Crash Modification Factors for High-Tension Cable Median Barriers in Pennsylvania

FINAL REPORT

June 12, 2023

By Vikash V. Gayah, Eric T. Donnell, Abhishek Prajapati and Hao Liu

The Pennsylvania State University

PennState College of Engineering
LARSON TRANSPORTATION INSTITUTE

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

CONTRACT # 4400015622
WORK ORDER # PSU WO 014

Crash Modification Factors for High-Tension Cable Median Barriers in Pennsylvania

Final Report

Prepared by:

Vikash V. Gayah
Associate Professor

Eric T. Donnell
Professor

Abhishek Prajapati
Graduate Student Researcher

Hao Liu
Postdoctoral Researcher

Department of Civil and Environmental Engineering
The Pennsylvania State University
217 Sackett Building
University Park, PA 16802

Prepared for:
The Pennsylvania Department of Transportation

June 12, 2023

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
PennDOT-2023-ECMS-E04834-WO14		

4. Title and Subtitle Crash Modification Factors for High-Tension Cable Median Barriers in Pennsylvania	**5. Report Date** June 12, 2023 **6. Performing Organization Code**
7. Author(s) Vikash V. Gayah, Eric T. Donnell, Abhishek Prajapati and Hao Liu	**8. Performing Organization Report No.** LTI 2023-06
9. Performing Organization Name and Address Thomas D. Larson Pennsylvania Transportation Institute Pennsylvania State University 201 Transportation Research Building University Park, PA 16802	**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** 4400015622, PSU WO 014
12. Sponsoring Agency Name and Address The Pennsylvania Department of Transportation Bureau of Planning and Research Commonwealth Keystone Building 400 North Street, 6th Floor Harrisburg, PA 17120-0064	**13. Type of Report and Period Covered** Final Report 09/01/2022 – 06/30/2023 **14. Sponsoring Agency Code**

15. Supplementary Notes
Dillan Bujak, Senior Civil Engineer, Bureau of Operations, served as the project technical advisor. The authors also thank Pete Jenior, Associate Engineering at Kittelson and Associates, Inc, who served as the project manager.

16. Abstract
The objective of this project was to develop a suite of crash modification factors (CMFs) to quantify the safety impacts of installing high-tension cable median barriers (HTCMBs) on freeway segments within the Commonwealth of Pennsylvania. An empirical Bayes observational before-after study was performed to develop CMFs for this countermeasure. The analysis revealed that the installation of HTCMBs was associated with increases in total, fatal + injury, property-damage-only, and hit-barrier crash frequencies. With the exception of the total fatal and injury crash type, the results were statistically significant. The results are consistent with engineering expectations because, when an object (longitudinal barrier) is placed adjacent to the traveled way, it is expected that run-off-road crashes will increase because the barrier limits the lateral distance for a vehicle to recover. However, the installation of HTCMBs was associated with statistically significant decreases in cross-median, fatal + A injury (i.e., suspected serious injury), and cross-median fatal + A injury crash frequencies. These results were also consistent with engineering expectations, as the longitudinal barrier is intended to mitigate severe crashes resulting from vehicles crossing the median and colliding with vehicles traveling in the opposite direction.

17. Key Words	18. Distribution Statement
High-tension cable median barriers, crash modification factors, empirical Bayes before-after method	No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	40	

Form DOT F 1700.7 **(8-72)** **Reproduction of completed page authorized**

DISCLAIMER

Table of Contents

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

High-tension cable median barriers (HTCMBs) are a type of safety countermeasure installed in the medians of freeway segments that are designed to prevent vehicles from crossing over into oncoming traffic. They are typically used on high-speed divided highways with high traffic volumes. Median barriers are designed to improve road safety by reducing the risk of head-on collisions and other severe crash outcomes. Unlike rigid or semi-rigid barriers, which are made of concrete or metal, cable barriers are flexible systems made up of a series of steel cables supported by posts anchored to the ground. HTCMBs are tensioned to absorb and redirect the energy of a colliding vehicle. Because they are not as rigid as metal or concrete barriers, they often deflect significantly after impact and, therefore, often require more lateral space to be installed than semi-rigid or rigid barriers. Further, there is relatively little information available on the overall safety effectiveness of HTCMB as a safety countermeasure.

Over the past decade, the Pennsylvania Department of Transportation (PennDOT) has installed HTCMB on over 500 miles of freeway segments throughout Pennsylvania. The objective of this project was to develop a set of crash modification factors (CMFs) that can be used to quantify the safety impacts of installing HTCMB along freeway segments in Pennsylvania. The CMFs are compatible with the methods recommended in the *Highway Safety Manual* (HSM) (American Association of State Highway and Transportation Officials, 2010) and in Pennsylvania's safety management processes described in PennDOT Publication 638A (Pennsylvania Department of Transportation, 2021). This report documents the steps taken to perform the evaluation and the final CMFs that were obtained.

The remainder of this document is organized as follows. The first section summarizes the data collected from PennDOT and other sources to use in this safety evaluation. The second section describes the development of the analysis database used to support the evaluation. The third section provides a description of the analysis plan, specifically the empirical Bayes (EB) before-after methodology that was used. The fourth section describes the CMFs that were developed, while the fifth section provides a summary of the research.

DATA SUMMARY

An inventory of HTCMB locations within Pennsylvania was provided by PennDOT for the purpose of this study. The inventory consisted of the following information for each HTCMB installation within Pennsylvania:

- Location of the HTCMB installation, including:
  - PennDOT Engineering District
  - County
  - State route number
  - Beginning segment/offset location
  - Ending segment/offset location
- Cost
- Installation date
- Installation details, such as:
  - HTCMB manufacturer
  - Relative placement within the median
  - Number of cables
  - Post embedment type
  - Cross slope information
  - Potential field issues

The research team thoroughly reviewed this information to identify potential erroneous or questionable data. Examples of issues that were identified included:

- HTCMB installations not along a freeway
- Duplicate entries
- Incorrect starting or ending segments/offsets

These issues were noted and discussed with PennDOT to determine how these locations should be considered in the evaluation. With PennDOT guidance, the research team revised entries to reflect actual conditions or omitted HTCMB sites that were not installed along freeways to obtain a final set of locations for consideration in this study. The final set of locations consisted of a total of 500.86 miles of HTCMB installed along freeways in Pennsylvania. Table 1 provides a summary of these installations categorized by PennDOT Engineering District. As shown, some PennDOT Engineering Districts have no (District 10) or negligible (District 12) HTCMB mileage.

Table 1. Summary of HTCMB installations by PennDOT Engineering District

PennDOT Engineering District	Total length (miles)
1	28.36
2	13.92
3	62.43
4	29.00
5	49.45
6	60.75
8	103.46
9	76.38
10	0.00
11	76.57
12	0.54
Total	**500.86**

Table 2 provides a summary of HTCMB installation sites based on installation year. Note that to balance data availability, consistency, and timeliness, an analysis period of 2007 to 2021 was considered for this evaluation. Thus, HTCMB installations before 2008 or after 2020 were removed because at least one full year of crash data was not available in the period before or after the HTCMB was installed at those locations. After removing these years, the total HTCMB installation shown in Table 2 is 428.61 miles.

Table 2. Summary of HTCMB installations by installation year

HTCMB installation year	Total length (miles)
2008	5.25
2009	18.07
2010	43.12
2011	16.38
2012	12.06
2013	2.13
2014	14.24
2015	54.31
2016	55.74
2017	66.16
2018	51.05
2019	78.34
2020	11.76
Total	**428.61**

ANALYSIS DATABASE DEVELOPMENT

The previous section described the set of HTCMB locations that were available for use in this study. These locations were then incorporated into a set of analysis databases that were used to develop the CMFs for HTCMB within Pennsylvania. This section describes the data that were used to create these analysis databases, including their source and the steps that were performed in this process.

Mapping of HTCMB sites to freeway segments and conversion to unidirectional segments

The research team obtained a database of existing freeway segments in Pennsylvania from Kittelson and Associates, Inc. (KAI) – hereafter known as the KAI freeway database – for use in this study. This database was developed in a previous project for network screening purposes to identify freeway locations with safety performance issues. The KAI database included the following information for each PennDOT-defined freeway segment in Pennsylvania:

- County
- Roadway name
- State route number
- Segment number
- Length
- Number of lanes
- Area type
- Length and radius of curves within the segment
- Pavement width
- Inside and outside shoulder widths
- Median width

The KAI freeway database was originally used for network screening purposes. The original project applied safety performance functions (SPFs) from the HSM to estimate crash frequency for all Pennsylvania freeways. However, the freeway SPFs in the HSM include both freeway travel directions as a single “segment” for analysis. This might lead to imbalances in traffic volumes, ramp presence, or other safety-influencing features among the opposing travel directions. Further, PennDOT defines and uses unique segments for each direction on divided roadway facilities, such as freeways. Thus, the research team split each segment in the KAI database into two travel directions based on the PennDOT-defined segments. This is illustrated in Figure 1. Note that in most cases, this was done by using an even-numbered segment number for one travel direction and that number plus one for the other travel direction. The result is that the mileage of segments used in the analysis essentially doubled, since now two roadway segments are influenced by a given HTCMB installation.

