In-Service Evaluation of High Tension Cable Barrier Systems

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Brifen CMB System

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In-Service Evaluation of High Tension Cable Barrier Systems

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The Kentucky Transportation Cabinet has installed hundreds of miles of high-tension cable median barrier (CMB) as a safety innovation. The usage of CMB aids in the prevention of crossover crashes, where a vehicle departs the roadway on the left shoulder, crosses the median, and enters the opposing lane(s) of traffic. KYTC officials have questioned whether all three barrier products perform similarly. Some installed cable barrier systems have lost tension across the entire cable length after a single vehicle impact. If a second vehicle were to strike the cable barrier system in a location other than the damaged area of the first vehicle's crash, ideally, the high-tension cable barrier system should continue to prevent errant vehicles from crossing the median and causing a head-on collision. The goal of this research was to improve the safety and effectiveness of Kentucky's cable barrier systems by reviewing state DOT best practices for cable barrier, conducting on-site evaluation of current cable barrier installations, and examining crash data. The research team analyzed each CMB vendor product's performance and maintenance requirements, and recommended modifications to KYTC policies, specifications, and maintenance procedures. The study showed that CMB systems have decreased crossover crashes in Kentucky, which warrants the continued use of high-tension cable barrier across the state. One recommendation of the study is to institute and enforce tension-monitoring programs, as applicable, for both annual inspections and after repairs.</td></tr>
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Executive Summary

Cable Median Barrier (CMB) represents a recent safety innovation in Kentucky, since the first installation in 2006 on Interstate 64 in Jefferson County. The Kentucky Transportation Cabinet (KYTC) has installed hundreds of miles of high-tension cable barrier systems, primarily along interstate routes. Cable barrier prevents crossover crashes, where a vehicle departs the roadway on the left shoulder, crosses the median, and enters the opposing lane(s) of traffic.

KYTC authorizes three types of high-tension cable barrier for use, including Brifen, Trinity, and Gibraltar. All are proprietary; however, KYTC officials have questioned whether all the barrier products are performing to a similar level. Some installed cable barrier systems have lost tension across their whole length after experiencing a single vehicular impact. Vehicle impacts with a CMB typically result in damaged steel posts, which require replacement because posts hold the cable wire ropes in place, providing the necessary high tension. If a second vehicle were to strike the cable barrier system somewhere other than the area of the first crash, ideally the high-tension cable barrier system would maintain much of its tension and continue to prevent errant vehicles from crossing the median and causing a head-on collision.

This project aims to improve the safety and effectiveness of cable barrier systems across Kentucky. The study objectives are as follows:

- Conduct a literature review of several state DOT's best practices that apply to cable barrier.
- Evaluate the effectiveness of cable barrier installations through on-site visits, case studies, and crash analysis, with the goal of reducing and mitigating the impact of crashes in Kentucky.
- Evaluate each vendor product's performance in terms of proper installation, routine maintenance, and crash maintenance.

Of the three vendor CMB systems used in Kentucky, Brifen is the most commonly installed. NCHRP Report 711 documents that as post and anchor spacing increase, deflection distances during crashes increase. However, comparison of all systems show that Brifen offers lesser lateral deflections, even with increased post and anchor spacing. Brifen tends to maintain tension better after an impact, making maintenance more complex, particularly for vehicle extractions. The Trinity CASS system offers the lowest maintenance cost per crash and per mile basis due to the larger post spacing. Brifen maintenance costs are the second lowest; Gibraltar has the highest costs, despite its ease of repair. When collisions occur near the end treatment, Brifen maintains its cable tension best. There are more concerns over this type of crash when Trinity or Gibraltar systems are involved.

Executive Summary (cont.)

The research team offers the following CMB recommendations to KYTC:

• Cable median barrier installations greatly reduced the number of median crossover crashes when compared to roadways with no median barrier. Cable median barrier effectiveness justifies continued use and additional installations at appropriate locations.

• The concrete mow pad has performed well — increasing the overall strength of the cable barrier systems. The mow pad has resulted in reduced maintenance issues compared to cable barrier with no mow pad. Mow pads should continue to be used in cable barrier installations.

• Quality assurance during installation is needed to ensure cable median barrier meet all applicable standards and guidelines, most notably, appropriate post spacing, post vertical angles, and end post weakening cuts. Additional training and/or guidelines should be provided to KYTC inspectors to aid construction inspection during CMB projects.

• New cable median barrier installations should be installed on the high-elevation side of divided median roadways when the difference in elevation is significant.

• KYTC District Offices should institute and enforce tension-monitoring programs, as applicable, for both annual inspections and after repairs. The contract repair personnel should maintain a tension log and document tension readings for cable median barrier sites at set distance intervals (as determined by the district). This should occur approximately 72 hours following repairs.

• In recent years, the installation of additional CMB systems coupled with districts relying extensively on posts "furnished by vendor" have led to increasing costs for in-line post repairs. If KYTC were to furnish posts, there could be a potential savings opportunity.

• Additional CMB specifications and requirements, especially tolerances in the specifications, should be provided in future KYTC district installation and maintenance contracts.

• KYTC could consult manufacturers to inquire about improved end treatments or methods to mitigate system tension loss when crashes occur near the end treatment.

• If KYTC is interested in studying the performance of CMB systems following crashes, consideration should be given to collecting tension data prior to repairs of CMB systems.

CHAPTER 1
Background

Gibraltar CMB System

Chapter 1: Background

1.1 Introduction

Cable barriers have grown increasingly important in recent years, as KYTC has installed hundreds of miles of these barrier systems—primarily along interstate routes—to prevent errant vehicles from crossing medians and potentially causing head-on crashes. These high-tension cable systems consist of four pre-stretched cable ropes supported by intermittent steel posts. During installation, the cables are placed on or through the posts, and then tightened to a specific tension according to temperature. When a vehicle crashes into the high-tension cable barrier, the cable ropes absorb the impact force while deflecting from their original position. The cable ropes then rebound to their original positions thereby preventing the errant vehicle from reaching the opposing lane of traffic.

Presently, KYTC only uses the high-tension type of cable barrier and therefore all cable barrier systems discussed in this report are high-tension systems unless noted otherwise. All high-tension cable barrier systems are proprietary and KYTC authorizes three types for use including Brifen, Trinity, and Gibraltar. Each approved vendor is shown on KYTC's Division of Materials approved materials list. The three vendors provide unique cable barrier products, each with different characteristics. KYTC has questioned whether all the vendor products are performing to a similar level of success. Furthermore, KYTC officials have noticed that some installed cable barrier systems have lost tension across their whole length (between the two end-anchors) and sagged after experiencing a single vehicular impact. This raises concerns should a second vehicle strike the damaged cable barrier system before it can be repaired. The goal is that the high-tension cable barrier system will maintain much of its tension after a crash (other than the crash impact point area) and continue to provide an effective cross-over barrier that prevents errant vehicles from crossing the median. Only in extreme cases (such as an excessive number of damaged posts) should the high-tension cable barrier fail across the whole system length. However, visual observations in recent years have shown some cable barriers sag from end anchor to end anchor after an initial impact, which requires follow-up repairs to bring them back to a serviceable condition.

1.2 Problem Statement

Cable Median Barrier (CMB) represents a recent safety innovation in Kentucky with the first installation completed in 2006 on Interstate 64 in Jefferson County. The objective of installing cable guardrail is to provide a barrier to prevent an errant vehicle from crossing the median which could result in severe head-on collisions. An evaluation of the initial installations was completed in 2008, with the recommendation that their performance in crashes warranted expanded use (which has occurred in recent years). The high tension cable barrier systems are designed to retain much of their cable-rope tension after a typical vehicular impact (although this may not apply for severe impacts). This frequently simplifies repair procedures since damaged posts can be quickly replaced and allow for the cable barrier system to remain functional for future impacts. KYTC has installed cable guardrail in recent years from three main vendors. However, there have been reports of performance discrepancies with some systems not maintaining a proper height and/or tension following a typical impact. Inconsistent performance across vendors may lead to an inability to safely redirect vehicular impacts. Also, cable barrier deficiencies require increased maintenance efforts, resulting in additional life-cycle costs borne by KYTC.

1.3 Objectives

KYTC asked the Kentucky Transportation Center (KTC) to evaluate currently installed high tension cable barrier systems, assess CMB installation and maintenance practices, and offer recommendations to improve KYTC's cable barriers.

The project objectives are as follows:

1. Conduct a literature review of other state DOT best practices for cable barrier.
2. Evaluate the effectiveness of cable barrier installations in reducing and mitigating the impact of crashes in Kentucky, using select case studies.
3. Evaluate the product performance of cable barrier installations in Kentucky in terms of proper installation, routine maintenance, and crash maintenance.

CHAPTER 2
Literature Review

Brifen CMB System

Chapter 2: Literature Review

2.1 Introduction

State departments of transportation have greatly increased their use of cable median barrier (CMB) systems over the last decade as studies have reinforced their safety benefits, most notably through reductions in cross-over crashes. The American Association of State Highway and Transportation Officials (AASHTO) has compiled many of these study results to generate its Highway Safety Manual (HSM). The HSM provides tools and methods to quantify the expected benefits stemming from installed roadway countermeasure infrastructure, including CMB. In the last five years, the National Cooperative Highway Research Program has prioritized CMB research as evidenced in its release of both a report and synthesis during this time span. Finally, many state DOTs have conducted their own internal studies on CMB systems within their states, including Michigan and Oregon, among others.

