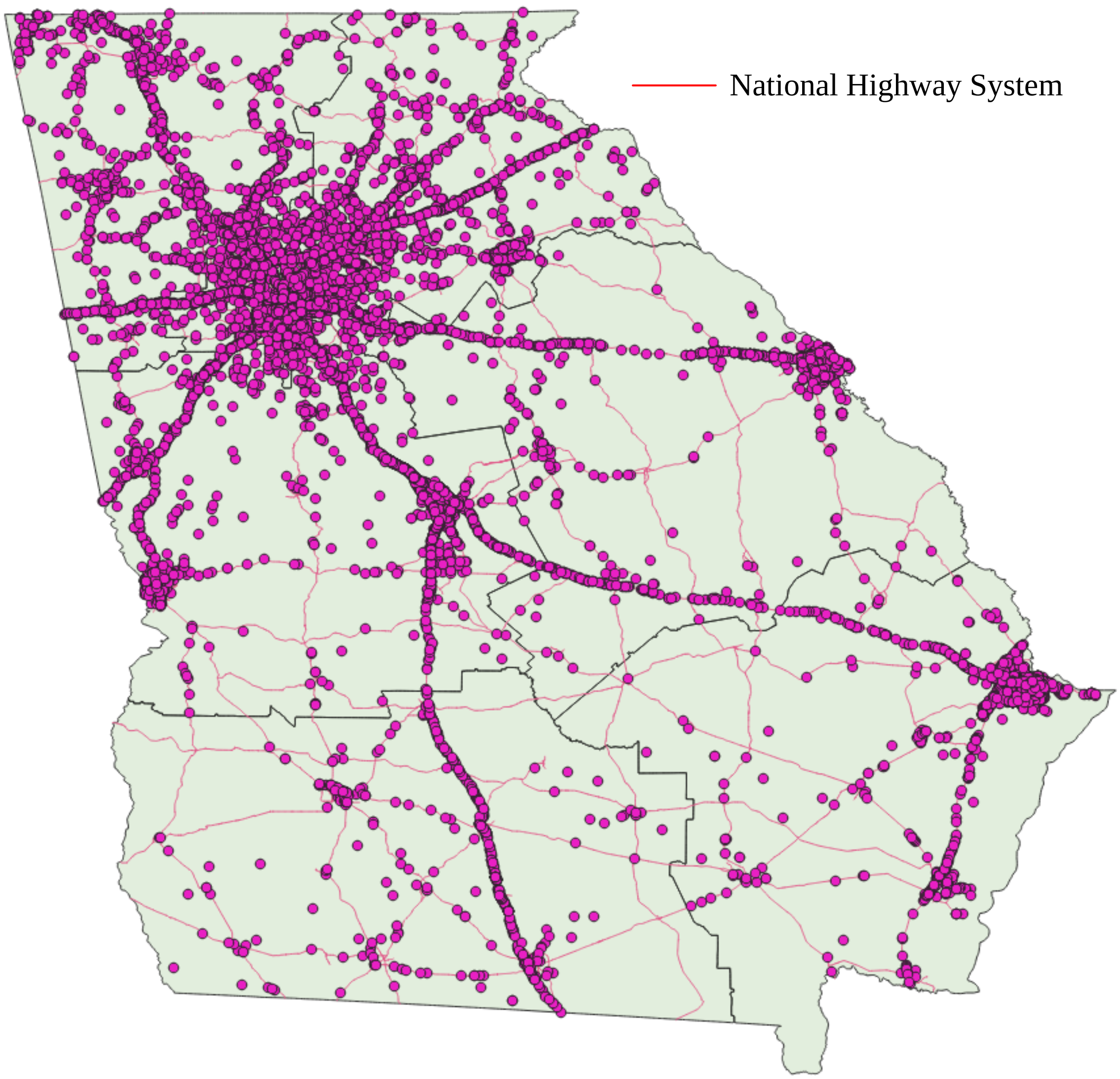

Figure 2. Map. Vehicle collisions with roadside barriers 2017–2020.
(Data source: GEARS)

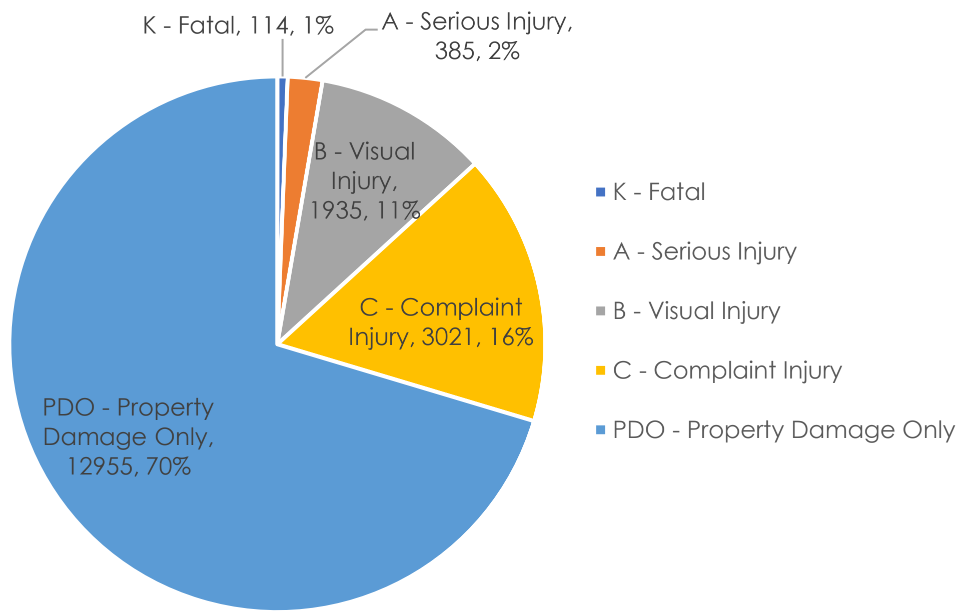

Figure 3. Chart. KABCO severity of single-vehicle barrier-collision crashes in Georgia.(Data source: GEARS, 2017–2020)

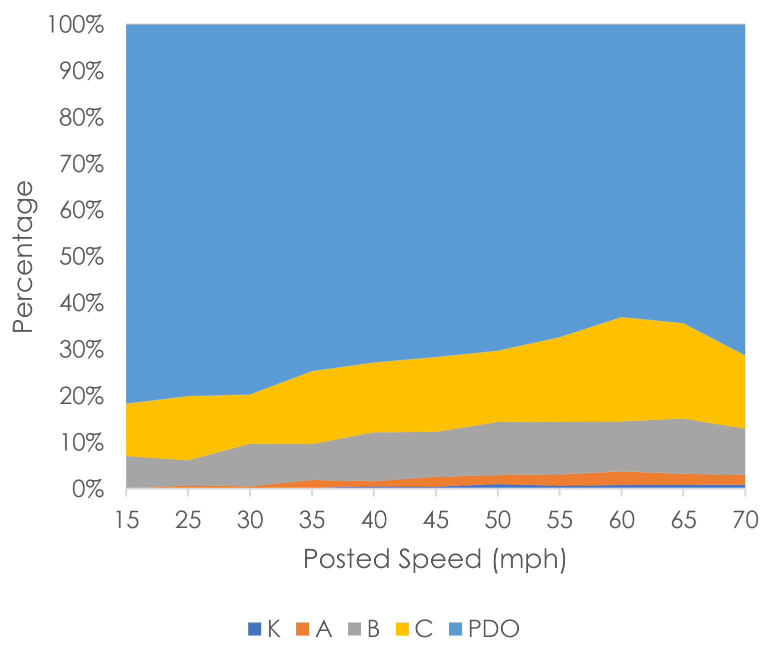

Figure 4. Chart. KABCO severity of single-vehicle barrier-collision crashes at different posted speeds.(Data source: GEARS, 2017–2020)

MAINTANANCE DATA

Another source of information about roadside-barrier collisions is the barrier-maintenance data. In the past, the guardrail and cable barrier–maintenance records have been kept by each district in different table formats. There is an ongoing effort to transfer all these maintenance data into a central GIS database. However, at the time of this research project, only a small amount of the maintenance data has been transferred into the new database. Another drawback of the barrier-maintenance data is that it does not show collisions with concrete barriers because concrete barriers are rarely damaged by a traffic crash. Therefore, the barrier-maintenance data are used only as a supplemental data source in this research.

HIGH-RISK BARRIER SECTIONS

Based on the crash-report and roadside barrier–maintenance data, 28 high-risk sections were selected for further analysis, including 15 concrete-barrier sections and 13 guardrail sections. General information about the selected barrier sections is presented in table 1. The locations of the selected barrier sections are shown in figure 5. Of the 28 high-risk sections selected, 14 sections are located in the Atlanta metropolitan area (District 7). All the selected road sections in this research showed more frequent barrier collisions compared to nearby road sections on the same route.

The 2017–2020 crash report information on each barrier section was collected from GEARS. Note that when counting barrier collisions at each section, only collisions on one side (either median or shoulder) of the barrier were counted. In the case where the two sides of the road have the same barrier type, the side with more barrier collisions was selected. A significant effort was made to read the descriptions in police crash reports to determine the exact location and nature of the accident. From 2017 to 2020, the single-vehicle barrier collision accidents on these high-risk sections totaled 590. On average, each section has 5.3 reported single-vehicle barrier collisions every year. The actual collision frequency is expected to be higher due to unreported crashes, a well-known issue with crash report data.