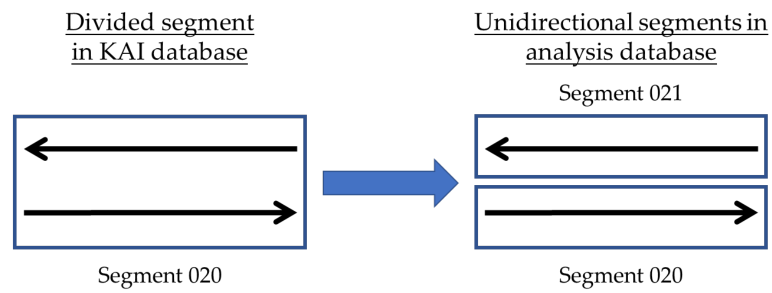

Figure 1. Illustration of conversion of bidirectional to unidirectional freeway segmentation

The research team matched the HTCMB installation locations provided by PennDOT to these freeway segments using the PennDOT roadway management system (RMS) linear referencing system information; specifically, by matching county, state route, and segment numbers. In most cases, the starting/ending point of the HTCMB did not exactly align with the segments defined by PennDOT. This resulted in some segments having HTCMB installed on just a portion of its length. This partial HTCMB installation within a segment presents an issue, as crashes that occur on that segment may or may not be influenced by the presence of the HTCMB. For example, a segment may only have HTCMB installed within a small fraction of its length but be considered as partial; in such a case, the HTCMB would not be expected to have any significant safety benefits. The inclusion of these partial segments might negatively influence the assessment of the safety performance of HTCMB by “watering down” its effects. For this reason, the research team decided to remove the segments with partial installation of HTCMB within the segment boundary for further consideration in the analysis.

A summary of the HTCMB installation locations mapped to unidirectional segments converted from the original KAI database and whether or not the HTCMB is installed on the entire segment, or a portion of the segment, is provided in Table 3. As shown, approximately 763 miles of PennDOT-defined segments have HTCMB installed along their full length.

Table 3. Summary of HTCMB locations mapped to PennDOT-defined freeway segments

PennDOT District	HTCMB installed on entire segment		HTCMB installed on a portion of a segment	
	Number of segments	Total length (miles)	Number of segments	Total length (miles)
1	106	52.99	10	4.74
2	8	3.44	70	35.68
3	225	98.38	36	16.97
4	90	44.78	28	14.17
5	166	82.22	64	31.27
6	144	67.46	12	6.17
7	0	0.00	0	0.00
8	390	202.40	36	18.37
9	200	95.11	46	22.63
10	0	0.00	0	0.00
11	232	115.62	63	29.86
12	2	0.75	2	0.74
Total	**1,563**	**763.16**	**367**	**180.61**

Table 4 provides a summary of HTCMB locations on unidirectional freeway segments based on the type of HTCMB installed. As shown, the majority of sites in Pennsylvania (56%) have HTCMB installed on one side of the shoulder. The remaining installations are single-run HTCMB installed in the center of the median (33%) or installed on both sides on the median, adjacent to the inside shoulder on opposing travel directions (21%). Sufficient sample size was available to estimate CMFs for the shoulder (one side) and single-run (center of median) HTCMB installation types.

Table 4. Summary of full segments with HTCMB by type

HTCMB type	Number of segments	Total length (miles)
Shoulder (one side)	903	433.23
Single-run (center of median)	498	253.74
Shoulder (both sides)	162	76.19
Total	**1,563**	**763.16**

Supplemental data collection

Additional data elements were needed to supplement those in the KAI freeway data to support the analysis. For one, traffic volumes on each unidirectional roadway segment were obtained for each year in the analysis period (2007 to 2021, inclusive) from the PennDOT RMS. These roadway volumes were appended to the existing file.

Additionally, several data elements were only available for a subset of freeway segments in the original KAI freeway database, including the following:

- Median barrier presence and location
- Weaving presence
- Ramp locations
- Inside and outside shoulder rumble strip presence
- Clear zone width
- Roadside barrier presence and location

The research team manually collected a subset of these elements using available imagery in the PennDOT video photolog system (http://www.dot7.state.pa.us/VideoLog/Open). To balance between data completeness and accuracy, these data elements were collected in a categorical manner as follows:

- Median barrier presence: for each segment, the presence of a median barrier within the segment was collected as a categorical variable. The options available were:
    - Median barrier exists for the entire segment (more than 90% of its length)
    - Median barrier exists for most of the segment (between 50% and 90% of its length)
    - Median barrier exists for some of the segment (less than 50% of its length)
    - Median barrier exists for none of the segment (not observed on the segment)
- Ramp locations: for each segment, the number of on-ramps and the number of off-ramps within the segment were collected.
- Rumble strips: inside and outside shoulder rumble strip presence was collected in a categorical manner. The categories used were similar to those for median barrier presence.
- Roadside barrier: barriers on the outside (right-hand side) of the travel direction were collected in a categorical manner similar to median barrier presence.

Merging of crash data

The research team obtained the most recent crash data to estimate CMFs in this evaluation. Crash datafiles were obtained from the Pennsylvania Crash Information Tool (PCIT) website (https://crashinfo.penndot.gov/PCIT/queryTool.html) for the years 2007 to 2021, inclusive. The following data elements were used in this analysis:

- Crash location: defined using the PennDOT linear referencing system, via county, state route number, segment number, and offset
- Crash date
- Collision type
- Injury severity level

Several of the crash data elements were used to identify crashes occurring on freeway segments of interest for the present study. For example, crashes in construction work zones were not included in the analysis files, as these conditions are temporary.

Crashes were then assigned to individual unidirectional roadway segments in the analysis database based on the location of the crash (county, route, segment). Crash counts for each roadway segment were then generated for each analysis year for various crash types that were considered in this analysis. These included:

- All crashes
- All fatal + injury crashes
- All fatal and suspected major injury (KA) crashes
- All PDO crashes
- Hit-barrier crashes (including both median and roadside barrier)

Finally, PennDOT provided the research team with a list of crashes that were specifically identified as cross-median crashes, which is the crash type expected to be reduced/minimized with the installation of HTCMB. These were included in the analysis database in several categories, including:

- All cross-median crashes
- Fatal + injury cross-median crashes
- KA cross-median crashes

Locations that did not experience a crash during any one or more years were retained in the analysis database. The segments with no crashes were included with an observed frequency of zero crashes for the respective crash types.

ANALYSIS PLAN

The research team implemented the EB before-after approach (Hauer, 1997) for this project to develop CMFs to describe the expected change in crash frequency at freeway segments with HTCMB installed. This method is widely accepted as the state-of-the-practice in observational before-after studies of crash data (Gross et al., 2010). The proposed EB analysis properly accounts for statistical factors such as: regression-to-the-mean, differences in traffic volume, and crash trends (time series effects) between the periods before and after HTCMB were installed.

The empirical Bayes approach is comprised of three basic steps, each defined as follows:

Step 1: Develop safety performance functions (SPFs) to predict what the safety performance of freeway segments with HTCMB installed would have been had the HTCMB not been implemented.

Step 2: Estimate what the actual (reported) safety performance should be for treatment sites (i.e., segments where HTCMB were installed) in the after period if HTCMB were not installed.

Step 3: Compare the predicted performance obtained from Step 2 with the reported safety performance to determine the safety effect of HTCMB.

Each of these steps is described in more detail below.

Step 1 – Prediction of safety performance

In this step, a reference group is used to account for the effects of traffic volume changes and temporal effects on safety due to variations in weather, demographics, and crash reporting. This is done through the development of SPFs, which relate the frequency of different crash types and severities to traffic volumes and other safety-influencing factors for a reference group of sites.

Negative binomial count regression models were used to estimate all freeway segment SPFs in this study. The negative binomial regression model was a logical choice to estimate the expected number of crashes per year at these locations because it accounts for the overdispersion common in crash data. The general functional form of the negative binomial regression model is:

$$\ln \lambda_i = \beta X_i + \varepsilon_i \quad (1)$$

where λ_i = expected number of crashes on freeway segment i; β = vector of estimable regression parameters; X_i = vector of geometric design, traffic volume, and other site-specific data (e.g., presence of rumble strips or outside barriers) for freeway segment i; and ε_i = gamma-distributed error term.