2.2 Highway Safety Manual

AASHTO released its first HSM edition in 2010, which represented the culminating effort of many years of research into highway safety practices. The HSM provides transportation practitioners with tools to evaluate the overall safety benefits provided by the installation of roadway safety countermeasures, and can be used as a basis of comparison for deciding upon solutions. One primary tool is the Safety Performance Function, or SPF.[1] An SPF is a measure used by transportation officials to predict future crash frequencies for a given road segment or intersection. It draws upon known roadway determinant values such as average annual daily traffic (AADT) or roadway length. SPFs are generated and assigned within the parameters of roadway base conditions. For example, an SPF might be generated for two-lane rural roadways with 11-foot lanes, AADT within a prescribed volume range, and roadways lacking shoulders. An SPF generated for these roadway conditions would only be used as a basis of comparison to other similar-type roadways. In other words, this SPF could not accurately predict crash frequencies for urban roadways or interstates, nor could it be used on rural roadways with different geometric features, such as 10-foot lanes.

The Highway Safety Manual uses SPFs in conjunction with crash modification factors (CMFs) to estimate potential safety benefits derived from prescribed roadway countermeasures. For example, a transportation official might want to reduce the number of crashes occurring along a high-risk roadway corridor, but does not know which methods would prove most cost-effective. In this case, the official may need to determine SPFs for similar-type roadways but alter one unique base condition each time. Next, the newly created SPF is compared with the original base condition to assess how the crash prediction changes. This ratio is the crash modification factor and may be represented per the following equation:

$$CMF = \frac{\text{Expected Average Crash Frequency with Site Condition b}}{\text{Expected Average Crash Frequency with Site Condition a}}$$

Finally, the Empirical Bayes Theorem combines the statistical modeling outputs with known crash observations to form a weighted average, or expected crash frequency. As mentioned, an SPF provides a means to predict future crashes under established roadway base conditions and follows an SPF curve as AADT increases. Observed crashes are those crashes that are known to have occurred and are commonly obtained from state police records. The Empirical Bayes Theorem combines these two in order to minimize potential regression-to-the-mean (ROTM). ROTM occurs when researchers conduct before-and-after studies and postulate that "X" occurred as the result of treatment "Y". However, this assumption may be erroneous if the roadway had either a lower-than-expected or higher-than-expected number of crashes during the before period. In other words, the "before" period studied may not be indicative of the true number of crashes that typically occur. To counteract this effect, researchers use the Empirical Bayes Theorem to statistically model how many crashes should have occurred (i.e., predicted). Finally, the observed crashes are combined with the predicted crashes to derive an expected crash frequency, which represents the closest approximation for true crashes. A graphical depiction for these crash frequencies, taken from the Highway Safety Manual, is seen in Figure A.

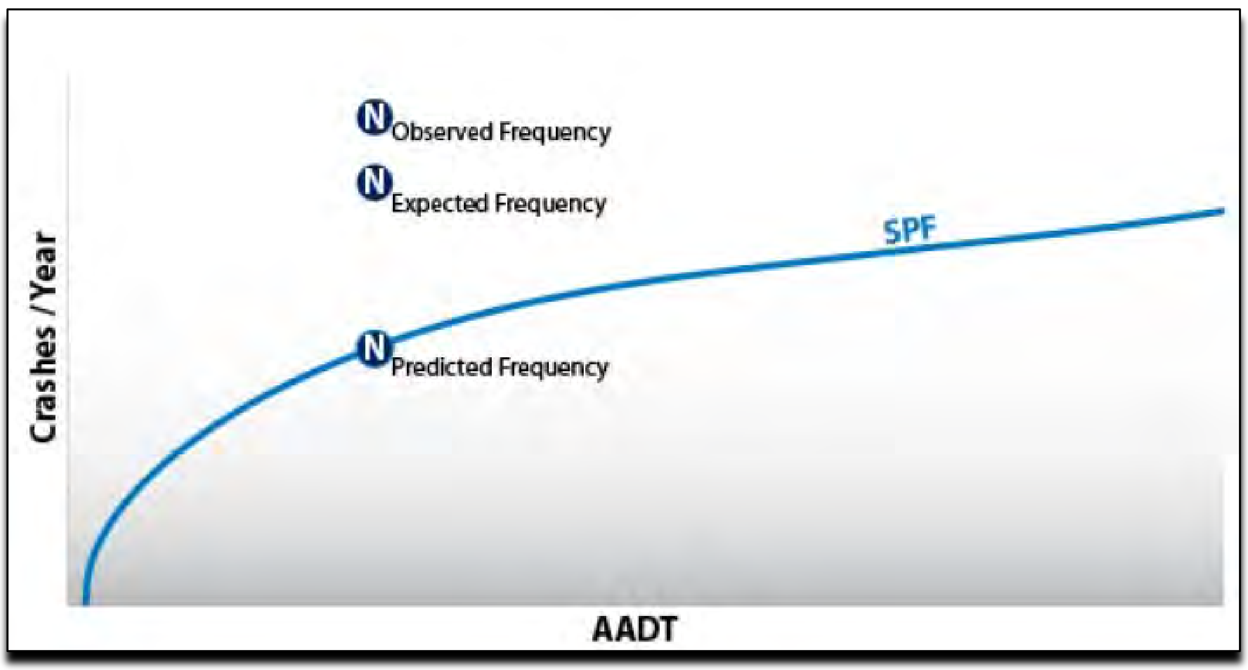


Figure A: Crash Frequencies[2]

2.3 National Research

2.3.1 NCHRP Report 493

KLS Engineering recently conducted a nationwide survey of state DOTs to identify the state of practice for high-tension CMB systems. The study obtained survey responses from all 50 states and published the results in the *National Cooperative Highway Research Program (NCHRP) Synthesis 493 – Practices for High Tension Cable Barriers*.[3] The study found that 42 states currently use or allow CMB on their roadway medians as a safety countermeasure. Most states rely upon Test Level (TL) 3 or 4 cable designs as defined in the original NCHRP Report 350 or the newly released AASHTO *Manual for Assessing Safety Hardware* (MASH).

Manufacturers provide the primary CMB support to state DOTs in terms of installation and maintenance design and recommendations. In fact, all of the CMB systems currently eligible for federal funding are proprietary and therefore, most state DOTs rely heavily on their specifications when installing systems. In some cases, state DOTs produce additional specifications for these systems, but they can only supplement the original manufacturer specifications (and not supersede them). In many cases, the manufacturers also provide training support to state DOTs and/or their contractors for maintenance support.[4]

CMB systems differ from some roadside barrier systems in that they require a higher level of maintenance. Vehicle impacts with a CMB typically result in damaged steel posts, which require replacement. CMB posts hold the cable wire ropes in place, which provide the requisite high tension levels needed to ensure the system operates correctly in the event of a crash impact. In addition, state DOT maintenance personnel and/or contractors should periodically monitor and check tension levels on CMB ropes to ensure they maintain minimum tension levels. Typically, the cable rope will receive a tension check within a few weeks following installation or repair. A survey found that 36 states checked the cable tension following major or minor repairs.[5]

2.3.2 NCHRP Report 711

In 2012, George Washington University and Bucknell University researchers released NCHRP Report 711 providing detailed guidance on the selection, use, and maintenance of low- and high-tension CMB systems.[6] The study highlighted the benefits achieved from the reduction in cross-over median crashes, while noting serious issues which may arise if CMB systems are improperly installed. CMB systems may fail or not meet intended standards should they experience "overrides, underrides, shearing vehicle roof pillars, post fracture, and anchorage failures". The study provided several recommendations for the installation of CMB including their placement within the roadway median, post spacing, anchor spacing, and deflection characteristics.

CMB placement is critical to ensure the system performs properly. Most systems are installed and approved for installation on 6:1 (horizontal to vertical) slopes, but they may also be installed on 4:1 slopes provided other minimum conditions are met. For 6:1 slopes, researchers recommended placing the CMB as far from the travel lane edge as possible to minimize the potential for crash impacts. At the same time, CMB should never be installed near the median center due to poor soil conditions and should be installed at least 8 feet from the ditch bottom (see Figure B).