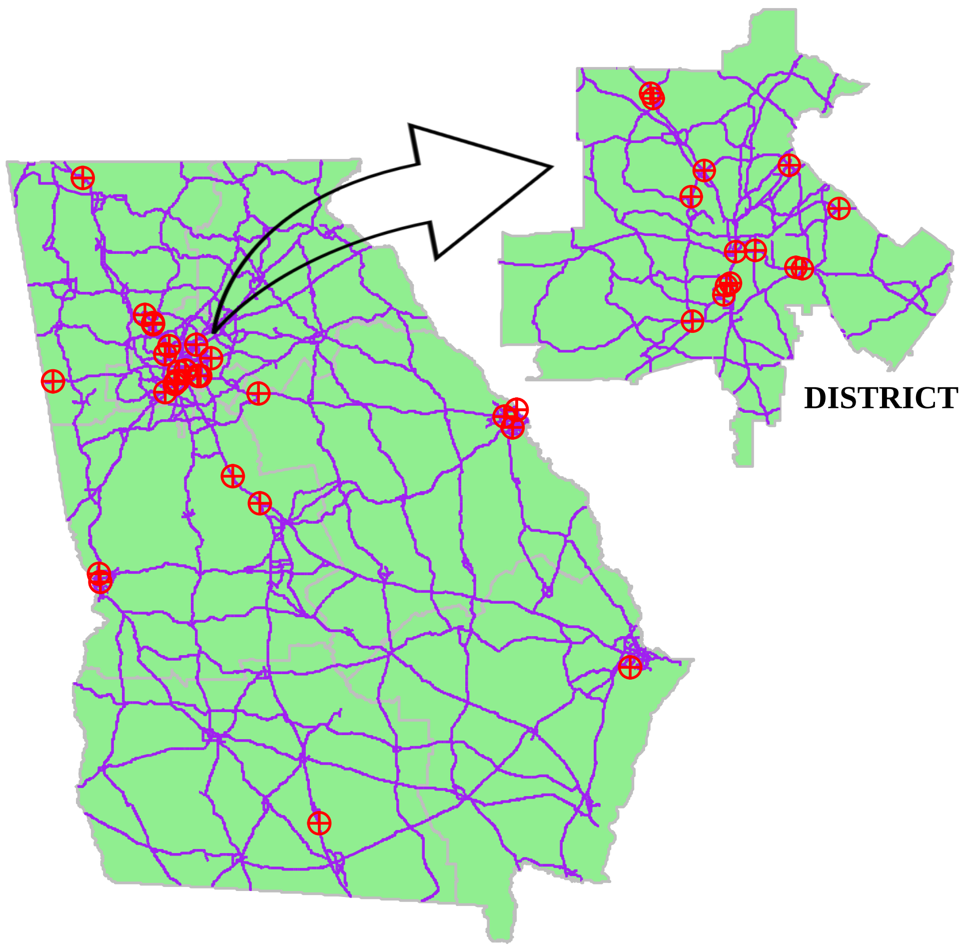

Figure 5. Map. Selected high-risk barrier sections.

Table 1. General information of the selected high-risk barrier sections.

Section No.	Barrier Type*	Route	Route Type	Speed (mph)	Length (ft)	AADT (One-Way)	Reported Single-Vehicle Barrier Crashes (2017–2020)
1	CB	I-520	Freeway	60	4,330	30,000	11
2	CB	SR-104	Freeway	45	1,848	11,950	9
3	CB	I-520	Freeway	65	1,267	45,700	11
4	CB	SR-204	Ramp	25	1,056	22,100	19
5	CB	I-75	Freeway	70	1,214	22,400	23
6	CB	I-75	Freeway	65	686	62,500	23
7	CB	I-285/I-75	Ramp	40	106	12,510	18
8	CB	I-20	Ramp	65	1,267	70,000	53
9	CB	I-285	Freeway	65	1,109	84,000	21
10	CB	I-185	Freeway	70	475	37,050	16
11	CB	I-20	Freeway	70	2,165	23,550	14
12	CB	I-20	Ramp	35	1,426	54,550	43
13	CB	I-20/I-75	Ramp	25	370	48,900	54
14	CB	I-85	Freeway	55	1,901	85,750	54
15	GR	I-85	Freeway	55	1,056	85,750	21
16	GR	I-285	Ramp	15	158	8,160	16
17	GR	I-285/I-85	Ramp	25	264	12,510	8
18	GR	I-20	Freeway	70	686	18,200	13
19	GR	I-75	Freeway	70	2,218	38,100	9
20	GR	I-75	Freeway	70	1,109	46,350	13
21	GR	SM Fwy	Ramp	30	317	4,980	23
22	GR	I-20	Ramp	25	264	7,930	13
23	GR	I-75	Freeway	65	1,056	64,000	17
24	GR	US80/I-185	Ramp	30	581	6,940	12
25	GR	I-20	Freeway	70	581	38,800	25
26	GR	I-75	Ramp	25	106	1,790	24
27	GR	I-75	Freeway	70	2,640	44,750	12
28	GR	I-85	Freeway	55	1,000	85,750	15

*CB = Concrete Barrier, GR = Guardrail

ROAD AND TRAFFIC DATA COLLECTION

The road and traffic information was collected from several different sources, including Georgia DOT (GDOT) Office of Transportation data, the GDOT Traffic Analysis & Data

Application (TADA), Google Earth, and Google satellite image. The collected information is presented in the appendix of this report.

CHAPTER 3. FREQUENCY AND SEVERITY OF ROADSIDE-BARRIER COLLISIONS

In this chapter, the frequency and severity of the roadside-barrier collisions are evaluated at the 28 high-risk barrier sections. The goal is to identify sensitive parameters from road, traffic, and barrier characteristics and develop prediction models for the frequency and severity of barrier crashes for high-risk sections. These prediction models are the basis of the subsequent benefit–cost analysis for comparing different roadside barriers.

UNREPORTED CRASHES

Unreported crashes are traffic crashes that did not generate a police report record. A national telephone survey conducted in 2010 estimated that about 30 percent of traffic crashes went unreported.[11] Although many of the unreported crashes can be assumed to be PDO, the repair cost of the roadside barrier should be considered in the benefit–cost analysis. The number of unreported crashes can be estimated from the maintenance records or from the crash severity.

Estimation Based on Maintenance Record

One way to estimate the number of unreported crashes is to investigate the guardrail maintenance record of the site. For example, figure 6 shows the crash and maintenance records for the guardrail on the Exit 32 ramp of I-285EB between May 2019 and March 2021. During that period, the W-beam guardrail has been repaired 10 times, of which 6 repairs do not have a clear corresponding reported crash. Knowing that not all damages to the guardrail need a repair, it can be estimated that this guardrail section has at least 60 percent unreported crashes.

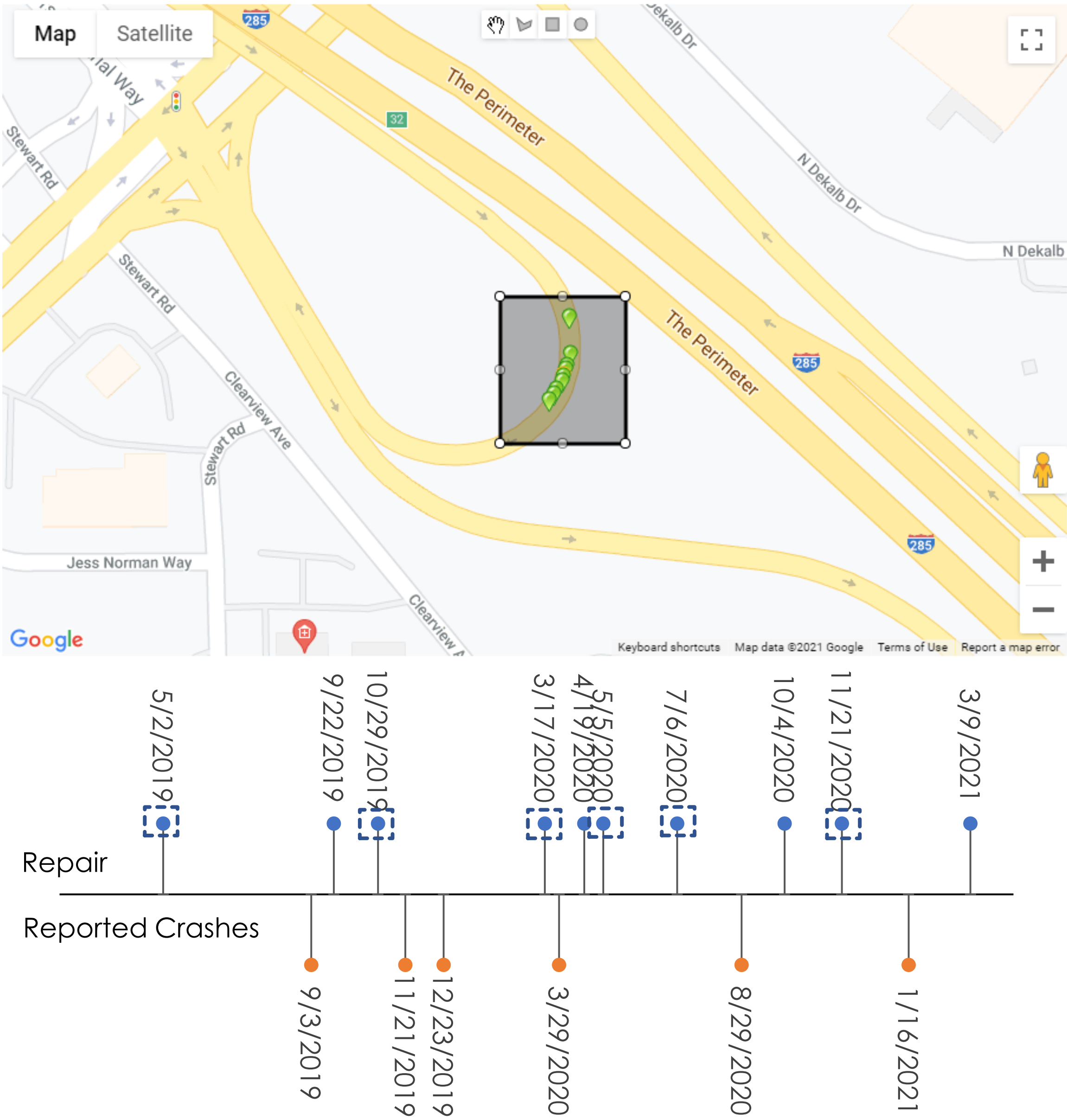

Figure 6. Map. Crash and maintenance records at the Exit 32 ramp on I-285EB.

Figure 7 shows the crash and maintenance records of another guardrail section on I-85SB near Exit 77 in Atlanta. Between June 2019 and March 2021, the guardrail section has been repaired 11 times, of which 5 repairs do not have a clear corresponding reported crash.

Knowing not all damages to the guardrail need a repair, it can be estimated that this guardrail section has at least 45 percent unreported crashes.