The mean-variance relationship for the negative binomial distribution is:

$$\mathrm{Var}(\lambda_i) = E(\lambda_i)[1 + \alpha \mathrm{E}(\lambda_i)] \quad (2)$$

where $\mathrm{Var}(\lambda_i)$ = variance of observed crashes occurring at location i; $E(\lambda_i)$ = expected crash frequency at location i; and, α = overdispersion parameter.

Equation 3 shows the general form of the SPF that was estimated for freeway segments in this study. This form is consistent with Equation 1.

$$N_{i,SPF} = AADT^{\beta_{AADT}} \times Segment\ Length^{\beta_{Length}} \times \exp\left(\beta_0 + \sum x_{ij}\beta_j\right) \quad (3)$$

where $N_{i,SPF}$ = predicted crash frequency for freeway segment i using a SPF created from the reference group [crashes/year]; β_{AADT} = estimated coefficient for traffic volume on the segment; β_{Length} = estimated coefficient for segment length; β_0 = a regression constant; and, β_j = estimated coefficient for other variables x_{ij} that describe the freeway segment.

Step 2 – Before-after analysis with empirical Bayes

An empirical Bayes adjustment is applied to SPF predictions obtained from Equation 3 to incorporate reported crash frequency in the prediction of crash frequency at each location. This EB adjustment is shown in Equation 4 (Hauer, 1997).

$$N_{i,EB} = w_i * N_{i,SPF} + (1 - w_i) * N_{i,obs} \quad (4)$$

where $N_{i,EB}$ = predicted crash frequency at location i based on EB adjustment [crashes/year]; w_i = adjustment weight for predicted crash frequency for location i; $N_{i,SPF}$ = predicted crash frequency at location i based on the SPF (e.g., Equation 3) [crashes/year]; and $N_{i,obs}$ = reported or observed crash frequency at location i [crashes/year].

The weight (w_i) used for the EB adjustment for any location i is derived using Equation 5 (Hauer, 1997):

$$w_i = \frac{1}{1+\alpha * \sum_{all\ study\ years} N_{i,SPF}} \quad (5)$$

Equations 3, 4, and 5 are used to determine N_{EB}^{Before} for the treatment sites in the before period by applying the SPFs generated in Step 1.

The SPF is then used to calculate the predicted crash frequency, N_{SPF}^{After}, for all roadway segments with the treatment in the after period. Finally, the EB-adjusted expected crash frequency in the after period, N_{EB}^{After}, was calculated using Equation 6 and the adjustment factor, r, from Equation 7.

$$N_{EB}^{After} = N_{EB}^{Before} * r \tag{6}$$

$$r = \frac{\sum_{after\ years} N_{SPF}^{After}}{\sum_{before\ years} N_{SPF}^{Before}} \tag{7}$$

where r = adjustment factor for differences in duration and traffic volume between before and after periods; and N_{EB}^{After} = EB-adjusted crash frequency prediction during the after period.

This EB-adjusted value obtained from Equation 6 provides the expected crash frequency if no treatment was applied. This expected crash frequency was then compared with the reported crash frequency after the treatment was applied to assess the safety effects of the treatment.

<u>Step 3 – Compare predicted and actual safety performance</u>

An unbiased estimate of the safety effect (θ) of the treatment is obtained using Equations 8 and 9.

$$\theta = \frac{N_{observed}^{After}}{N_{EB}^{After}\left[1+\frac{Var\left(N_{EB}^{After}\right)}{N_{EB}^{After^2}}\right]} \tag{8}$$

$$Var\left(N_{EB}^{After}\right) = \sum_{all\ sites} r^2(1-w)N_{EB}^{After} \tag{9}$$

where θ = unbiased estimate of safety effect of the countermeasure; and $N_{observed}^{After}$ = reported or observed crashes along the freeway segment during the after period.

Finally, the standard error associated with this safety effect estimate was computed using Equations 10 and 11.

$$Std\ Error(\theta) = \sqrt{\theta^2 \left[\frac{\left(\frac{Var\left(N_{observed}^{After}\right)}{N_{observed}^{After^2}} \right) + \left(\frac{Var\left(N_{EB}^{After}\right)}{N_{EB}^{After^2}} \right)}{\left(1 + \frac{Var\left(N_{EB}^{After}\right)}{N_{EB}^{After^2}} \right)^2} \right]} \tag{10}$$

$$Var\left(N_{observed}^{After}\right) = \sum\nolimits_{all\ sites} N_{observed}^{After} \tag{11}$$

CMF DEVELOPMENT

This section describes the specific steps taken to estimate the CMFs developed as part of this project using the EB before-after methodology described in the previous section. The remainder of this section is divided into several subsections that discuss each of the steps in the EB method.

Step 1 – SPF development

As described in Step 1 of the EB before-after process, SPFs are required to predict the safety performance of freeway segments at which HTCMBs are not installed. Since Pennsylvania-specific SPFs were not available for freeway segments, these SPFs had to be manually developed as a part of this project. The research team used the set of freeway segments with no median barrier installed as a reference group to develop these SPFs. In doing so, the resulting CMFs would describe the change in safety performance when HTCMBs were installed at a location without any existing median barrier present. A total of 836.75 miles (1,717 segments) of freeways with no median barrier were available for this SPF development. Each of these segments had 15 years of data available for SPF development (2007 to 2021, inclusive). Of this, 666.33 miles (1,363 segments) represented rural freeway and 170.42 miles (354 segments) represented urban freeways. A summary of the rural and urban freeway databases used for SPF developed is provided in Table 5 and Table 6.

Table 5. Summary of data used for development of rural freeway SPFs

Continuous variable	Mean	Standard deviation	Minimum	Maximum
Length (mi)	0.49	0.067	0.087	0.73
Single-direction AADT (veh/day)	10,444	4,206	300	51,432
Median width (ft)	72	21	1	90
Total crash frequency	0.71	0.99	0	12
Fatal crash frequency	0.01	0.1	0	2
Suspected serious injury crash frequency	0.016	0.13	0	2
Suspected minor injury crash frequency	0.086	0.31	0	4
Possible injury crash frequency	0.14	0.4	0	7
Fatal + injury crash frequency	0.25	0.55	0	8
PDO crash frequency	0.46	0.74	0	9
HB crash frequency	0.01	0.11	0	4
CM crash frequency	0.018	0.14	0	2
KA crash frequency	0.027	0.16	0	2
KACM crash frequency	0.0025	0.05	0	1
Lane width (ft)	12	0	12	12
Inside shoulder width (ft)	4.2	0.87	0	10
Outside shoulder width	9.8	1.2	2	12
Degree of curvature per mile (deg/mi)	7.2	13	0	231
Categorical variable	**Category**		**Proportion %**	
Presence of inside shoulder rumble strips	most		4.6%	
	no		11.2%	
	partial		2.3%	
	yes		82.0%	
Presence of outside shoulder rumble strips	most		6.5%	
	no		11.2%	
	partial		3.8%	
	yes		78.4%	
On-ramp count	0		88.9%	
	1		11.0%	
	2		0.1%	
	3		0.0%	
Off-ramp count	0		90.1%	
	1		9.8%	
	2		0.1%	
	3		0.0%	
Presence of outside barrier	most		15.4%	
	no		32.1%	
	partial		45.0%	
	yes		7.6%	
Posted speed limit (mph)	30		0.0%	
	35		0.0%	
	40		0.1%	
	45		0.2%	
	50		0.6%	
	55		9.4%	
	65		44.5%	
	70		45.3%	
Number of lanes per direction	2		96.6%	
	3		3.4%	

Table 6. Summary of data used for development of urban freeway SPFs

Continuous variable	Mean	Standard deviation	Minimum	Maximum
Length (mi)	0.48	0.1	0.085	0.71
AADT (veh/day)	16,823	10,313	3,474	63,805
Median width (ft)	59	26	1	90
Total crash frequency	1.2	1.6	0	17
Fatal crash frequency	0.013	0.12	0	2
Suspected serious injury crash frequency	0.028	0.17	0	2
Suspected minor injury crash frequency	0.14	0.41	0	4
Possible injury crash frequency	0.27	0.63	0	8
Fatal + injury crash frequency	0.45	0.84	0	8
PDO crash frequency	0.74	1.1	0	12
HB crash frequency	0.052	0.27	0	4
CM crash frequency	0.034	0.19	0	2
KA crash frequency	0.04	0.21	0	3
KACM crash frequency	0.0066	0.09	0	2
Lane width (ft)	12	0.3	10	14
Inside shoulder width (ft)	4	1.2	0	9
Outside shoulder width	9.5	1.9	2	12
Degree of curvature per mile (deg/mi)	13	29	0	217