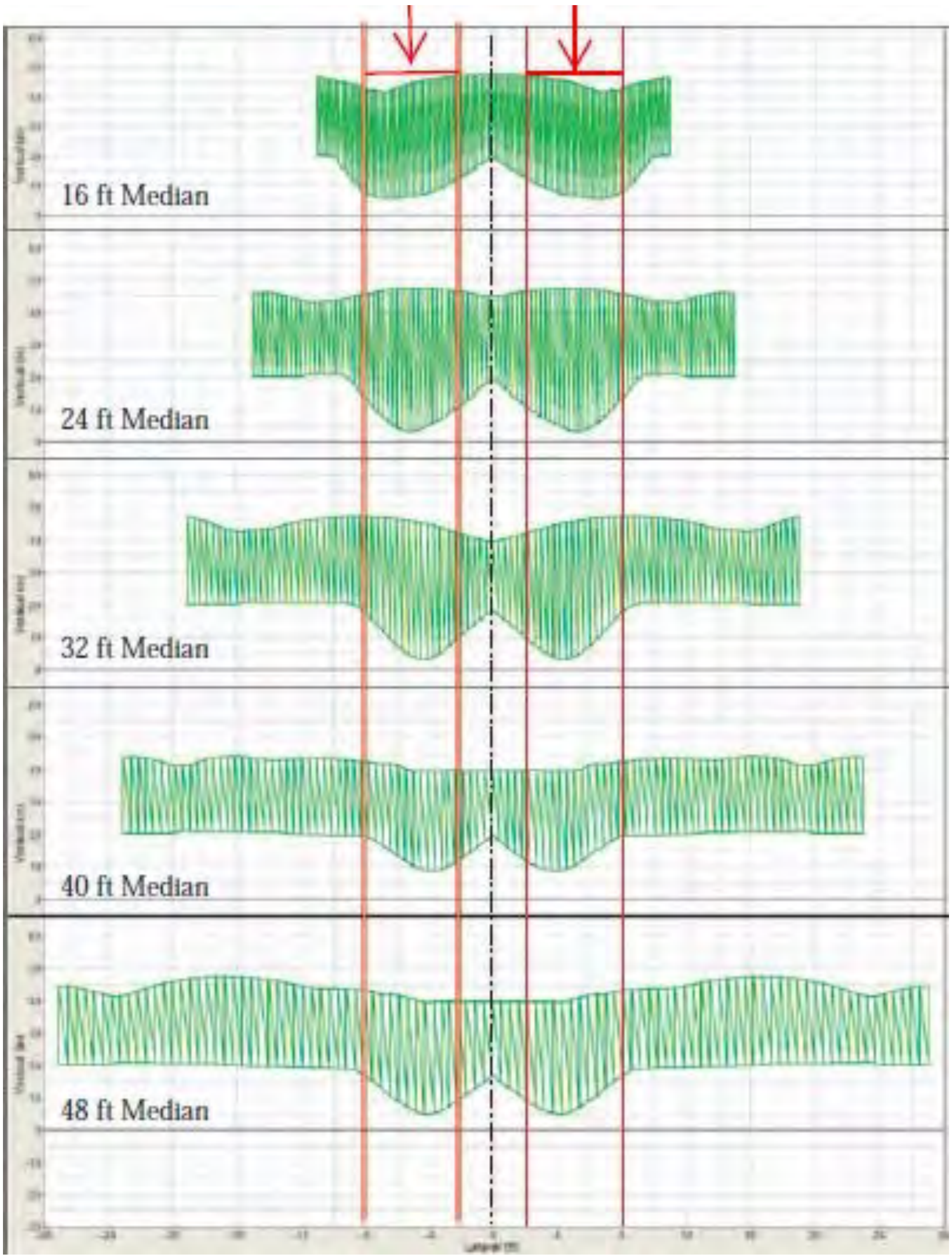


Figure B: Vehicle trajectories for a pick-up on a 6:1 sloped median, NCHRP Report 711[7]

CMB systems typically appear in 3-rope and 4-rope configurations. These steel-woven ropes serve as the critical link in containing vehicle impacts and preventing serious median crossover crashes. Ideally, the ropes provide full enveloping coverage at their point of impact to prevent large vehicles from overriding the cables or small vehicles from under-riding the cables. In addition, the ropes should prevent penetration of vehicles from going through them. NCHRP Report 711 displayed multiple vehicle trajectory simulations involving various median width distances. In Figure B, the parallel convex regions on each side of the median centerline present these high-risk zones; therefore, these regions are most susceptible to vehicle crossovers due to overrides, underrides, and penetration. State DOTs should avoid installing CMB systems anywhere within these median areas. The figure also provides red line borders around the high-risk areas for additional clarity.

CMB post spacing, anchor spacing, and deflection characteristics are all critical to the underlying performance of the system. The attributes are interrelated and can affect one another. NCHRP Report 711 demonstrated these relationships through numerous crash simulations at the National Crash Analysis Center (George Washington University). Each simulation tested a different cable barrier manufacturer under various post and anchor spacing conditions. The study assessed five manufactured CMB systems: Brifen, Gibraltar, Nucor, Safence, and Trinity CASS. The simulations all revealed consistent relationships between spacing and deflection performance. For instance, increased distances in anchor and post spacing corresponded to increased cable rope deflection distances. This relationship was consistent for all tested CMB systems. The simulation results for a 4-cable rope barrier system configuration of Brifen, Gibraltar, and Trinity CASS are shown in the following graphs (Kentucky only authorizes these three systems).

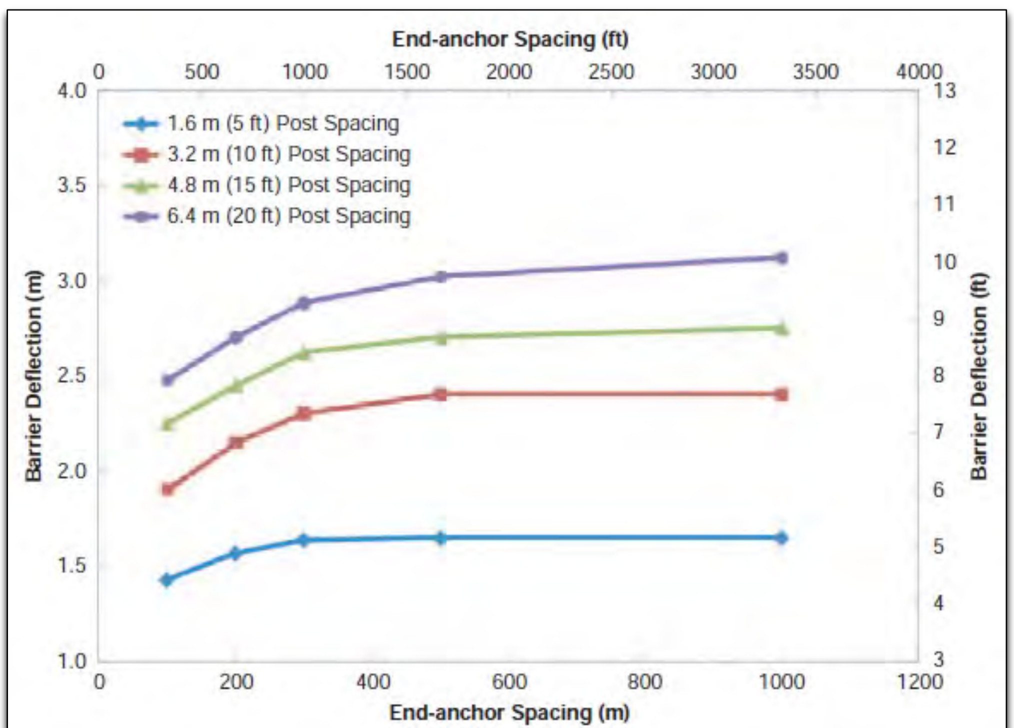


Figure C: Brifen Cable Barrier Deflection Simulation[8]

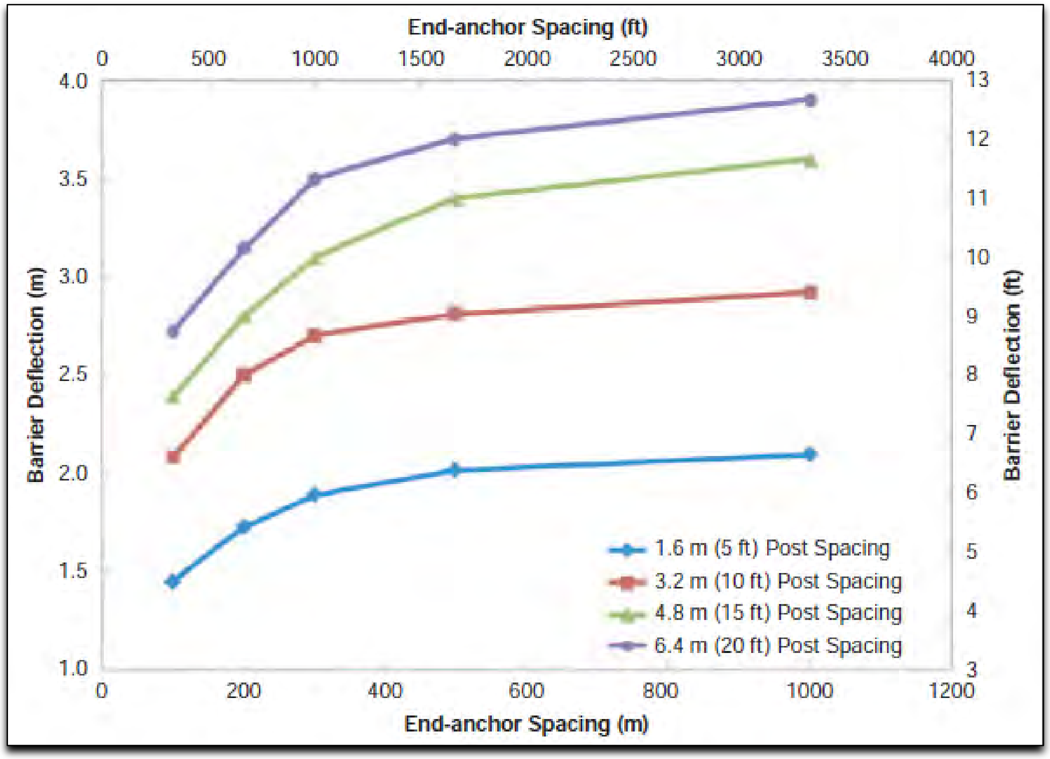


Figure D: Gibraltar Cable Barrier Deflection Simulation[9]