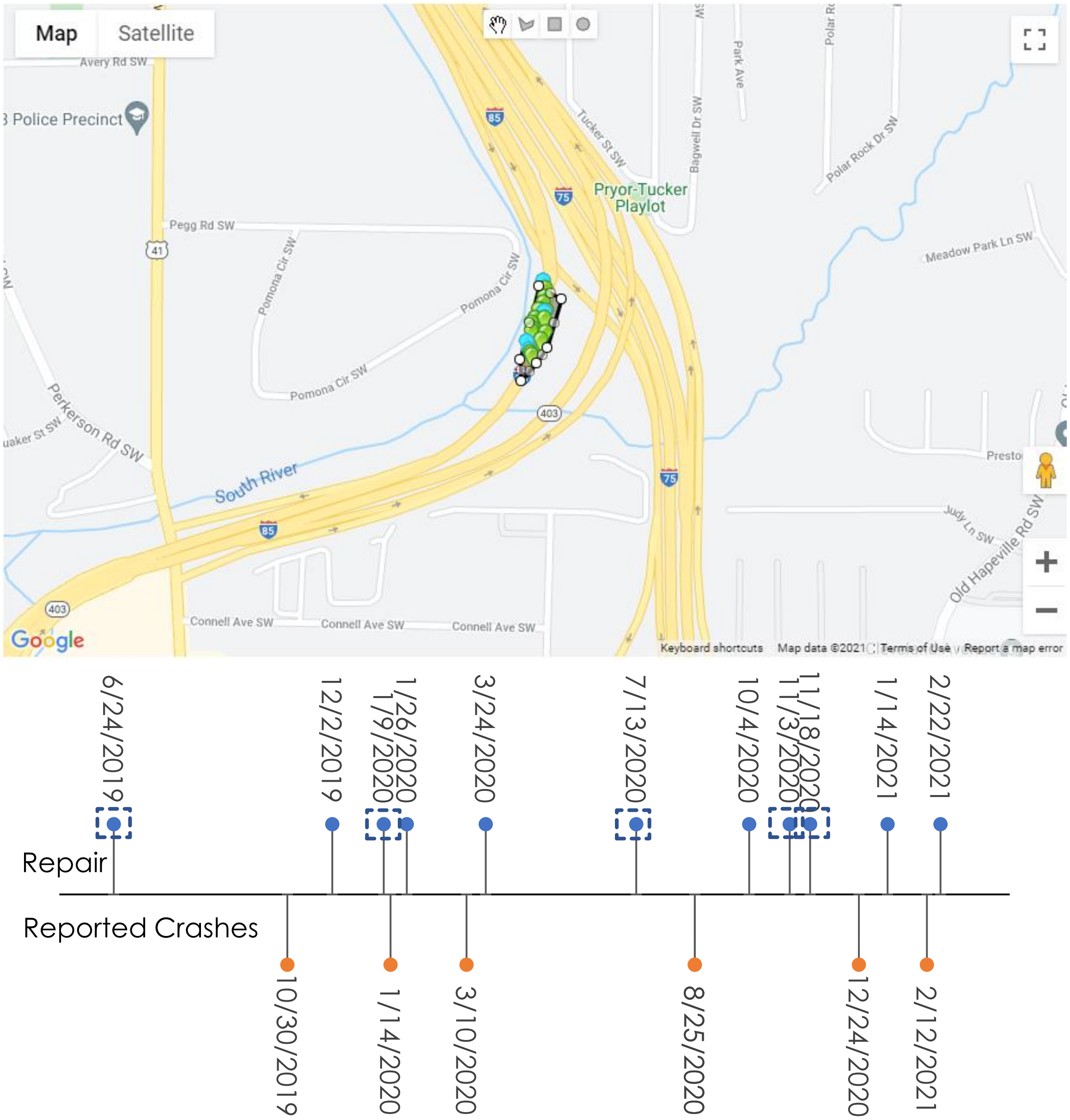

Figure 7. Map. Crash and maintenance records on I-85SB near Exit 77.

Figure 8 shows the crash and maintenance records of another guardrail section on the I-75SB Exit 237 ramp south of Atlanta. Between April 2019 and June 2021, the guardrail section has been repaired 13 times, of which 9 repairs do not have a clear corresponding reported crash. Knowing not all damages to the guardrail need a repair, it can be estimated that this guardrail section has at least 70 percent unreported crashes.

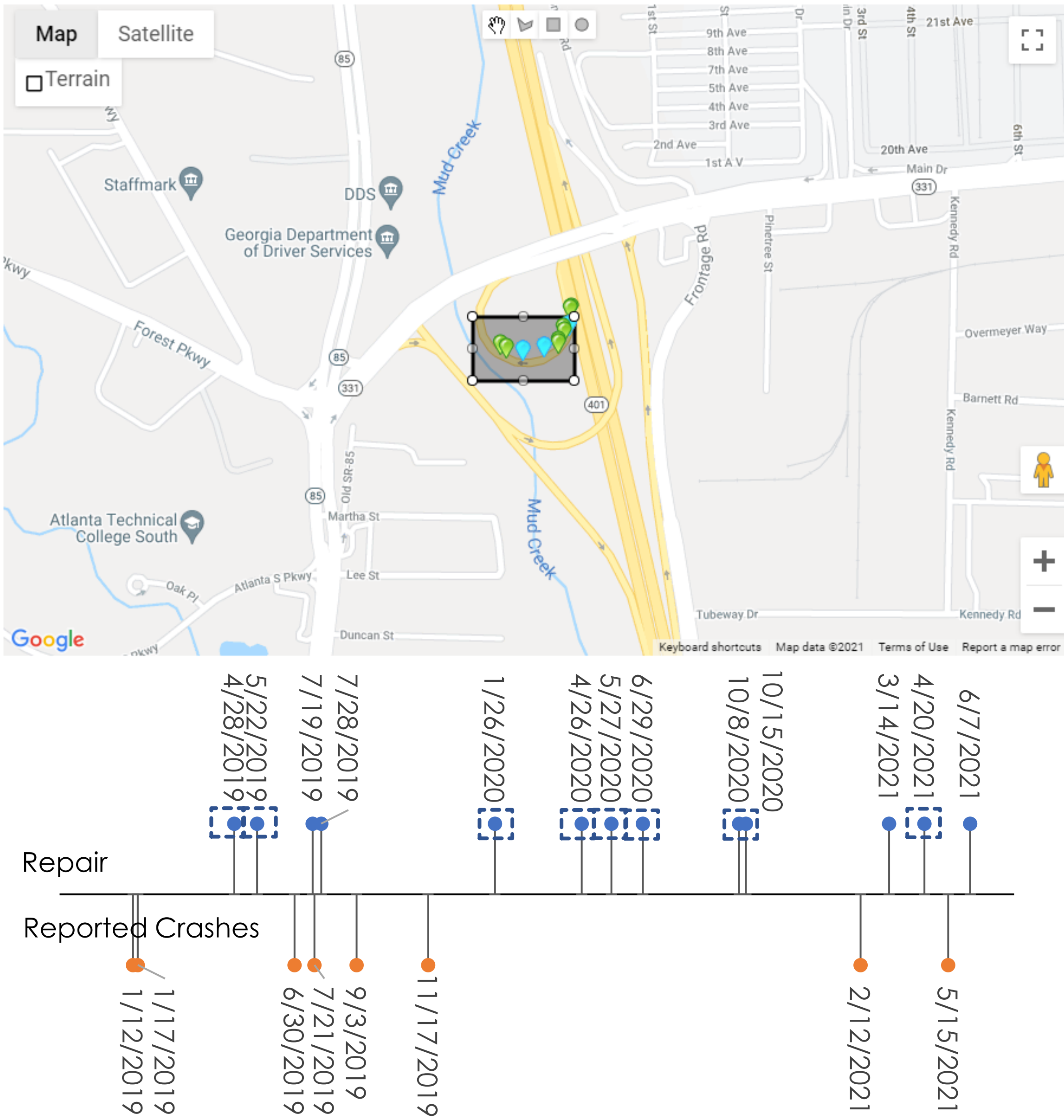

Figure 8. Map. Crash and maintenance records at the Exit 237 ramp on I-75SB.

At the time of this research, only District 7 has about two years of relatively complete guardrail maintenance records in the GDOT 411 database. Thus, the above analysis cannot be performed for all selected guardrail sections. Furthermore, as discussed in chapter 2, concrete barrier sections are rarely damaged by vehicle collisions; therefore, this method cannot be applied to determine the percentage of unreported crashes in concrete-barrier sections.

Estimation Based on Crash Severity

The National Cooperative Highway Research Program (NCHRP) Project 22-27 proposed a method to estimate the number of unreported crashes based on the crash severity data.[12] The basic assumption is that the percentage of non-PDO crashes increases with the posted speed of the road with a square-power relationship. Then, the percentage of unreported crashes (assumed to be PDO) at different posted speeds can be estimated by fitting the square-power relationship. The strength of this method is that it considers the effect of the posted speed. Intuitively, lower-speed roads should have more unreported crashes on roadside barriers. This method can also be applied to all barrier types. However, the GEARS data do not clearly differentiate between concrete barriers and guardrails in the "First Harmful Event" field. A collision on a double-face W-beam median can be classified as "median barrier," and a collision on a concrete shoulder barrier can be classified as "guardrail face."

To identify crashes on a particular type of barrier, we filtered the "Crash Narrative" field in the GEARS data and looked for entries in which the keyword "guardrail" or "concrete" closely followed (within 40 characters) the keyword "struck." With the 2017–2020 crash data, we identified 4,174 guardrail collisions and 1,408 concrete-barrier collisions. Table 2 and table 3 show the statistics of KABCO severity ratings on roads with different posted speeds for collisions on guardrails and concrete barriers, respectively.

Table 2. Estimated unreported crashes for collisions on guardrails.

Speed	K	A	B	C	PDO	Total	Observed Injury Rate*	Estimated Injury Rate	Est. Unreported Crashes	Est. % Unreported Crashes
30	0	0	5	2	21	28				
35	2	6	27	40	195	270	0.28	0.08	662	71.03
40	0	2	9	5	42	58	0.28	0.11	94	61.84
45	5	17	67	61	371	521	0.29	0.13	606	53.77
50	2	1	10	10	44	67	0.34	0.16	73	52.14
55	9	20	111	115	542	797	0.32	0.20	486	37.88
60	1	5	12	15	58	91	0.36	0.24	48	34.53
65	14	19	114	123	539	809	0.33	0.28	163	16.77
70	20	42	186	246	1,039	1,533	0.32	0.32	1	0.07
					Total	4,174				

*Injury Rate = (K+A+B+C)/Total

Table 3. Estimated unreported crashes for collisions on concrete barriers.