Categorical variable	Category	Proportion %
Presence of inside shoulder rumble strips	most	5.9%
	no	18.1%
	partial	2.0%
	yes	74.0%
Presence of outside shoulder rumble strips	most	9.0%
	no	14.7%
	partial	4.5%
	yes	71.8%
On-ramp count	0	75.4%
	1	22.3%
	2	2.0%
	3	0.3%
Off-ramp count	0	77.4%
	1	20.9%
	2	1.1%
	3	0.6%
Presence of outside barrier	most	15.5%
	no	31.9%
	partial	44.1%
	yes	8.5%
Posted speed limit (mph)	30	0.6%
	35	2.0%
	40	0.0%
	45	3.1%
	50	0.6%
	55	36.7%
	65	44.4%
	70	12.7%
Number of lanes per direction	2	97.2%
	3	2.8%

SPFs were developed separately for rural and urban freeway segments due to the differences in safety performance between these two freeway types. For each of the rural and urban settings, SPFs were developed for the following crash types:

- All crashes
- Fatal + injury crashes
- KA crashes
- PDO crashes
- Hit-barrier crashes
- Cross-median crashes
- KA cross-median crashes

The resulting SPFs are summarized in Appendix A of this report. These SPFs were developed using PennDOT-defined roadway segments as the unit of analysis. Thus, individual segments were not further subdivided into basic freeway segments or speed change lanes as is done in the HSM. Instead, the existence of on- and off-ramps was incorporated into the SPFs as indicator variables. While this is less detailed than the HSM, this provided the best balance between data collection and accuracy from a safety prediction standpoint. In general, the resulting SPFs seem reasonable and have coefficient estimates that align with engineering expectations.

Note also that the SPFs include indicator variables to account for each year in the analysis period (using 2007 as the base condition). This was done to account for changes in safety performance over time, since the analysis period is long (2007-2021). Additionally, several variables were included in a categorical format – as described in the Supplemental Data Collection section above – due to data availability. For these reasons, these SPFs should not be used outside of the scope of this safety evaluation or for design decision purposes.

Step 2 – Before-after analysis with empirical Bayes

The SPFs identified and developed as part of Step 1 were used to predict crash frequencies at all treatment locations using the EB procedure outlined above. These predicted values were then combined with reported crash frequencies using a weighting factor (Equation 4) to estimate expected crash frequencies at each HTCMB treatment site in the before period. Then, the expected crash frequencies in the before period were used to estimate the expected crash frequencies in the after period (Equation 6) based on changes in traffic volumes. Expected crash frequencies in the after period were computed for each roadway segment in this manner.

Step 3 – Comparison of predicted and actual safety performance

In this step, predicted and actual (reported) safety performance were compared to estimate CMFs for the installation of HTCMB on freeway facilities.

Table 7 provides a summary of the CMFs estimated across all freeway locations in Pennsylvania for all crashes (total), fatal + injury crashes (FI), property-damage-only crashes (PDO), hit-barrier crashes (HB), cross-median crashes (CM), fatal and suspected serious injury crashes (KA), and fatal and suspected serious injury cross-median crashes (KA CM). The standard errors of all CMFs were also estimated and used to identify if the CMF was statistically significant at the 95% confidence level; those that are statistically significant are noted in the table. As shown, the installation of HTCMB is found to be associated with a statistically significant increase in total crash frequency of approximately 13.3%, a statistically significant increase in PDO crash frequency of approximately 20.2%, and a statistically significant increase in HB crash frequency of approximately 183.5%. These results are in line with expectation: the barrier serves as another object in the roadway median that a vehicle can strike, which would increase the number of crashes, particularly hit-barrier crashes, and these crashes tend to be PDO crashes. An increase in FI crash frequency of 2.6% was observed, but this is not statistically significant. However, the HTCMB is found to be associated with a decrease in cross-median crashes of 79.1%, KA crashes of 34.2%, and a decrease in KA CM crashes of 89.9%, and all of these changes are statistically significant. This is also in line with expectation, as HTCMB would reduce cross-median crashes significantly, and these crashes tend to lead to the most severe injury outcomes.

Table 7. Summary of HTCMB CMFs for all freeway segments

Crash type	Number of segments	Total length (miles)	Reported crashes in after period	EB estimate in after period	Unbiased CMF	CMF standard error
Total	1563	763.16	11,424	10,081.46	1.133*	0.019
FI			3,736	3,624.00	1.031	0.025
PDO			7,688	6,393.08	1.202*	0.023
HB			1,213	426.57	2.835*	0.178
CM			78	371.82	0.209*	0.025
KA			308	467.25	0.658*	0.044
KA CM			7	68.30	0.101*	0.039

* statistically significant to the 95% confidence level

Note that while the CMF for KA CM crashes is statistically significant, the relatively low number of crashes expected in the after period (68.3) and observed in the after period (7) means that the actual CMF estimate would be highly subject to randomness in the number of observed crashes. Thus, while HTCMB is expected to significantly decrease this crash type, a more precise estimate of the magnitude of this decrease should be further refined when additional years of crash data are available.

Table 8 and Table 9 provide a summary of the CMFs for urban freeway segments and rural freeway segments, respectively. The results are generally consistent with the results for all freeway segments. The results suggest that total, PDO, and HB crash frequency tends to increase more on rural segments than on urban segments, and the decrease in CM and KA crashes is lower on rural segments than on urban segments. However, this could be due to the relatively lower amount of these crashes on rural segments compared to urban segments, which would make the results subject to more randomness. Nevertheless, HTCMB appears to provide a significant safety benefit for CM crashes and crashes of the highest injury severity levels on both urban and rural freeway segments.

Table 8. Summary of HTCMB CMFs for urban freeway segments

Crash type	Number of segments	Total length (miles)	Reported crashes in after period	EB estimate in after period	Unbiased CMF	CMF standard error
Total	808	398.74	8,609	7,745.48	1.111*	0.023
FI			2,868	2,805.51	1.022	0.030
PDO			5,741	4,836.72	1.187*	0.028
HB			948	349.92	2.698*	0.192
CM			48	268.61	0.178*	0.027
KA			219	358.46	0.610*	0.049
KACM			7	49.43	0.139*	0.055

* statistically significant to the 95% confidence level

Table 9. Summary of HTCMB CMFs for rural freeway segments

Crash type	Number of segments	Total length (miles)	Reported crashes in after period	EB estimate in after period	Unbiased CMF	CMF standard error
Total	755	364.42	2,815	2,335.98	1.205*	0.030
FI			868	818.49	1.060	0.044
PDO			1,947	1,556.37	1.251*	0.036
HB			265	76.65	3.416*	0.426
CM			30	103.22	0.290*	0.055
KA			89	108.79	0.817*	0.092
KACM			0	18.87	0.000	N/A

* statistically significant to the 95% confidence level

N/A – could not be computed due to no crashes being observed on this type

CMFs were also estimated for the two most common installation locations of HTCMB on Pennsylvania freeway segments: shoulder (one side) and center of median (single-run). The CMF results are provided in Table 10 and Table 11, and the findings are consistent with the previous findings for all HTCMB installations. HTCMB installed on the shoulder are associated with larger increases in HB crash frequency (213%) than HTCMB installed along the center of the median (130%); this is expected due to the proximity of the HTCMB to the travel lanes, where installations along the center of the median would be equidistant from both directions of travel, while shoulder installations will be close to one travel direction. However, the shoulder installation is associated with a smaller increase in total and PDO crash frequency. One potential explanation for this is that minor crashes near the shoulder may be more likely to go unreported, as opposed to those that occur within the median. However, both installation types seem to be associated with nearly equal reductions in CM, KA, and KA CM crash frequency. Due to data collection limits, it was not possible to differentiate if the HTCMB was placed on the nearest shoulder of the unidirectional segment or on the opposite side of the median for the shoulder (one side) installation type.

Table 10. Summary of shoulder (one side) HTCMB CMFs on urban and rural segments (combined)

Crash type	Number of segments	Total length (miles)	Reported crashes in after period	EB estimate in after period	Unbiased CMF	CMF standard error
Total	903	433.23	6,633	6,063.11	1.094*	0.025
FI			2,186	2,141.57	1.020	0.034
PDO			4,447	3,835.57	1.159*	0.030
HB			750	237.84	3.133*	0.275
CM			42	210.38	0.199*	0.032
KA			163	263.51	0.617*	0.057
KACM			3	38.30	0.076*	0.045

* statistically significant to the 95% confidence level

Table 11. Summary of middle (single-run) HTCMB CMFs on urban and rural segments (combined)

Crash type	Number of segments	Total length (miles)	Reported crashes in after period	EB estimate in after period	Unbiased CMF	CMF standard error
Total	498	253.74	4,242	3,539.61	1.198*	0.031
FI			1,408	1,323.75	1.063	0.041
PDO			2,834	2,225.51	1.273*	0.039
HB			411	176.93	2.308*	0.216
CM			26	136.70	0.189*	0.039
KA			127	182.14	0.695*	0.072
KACM			3	27.02	0.108*	0.063

* statistically significant to the 95% confidence level

SUMMARY

The purpose of this evaluation was to estimate CMFs for HTCMB installations on rural and urban freeways in Pennsylvania. A database from a prior PennDOT-funded project, to conduct network screening of freeway segments, formed the preliminary database for the evaluation. These data were re-structured into a directional format and supplemental data were added to form a robust data file to estimate the CMFs. An empirical Bayes before-after observational study design was used to estimate the CMFs for a variety of crash types and severity levels.