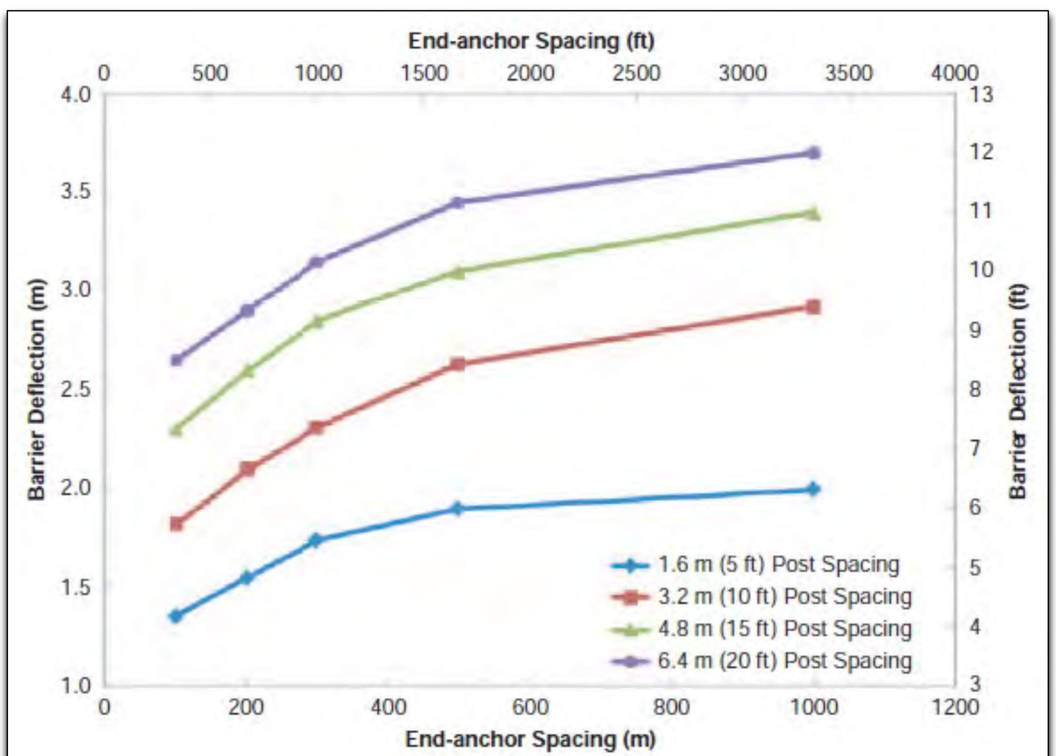


Figure E: Trinity CASS Cable Barrier Deflection Simulation[10]

Each graph demonstrates that increased post and anchor spacing increases the barrier deflection upon impact. However, the simulations also show each manufacturer CMB system performs differently under different conditions. All three systems appear to perform similarly under ideal conditions at the minimum post spacing (five feet) and end-anchor spacing (330 feet). However, as post spacing and end-anchor spacing increase, the Brifen CMB tends to outperform the other systems. This is due to the interwoven nature of the Brifen system, which provides increased tension upon impact. Therefore, the Brifen CMB is less reliant on end-anchors for their tension support. The other systems, Gibraltar and Trinity CASS, use in-line cable ropes that are straight and held in place through loops or postholes. Therefore, the posts do not provide any additional tension support for these systems.

2.4 State DOT Research

2.4.1 Michigan DOT

CMB systems have become increasingly popular over the last decade as numerous state DOTs have installed them along their interstates and freeways. Their increased usage stems from their relatively low cost of installation, ease of repair, and ability to reduce crossover crashes. Numerous research studies have attempted to estimate their safety benefits using Highway Safety Manual principles. Russo et al. recently developed crash modification factors for high-tension CMB systems along Michigan's highways. This study combined a before-and-after analysis with an Empirical Bayes statistical analysis to determine crash modification factor changes by crash severity (e.g., KABCO injury severity scale).[11] Their study demonstrated significant decreases in the number of fatalities and incapacitating injuries after CMBs were installed but a corresponding increase in the overall number of property-damage crashes.

2.4.2 Oregon DOT

Another study involved recent CMB installation within a narrow median along an Oregon state highway.[12] The study's authors examined the safety effects stemming from this installation, chosen in part by the highway's historically high number of crossover crashes. The research analyzed crash frequency and severity before and after, as well as assessed a corresponding control highway segment lacking CMB (but possessing similar characteristics). Similar to Russo et al., this research demonstrated a decrease in severe crashes but an increase in the overall number of crashes.

CHAPTER 3
Crash Effectiveness

Trinity CMB System

Chapter 3: Crash Effectiveness

3.1 Crash Reductions

Existing research studies have assessed CMB's expected benefits based upon the estimated reduction in crashes expected from the Highway Safety Manual methodology. However, it is unclear if previous research studies have taken this methodology a step further and compared their derived safety benefits with fully realized costs, both installation and maintenance. Only a full assessment identifying expected benefits and costs can provide the needed insight to fully compare CMB systems with more established roadside hardware devices, such as guardrail and concrete barriers. This research will address this knowledge gap and advance the overall body of knowledge in this domain. Subsequently, policymakers will be better equipped to make fully informed decisions going forward.

3.2 Crash Data

For this study, the research team selected seven Kentucky interstate segments for analysis. These seven segments were selected in part, due to the availability of median crossover crash data from previous studies on these roadways, and because they use both the Gibraltar and Brifen CMB systems, which are the most frequently used systems in the state. The seven segments were previously used by KTC researchers as a part of Kentucky's Highway Safety Improvement Program (HSIP) 2016 Annual Report to estimate the effectiveness of CMBs at preventing median crossover crashes using benefit-cost ratios.[13] However, comprehensive cost data were not available at the time of reporting, prompting the use of cost estimates. The reuse of these segments and their previously collected crash data, combined with increased accuracy and cost data collected during this research produced a more robust benefit-cost ratio, and in turn, a more meaningful effectiveness evaluation. The seven segments, including roadway names, milepoints, CMB vendor, and CMB installation dates, are displayed below in Table 1.

ID	Route	BMP	EMP	Vendor	Install Year
3	056-KY-0841 -000	0.73	10.236	Gibraltar	2009
4	015-I -0065 -000	109.36	115.574	Gibraltar	2009
6	047-I -0065 -000	91.086	100.509	Brifen	2009
7	102-I -0075 -000	55.368	64.5	Brifen	2009
8	059-I -0275 -000	0.7	1.7	Gibraltar	2010
9	008-I -0275 -000	1.7	13.9	Gibraltar	2010
10	118-I -0075 -000	9.3	25.2	Brifen	2010

Table 1: Effectiveness Evaluation CMB Segments

As seen in Table 1, 10 segments were originally used in the 2016 HSIP report. Three HSIP segments were locations where cable barriers were removed during a 2015 road widening project, resulting in incomplete maintenance cost data for that year. Therefore, KTC researchers excluded three segments from this evaluation. In order to fully satisfy evaluation data requirements, KTC researchers obtained crash data for median crossover crashes and total crashes along the study segments. The crash data periods ranged from five years before to five years after the CMB installation. The Highway Safety Manual recommends using three to five years of data for safety evaluations. The project team obtained three years of cost data for all seven segments, and five years of cost data for four of the segments, hence the need for five years of crash data. Researchers collected the median crossover data to estimate the crash reduction benefit of CMB installation in accordance with the Highway Safety Manual.[14] This procedure is discussed further in Section 3.3.1. In the last step, researchers collected crash data to use in the Wilcoxon test, which researchers used to evaluate the statistical significance of the median crossover crash reduction. The Wilcoxon test is detailed in Section 3.3.2.

3.2.1 Pre-CMB Installation Crashes

KYTC installed CMB on the selected roadway segments between 2009 and 2010. Consequently, the research team examined crashes for a five-year period both before and after installation, excluding crash data at a segment during the year CMBs were installed. The pre-CMB period for both 2009 and 2010 installations ran from January 1, 2004, through December 31, 2008. The research team used the Kentucky State Police crash database, called KyOPS, to conduct the crash research. The target crashes in the pre-installation phase only included crash records that indicated a crossover crash. A crossover crash is one where a vehicle departs the roadway on the left shoulder, crosses the median, and enters the opposing lane(s) of traffic.

3.2.1.1 Pre-CMB Query Criteria

Previous KTC research developed a methodology to query median crossover crashes at locations without a CMB. This method was adopted for this data collection effort. In this procedure, a KyOPS query identified median crossover crashes with 83 percent accuracy, an increase of 31 percent over the traditional median crossover query.[15] The traditional KyOPS method simply selected crash reports where the median crossover indicator was set to “Yes” and the directional analysis code was either “Head-on collision” or “Opposite direction sideswipe”. The traditional method yielded less accurate results due to poor/inaccurate crash reporting. Conversely, the most accurate median crossover crash data collection effort would involve manually sorting and evaluating all KyOPS crash reports for the seven roadway segments over a five-year period. The research team chose not to use this method due to the excessive time demand and corresponding budgetary constraint. The selected query logic is shown as a flowchart in Appendix A. By design, this query only applies to locations lacking an installed CMB, as the original design sought to identify locations that might benefit from CMB installation.

The query identified median crossover crashes based on several crash reporting codes, including (a) median crossover indicator, (b) location of the first event, (c) pre-collision vehicle action, (d) direction analysis code, (e) manner of collision, (f) vehicle load factor, (g) environmental factor, and (h) event location codes. Researchers entered the query logic into the KyOPS database, along with the segment route names and milepoints across the required calendar years. In addition, the query required setting the collision date, roadway name, and milepoints to the corresponding segments and years.

3.2.1.2 Pre-CMB Crashes

The median crossover and total crashes queries produced the annual crash values in Tables 2 and 3. The segment IDs correspond to the segment IDs in Table 1.