Speed	K	A	B	C	PDO	Total	Observed Injury Rate*	Estimated Injury Rate	Est. Unreported Crashes	Est. % Unreported Crashes
30	0	0	1	0	3	4				
35	0	1	6	6	33	46				
40	0	0	1	6	11	18				
45	0	2	7	17	92	118	0.22	0.12	606	53.77
50	0	1	5	7	22	35				
55	0	3	37	68	249	357	0.30	0.17	486	37.88
60	0	1	6	10	41	58	0.29	0.20	48	34.53
65	0	6	32	67	216	321	0.33	0.24	163	16.77
70	1	4	62	59	325	451	0.28	0.28	1	0.07
					Total	1,408				

*Injury Rate = (K+A+B+C)/Total

Table 2 and table 3 also show the estimated percentages of unreported crashes based on the observed injury rates. Note that the calculation was only performed when the total observed crashes exceeded 50 to obtain a reliable estimation. Figure 4 presents the estimated percentages of unreported crashes for guardrails and concrete barriers. Percentage of unreported crashes decreases with the posted speed of the road. Concrete-barrier sections showed lower percentage of unreported crashes than guardrail sections, especially for lower-speed roads. This result is expected because a concrete barrier is more likely to disable a vehicle and result in a police report.

Two smoothed curves were drawn in figure 9 to fit the data. These curves were used to estimate the actual frequency of crashes for each of the high-risk sections selected in this research. Meanwhile, the observed minimum unreported crashes from the three road sections in District 7 were also plotted on figure 9. The field observation matched reasonably well with the fitted curves.

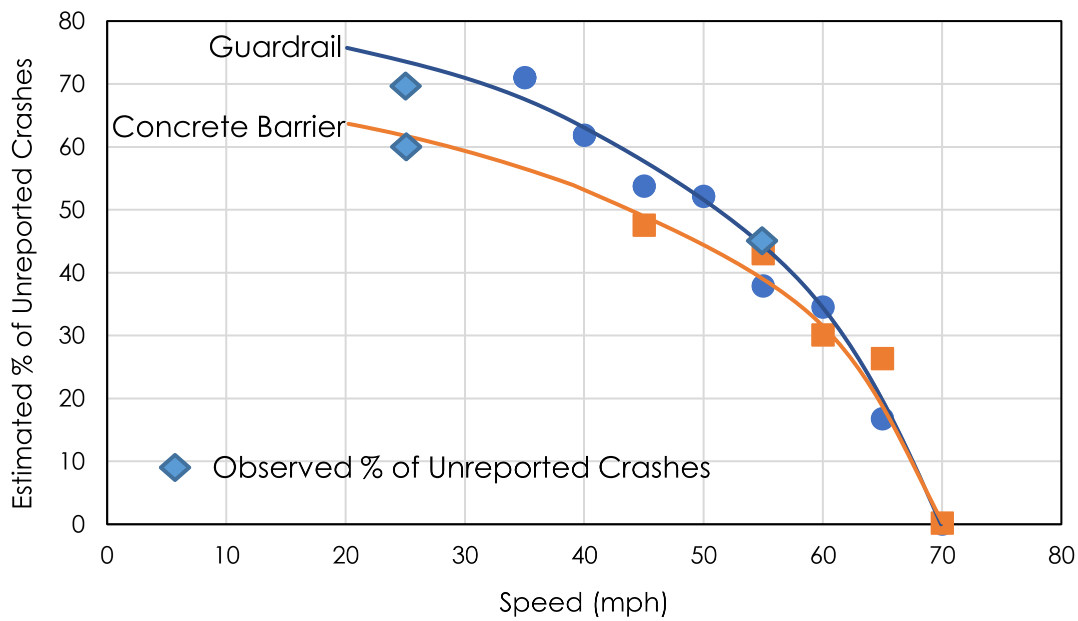

Figure 9. Graph. Unreported crashes at different speeds.

CRASH FREQUENCY AND CRASH RATE

Crash frequency is defined as the number of single-vehicle barrier collisions per year. The This parameter does not consider the traffic volume or the length of the road. The crash rate of the barrier section in this study is defined as the number of single vehicle barrier collisions per unit 1000 ft of road per 1,000,000 traffic exposures, as shown in equation 1.

$$Rate = \frac{1{,}000{,}000{,}000\ C}{365\ (ADT)(L)(N)} \quad (1)$$

where C is the number of single vehicle barrier collisions, L is the length of the barrier section in ft, ADT is the average daily traffic (one-way), and N is the number of years of record. Table 4 shows the calculated frequency and rate of single vehicle barrier collisions for the 28 high-risk sections.

The Roadside Safety Analysis Program (RSAP) developed by the NCHRP Project 22-27 includes a crash-frequency prediction model.[13] The prediction is based on the road, traffic, barrier, and roadside slope features. A comparison was made between the predicted and the estimated actual number of crashes for the 28 selected barrier sections (figure 10). The RSAP underpredicts number of crashes for most of the barrier sections. This is reasonable because the baseline encroachment model in the program is not designed to represent high-risk road sections. Further evaluation showed that the RSAP is not sensitive to the radius of the horizontal curve. Therefore, the program significantly underpredicted the number of barrier crashes for highly curved highway ramps.

Table 4. Frequency and Rate Single Vehicle Barrier Collisions of High-Risk Sections

ID	Reported Crashes	Estimated Unreported Crashes	Total Crashes	Crash Frequency (Reported)	Crash Rate (Reported)	Crash Frequency (Total)	Crash Rate (Total)
1	11	3	14	2.75	0.082	3.5	0.104
2	9	8	17	2.25	0.279	4.25	0.527
3	11	3	14	2.75	0.130	3.5	0.166
4	19	31	50	4.75	1.115	12.5	2.935
5	23	0	23	5.75	0.351	5.75	0.351
6	23	5	28	5.75	0.298	7	0.363
7	18	20	38	4.5	9.333	9.5	19.702
8	53	12	65	13.25	0.409	16.25	0.502
9	21	5	26	5.25	0.154	6.5	0.191
10	16	0	16	4	0.509	4	0.509
11	14	0	14	3.5	0.188	3.5	0.188
12	43	57	100	10.75	0.465	25	1.081
13	54	88	142	13.5	1.592	35.5	4.186
14	54	33	87	13.5	0.227	21.75	0.366
15	21	13	34	5.25	0.159	8.5	0.257
16	16	54	70	4	8.479	17.5	37.094
17	8	23	31	2	3.318	7.75	12.858
18	13	0	13	3.25	0.579	3.25	0.579
19	9	0	9	2.25	0.073	2.25	0.073
20	13	0	13	3.25	0.173	3.25	0.173
21	23	56	79	5.75	9.985	19.75	34.297
22	13	37	50	3.25	4.253	12.5	16.358
23	17	4	21	4.25	0.172	5.25	0.213
24	12	29	41	3	2.039	10.25	6.967
25	25	0	25	6.25	0.760	6.25	0.760
26	24	19	43	6	86.964	10.75	155.811
27	12	0	12	3	0.070	3	0.070
28	15	12	27	3.75	0.120	6.75	0.216

The Roadside Safety Analysis Program (RSAP) developed by the NCHRP Project 22-27 includes a crash-frequency prediction model.[13] The prediction is based on the road, traffic, barrier, and roadside slope features. A comparison was made between the predicted and the estimated number of crashes for the 28 selected barrier sections (figure 10). The RSAP underpredicts number of crashes for most of the barrier sections. This is reasonable because the baseline encroachment model in the program is not designed to represent high-risk road sections. Further evaluation showed that the RSAP is not sensitive to the radius of the horizontal curve. Therefore, the program significantly underpredicted the number of barrier crashes for highly curved highway ramps.

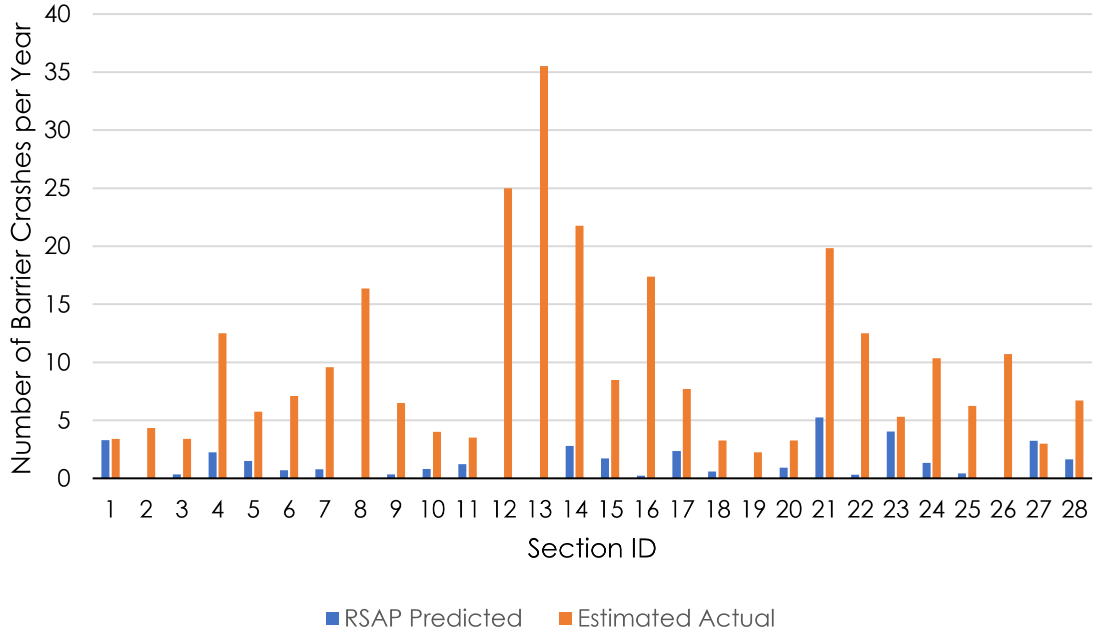

Figure 10. Graph. RSAP predicted vs. actual number of crashes.