The results of the evaluation indicate that, when combining rural and urban segments together, total, fatal + injury, property-damage only, and hit-barrier crashes were expected to increase after installation of HTCMB. With the exception of the total fatal + injury crash type, the results were statistically significant. The results are consistent with engineering expectations because, when an object (longitudinal barrier) is placed adjacent to the traveled way, it is expected that run-off-road crashes will increase because the barrier limits the lateral distance for a vehicle to recover. A recent study using freeway data from Michigan reported a CMF of 2.63 for possible injury and PDO crashes for HTCMB (Russo et al., 2016).

When combining all rural and urban freeway segments, the CMFs for cross-median, fatal + A-injury (serious injury), and fatal + A-injury cross-median crashes were all less than 1.0 and statistically significant, indicating that HTCMB is expected to be associated with a decrease in these crash types. These results were also consistent with engineering expectations, as the longitudinal barrier is intended to mitigate severe crashes resulting from vehicles crossing the median and colliding with vehicles traveling in the opposite direction. The study by Russo et al reported CMFs of 0.47 and 0.76 for fatal and A-injury crashes, respectively, on freeways in Michigan, for median widths ranging from 26 to 50 ft and from 51 to 94 ft, respectively (Russo et al., 2016). These results are consistent with the CMF of 0.658 for fatal and A-injury crashes in the present study.

When disaggregating the CMFs by area type, the rural and urban CMFs are similar to the CMFs for all freeway segments combined. When considering the placement of the HTCMB, the results are also similar to the CMFs for all rural and urban segments combined. An important distinction regarding placement, however, is that the hit-barrier CMF is 3.133 when the HTCMB is installed along the shoulder of the freeway in one direction of travel, while the CMF is 2.308 when the HTCMB is installed in the center of the median. This suggests that the lateral distance from the inside edge of the traveled way may influence the expected number of crashes with the barrier – placing the barrier further from the edge of the traveled way may result in fewer expected crashes than placing it along the edge of the traveled way.

References

American Association of State Highway and Transportation Officials, 2010. *Highway Safety Manual*.

Gross, F., Persaud, B., Lyon, C., 2010. *A Guide to Developing Quality Crash Modification Factors*. Washington.

Hauer, E., 1997. *Observational Before-After Studies in Road Safety: Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety*. Emerald Group Publishing Limited, Bingley, UK.

Pennsylvania Department of Transportation, 2021. *Pennsylvania Safety Predictive Analysis Methods Manual*. Pennsylvania Publication 638A.

Russo, B.J., Savolainen, P.T., Gates, T.J., 2016. Development of Crash Modification Factors for Installation of High-Tension Cable Median Barriers. *Transportation Research Record* 2588, 116–125.

APPENDIX A: SUMMARY OF SPFS DEVELOPED FOR FREEWAY SEGMENTS

Table 12. SPF developed for total crash frequency on urban freeway segments

Variable	Coefficient	Standard Error	t-statistic	p-value
Constant	-6.303	0.291	-21.645	<0.001
Natural logarithm of AADT (veh/day)	0.703	0.027	25.615	<0.001
Natural logarithm of length (miles)	0.879	0.078	11.227	<0.001
Indicator variable for presence of outside barrier on most of the segment (1 indicates yes, 0 indicates no)	0.069	0.045	1.538	0.124
Indicator variable for presence of outside barrier on entire segment (1 indicates yes, 0 indicates no)	0.123	0.058	2.139	0.032
Indicator variable for presence of shoulder rumble strip on segment (1 indicates none present, 0 some present)	0.338	0.048	6.987	<0.001
Indicator variable for inside shoulder width less than 4 ft (1 indicates yes, 0 indicates no)	0.343	0.050	6.873	<0.001
Indicator for posted speed limit greater than 55 mph (1 indicates yes, 0 indicates no)	-0.169	0.033	-5.148	<0.001
Indicator for on-ramp count greater than 0 (1 indicates yes, 0 indicates no)	0.224	0.037	6.021	<0.001
Indicator for off-ramp count greater than 0 (1 indicates yes, 0 indicates no)	0.254	0.038	6.636	<0.001
Degree of curvature per mile (degrees/mile)	0.005	0.002	2.667	0.008
Indicator for year 2008 (1 indicates yes, 0 indicates no)	-0.061	0.090	-0.676	0.499
Indicator for year 2009 (1 indicates yes, 0 indicates no)	-0.008	0.089	-0.084	0.933
Indicator for year 2010 (1 indicates yes, 0 indicates no)	-0.031	0.090	-0.340	0.734
Indicator for year 2011 (1 indicates yes, 0 indicates no)	0.191	0.087	2.193	0.028
Indicator for year 2012 (1 indicates yes, 0 indicates no)	0.229	0.086	2.650	0.008
Indicator for year 2013 (1 indicates yes, 0 indicates no)	0.273	0.086	3.178	0.001
Indicator for year 2014 (1 indicates yes, 0 indicates no)	0.270	0.086	3.136	0.002
Indicator for year 2015 (1 indicates yes, 0 indicates no)	0.271	0.086	3.162	0.002
Indicator for year 2016 (1 indicates yes, 0 indicates no)	0.315	0.085	3.728	<0.001
Indicator for year 2017 (1 indicates yes, 0 indicates no)	0.264	0.085	3.110	0.002
Indicator for year 2018 (1 indicates yes, 0 indicates no)	0.135	0.086	1.565	0.118
Indicator for year 2019 (1 indicates yes, 0 indicates no)	0.175	0.086	2.035	0.042
Indicator for year 2020 (1 indicates yes, 0 indicates no)	-0.082	0.090	-0.913	0.361
Indicator for year 2021 (1 indicates yes, 0 indicates no)	0.140	0.087	1.617	0.106
Overdispersion parameter = 0.366, 2 x LL = -14927.080				

Table 13. SPF developed for total crash frequency on rural freeway segments

Variable	Coefficient	Standard Error	t-statistic	p-value
Constant	-5.929	0.227	-26.072	<0.001
Natural logarithm of AADT (veh/day)	0.653	0.023	27.852	<0.001
Natural logarithm of length (miles)	0.988	0.070	14.180	<0.001
Indicator for number of lanes greater than 2 (1 indicates yes, 0 indicates no)	0.244	0.126	1.928	0.054
Indicator variable for presence of shoulder rumble strip on segment (1 indicates none present, 0 some present)	0.072	0.032	2.275	0.023
Indicator variable for outside shoulder width less than 10 ft (1 indicates yes, 0 indicates no)	0.165	0.037	4.481	<0.001
Indicator variable for inside shoulder width less than 4 ft (1 indicates yes, 0 indicates no)	0.178	0.085	2.084	0.037
Indicator for on-ramp count greater than 0 (1 indicates yes, 0 indicates no)	0.140	0.029	4.859	<0.001
Indicator for off-ramp count greater than 0 (1 indicates yes, 0 indicates no)	0.144	0.030	4.808	<0.001
Indicator for posted speed limit of greater than or equal to 65 mph (1 indicates yes, 0 indicates no)	0.079	0.038	2.085	0.037
Degree of curvature per mile (degrees/mile)	0.018	0.001	12.673	<0.001
Indicator for year 2008 (1 indicates yes, 0 indicates no)	0.139	0.051	2.730	0.006
Indicator for year 2009 (1 indicates yes, 0 indicates no)	0.024	0.053	0.448	0.654
Indicator for year 2010 (1 indicates yes, 0 indicates no)	0.025	0.053	0.485	0.628
Indicator for year 2011 (1 indicates yes, 0 indicates no)	0.042	0.052	0.814	0.416
Indicator for year 2012 (1 indicates yes, 0 indicates no)	-0.021	0.053	-0.406	0.684
Indicator for year 2013 (1 indicates yes, 0 indicates no)	0.075	0.052	1.446	0.148
Indicator for year 2014 (1 indicates yes, 0 indicates no)	0.150	0.051	2.913	0.004
Indicator for year 2015 (1 indicates yes, 0 indicates no)	0.092	0.051	1.787	0.074
Indicator for year 2016 (1 indicates yes, 0 indicates no)	0.093	0.051	1.826	0.068
Indicator for year 2017 (1 indicates yes, 0 indicates no)	0.164	0.051	3.228	0.001
Indicator for year 2018 (1 indicates yes, 0 indicates no)	0.179	0.050	3.555	<0.001
Indicator for year 2019 (1 indicates yes, 0 indicates no)	0.120	0.051	2.353	0.019
Indicator for year 2020 (1 indicates yes, 0 indicates no)	-0.009	0.053	-0.174	0.862
Indicator for year 2021 (1 indicates yes, 0 indicates no)	0.077	0.052	1.488	0.137
Overdispersion parameter = 0.333, 2 x LL = -45729.930				