ID	Vendor	Install Year	Total Crashes					
			2004	2005	2006	2007	2008	5-year Total
3	Gibraltar	2009	6	10	11	10	17	54
4	Gibraltar	2009	43	19	7	5	9	83
6	Brifen	2009	53	58	14	20	22	167
7	Brifen	2009	46	38	18	4	14	120
8	Gibraltar	2010	7	13	2	1	2	25
9	Gibraltar	2010	38	54	16	15	16	139
10	Brifen	2010	29	17	14	9	14	83

Table 2: Median Crossover Crashes in the 5-year Pre-CMB Installation Period

ID	Vendor	Install Year	Total Crashes					
			2004	2005	2006	2007	2008	5-year Total
3	Gibraltar	2009	21	35	58	50	58	222
4	Gibraltar	2009	45	54	37	39	50	225
6	Brifen	2009	106	86	76	69	82	419
7	Brifen	2009	79	67	73	45	58	322
8	Gibraltar	2010	12	17	12	11	12	64
9	Gibraltar	2010	119	143	111	126	123	622
10	Brifen	2010	72	49	70	59	65	315

Table 3: Total Crashes in the 5-year Pre-CMB Installation Period

During the pre-installation period, median crossover crashes represented a large percentage of the total crashes, which became evident when comparing the median crossover crashes to total crashes for corresponding segments during a given year. Total crashes variated among study segments due to their respective lengths, with shorter segments experiencing fewer crashes.

3.2.2 Post-CMB Installation Crashes

The post-CMB installation period encompassed a five-year period on the seven study segments installed in 2009 and 2010. This interval was identical in length to the pre-CMB period and covered January 1, 2011, through December 31, 2015. This selected period avoided any overlap in crash data collection with the years of installation. Similar to before, the research team used the KyOPS to query into median crossover crashes and total crashes.

3.2.2.1 Post-CMB Query Criteria

The project team used a manual review method for median crossover crash analysis in the post-CMB phase. The previously developed query was not applicable to this phase since it focused on roadways without a CMB. During this process, researchers reviewed the entirety of crash reports in the post-CMB phase. This review encompassed all study segments from 2011 through 2015. To begin, crash reports were obtained through a KyOPS query across segments and years through the following filters: road name, beginning milepoint, ending milepoint, and calendar year. Next, researchers read each crash report narrative to determine if a median crossover crash occurred. This detailed review also removed potentially erroneously median crossover crashes, such as crashes that involved only debris from a vehicle entering the opposing lane or a vehicle making a U-turn on an interstate.

3.2.2.2 Post-CMB Crashes

The median crossover and total crash segment queries during the post-CMB period produced the annual crash values presented in Tables 4 and 5.

			Median Crossover Crashes					
ID	Vendor	Install Year	2011	2012	2013	2014	2015	5-year Total
3	Gibraltar	2009	0	0	0	0	0	0
4	Gibraltar	2009	0	0	0	1	1	2
6	Brifen	2009	1	0	0	1	0	2
7	Brifen	2009	0	0	0	0	1	1
8	Gibraltar	2010	0	0	0	0	0	0
9	Gibraltar	2010	0	0	0	0	0	0
10	Brifen	2010	1	0	0	0	0	1

Table 4: Median Crossover Crashes in the 5-year Post-CMB Installation Period

			Total Crashes					
ID	Vendor	Install Year	2011	2012	2013	2014	2015	5-year Total
3	Gibraltar	2009	96	73	21	60	89	339
4	Gibraltar	2009	54	57	69	112	74	366
6	Brifen	2009	136	83	106	115	132	572
7	Brifen	2009	99	87	80	111	131	508
8	Gibraltar	2010	17	14	16	26	29	102
9	Gibraltar	2010	149	133	145	198	214	839
10	Brifen	2010	127	87	82	93	106	495

Table 5: Total Crashes in the 5-year Post-CMB Installation Period

Median crossover crashes declined significantly following the installation of CMB. This becomes readily apparent when comparing the results from Table 2 (pre-installation) and Table 4 (post-installation). However, recall that different query methods were used to determine median crossover crashes during the pre- and post-installation periods. This may lead to a slight bias in the magnitude of reduction indicated during the post-installation period. Nevertheless, the high accuracy (~83 percent) shown in the pre-installation query method minimizes any pronounced effect on the final results. Total crashes generally increased on each section post-installation, likely due to nuisance crashes with the CMB.

3.3 Benefits

The Highway Safety Manual (HSM) provides guidance and criteria for evaluating safety benefits from proposed or implemented countermeasures. One such method involves before-and-after evaluation on countermeasures and their realized safety benefits through the calculation of a benefit-cost ratio.[1] Recognizing this, the research team collected crash data from before and after the CMB installation date as described in the previous sections. Observed crashes were documented by frequency. The HSM provides statistical methodologies to determine the significance of a countermeasure's benefits (Wilcoxon Test). The HSM also recommends the use of safety performance functions (SPF) to estimate the expected number of median crossover crashes during the post-CMB installation. Researchers subtracted the actual number of median crossover crashes from the expected number of crashes to derive the accrued benefits. For this study, the research team did not employ the use of Kentucky-derived safety performance functions, or SPFs. Kentucky currently lacks a suitable SPF for use in this study. Furthermore, the data collection effort required to produce relevant SPFs were outside of the scope and resources available for this project. Therefore, the research team chose to employ a simple HSM crash comparison approach, the analysis of before and after crashes.

3.3.1 Methodology

The HSM before-and-after comparative approach assesses target crashes in the before and after periods and calculates their difference as the derived benefit. Crash reduction benefits may be expressed in terms of economic and comprehensive cost savings. Economic costs encompass wage losses, medical expenses, property damage, and employee costs. The comprehensive cost standpoint includes all economic costs in addition to the value of the loss of quality of life associated with deaths and injuries (KTC and Kentucky State Police. "Kentucky Traffic Collision Facts 2015", 2015.). The economic and comprehensive costs for crashes are reported annually by the National Safety Council (NSC). Kentucky uses these national values when estimating the crash costs in the state, which are shown in Table 6 below.

Collision Injury Type	Economic Cost Per Crash	Comprehensive Cost Per Crash
Fatality (K)	$1,500,000	$9,900,000
Incapacitation Injury (A)	$88,500	$1,100,000
Non-Incapacitating Injury (B)	$25,600	$298,000
Possible Injury (C)	$21,000	$138,000
Property Damage Only (O)	$4,200	$8,400

Table 6: Kentucky Economic and Comprehensive Crash Costs 2015

KABCO crash data were not available for the median crossover crashes at the identified locations. Therefore, the research team could not assign crash injury severity values to the identified crashes. The team also investigated the use of a weighted average for all crashes in the state, but decided against this approach since it would underestimate the costs borne from median crossover crashes, which are typically more severe. Moreover, the majority of Kentucky crashes result in vehicle property damage only, further reinforcing the use of a weighted average methodology as inappropriate. Ultimately, the research team decided upon a conservative approach that involved calculating the average cost of each crash type (KABCO) and applying that value to each prevented crash. This method assumes a median crossover crash was equally likely to be any one of the five injury types. The average economic and comprehensive costs per crash were calculated to be $327,860 and $2,288,880, respectively.

3.3.2 Results

KTC researchers aggregated the pre- and post-CMB median crossover crashes for each segment for both the three- and five-year intervals (corresponding to the availability of maintenance data). Next, the difference between the two values showed the crossover crash reduction per segment. Average economic and comprehensive costs per crash were applied to the crash reduction values to determine the total accrued benefit. The full range of benefits are displayed in Table 7.

Segment	Crossover Crash Reduction		Economic Benefit		Comprehensive Benefit	
ID	3-Year	5-Year	3-Year	5-Year	3-Year	5-Year
3	38	53	$12,458,680	$17,376,580	$86,977,440	$121,310,640
4	19	81	$6,229,340	$26,556,660	$43,488,720	$185,399,280
6	55	164	$18,032,300	$53,769,040	$125,888,400	$375,376,320
7	35	119	$11,475,100	$39,015,340	$80,110,800	$272,376,720
8	5	N/A	$1,639,300	N/A	$11,444,400	N/A
9	47	N/A	$15,409,420	N/A	$107,577,360	N/A
10	37	N/A	$12,130,820	N/A	$84,688,560	N/A
Total	236	417	$77,374,960	$136,717,620	$540,175,680	$954,462,960

Table 7: Crash reduction after CMB Installation with Economic and Comprehensive Benefits

3.4 Costs

3.4.1 Installation Costs

CMB installation projects are awarded by KYTC through a low-bid process. KYTC publishes a CMB proposal with plans and specifications detailing the desired project. The proposal documents constitute an advertisement for bids, which receive interest from prequalified construction contractors. Contractors submit a bid on the project, and the contract is awarded to the lowest responsible bidder whose proposal complies with the requirements of laws, regulations, and specifications relating to the project.

Per KYTC's CMB proposals, the contractors choose to install CMB from one of the three approved vendors. Given that the award process is low-bid, the contractors typically choose the proprietary CMB with the lowest installation costs. Some of the segments used in the benefit-cost analysis constituted only part of a larger CMB installation project; hence, they do not have a single cost associated with their construction. To derive a value for the installation cost of these segments, the total cost of the larger project was normalized by the total number of miles of cable barrier installed during that project, then multiplied by the length of the segment in miles. In addition to the imprecise installation costs for some segments, there was also a lack of early maintenance records at some of the selected segments. All of the selected segments had at least three years of maintenance records available; therefore, a three-year benefit-cost ratio can be calculated using all seven segments. Four of the segments had five years CMB maintenance records, allowing a five-year benefit-cost ratio to be calculated. Comparisons can be drawn from these two ratios and trends identified, such as the change in benefit-cost over time.