To develop a crash-prediction model for high-risk barrier sections, an analysis of variance (ANOVA) was first conducted to evaluate the relationship between the estimated actual crash frequency and different road characteristics. For the model development purpose, the crash frequency was normalized based on an average daily traffic (ADT) of 1,000 and a length of 1,000 ft. The result of the ANOVA is presented in table 5.

Out of the six factors evaluated, the two factors that showed significant effects on the crash rate are the degree of horizontal curve and posted speed. The most significant factor to the frequency of roadside-barrier collisions is the degree of horizontal curve (=5729.6/radius).

A sharper horizontal curve (such as that in a ramp) significantly increases the frequency of roadside-barrier collisions (figure 11).

Table 5. ANOVA on crash frequency.

	Df	Sum Sq	Mean Sq	F value	P-value
Degree of curve	1	7955	7955	26.658	0.0002*
Lane width	1	1134	1134	4.717	0.1091
Number of lanes	1	65	65	1.324	0.6926
Vertical grade	1	18	18	0.044	0.8371
Lateral clearance	1	764	764	3.139	0.1841
Posted speed	1	6147	6147	19.169	0.0008*
Residuals	21	8509	405		

*Significant factor (p-value<0.05)

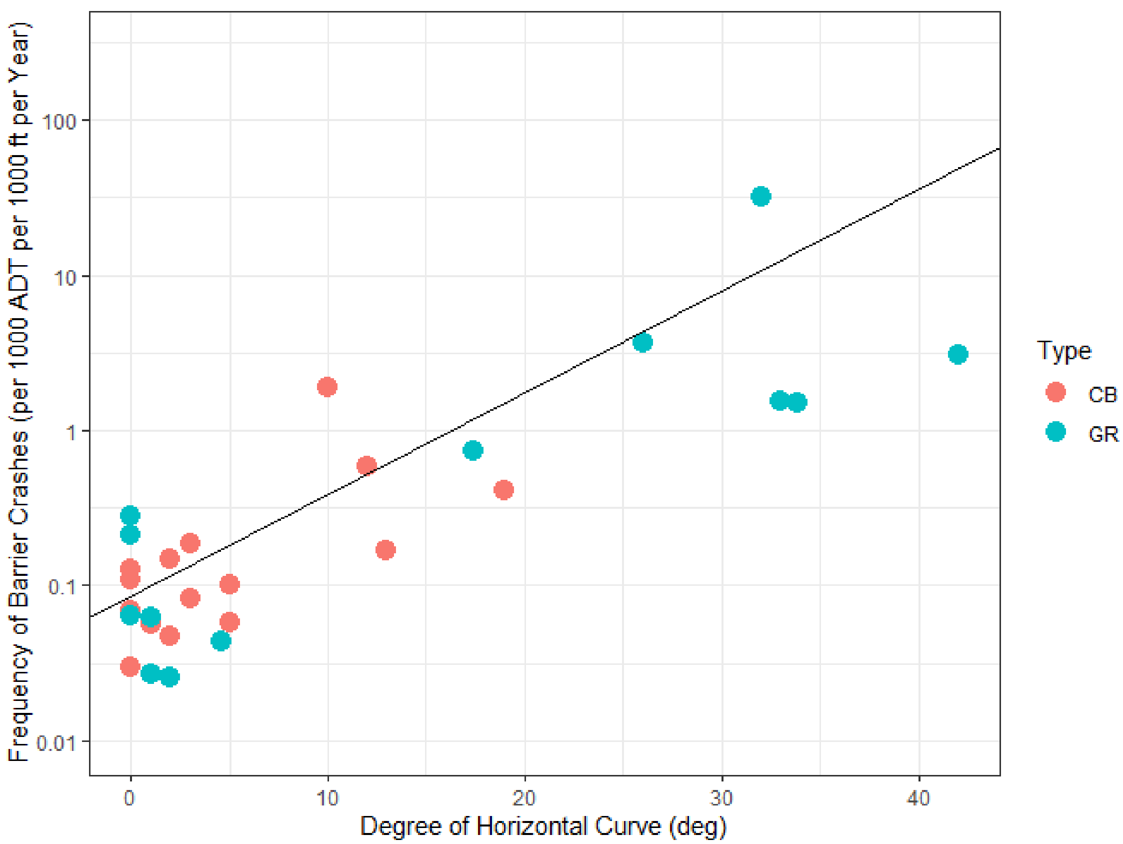

Figure 11. Chart. Crash frequency vs. degree of curve.

Based on the ANOVA, two multilinear regression models were developed to describe the crash rate of barrier collisions in high-risk sections. The first regression model (equation 2) considers both degree of the horizontal curve and the posted speed. The second regression model (equation 3) uses only the degree of the horizontal curve. The coefficients of determination (R^2) of the two models are 0.759 and 0.758, respectively. It appears that dropping the posted speed from the equation does not reduce the R^2 value of the regression model much. This is result understandable because the degree of the curve and the speed of the road are correlated variables in roadway design.

$$CR = e^{(0.1372D - 0.0069S - 0.9661)} \qquad R^2 = 0.759 \tag{2}$$

$$CR = e^{(0.1454D - 1.4053)} \qquad R^2 = 0.758 \tag{3}$$

where, CR = barrier crash rate (/1,000,000 exposure/1,000 ft/year) of single vehicle barrier collisions, D = degree of curve (D = 5729.6 / radius), and S = posted speed of the road.

It should be noted that equations 2 and 3 represent only the high-risk sections. In fact, there are many ramp sections showed lower numbers of crash rate. Therefore, these equations are not supposed to replace the performance functions in the RSAP programs.

CRASH SEVERITY

The KABCO severity information was collected from the GEARS database, including 200 crashes on guardrails and 390 crashes on concrete barriers. These crash data were combined with the 513 unreported crashes (all assumed to be PDO crashes) estimated based on figure 9. The combined KABCO severity distribution at different posted speeds is shown in figure 12 for guardrail sections and figure 13 for concrete-barrier sections, respectively. Both types of barriers showed increased crash severity with the increase of posted speed. This increasing trend is more obvious in guardrail sections, as low-speed sections showed very small injury rates. As for concrete barriers, collisions at all speeds can produce more than a 10 percent injury rate, and the increase of injury rate increases more gently with speed. At 70 mph, the injury rates of the two barriers become similar.

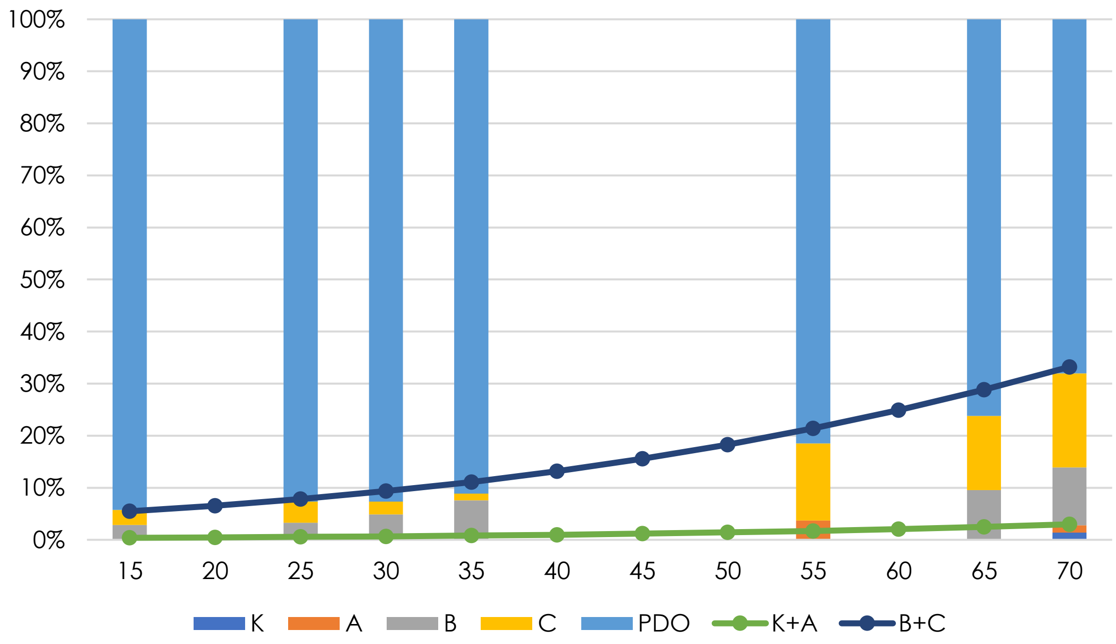

Figure 12. Graph. Crash severity in high-risk guardrail sections.

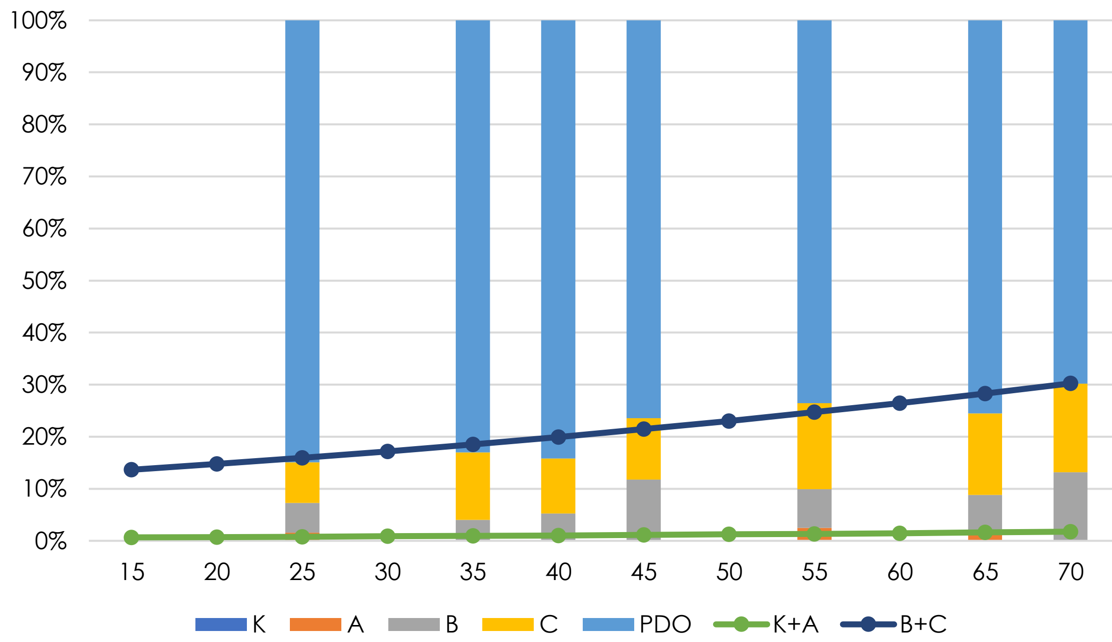

Figure 13. Graph. Crash severity in high-risk concrete-barrier sections.