Table 14. SPF developed for fatal + injury crash frequency on urban freeway segments

Variable	Coefficient	Standard Error	t-statistic	p-value
Constant	-7.763	0.428	-18.120	<0.001
Natural logarithm of AADT (veh/day)	0.762	0.040	18.974	<0.001
Natural logarithm of length (miles)	0.980	0.112	8.718	<0.001
Indicator variable for presence of shoulder rumble strip on segment (1 indicates none present, 0 some present)	0.388	0.071	5.472	<0.001
Indicator variable for outside shoulder width less than 10 ft (1 indicates yes, 0 indicates no)	0.175	0.067	2.611	0.009
Indicator variable for inside shoulder width less than 4 ft (1 indicates yes, 0 indicates no)	0.593	0.069	8.606	<0.001
Indicator for posted speed limit greater than 55 mph (1 indicates yes, 0 indicates no)	-0.257	0.049	-5.246	<0.001
Indicator for on-ramp count greater than 0 (1 indicates yes, 0 indicates no)	0.165	0.055	3.003	0.003
Indicator for off-ramp count greater than 0 (1 indicates yes, 0 indicates no)	0.233	0.056	4.188	<0.001
Degree of curvature per mile (degrees/mile)	0.004	0.003	1.525	0.127
Indicator for year 2008 (1 indicates yes, 0 indicates no)	0.008	0.132	0.062	0.950
Indicator for year 2009 (1 indicates yes, 0 indicates no)	0.044	0.131	0.337	0.736
Indicator for year 2010 (1 indicates yes, 0 indicates no)	0.042	0.131	0.320	0.749
Indicator for year 2011 (1 indicates yes, 0 indicates no)	0.397	0.124	3.217	0.001
Indicator for year 2012 (1 indicates yes, 0 indicates no)	0.345	0.125	2.773	0.006
Indicator for year 2013 (1 indicates yes, 0 indicates no)	0.158	0.129	1.225	0.221
Indicator for year 2014 (1 indicates yes, 0 indicates no)	0.273	0.126	2.155	0.031
Indicator for year 2015 (1 indicates yes, 0 indicates no)	0.299	0.125	2.380	0.017
Indicator for year 2016 (1 indicates yes, 0 indicates no)	0.197	0.126	1.556	0.120
Indicator for year 2017 (1 indicates yes, 0 indicates no)	0.178	0.126	1.407	0.160
Indicator for year 2018 (1 indicates yes, 0 indicates no)	-0.012	0.131	-0.094	0.925
Indicator for year 2019 (1 indicates yes, 0 indicates no)	0.042	0.129	0.327	0.744
Indicator for year 2020 (1 indicates yes, 0 indicates no)	-0.169	0.136	-1.244	0.214
Indicator for year 2021 (1 indicates yes, 0 indicates no)	0.143	0.128	1.121	0.262
Overdispersion parameter = 0.417, 2 x LL = -8890.803				

Table 15. SPF developed for fatal + injury crash frequency on rural freeway segments

Variable	Coefficient	Standard Error	t-statistic	p-value
Constant	-8.060	0.372	-21.685	<0.001
Natural logarithm of AADT (veh/day)	0.806	0.038	21.069	<0.001
Natural logarithm of length (miles)	1.035	0.111	9.314	<0.001
Indicator for number of lanes greater than 2 (1 indicates yes, 0 indicates no)	0.281	0.184	1.524	0.127
Indicator variable for presence of shoulder rumble strip on segment (1 indicates none present, 0 some present)	0.083	0.050	1.655	0.098
Indicator variable for outside shoulder width less than 10 ft (1 indicates yes, 0 indicates no)	0.160	0.057	2.776	0.006
Indicator variable for inside shoulder width less than 4 ft (1 indicates yes, 0 indicates no)	0.302	0.126	2.392	0.017
Indicator for on-ramp count greater than 0 (1 indicates yes, 0 indicates no)	0.139	0.045	3.086	0.002
Indicator for off-ramp count greater than 0 (1 indicates yes, 0 indicates no)	0.140	0.047	2.989	0.003
Indicator for posted speed limit of greater than or equal to 65 mph (1 indicates yes, 0 indicates no)	-0.095	0.057	-1.668	0.095
Degree of curvature per mile (degrees/mile)	0.021	0.002	9.634	<0.001
Indicator for year 2008 (1 indicates yes, 0 indicates no)	0.109	0.076	1.422	0.155
Indicator for year 2009 (1 indicates yes, 0 indicates no)	0.009	0.078	0.120	0.904
Indicator for year 2010 (1 indicates yes, 0 indicates no)	-0.094	0.080	-1.166	0.243
Indicator for year 2011 (1 indicates yes, 0 indicates no)	-0.033	0.079	-0.415	0.678
Indicator for year 2012 (1 indicates yes, 0 indicates no)	-0.125	0.080	-1.552	0.121
Indicator for year 2013 (1 indicates yes, 0 indicates no)	-0.059	0.080	-0.741	0.459
Indicator for year 2014 (1 indicates yes, 0 indicates no)	-0.006	0.079	-0.075	0.940
Indicator for year 2015 (1 indicates yes, 0 indicates no)	-0.110	0.080	-1.375	0.169
Indicator for year 2016 (1 indicates yes, 0 indicates no)	-0.085	0.079	-1.076	0.282
Indicator for year 2017 (1 indicates yes, 0 indicates no)	-0.186	0.082	-2.283	0.022
Indicator for year 2018 (1 indicates yes, 0 indicates no)	-0.062	0.079	-0.790	0.429
Indicator for year 2019 (1 indicates yes, 0 indicates no)	-0.114	0.079	-1.438	0.150
Indicator for year 2020 (1 indicates yes, 0 indicates no)	-0.365	0.085	-4.278	<0.001
Indicator for year 2021 (1 indicates yes, 0 indicates no)	-0.112	0.080	-1.395	0.163
Overdispersion parameter = 0.463, 2 x LL = -25005.203				

Table 16. SPF developed for KA crash frequency on urban freeway segments

Variable	Coefficient	Standard Error	t-statistic	p-value
Constant	-10.183	1.285	-7.924	<0.001
Natural logarithm of AADT (veh/day)	0.751	0.123	6.085	<0.001
Natural logarithm of length (miles)	0.681	0.311	2.190	0.029
Indicator variable for outside shoulder width less than 10 ft (1 indicates yes, 0 indicates no)	0.465	0.186	2.502	0.012
Indicator variable for inside shoulder width less than 4 ft (1 indicates yes, 0 indicates no)	0.578	0.202	2.858	0.004
Indicator for year 2008 (1 indicates yes, 0 indicates no)	0.086	0.386	0.223	0.824
Indicator for year 2009 (1 indicates yes, 0 indicates no)	0.036	0.391	0.092	0.927
Indicator for year 2010 (1 indicates yes, 0 indicates no)	-0.409	0.439	-0.932	0.351
Indicator for year 2011 (1 indicates yes, 0 indicates no)	0.354	0.369	0.959	0.337
Indicator for year 2012 (1 indicates yes, 0 indicates no)	-0.190	0.417	-0.455	0.649
Indicator for year 2013 (1 indicates yes, 0 indicates no)	-0.642	0.476	-1.347	0.178
Indicator for year 2014 (1 indicates yes, 0 indicates no)	-0.006	0.399	-0.014	0.989
Indicator for year 2015 (1 indicates yes, 0 indicates no)	-0.188	0.416	-0.452	0.652
Indicator for year 2016 (1 indicates yes, 0 indicates no)	0.353	0.364	0.969	0.332
Indicator for year 2017 (1 indicates yes, 0 indicates no)	-0.254	0.416	-0.612	0.541
Indicator for year 2018 (1 indicates yes, 0 indicates no)	-0.284	0.417	-0.681	0.496
Indicator for year 2019 (1 indicates yes, 0 indicates no)	0.216	0.371	0.582	0.561
Indicator for year 2020 (1 indicates yes, 0 indicates no)	0.232	0.371	0.623	0.533
Indicator for year 2021 (1 indicates yes, 0 indicates no)	0.510	0.354	1.443	0.149
Overdispersion parameter = 1.486, 2 x LL = -1736.492				