In accordance with the HSM, the research team converted all installation and maintenance costs associated with the CMBs at the identified locations into present year dollars using inflation adjustment factors from the Bureau of Labor Statistics. In this case, present year was set at 2015 as this was the most recent year the NCS crash costs were available, and this was the final year in the CMB maintenance cost inventory. This conversion resulted in the value of the costs (CMB installation and maintenance) being in the same dollars as the benefits (crash reduction). Table 8 summarizes the installation and annual maintenance costs for the seven segments selected in the benefit-cost analysis adjusted for inflation.

Segment Info			Initial Cost	3 Years Maintenance	5 Years Maintenance
ID	Type	Install Year	2009/2010	2013-2015	2011-2015
3	Gibraltar	2009	$1,233,401.15	$259,087.64	$427,632.44
4	Gibraltar	2009	$806,264.97	$216,074.40	$335,847.70
6	Brifen	2009	$1,157,664.80	$240,362.50	$320,937.10
7	Brifen	2009	$1,384,245.66	$314,664.61	$505,563.55
8	Gibraltar	2010	$108,454.39	$39,310.77	N/A
9	Gibraltar	2010	$1,323,143.50	$520,815.48	N/A
10	Brifen	2010	$1,757,608.74	$411,459.53	N/A

Table 8: Installation and maintenance cost in 3- and 5-year periods after CMB installation adjusted for inflation

District	County	Route	Item Number/ Contract ID	Date of Letting	Vendor Product	Length (Miles)	Total Costs
1	McCracken	I-24	01-9001.00/14-1230	6/27/2014	Brifen	15.8	$3,122,751 (k)
1	Marshall	I-24	01-9001.00/14-1230	6/27/2014	Brifen	0.2	(k)
1	Lyon	I-24	01-0908/16-1204	1/29/2016	Brifen	3.8	$2,395,554 (m)
1	Trigg	I-24	01-0908/16-1204	1/29/2016	Brifen	12.6	(m)
2	Christian	I-24	02-0906.00/13-1050	8/16/2013	Brifen	15.5	$2,098,185
2	Christian	I-24	02-9001.00/14-1230	6/27/2014	Brifen	7.9	(k)
2	Caldwell	I-24	01-0908/16-1204	1/29/2016	Brifen	2.5	(m)
4	Hart	I-65	03-2800.00/08-1029	10/31/2008	Gibraltar	10.5	$3,079,355 (c) *
4	Hardin	I-65	04-2801.00/08-1142	11/21/2008	Brifen	9.7	$1,946,894 (d)
4	Hardin	I-65	04-2800.00/08-1142	11/21/2008	Brifen	7.8	(d) *
4	Hardin	I-65	04-2802.00/12-1008	4/15/2012	Brifen	5.9	$868,440 *
4	Hardin	I-65	04-9001/15-1088	12/11/2015	Brifen	1.6	$289,617
5	Jefferson	I-71	05-2800.00/06-1012	3/31/2006	Brifen	11.6	$3,368,871 (a)
5	Jefferson	I-64	05-2801.00/06-1012	3/31/2006	Brifen	2.9	(a)
5	Jefferson	I-265	05-2802.02/07-1044	8/24/2007	Brifen	11.8	$2,495,622 (b)
5	Jefferson	I-64	05-2802.02/07-1044	8/24/2007	Brifen	0.8	(b)
5	Jefferson	I265	05-2802.00/06-1056	11/6/2007	Trinity	12.9	$1,447,782
5	Jefferson	I-265/KY 841	05-2803.00/08-1029	10/31/2008	Gibraltar	9.5	(c)
5	Bullitt	I-65	05-2804.00/08-1029	10/31/2008	Gibraltar	6.2	(c)
5	Bullitt	I-65	05-2805.00/11-1319	5/20/2011	Brifen	5.5	$626,948
5	Franklin	I-64	05-2806.00/11-1319	5/20/2011	Brifen	2.2	$933,110 (g)
5	Bullitt	I-65	05-0998.00/12-1311	4/20/2012	Brifen	6.3	$694,781 (h)
5	Jefferson	I-65	05-0998.00/12-1311	4/20/2012	Brifen	0.7	(h)
5	Oldham	I-71	05-0911.00/13-1201	8/16/2013	Brifen	2.8	$1,619,763 (j)
5	Henry/Oldham	I-71	5-9004.00,5-9005.00/14-1056	10/24/2014	Brifen	5.5	$3,685,203 (l)
6	Boone/Kenton	I-275	06-2800.10/10-1029	7/30/2010	Gibraltar	12.6	$1,231,767
6	Campbell	I-275	06-2800.20/10-1059	12/10/2010	Brifen	0.4	$455,783 (f)
6	Kenton	I-275	06-2800.20/10-1059	12/10/2010	Brifen	4.0	(f)
6	Campbell	I-275	06-2800.30/11-1321	6/17/2011	Brifen	1.5	$126,430
6	Gallatin	I-71	06-2801.00/12-1007	4/20/2012	Brifen	1.9	$291,263
6	Gallatin	I-71	06-0913.00/13-1201	8/16/2013	Brifen	1.7	(j)
6	Gallatin	I-71	06-0913.00/13-1201	8/16/2013	Brifen	6.1	(j)
6	Boone	I-71	06-9007.00/14-1056	10/24/2014	Brifen	6.7	(l)
6	Carroll	I-71	06-9008.00/14-1056	10/24/2014	Brifen	12.0	(l)
6	Campbell	I-275	06-0930/15-1276	11/20/2015	Brifen	1.1	$258,208
7	Fayette	KY 4	07-2800.00/07-1118	4/20/2007	Brifen	8.2	$2,419,328
7	Woodford	I-64	05-2806.00/11-1319	5/20/2011	Brifen	6.3	(g)
8	Rockcastle	I-75	08-2800.00/09-1006	4/24/2009	Brifen	9.1	$1,252,711
8	Rockcastle	I-75	08-2014.00/12-1068	12/14/2012	Brifen	4.2	$1,920,479 (i)
11	Whitley	I-75	11-2800.00/10-1015	5/28/2010	Brifen	19.6	$1,955,733
11	Laurel	I-75	08-8501.00/10-1028	7/30/2010	Gibraltar	3.0	$1,240,250 (e)
11	Laurel	I-75	08-8501.00/10-1028	7/30/2010	Gibraltar	6.1	(e)
11	Whitley	I-75	08-2014.00/12-1068	12/14/2012	Brifen	9.3	(i)
						Total Costs (All Years) =	$39,824,828

Table 9: CMB Installation Costs (Jan 1, 2006 – May 31, 2016)

In Table 9, the asterisk represents original CMB installations that have since been removed due to the addition of concrete barrier walls.

3.4.2 Maintenance Costs

Researchers obtained collective maintenance costs by aquiring available repair cost invoice sheets by year from KYTC highway districts where CMB has been installed. The research team collected and analyzed 3,957 CMB cost invoices. From this dataset, the team removed 44 invoices from further analysis due to data errors, including transcription or accounting errors. This resulted in a robust dataset of 98.9 percent available for use in the aggregated maintenance cost effort. The total and usable invoices by district are shown in the table below:

District	Total Invoices	Removed Invoices (a)	Usable Invoices	Percent Usable Invoice Data
District 1	52	1	51	98.1%
District 2	38	0	38	100.0%
District 4	660	4	656	99.4%
District 5	1,834	10	1,824	99.5%
District 6	427	14	413	96.7%
District 7	465	3	462	99.4%
District 8	225	3	222	98.7%
District 11	256	9	247	96.5%
Total:	3,957	44	3,913	98.9%

Table 10: KYTC Invoice Data

Each KYTC district is individually responsible for letting its own maintenance contracts that include CMB repairs. As a result, different Districts often have slightly different itemized costs they pay for CMB repairs in line with the winning contract bid in their District. Additionally, Districts have installed CMBs at different times, with the earliest installations in Districts 5 and 7.

Maintenance costs are categorized by repair component and/or action taken by the contractor. Although each maintenance contract is unique, the majority retain the same general category designations for CMB repair. The key difference is the cost assigned to each item per the terms of the winning contract. The full list of "Itemized Costs by District" is shown in its entirety in Appendix B. All itemized component costs include the full price of material and labor necessary to bring the item back into service. The single exception to this standard is any cost item with the designator "furnished by department" in which case the material is provided by the KYTC district and the labor is "furnished by vendor"; specifically, the maintenance contract vendor. Common repair items per maintenance contract and their corresponding definitions are listed below:

- Cable tension – the re-tensioning of the cable rope/s to increase the tension level back to the minimum standard
- Cable repair/replace – the repair of an existing cable rope/s, or replacement/s, as necessary, to ensure minimum structural strength standards
- In-line post (furnished by department) – the labor cost to replace any damaged steel post not located adjacent to the end terminal (last four posts) and new steel posts are provided by the KYTC District

- In-line post (furnished by vendor) – the replacement (labor and materials) of any damaged steel post not located adjacent to the end terminal (last four posts) and new steel posts are provided by the maintenance contract vendor

- End-line post (furnished by department) – the labor cost to replace any damaged steel post located directly adjacent to the end terminal (last four posts) and new steel posts are provided by the KYTC district

- End-line post (furnished by vendor) – the replacement (labor and materials) of any damaged steel post located directly adjacent to the end terminal (last four posts); new steel posts are provided by the maintenance contract vendor

- Post base – the embedded anchor for the in-line or end-line post, as applicable

- Lane closure – the closure of a lane adjacent to the work zone area

- Shoulder closure – the closure of the shoulder in the work zone area

- End anchor – repair or replacement of the end anchor terminal

- Post hardware – any additional hardware required to repair Gibraltar's the in-line or end-line post (e.g., hairpins and lockplates)

- Other component – any item not previously listed including, but not limited to, turnbuckles, fittings, and other miscellaneous components; each item in this category will be listed as a separate cost item by the maintenance contractor

The research team analyzed all district CMB cost invoices and compiled them into a spreadsheet database. This database itemized each individual repair using the item component repairs listed above, as well other related criteria. The other categories listed in this database included: district number, county, beginning mile point of CMB repair, route name, repair date, repair year, CMB brand, and the total cost of repair for the entire invoice. Furthermore, the researchers were able to dissect the individual component costs using the "Itemized Costs by District" data along with the total repair cost listed. A screenshot of this comprehensive CMB cost database is shown in T Table 11.