A prediction model for the barrier crash severity was developed by performing an ordinal logistic regression (OLR) analysis. Ordinal logistic regression is a statistical analysis tool suitable when the dependent (e.g., crash severity) falls into several ordered classes (e.g., K, A, B, C, and O). Because fatal-injury (K), severe-injury (A), and visible-injury (B) crashes are rare events, it is difficult to develop a reliable regression for each class with a small amount of crash data. In this study, the five severity classes were combined into three: K+A, B+C, and PDO.

The OLR analysis was conducted using the statistical analysis program R. The resultant regression models for guardrail and concrete barriers are provided in table 6. For comparison, the predicted cumulative probabilities of K+A, B+C, and PDO crashes are plotted in figure 12 for guardrail barriers and figure 13 for concrete barriers, respectively.

The OLR model provides a reasonable match to the crash-severity distribution for both types of barriers.

Table 6. Ordinal logistic regression model for crash severity.

	Guardrail	Concrete Barrier
K+A	$P_{K+A} = \frac{1}{1 - e^{(-0.03796S*S+6.1415)}}$	$P_{K+A} = \frac{1}{1 - e^{(-0.01785S*S+5.2731)}}$
B+C	$P_{B+C} = \frac{1}{1 - e^{(-0.03796*S+3.4935)}} - P_{K+A}$	$P_{B+C} = \frac{1}{1 - e^{(-0.01785*S+2.1701)}} - P_{K+A}$
PDO	$P_{PDO} = 1 - \frac{1}{1 - e^{(-0.03796*S+3.4935)}}$	$P_{PDO} = 1 - \frac{1}{1 - e^{(-0.01785*S+2.1701)}}$

CHAPTER 4. BENEFIT–COST ANALYSIS

INTRODUCTION TO BENEFIT-COST ANALYSIS

In this study, the benefit–cost analysis considers two roadside-barrier alternatives:

- Alternative A: 31″ Guardrail
- Alternative B: Single-Slope Concrete Barrier

The decision to switch from Alternative A to Alternative B is made by determining the benefit–cost ratio (BCR). A BCR greater than 1 indicates that concrete barrier is more effective; otherwise, guardrail is more effective. According to the *Highway Safety Benefit–Cost Analysis Guide*, BCR can be calculated as the ratio between the present value benefit (PVB) and the present value cost (PVC) (equation 4). Both present values are calculated from the life-cycle cost of the barrier with an annual discount rate.

$$BCR = \frac{PVB}{PVC} \tag{4}$$

The life-cycle cost of a roadside barrier includes the installation cost and the continuous cost. The continuous cost also includes two parts: the comprehensive crash cost and the repair cost. When switching from a guardrail to a concrete barrier, any reduction in the life-cycle cost is counted into the PVB, and any increase in the life-cycle cost is counted into the PVC. Table 7 lists the unit life-cycle costs used in the BCA of this study. For a simple analysis, the BCA compares the two barrier options for a period of 40 years.

Table 7. Unit life-cycle cost for BCA.

	Alternative 1: Guardrail	**Alternative 2: Concrete Barrier**
Initial Construction Cost (/ft)	$25	$375
Repair Cost (/crash)	$1,000	$20
Service Life (year)	20	40

Since the crash-severity model in this study was developed based on three combined severity levels (K/A, B/C, and PDO), the weighed comprehensive crash costs (table 8) were calculated following the FHWA guideline.[3] Considering the crash-severity model, the expected comprehensive crash cost per accident can be determined for different speeds. Figure 14 shows that the when the posted speed of the road is 55 mph, the expected comprehensive crash costs per barrier-collision accident for guardrail and concrete barrier are approximately the same. At higher speeds, crashes on guardrail barriers costs more than crashes on concrete barriers. At lower speeds, the trend is the opposite.

Table 8. Weighted comprehensive crash cost.

K/A	$3,085,873
B/C	$154,063
PDO	$11,900

For high-risk guardrail sections, the time period when the guardrail is damaged and not functioning should be considered. In this study, a crash is assumed to make a 100-ft-long guardrail section nonfunctioning for two weeks. The crash cost during this period is assumed to be doubled. Note that these numbers were selected arbitrarily. In reality, the effect of a nonfunctioning guardrail depends on the more hazardous obstacles behind the guardrail. The adjustment factor to the crash cost of guardrail sections is shown in equation (5)

$$F_D = \mathrm{N} * \frac{100}{L} * \frac{2}{52} + 1 < 2 \tag{5}$$

where,

F_D = crash cost adjustment factor for the damaged guardrails

N = number of predicted crashes in a year

L = length of the section

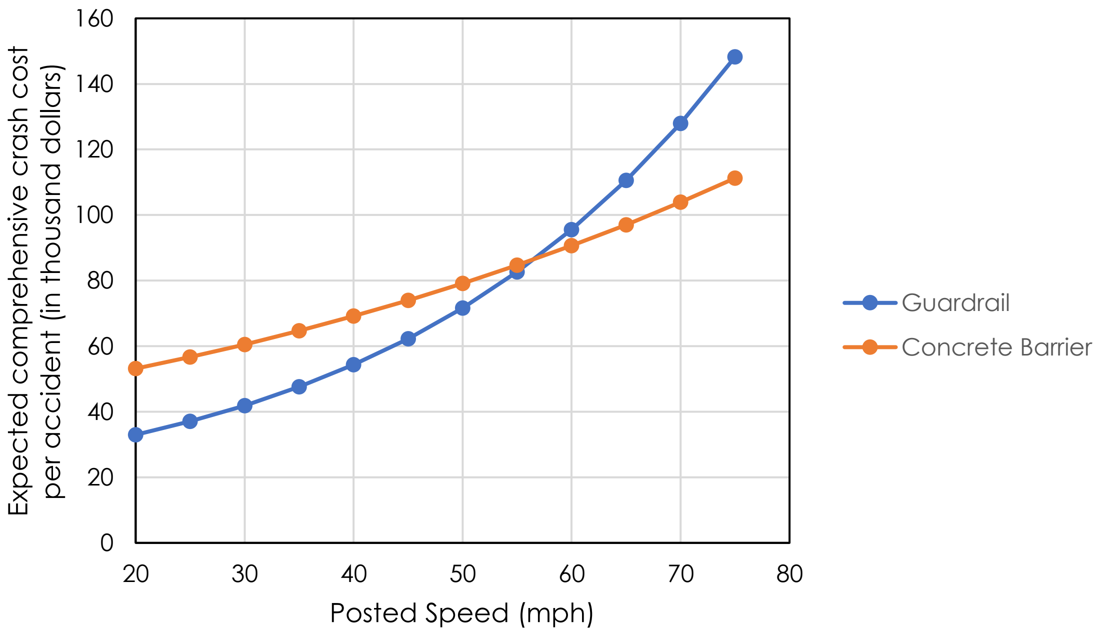

Figure 14 Graph. Expected comprehensive crash cost per accident at different speeds

BENEFIT-COST ANALYSIS FOR HIGH-RISK SECTIONS

The thirteen high-risk guardrail sections (sections 16–28) were analyzed to determine whether concrete barrier is a more economical solution. In the BCA, the number of the barrier collisions was estimated based on the crash data from GEARS instead of the crash-frequency model. Table 9 shows the calculated BCRs for the selected high-risk sections. All sections with greater than 55 mph posted speed showed that concrete barrier is the more economic barrier type compared to guardrail. This result can be explained from figure 12 to figure 14. Crashes at this speed into a guardrail have a higher chance to result in a K/A injury than those collisions into a concrete barrier. By switching to a concrete barrier, the reduction in crash cost (as well as repair cost) outweighs the increased installation cost. For sections with less than 55 mph posted speed, although the frequent crashes produced a higher repair cost for a guardrail barrier, the reduced crash cost still made the guardrail barrier more economic compared to a concrete barrier. It was also observed from the BCA that the change in the construction or repair cost was usually insignificant compared to the change in the crash cost.

Table 9. BCA for the selected guardrail sections.

ID	Route	Speed	Degree of Curve	Current Barrier Type*	Crash per Year	BCR	Economic Barrier Type*
16	I-285	15	42	GR	17.5	0.1	GR
17	I-285/I-85	25	33.9	GR	7.8	0.1	GR
18	I-20	70	0	GR	3.3	37.9	CB
19	I-75	70	1	GR	2.3	26.1	CB
20	I-75	70	0	GR	3.3	37.9	CB
21	SM Fwy	35	26	GR	19.8	0.1	GR
22	I-20	25	33	GR	12.5	0.1	GR
23	I-75	65	1	GR	5.3	42.2	CB
24	US80/I-185	30	17.4	GR	10.3	0.1	GR
25	I-20	70	0	GR	6.3	75.4	CB
26	I-75	25	32	GR	10.8	0.1	GR
27	I-75	70	2	GR	3.0	34.3	CB
28	I-85	55	4.6	GR	6.8	16.3	CB

* GR = Guardrail; BC = Concrete Barrier

BENEFIT-COST ANALYSIS FOR ROAD SECTIONS WITH KNOWN CRASH FREQUENCY

To understand the cost-effectiveness of the two barrier types, the BCA was repeated for a range of speeds and crash frequencies. Two examples are provided below.

The first example (see table 10) is a 1000-ft slightly curved freeway segment with a radius of 1,500 ft and a speed limit of 60 mph. Given there are 10 crashes per year observed in this section. The concrete barrier reduces crash cost and repair cost with a total PVB of $17,197,000, which outweighs the increase in installation cost of $339,000. Therefore, the concrete barrier is a more economical alternative compared to guardrail.

Table 10. BCA Example 1 – freeway segment.