Table 17. SPF developed for KA crash frequency on rural freeway segments

Variable	Coefficient	Standard Error	t-statistic	p-value
Constant	-12.734	1.117	-11.401	<0.001
Natural logarithm of AADT (veh/day)	1.035	0.115	9.034	<0.001
Natural logarithm of length (miles)	0.977	0.342	2.859	0.004
Degree of curvature per mile (degrees/mile)	0.023	0.006	3.654	<0.001
Indicator for year 2008 (1 indicates yes, 0 indicates no)	0.469	0.229	2.049	0.040
Indicator for year 2009 (1 indicates yes, 0 indicates no)	0.107	0.248	0.432	0.666
Indicator for year 2010 (1 indicates yes, 0 indicates no)	0.085	0.250	0.338	0.736
Indicator for year 2011 (1 indicates yes, 0 indicates no)	-0.110	0.261	-0.421	0.674
Indicator for year 2012 (1 indicates yes, 0 indicates no)	-0.119	0.261	-0.455	0.649
Indicator for year 2013 (1 indicates yes, 0 indicates no)	0.267	0.241	1.108	0.268
Indicator for year 2014 (1 indicates yes, 0 indicates no)	0.263	0.242	1.087	0.277
Indicator for year 2015 (1 indicates yes, 0 indicates no)	-0.204	0.266	-0.767	0.443
Indicator for year 2016 (1 indicates yes, 0 indicates no)	0.204	0.237	0.861	0.389
Indicator for year 2017 (1 indicates yes, 0 indicates no)	0.265	0.238	1.113	0.266
Indicator for year 2018 (1 indicates yes, 0 indicates no)	0.090	0.245	0.367	0.714
Indicator for year 2019 (1 indicates yes, 0 indicates no)	0.226	0.237	0.956	0.339
Indicator for year 2020 (1 indicates yes, 0 indicates no)	0.066	0.248	0.268	0.789
Indicator for year 2021 (1 indicates yes, 0 indicates no)	0.231	0.239	0.963	0.335
Overdispersion parameter = 0.569, 2 x LL = -4915.151				

Table 18. SPF developed for PDO crash frequency on urban freeway segments

Variable	Coefficient	Standard Error	t-statistic	p-value
Constant	-6.627	0.343	-19.348	<0.001
Natural logarithm of AADT (veh/day)	0.679	0.032	21.069	<0.001
Natural logarithm of length (miles)	0.788	0.090	8.724	<0.001
Indicator variable for presence of outside barrier on most of the segment (1 indicates yes, 0 indicates no)	0.104	0.052	2.000	0.046
Indicator variable for presence of outside barrier on entire segment (1 indicates yes, 0 indicates no)	0.236	0.066	3.575	<0.001
Indicator variable for presence of shoulder rumble strip on segment (1 indicates none present, 0 some present)	0.340	0.055	6.150	<0.001
Indicator for posted speed limit greater than 55 mph (1 indicates yes, 0 indicates no)	-0.116	0.039	-2.997	0.003
Indicator for on-ramp count greater than 0 (1 indicates yes, 0 indicates no)	0.271	0.043	6.358	<0.001
Indicator for off-ramp count greater than 0 (1 indicates yes, 0 indicates no)	0.269	0.044	6.084	<0.001
Degree of curvature per mile (degrees/mile)	0.005	0.002	2.399	0.016
Indicator for year 2008 (1 indicates yes, 0 indicates no)	-0.106	0.108	-0.981	0.327
Indicator for year 2009 (1 indicates yes, 0 indicates no)	-0.054	0.107	-0.505	0.613
Indicator for year 2010 (1 indicates yes, 0 indicates no)	-0.078	0.108	-0.726	0.468
Indicator for year 2011 (1 indicates yes, 0 indicates no)	0.030	0.106	0.286	0.775
Indicator for year 2012 (1 indicates yes, 0 indicates no)	0.148	0.103	1.433	0.152
Indicator for year 2013 (1 indicates yes, 0 indicates no)	0.326	0.100	3.252	0.001
Indicator for year 2014 (1 indicates yes, 0 indicates no)	0.261	0.102	2.571	0.010
Indicator for year 2015 (1 indicates yes, 0 indicates no)	0.256	0.101	2.529	0.011
Indicator for year 2016 (1 indicates yes, 0 indicates no)	0.388	0.098	3.943	0.000
Indicator for year 2017 (1 indicates yes, 0 indicates no)	0.307	0.099	3.096	0.002
Indicator for year 2018 (1 indicates yes, 0 indicates no)	0.204	0.101	2.030	0.042
Indicator for year 2019 (1 indicates yes, 0 indicates no)	0.243	0.100	2.426	0.015
Indicator for year 2020 (1 indicates yes, 0 indicates no)	-0.041	0.106	-0.385	0.700
Indicator for year 2021 (1 indicates yes, 0 indicates no)	0.126	0.103	1.228	0.219
Overdispersion parameter = 0.344, 2 x LL = -11840.890				

Table 19. SPF developed for PDO crash frequency on rural freeway segments

Variable	Coefficient	Standard Error	t-statistic	p-value
Constant	-5.772	0.269	-21.444	<0.001
Natural logarithm of AADT (veh/day)	0.569	0.028	20.562	<0.001
Natural logarithm of length (miles)	0.962	0.085	11.372	<0.001
Indicator for number of lanes greater than 2 (1 indicates yes, 0 indicates no)	0.246	0.150	1.642	0.101
Indicator variable for presence of shoulder rumble strip on segment (1 indicates none present, 0 some present)	0.066	0.037	1.763	0.078
Indicator variable for outside shoulder width less than 10 ft (1 indicates yes, 0 indicates no)	0.166	0.044	3.767	<0.001
Indicator for on-ramp count greater than 0 (1 indicates yes, 0 indicates no)	0.139	0.034	4.066	<0.001
Indicator for off-ramp count greater than 0 (1 indicates yes, 0 indicates no)	0.147	0.035	4.142	<0.001
Indicator for posted speed limit of greater than or equal to 65 mph (1 indicates yes, 0 indicates no)	0.164	0.046	3.586	<0.001
Degree of curvature per mile (degrees/mile)	0.017	0.002	9.613	<0.001
Indicator for year 2008 (1 indicates yes, 0 indicates no)	0.157	0.063	2.483	0.013
Indicator for year 2009 (1 indicates yes, 0 indicates no)	0.028	0.065	0.436	0.663
Indicator for year 2010 (1 indicates yes, 0 indicates no)	0.095	0.064	1.474	0.140
Indicator for year 2011 (1 indicates yes, 0 indicates no)	0.086	0.064	1.337	0.181
Indicator for year 2012 (1 indicates yes, 0 indicates no)	0.041	0.065	0.627	0.531
Indicator for year 2013 (1 indicates yes, 0 indicates no)	0.154	0.064	2.425	0.015
Indicator for year 2014 (1 indicates yes, 0 indicates no)	0.241	0.063	3.843	<0.001
Indicator for year 2015 (1 indicates yes, 0 indicates no)	0.207	0.062	3.319	0.001
Indicator for year 2016 (1 indicates yes, 0 indicates no)	0.198	0.062	3.195	0.001
Indicator for year 2017 (1 indicates yes, 0 indicates no)	0.348	0.061	5.720	<0.001
Indicator for year 2018 (1 indicates yes, 0 indicates no)	0.314	0.061	5.154	<0.001
Indicator for year 2019 (1 indicates yes, 0 indicates no)	0.251	0.062	4.075	<0.001
Indicator for year 2020 (1 indicates yes, 0 indicates no)	0.175	0.063	2.791	0.005
Indicator for year 2021 (1 indicates yes, 0 indicates no)	0.186	0.063	2.958	0.003
Overdispersion parameter = 0.297, 2 x LL = -35979.406				