District	County	Begin MP of CMB Repair	Route	CMB Vendor	Cable Tension (LF)	Cable Repair/ Replace (HR or LF)	In-Line Post (EA) (F by D)	In-Line Post (EA) (F by V)	End-Line Post (EA) (F by D)	End-Line Post (EA) (F by V)	Post Base (EA)	Lane Closure (EA)	Shoulder Closure (EA)	End Anchor (EA)	Post Hardware (EA)	Other Item? (List)	Repair Date	Repair Year	Total Cost
5	Jefferson	1.6	I-71	Brifen				5				1					11/4/2010	2010	$1,150
5	Jefferson	11.3	I-71	Brifen				5				1					11/4/2010	2010	$1,150
5	Jefferson	9.0	I-71	Brifen				1									11/4/2010	2010	$150
5	Jefferson	2.4	KY-841	Gibraltar				5				1					11/4/2010	2010	$1,150
5	Jefferson	0.5	KY-1934	Brifen				1									11/4/2010	2010	$150
5	Jefferson	17.6	I-265	Trinity				6				1					11/4/2010	2010	$1,300
5	Jefferson	9.0	I-71	Brifen				4				1					11/4/2010	2010	$1,000
5	Jefferson	6.0	KY-841	Gibraltar		7		5		3		1					11/8/2010	2010	$4,400
5	Jefferson	3.5	I-71	Brifen				3									11/11/2010	2010	$450
5	Jefferson	3.4	I-71	Brifen				8				1					11/11/2010	2010	$1,600
5	Jefferson	3.6	I-71	Brifen				3									11/11/2010	2010	$450
5	Jefferson	3.6	I-71	Brifen				2									11/11/2010	2010	$300
5	Jefferson	1.9	KY-841	Gibraltar				5									11/17/2010	2010	$750
5	Jefferson	8.8	KY-841	Gibraltar				31				1					11/17/2010	2010	$5,050
5	Jefferson	2.6	I-71	Brifen				16				1					11/17/2010	2010	$2,800
5	Jefferson	9.0	I-71	Brifen				5				1					11/19/2010	2010	$1,150
5	Jefferson	9.1	I-71	Brifen				5									11/19/2010	2010	$750
5	Jefferson	35.6	KY-841	Gibraltar				6				1					11/19/2010	2010	$1,300
5	Jefferson	10.0	I-71	Brifen				10				1					11/19/2010	2010	$1,900
5	Jefferson	32.6	I-265	Brifen				1									11/19/2010	2010	$150
5	Jefferson	6.0	KY-841	Gibraltar				9				1					11/19/2010	2010	$1,750
5	Jefferson	24.7	I-265	Brifen				3									11/22/2010	2010	$450
5	Jefferson	18.1	I-265	Trinity				12				1					11/22/2010	2010	$2,200
5	Jefferson	11.0	I-64	Brifen				5									11/22/2010	2010	$750
5	Jefferson	8.0	I-71	Brifen				5									11/22/2010	2010	$750
5	Jefferson	10.8	I-64	Brifen				3									11/22/2010	2010	$450

Table 11: KYTC Cable Median Barrier Invoice Database (excerpt)

3.5 Benefit-Cost Ratio

The research team determined a benefit-cost ratio to evaluate the utility of installing CMB measures along Kentucky highways. First, the HSM method requires use of Wilcoxon Signed Rank Tests. These tests measure whether crash differences between the pre- and post-CMB installation phase are statistically significant. The first Wilcoxon Test compared all seven segments where three years of crash and repair cost data were available. The second Wilcoxon Test compared the four segments where five years of crash and repair data were available. The datasets used in each Wilcoxon test are shown in Tables 12 and 13, where median crashes indicate median crossover crashes and total crashes includes any crash.

Segment Info			Median Crossover Crashes		Total Crashes	
ID	Vendor	Install Year	2013-2015	2006-2008	2013-2015	2006-2008
3	Gibraltar	2009	0	38	170	166
4	Gibraltar	2009	2	21	255	126
6	Brifen	2009	1	56	353	227
7	Brifen	2009	1	36	322	176
8	Gibraltar	2010	0	5	71	35
9	Gibraltar	2010	0	47	557	360
10	Brifen	2010	0	37	281	194

Table 12: Wilcoxon Test Data for 3-year Crash Data

Segment Info			Median Crashes		Total Crashes	
ID	Vendor	Install Year	2011-2015	2004-2008	2011-2015	2004-2008
3	Gibraltar	2009	1	54	339	222
4	Gibraltar	2009	2	83	366	225
6	Brifen	2009	3	167	572	419
7	Brifen	2009	1	120	508	322

Table 13: Wilcoxon Test Data for 5-year Crash Data

In this analysis, target crashes (i.e., median crossover crashes) were divided by total crashes for each segment; then the normalized ratios were compared for pre- and post-installation. The p-value for the three-year data segments was 0.02 and significant at the 95 percent confidence level. The p-value for the five-year data segments was 0.07 and significant at the 90 percent level. Typically, Wilcoxon tests are most appropriate for samples sizes equal to or greater than 10, which was not the case for these tests. However, both test segment populations produced a lower median crossover to total crashes ratio following CMB installation. The cumulative body of evidence from both these research results combined with past CMB studies support the claim that the median crossover crash reduction due to CMB installation is significant.[11,12] Therefore, derived benefit-cost ratios are both meaningful and appropriate to evaluate the CMB effectiveness in reducing median crossover crashes.

Both the three- and five-year maintenance costs from Table 8 were used to derive the total cost of each segment and the total cost for all segments for each time interval. Researchers then divided the three- and five- year benefits from Table 7 with their respective combined costs, arriving at a benefit-cost ratio for each segment and for all segments combined in the three- and five-year intervals. The resulting ratios are displayed in Table 11.

Segment	Economic B/C		Comprehensive B/C	
ID	3-year	5-year	3-year	5-year
3	8.35	10.46	58.28	73.03
4	6.09	23.25	42.54	162.33
6	12.9	36.36	90.05	253.87
7	6.75	20.65	47.15	144.13
8	11.09	N/A	77.45	N/A
9	8.36	N/A	58.34	N/A
10	5.59	N/A	39.04	N/A
Total	7.92	22.15	55.27	154.66

Table 14: Three- and five-year Economic and Comprehensive Benefit-cost Ratios for Select CMB Segments

Both the cumulative three- and five-year benefit-cost ratios indicate a measurable, positive ratio thereby inferring tangible safety and monetary benefits. Assessing these outcomes, the research team noted that benefit-cost ratios trend higher from the three-year to the five-year assessment period. This increase occurs because the initial construction cost is more highly weighted in the three-year ratio. The five-year ratio has the benefit of an additional two years of road use, leading to greater gains in crash reductions. It is expected that the benefit-cost ratio should continue to increase for many years during the CMB lifespan since significant foundation (e.g., concrete) repairs have been minimal to date.

CHAPTER 4
Product Evaluation

Gibraltar CMB System

Chapter 4: Product Evaluation

4.1 KYTC Vendors

KYTC currently lists the following three CMB vendors on its Division of Materials approved material list: Brifen, Gibraltar, and Trinity. Only products found on the approved material list may be installed on state maintained roads. Other state DOTs similarly use these vendors; for example, a recent NCHRP 493 survey revealed that the number of state DOTs using Brifen, Trinity, and/or Gibraltar cable barrier systems totaled 40, 38, and 35, respectively.[16] Each CMB brand is shown in the figures below.

Figure F: Brifen, Gibraltar, and Trinity (CASS) CMB systems in Kentucky (left to right)

Overall, KYTC officials expressed high confidence that CMB installations across the state have resulted in safety gains through a reduction in crossover median crashes. These crash types are often the most serious and result in severe injuries and/or fatalities. This conclusion is supported by the methodology and results in Chapter 3 (Crash Effectiveness), as well as previous research from the literature review. However, other CMB parameters remain less certain, such as the post-impact performance of the different vendor products.

KYTC officials expressed concern that performance discrepancies may exist between different CMB systems, or that there could be installation or maintenance deficiencies. Each CMB installed on a Kentucky roadway must adhere to the original contract proposal specifications. Many proposals contain similar requirements related to maximum post spacing, required offset distances from the roadway/ditchline, and other conditions conforming to the system's corresponding FHWA acceptance letter (e.g., median slopes). Officials noted that some installed CMBs may not meet the levels of performance stated in the original proposal contract. This is due to KYTC's concern that some systems may not have been installed in a uniform manner across different districts. Some installed CMBs have lost tension and sagged from end anchor to end anchor after a single vehicle impact. This temporary loss of tension could present a safety hazard should another vehicle depart the roadway and strike the downed cable barrier; the vehicle will no longer be shielded from a crossover crash. Moreover, high-tension cable barrier should continue to function properly after an initial impact except in the case of extreme crashes (e.g., heavy tractor-trailer, excessive number of damaged posts). Due to these concerns, the research team conducted an analysis of installation and maintenance practices across all three vendor systems.