<table>
<tr><td colspan="5">Input:
Interest Rate = 4%
Posted Speed = 60 mph
Radius = 1,500 ft
Length = 1,000 ft
Number of Crashes = 10/year

Output:
Estimated Crashes in each KABCO category
1. Guardrail 2: Concrete Barrier
K + A = 0.2 K + A = 0.1
B + C = 2.1 B + C = 2.4
PDO = 7.7 PDO = 7.5
Adjustment Factor = 1.04</td></tr>
<tr><td>Life-cycle Costs</td><td>NPV1
(×$1000)</td><td>NPV2
(×$1000)</td><td>Benefit
(×$1000)</td><td>Cost
(×$1000)</td></tr>
<tr><td>Construction Cost</td><td>36</td><td>375</td><td>–</td><td>339</td></tr>
<tr><td>Crash Cost</td><td>103,300</td><td>86,140</td><td>17,160</td><td>–</td></tr>
<tr><td>Repair Cost</td><td>950</td><td>19</td><td>37</td><td>–</td></tr>
<tr><td></td><td></td><td></td><td>BCR</td><td>50.7</td></tr>
</table>

The second example (see table 11) is a 200-ft curved freeway ramp section with a radius of 250 ft and a speed limit of 30 mph. Given there are 10 crashes per year observed in this section. Compared to guardrail, the concrete-barrier option increased the crash cost due to rigid barrier with a total PVC of $7,998,000. Although the repair cost reduced with a PVB of $931,000, the benefit is insignificant compared to the cost. Therefore, the guardrail is still a more economical barrier type compared to the concrete barrier.

Table 11. BCA Example 2 – freeway ramp.

<table>
<tr><td colspan="5"><u>Input:</u>
Interest Rate = 4%
Posted Speed = 30 mph
Radius = 250 ft
Length = 200 ft
Number of Crashes = 10/year

<u>Output:</u>
Estimated Crashes in each KABCO category
1. Guardrail — 2: Concrete Barrier
K + A = 0.1 — K + A = 0.1
B + C = 0.8 — B + C = 1.5
PDO = 9.1 — PDO = 8.4
Adjustment Factor = 2</td></tr>
<tr><td>Life-cycle Costs</td><td>NPV1 (×$1000)</td><td>NPV2 (×$1000)</td><td>Benefit (×$1000)</td><td>Cost (×$1000)</td></tr>
<tr><td>Construction Cost</td><td>7</td><td>75</td><td>–</td><td>68</td></tr>
<tr><td>Crash Cost</td><td>49,620</td><td>57,550</td><td>–</td><td>7,930</td></tr>
<tr><td>Repair Cost</td><td>950</td><td>19</td><td>931</td><td>–</td></tr>
<tr><td></td><td></td><td></td><td>BCR</td><td>0.12</td></tr>
</table>

The above analysis was repeated for a range of posted speeds and crash frequencies. The resulted BCR values are presented in table 12. The shaded cells in the table indicate BCR values greater than 1. The BCA result showed that concrete barrier is more cost-effective for road sections with a posted speed of 55mph or higher. Guardrail barrier is more cost-effective for road sections with a posted speed of 35 mph or less for the range of of crash frequencies analyzed. For roads with a posted speed of 40 to 50 mph, concrete barrier should be considered for higher-risk road sections. Table 14 can be used as a guide in selecting roadside barriers for high-risk road sections. It should noted that the maintenance record is a preferred way to estimate the crash frequency when using table 14. If the crash record is used, the number of unreported crashes should be estimated based on figure 9.

Table 12. BCR result with known crash frequency.

Crash Frequency (/1000-ft /year)	Posted Speed										
	20	25	30	35	40	45	50	55	60	65	70
50	0.1	0.1	0.1	0.2	2.5	92.3	197.8	329.8	492.9	692.3	933.6
45	0.1	0.1	0.1	0.2	0.6	66.9	159.2	275.0	418.2	593.4	805.7
40	0.1	0.1	0.1	0.1	0.4	45.0	124.8	225.0	349.1	501.2	685.5
35	0.1	0.1	0.1	0.1	0.3	26.8	94.6	179.9	285.7	415.5	573.0
30	0.1	0.1	0.1	0.1	0.2	12.2	68.6	139.6	227.9	336.4	468.1
25	0.1	0.1	0.1	0.1	0.2	1.0	46.7	104.2	175.8	263.9	370.9
20	0.1	0.1	0.1	0.1	0.1	0.4	29.0	73.7	129.4	197.9	281.4
15	0.1	0.1	0.1	0.1	0.1	0.3	15.5	48.0	88.6	138.6	199.5
10	0.1	0.1	0.1	0.1	0.1	0.2	6.1	27.1	53.4	85.8	125.4
5	0.1	0.1	0.1	0.1	0.1	0.1	1.0	11.1	23.9	39.6	58.8

Table 13. Recommended barrier type for sections with known crash frequency.

Crash Frequency* (/1000-ft /year)	Posted Speed										
	20	25	30	35	40	45	50	55	60	65	70
50	GR	GR	GR	GR	CB	CB	CB	CB	CB	CB	CB
45	GR	GR	GR	GR	GR	CB	CB	CB	CB	CB	CB
40	GR	GR	GR	GR	GR	CB	CB	CB	CB	CB	CB
35	GR	GR	GR	GR	GR	CB	CB	CB	CB	CB	CB
30	GR	GR	GR	GR	GR	CB	CB	CB	CB	CB	CB
25	GR	GR	GR	GR	GR	CB	CB	CB	CB	CB	CB
20	GR	GR	GR	GR	GR	GR	CB	CB	CB	CB	CB
15	GR	GR	GR	GR	GR	GR	CB	CB	CB	CB	CB
10	GR	GR	GR	GR	GR	GR	CB	CB	CB	CB	CB
5	GR	GR	GR	GR	GR	GR	CB	CB	CB	CB	CB

*GR=Guardrail, CB=Concrete Barrier

BENEFIT-COST ANALYSIS FOR ROAD SECTIONS WITH UNKNOWN CRASH FREQUENCY

If the past crash record is unavailable, equation 3 and figure 11 can be used to estimate the crash rate. The BCA was repeated for a range of degrees of curve and traffic volumes. The resulted BCR values are listed in table 14. The shaded cells in the table indicate BCR values greater than 1. Conditions that favor a concrete barrier over guardrail are road sections that are straight (or slightly curved) or with a one-way AADT of 40,000 or more. Sharply curved road sections (e.g., a freeway exit ramp) with a high traffic count also justifies a concrete barrier according to table 14. However, The crash data analyzed in this study did not cover concrete barriers on roadways with a degree of curve > 20° (or radius < 300ft). Therefore, at this moment, concrete barriers are not recommended in these sharp ramps because a collision from a speeding vehicle into a concrete barrier may cause a severe accident.

The results in table 14 can be converted to graph form (see figure 15) for roadside-barrier selection when past the crash record is unavailable. It should be noted that figure 15 is based on the BCA result on high-risk freeway barrier sections. In practice, other factors should also be considered in the selection of roadside barriers, such as the deflection limitation.

Table 14. BCR result with estimated crash frequency.

AADT	Degree of Curve (°)										
	0	**3**	**6**	**9**	**12**	**15**	**18**	**21**	**24**	**27**	**30**
100,000	106.3	176.9	222.8	140.6	133.7	224.8	548.6	1465.0	2914.2	4137.8	5959.1
50,119	50.4	81.6	96.6	44.6	15.5	1.2	29.8	175.1	645.2	1966.3	2986.6
25,119	24.6	39.2	44.6	15.9	0.4	0.2	0.2	0.2	0.9	221.8	925.2
12,589	12.1	19.2	21.4	6.3	0.2	0.1	0.1	0.1	0.1	0.2	1.5
6,310	6.0	9.5	10.5	2.8	0.2	0.1	0.1	0.1	0.1	0.1	0.1
3,162	3.0	4.7	5.2	1.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1
1,585	1.5	2.4	2.6	0.6	0.1	0.1	0.1	0.1	0.1	0.1	0.1
794	0.8	1.2	1.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1
398	0.4	0.6	0.6	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.1
200	0.2	0.3	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1

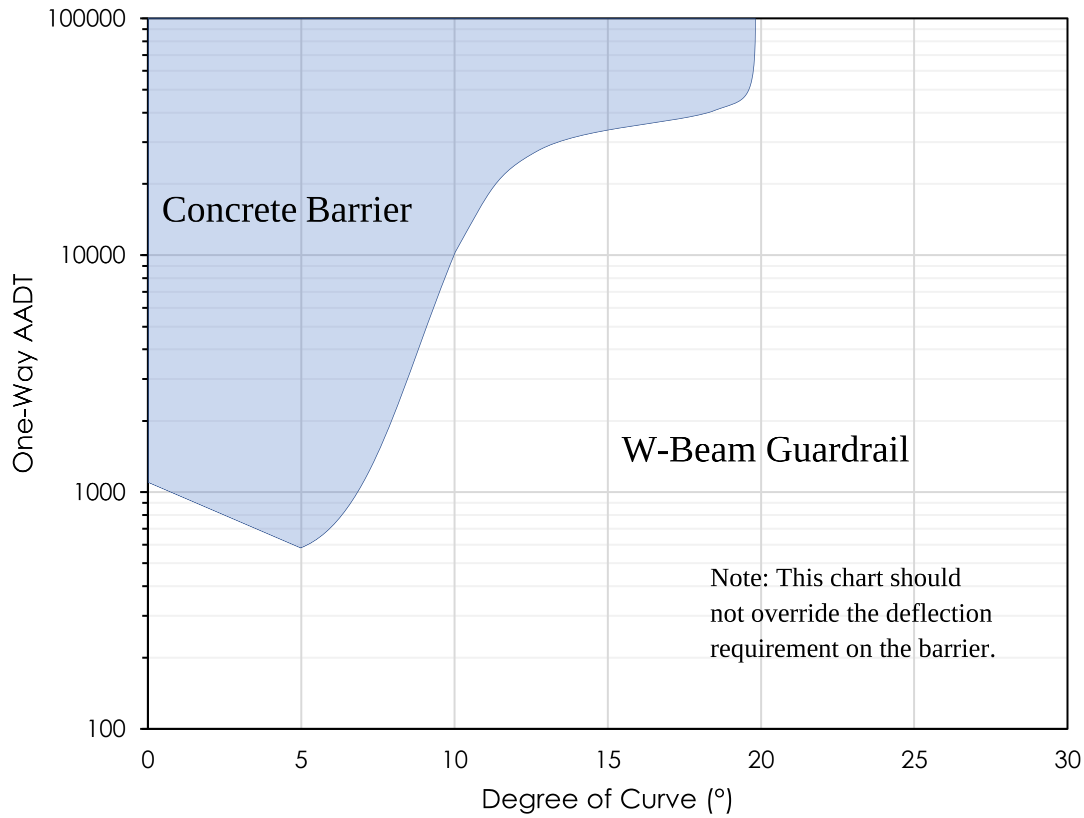

Figure 15. Graph. Barrier Selection Chart for Sections without Crash Record.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

Twenty-eight (28) freeway sections with frequent roadside-barrier collisions were identified in Georgia. Road design, traffic, and crash records pertaining to the selected road sections have been collected. Statistical analysis was performed on the barrier crash rate and the crash severity. The regression models were used in the benefit–cost analysis (BCA) to determine whether a concrete barrier is a more cost-effective alternative to a guardrail barrier. The results of the BCA were converted to simple decision-making tools for selecting the cost-effective barrier type for different road sections.