Table 20. SPF developed for HB crash frequency on urban freeway segments

Variable	Coefficient	Standard Error	t-statistic	p-value
Constant	-14.338	1.328	-10.794	<0.001
Natural logarithm of AADT (veh/day)	1.237	0.127	9.779	<0.001
Natural logarithm of length (miles)	1.067	0.303	3.523	<0.001
Indicator variable for presence of outside barrier on most of the segment (1 indicates yes, 0 indicates no)	0.521	0.194	2.684	0.007
Indicator variable for presence of outside barrier on entire segment (1 indicates yes, 0 indicates no)	0.679	0.220	3.087	0.002
Indicator for posted speed limit greater than 55 mph (1 indicates yes, 0 indicates no)	-0.561	0.150	-3.754	<0.001
Indicator for on-ramp count greater than 0 (1 indicates yes, 0 indicates no)	0.809	0.149	5.432	<0.001
Indicator for off-ramp count greater than 0 (1 indicates yes, 0 indicates no)	0.804	0.154	5.210	<0.001
Degree of curvature per mile (degrees/mile)	0.024	0.007	3.313	0.001
Indicator for year 2008 (1 indicates yes, 0 indicates no)	-0.524	0.345	-1.519	0.129
Indicator for year 2009 (1 indicates yes, 0 indicates no)	-0.178	0.322	-0.554	0.579
Indicator for year 2010 (1 indicates yes, 0 indicates no)	-0.256	0.327	-0.781	0.435
Indicator for year 2011 (1 indicates yes, 0 indicates no)	-0.346	0.338	-1.025	0.305
Indicator for year 2012 (1 indicates yes, 0 indicates no)	-0.677	0.366	-1.850	0.064
Indicator for year 2013 (1 indicates yes, 0 indicates no)	-0.316	0.336	-0.940	0.347
Indicator for year 2014 (1 indicates yes, 0 indicates no)	-0.429	0.347	-1.238	0.216
Indicator for year 2015 (1 indicates yes, 0 indicates no)	-0.620	0.362	-1.715	0.086
Indicator for year 2016 (1 indicates yes, 0 indicates no)	-0.779	0.368	-2.117	0.034
Indicator for year 2017 (1 indicates yes, 0 indicates no)	-0.626	0.350	-1.789	0.074
Indicator for year 2018 (1 indicates yes, 0 indicates no)	-1.417	0.437	-3.240	0.001
Indicator for year 2019 (1 indicates yes, 0 indicates no)	-0.984	0.380	-2.587	0.010
Indicator for year 2020 (1 indicates yes, 0 indicates no)	-0.457	0.337	-1.357	0.175
Indicator for year 2021 (1 indicates yes, 0 indicates no)	-0.572	0.348	-1.646	0.100
Overdispersion parameter = 2.583, 2 x LL = -1878.422				

Table 21. SPF developed for HB crash frequency on rural freeway segments

Variable	Coefficient	Standard Error	t-statistic	p-value
Constant	-12.688	1.647	-7.703	<0.001
Natural logarithm of AADT (veh/day)	1.089	0.171	6.352	<0.001
Natural logarithm of length (miles)	0.713	0.486	1.465	0.143
Median width (ft)	-0.005	0.004	-1.239	0.215
Indicator variable for presence of outside barrier on entire segment (1 indicates yes, 0 indicates no)	0.540	0.242	2.232	0.026
Indicator for on-ramp count greater than 0 (1 indicates yes, 0 indicates no)	0.610	0.192	3.176	0.001
Indicator for off-ramp count greater than 0 (1 indicates yes, 0 indicates no)	0.446	0.208	2.147	0.032
Indicator for posted speed limit of 65 mph (1 indicates yes, 0 indicates no)	-0.548	0.216	-2.541	0.011
Indicator for posted speed limit of 70 mph (1 indicates yes, 0 indicates no)	-1.498	0.259	-5.774	<0.001
Degree of curvature per mile (degrees/mile)	-0.011	0.013	-0.828	0.407
Indicator for year 2008 (1 indicates yes, 0 indicates no)	-0.578	0.370	-1.563	0.118
Indicator for year 2009 (1 indicates yes, 0 indicates no)	-0.637	0.378	-1.687	0.092
Indicator for year 2010 (1 indicates yes, 0 indicates no)	-0.835	0.402	-2.077	0.038
Indicator for year 2011 (1 indicates yes, 0 indicates no)	-0.834	0.401	-2.080	0.038
Indicator for year 2012 (1 indicates yes, 0 indicates no)	-1.070	0.433	-2.473	0.013
Indicator for year 2013 (1 indicates yes, 0 indicates no)	-0.432	0.360	-1.200	0.230
Indicator for year 2014 (1 indicates yes, 0 indicates no)	-0.215	0.342	-0.630	0.529
Indicator for year 2015 (1 indicates yes, 0 indicates no)	-0.230	0.338	-0.680	0.496
Indicator for year 2016 (1 indicates yes, 0 indicates no)	-0.433	0.349	-1.240	0.215
Indicator for year 2017 (1 indicates yes, 0 indicates no)	-0.740	0.388	-1.909	0.056
Indicator for year 2018 (1 indicates yes, 0 indicates no)	-0.394	0.347	-1.135	0.256
Indicator for year 2019 (1 indicates yes, 0 indicates no)	-0.372	0.344	-1.081	0.280
Indicator for year 2020 (1 indicates yes, 0 indicates no)	-0.685	0.379	-1.809	0.070
Indicator for year 2021 (1 indicates yes, 0 indicates no)	-1.239	0.455	-2.725	0.006
Overdispersion parameter = 6.050, 2 x LL = -2134.629				

Table 22. SPF developed for CM crash frequency on urban freeway segments

Variable	Coefficient	Standard Error	t-statistic	p-value
Constant	-8.076	1.381	-5.849	<0.001
Natural logarithm of AADT (veh/day)	0.507	0.130	3.892	<0.001
Natural logarithm of length (miles)	0.833	0.382	2.184	0.029
Indicator for year 2008 (1 indicates yes, 0 indicates no)	0.328	0.476	0.690	0.490
Indicator for year 2009 (1 indicates yes, 0 indicates no)	-1.379	0.797	-1.730	0.084
Indicator for year 2010 (1 indicates yes, 0 indicates no)	0.321	0.478	0.672	0.501
Indicator for year 2011 (1 indicates yes, 0 indicates no)	0.343	0.478	0.719	0.472
Indicator for year 2012 (1 indicates yes, 0 indicates no)	0.593	0.456	1.301	0.193
Indicator for year 2013 (1 indicates yes, 0 indicates no)	0.439	0.469	0.936	0.349
Indicator for year 2014 (1 indicates yes, 0 indicates no)	0.663	0.451	1.470	0.142
Indicator for year 2015 (1 indicates yes, 0 indicates no)	0.990	0.430	2.305	0.021
Indicator for year 2016 (1 indicates yes, 0 indicates no)	0.466	0.463	1.007	0.314
Indicator for year 2017 (1 indicates yes, 0 indicates no)	0.382	0.469	0.816	0.415
Indicator for year 2018 (1 indicates yes, 0 indicates no)	0.182	0.487	0.374	0.708
Indicator for year 2019 (1 indicates yes, 0 indicates no)	0.363	0.469	0.773	0.440
Indicator for year 2020 (1 indicates yes, 0 indicates no)	0.288	0.478	0.603	0.546
Indicator for year 2021 (1 indicates yes, 0 indicates no)	0.789	0.439	1.799	0.072
Overdispersion parameter = 1.981, 2 x LL = -1541.514				

Table 23. SPF developed for CM crash frequency on urban freeway segments

Variable	Coefficient	Standard Error	t-statistic	p-value
Constant	-10.601	1.260	-8.411	<0.001
Natural logarithm of AADT (veh/day)	0.911	0.129	7.050	<0.001
Natural logarithm of length (miles)	2.001	0.448	4.464	<0.001
Median width (ft)	-0.020	0.002	-8.723	<0.001
Degree of curvature per mile (degrees/mile)	0.020	0.008	2.583	0.010
Indicator for year 2008 (1 indicates yes, 0 indicates no)	1.239	0.363	3.417	0.001
Indicator for year 2009 (1 indicates yes, 0 indicates no)	-0.469	0.519	-0.904	0.366
Indicator for year 2010 (1 indicates yes, 0 indicates no)	1.240	0.364	3.405	0.001
Indicator for year 2011 (1 indicates yes, 0 indicates no)	0.430	0.411	1.046	0.295
Indicator for year 2012 (1 indicates yes, 0 indicates no)	0.546	0.401	1.359	0.174
Indicator for year 2013 (1 indicates yes, 0 indicates no)	1.130	0.370	3.058	0.002
Indicator for year 2014 (1 indicates yes, 0 indicates no)	0.997	0.377	2.647	0.008
Indicator for year 2015 (1 indicates yes, 0 indicates no)	1.288	0.360	3.581	<0.001
Indicator for year 2016 (1 indicates yes, 0 indicates no)	0.802	0.379	2.113	0.035
Indicator for year 2017 (1 indicates yes, 0 indicates no)	0.525	0.401	1.309	0.191
Indicator for year 2018 (1 indicates yes, 0 indicates no)	1.090	0.367	2.974	0.003
Indicator for year 2019 (1 indicates yes, 0 indicates no)	1.107	0.365	3.031	0.002
Indicator for year 2020 (1 indicates yes, 0 indicates no)	0.855	0.379	2.256	0.024
Indicator for year 2021 (1 indicates yes, 0 indicates no)	0.968	0.373	2.594	0.009
Overdispersion parameter = 1.155, 2 x LL = -3457.658				

Table 24. SPF developed for KA CM crash frequency on urban + rural freeway segments

Variable	Coefficient	Standard Error	t-statistic	p-value
Constant	-16.799	2.088	-8.046	<0.001
Natural logarithm of AADT (veh/day)	1.335	0.213	6.272	<0.001
Natural logarithm of length (miles)	1.000*	---	---	---
Median width	-0.011	0.005	-2.366	0.018
Overdispersion parameter = 18.762, 2 x LL = -1091.129				

* entered as an offset variable