CONCLUSIONS

The following conclusions can be drawn from this research:

4. The frequency of roadside-barrier collisions is mostly affected by the traffic volume and the degree of horizontal curve of the road.
5. The existence of unreported crashes poses a challenge to the barrier safety research. It leads to a mismatch between the crash data and the maintenance record. The percentage of unreported crashes reduces nonlinearly with the posted speed of the road. Concrete barrier shows a slightly lower percentage of unreported crashes than guardrail.
6. The severity of barrier collisions is mostly affected by the posted speed of the road and the barrier type. The crash severity in general increases exponentially with the posted speed of the road. When the posted speed of the road is less than 55 mph, concrete barriers

produce more severe crashes than guardrail due to the rigidity of the barrier. When the posted speed of the road is more than 55 mph, guardrails produce more fatal and severe (K/A) crashes due to the increased odds of penetrating/ vaulting.

7. The BCA result showed that concrete barrier is more cost-effective for road sections with a posted speed of 55mph or higher. Guardrail barrier is more cost-effective for road sections with a posted speed of 35 mph or less for the range of of crash frequencies analyzed. For roads with a posted speed of 40 to 50 mph, concrete barrier should be considered for higher-risk road sections.
8. When the past crash record is unavailable, the cost-effective barrier type can also be determined based on an estimated barrier collision rate. In general, conditions that favor a concrete barrier over guardrail are straight (or slightly curved) road sections or sections with a one-way AADT of 40,000 or more.

RECOMMENDATIONS

1. The Roadside Safety Analysis Program (RSAP) developed from the National Cooperative Highway Research Program (NCHRP) Project 22-27 is the most sophisticated tool available for benefit–cost analysis of roadside safety features. However, the RSAP baseline model often underestimates the actual crash frequency of "high-risk" barrier sections, especially for sharp horizontal curves (e.g., ramps). Although the program allows use of a modification factor to boost the predicted crash frequency, it still requires a judgment of the total number of crashes (including the unreported crashes) of the road. It is recommended that the Georgia Department of Transportation (GDOT) wait for the next updated version of the program.

2. The roadside barrier selection tools (table 14 and figure 15) developed in this research can be used as a quick decision-making tool for barrier-upgrade projects. When a more accurate benefit–cost analysis is needed, the barrier crash-frequency model and the crash-severity model developed in this research can be applied in a spreadsheet or other computation program. Guardrail maintenance record should be used when available to determine the past average crash frequency of the road. When crash records are used, unreported crashes must be considered using the method presented in this study.
3. It is recommended GDOT build an inventory database for roadside barriers and use an asset management system for tracking the history and condition of roadside barriers.

APPENDIX A. SELECTED ROADWAY SECTIONS DATA

Table 15. Road and traffic characteristics.

ID	Route	Dir.	LAT	LONG	Length (ft)	AADT One-Way	Post_ Speed	Degree of Curve	Vertical Grade (%)	Barrier Location	Barrier Type*	Barrier Clear.	No. of Lanes	Lane Width
1	I-520	EB	33.40788	-82.0347	4330	30,000	65	0	-3.5	Median	CB	16	2	12
2	SR-104	WB	33.51786	-82.0053	1848	11,950	45	5	1.1	Median	CB	10	2	12
3	I-520	NB	33.47510	-82.0862	1267	45,700	65	2	1	Median	CB	12	4	12
4	SR-204	Ramp	31.98267	-81.2004	1056	22,100	25	19	-1	Median	CB	12	2	10
5	I-75	SB	31.06391	-83.4016	1214	22,400	70	0	-1.3	Median	CB	12	3	12
6	I-75	NB	34.03271	-84.5766	686	62,500	65	0	0.8	Median	CB	9	3	12
7	I-285/I-75	Ramp	33.89180	-84.4592	106	12,510	40	10	0	Shoulder R	CB	20	2	12
8	I-20	WB	33.71616	-84.2599	1267	70,000	65	2	-1.6	Median	CB	12	5	12
9	I-285	SB	33.84371	-84.4876	1109	84,000	65	1	0	Median	CB	9	4	12
10	I-185	NB	32.49149	-84.9431	475	37,050	70	3	4.3	Median	CB	8	3	12
11	I-20	EB	33.61288	-83.8266	2165	23,550	70	0	-1	Median	CB	18	2	12
12	I-20	Ramp	33.71283	-84.2433	1426	54,550	35	13	0	Shoulder L	CB	12	2	12
13	I-20/I-75	Ramp	33.74393	-84.3899	370	48,900	25	12	3	Shoulder R	CB	12	2	12
14	I-85	NB	33.66611	-84.4169	1901	85,750	55	3	-1.8	Median	CB	8	3	12
15	I-85	NB	33.68327	-84.4101	1056	85,750	55	5	0	Median	CB	8	3	12
16	I-285	Ramp	33.90165	-84.2728	158	8,160	15	42	-1	Shoulder	GR	16	1	12
17	I-516	EB	32.04268	-81.1469	1162	12510	55	4	-1.7	Shoulder	GR	12	2	12
18	I-20	EB	33.68162	-85.2816	686	18,200	70	0	-2.2	Shoulder L	GR	12	2	11
19	I-75	SB	33.12454	-84.0062	2218	38,100	70	1	-2.4	Median	GR	12	3	12
20	I-75	NB	32.96043	-83.8143	1109	46,350	70	0	2.6	Shoulder R	GR	12	2	12
21	SM Fwy	Ramp	33.82236	-84.1647	317	4,980	30	26	-1	Shoulder	GR	15	1	10
22	I-20	Ramp	33.71640	-84.2591	264	7,930	25	33	1	Shoulder L	GR	35	1	12
23	I-75	NB	34.02303	-84.5709	1056	64,000	65	1	0	Median	GR	13	3	12
24	US-80/I-185	Ramp	32.54461	-84.9583	581	6,940	30	17.4	0	Shoulder L	GR	7	1	12
25	I-20	WB	33.40788	-82.0347	581	38,800	70	0	0	Shoulder R	GR	16	3	12
26	I-75	Ramp	34.89399	-85.0744	106	1,790	25	32	1	Shoulder R	GR	12	1	14
27	I-75	NB	34.08167	-84.6297	2640	44,750	70	2	-2.2	Shoulder	GR	12	3	12
28	I-85	SB	33.68655	-84.4018	1000	85,750	55	4.6	0	Shoulder L	GR	8	4	12

*CB = Concrete Barrier, GR = Guardrail

Table 16. Crashes and severity.

ID	K	A	B	C	O	U	Total Crash	Posted Speed	Degree of Curve	Vertical Grade (%)	Barrier Location	Barrier Type	Barrier Clear.	No. of Lanes	Lane Width
1	0	0	0	2	9	0	11	65	0	-3.5	Median	CB	16	2	12
2	0	0	2	2	5	0	9	45	5	1.1	Median	CB	10	2	12
3	0	0	1	4	6	0	11	65	2	1	Median	CB	12	4	12
4	0	0	1	5	13	0	19	25	19	-1	Median	CB	12	2	10
5	0	0	4	3	16	0	23	70	0	-1.3	Median	CB	12	3	12
6	0	0	2	6	15	0	23	65	0	0.8	Median	CB	9	3	12
7	0	0	2	4	12	0	18	40	10	0	Shoulder R	CB	20	2	12
8	0	1	5	9	38	0	53	65	2	-1.6	Median	CB	12	5	12
9	0	1	3	2	14	1	21	65	1	0	Median	CB	9	4	12
10	0	0	1	4	11	0	16	70	3	4.3	Median	CB	8	3	12
11	0	0	2	2	10	0	14	70	0	-1	Median	CB	18	2	12
12	0	0	4	13	26	0	43	35	13	0	Shoulder L	CB	12	2	12
13	0	3	10	10	29	2	54	25	12	3	Shoulder R	CB	12	2	12
14	0	1	5	14	33	1	54	55	3	-1.8	Median	CB	8	3	12
15	0	2	4	6	9	0	21	55	5	0	Median	CB	8	3	12
16	0	0	2	2	12	0	16	15	42	-1	Shoulder	GR	16	1	12
17	0	0	1	2	5	0	8	55	4	-1.7	Shoulder	GR	12	2	12
18	0	1	2	1	9	0	13	70	0	-2.2	Shoulder L	GR	12	2	11
19	0	0	2	2	5	0	9	70	1	-2.4	Median	GR	12	3	12
20	0	0	0	5	8	0	13	70	0	2.6	Shoulder R	GR	12	2	12
21	0	0	6	1	16	0	23	30	26	-1	Shoulder	GR	15	1	10
22	0	1	1	2	7	2	13	25	33	1	Shoulder L	GR	35	1	12
23	0	0	2	3	12	0	17	65	1	0	Median	GR	13	3	12
24	0	0	2	1	9	0	12	30	17.4	0	Shoulder L	GR	7	1	12
25	0	0	1	2	22	0	25	70	0	0	Shoulder R	GR	16	3	12
26	0	1	1	1	21	0	24	25	32	1	Shoulder R	GR	12	1	14
27	1	0	3	3	5	0	12	70	2	-2.2	Shoulder	GR	12	3	12
28	0	1	0	4	10	0	15	55	4.6	0	Shoulder L	GR	8	4	12

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