4.2 Installation Evaluation

Initially, the research team evaluated CMB installation practices across Kentucky. The assessment began by determining the proper installation specifications. These specifications were used as the basis of evaluation. The specifications spanned three functional areas: manufacturer guidelines, FHWA acceptance letter test conditions, and KYTC proposal specifications. First, each manufacturer has issued definitive installation standards and guidelines for state DOTs using their products. Oftentimes, state DOTs rely on the manufacturer's guidelines as the primary means to guide their installation practices. Second, CMB manufacturers test their roadside hardware products—including CMB—through NCHRP 350-1 crash test standards (and now the AASHTO MASH-adopted standards).[17,18] This process ensures their product meets crashworthy standards. The FHWA issues formal acceptance letters to the manufacturer after proof that all crash test standards were met. The acceptance letters contain specified crash test conditions outlining the parameters under which the product must be installed on the national highway system. Third, KYTC specifies its own specifications through issued proposal contracts, which the winning contract bidder must follow. Failure to do so violates the terms of the contract. In addition, failure to follow specifications may also result in non-conformance with the manufacturer's intended guidelines and/or federal and state safety standards. The research team relied on these three sources of information when determining their site survey assessment specifications. Engineering tolerances were not specified for all features of the CMB.

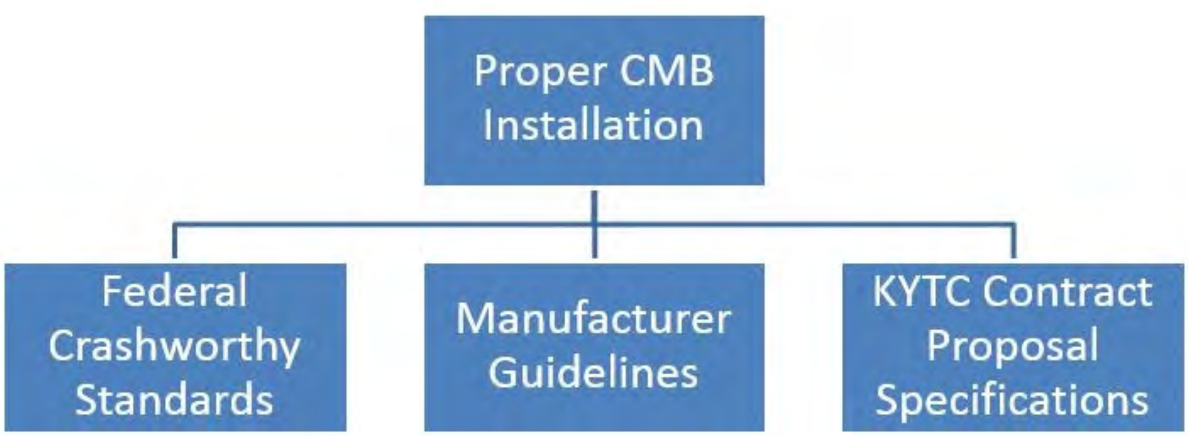


Figure G: Three Components of Proper CMB Installation

4.2.1 Site Surveys on As-Built Conditions

The research team conducted numerous site surveys across the state to assess the as-built conditions for CMB installation. This effort assessed the state of practice for CMB installation for each vendor. Researchers then compared the evaluated conditions with the KYTC proposal standards required for installation. In addition, the manufacturer's guidelines and FHWA standards per NCHRP 350-1 acceptance letters were used to further assess the conditions. In all cases, the KYTC contract proposals delineated requirements that were at least as stringent as the manufacturer guidelines and FHWA crash test standards. In some instances, the manufacturer guidelines and FHWA standards provided additional criteria for evaluation, which could be used to evaluate cable survey conditions. Each applicable metric used during assessment is discussed below, following each summary of CMB site survey results.

In all, the team conducted 100 individual site surveys across each KYTC district with CMB. This included 47 surveys for Brifen, 39 surveys for Gibraltar, and 14 surveys for Trinity. The small survey sample size for Trinity coincided with its low number of installations across the state (about 13 miles total). A map displaying CMB installations by location and the accompanying site survey locations is shown in Figure G.

CMB installation summary results for Brifen and Gibraltar are provided, along with a discussion of results. There is inconsistent information on repair of the Trinity system, since it has not been widely used in Kentucky since 2007, the first year of CMB installations. Initially, the research team conducted surveys on the Trinity system. However, the research team decided to exclude it from further analysis for two reasons. First, it was one of the first systems installed when the national transportation community, including KYTC, was still deciding upon best practices. For this same reason, the research team also excluded other 2006 and 2007 CMB installations from this portion of the analysis. Second, KYTC has not installed Trinity CMB systems since its first installation in 2007.

District

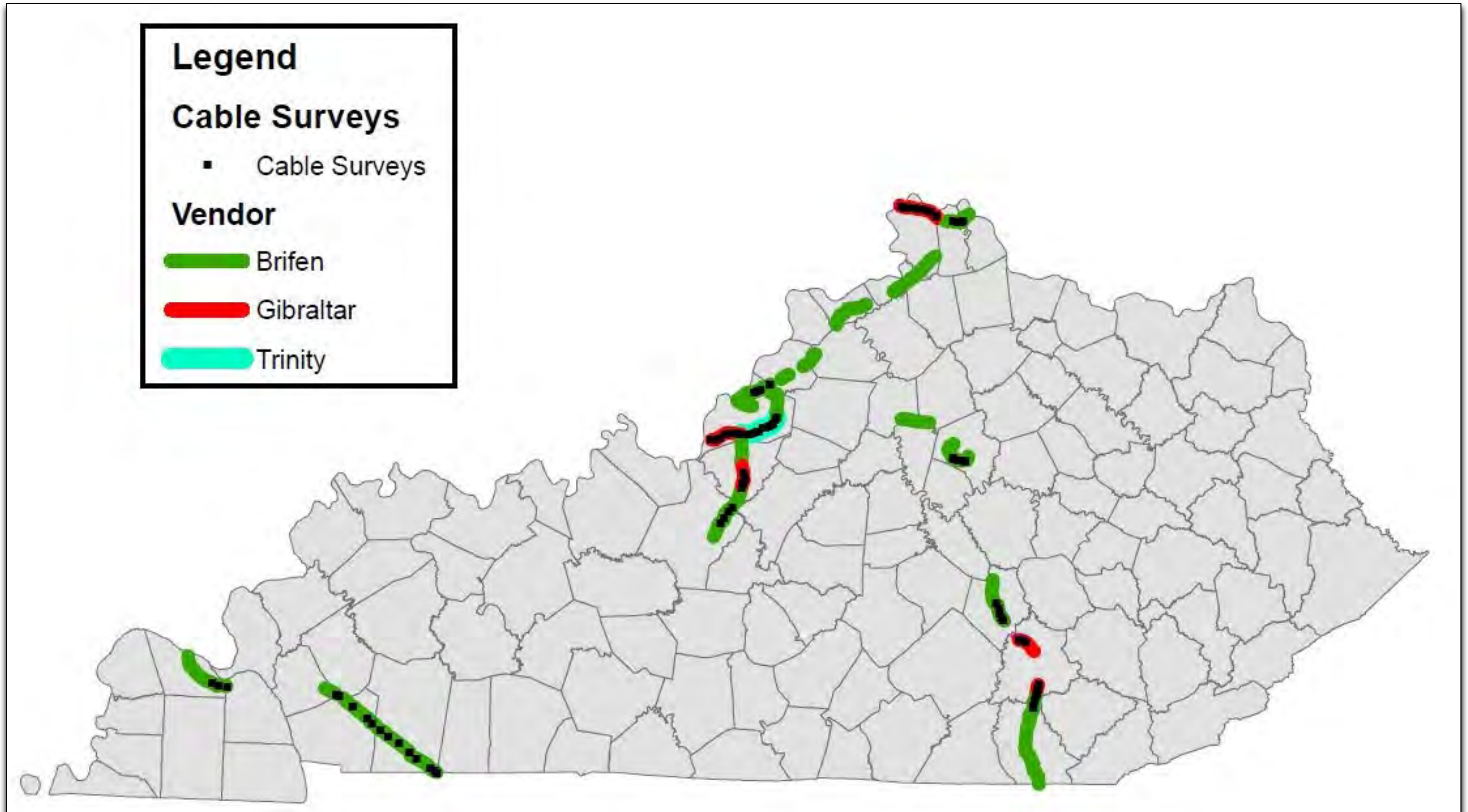


Figure H: Cable Barrier Locations and Site Surveys by Vendor

Cable Median Barrier Installation Criteria	Brifen Guidelines	FHWA Standards	KYTC Proposals	Sample Size Per Row	Average Value	Standard Deviation	Site Surveys within Tolerance	Site Surveys outside of Tolerance
Site Survey:								
(1) Route	--	--	--	NA	NA	NA	NA	NA
(2) Milepoint	--	--	--	NA	NA	NA	NA	NA
(3) Latitude	--	--	--	NA	NA	NA	NA	NA
(4) Longitude	--	--	--	NA	NA	NA	NA	NA
(5) Date	--	--	--	NA	NA	NA	NA	NA
(6) End or In-Line Posts	--	--	--	NA	NA	NA	NA	NA
(7) District			--	NA	NA	NA	NA	NA
Post Spacing (feet, inches)								
(1) In-Line Post #1	See (a) below	10.5 feet	10.5 feet	17	10.5	0.4	11	6
(2) In-Line Post #2	See (a) below	10.5 feet	10.5 feet	17	10.4	0.6	9	8
(3) Anchor-End Post #1	8 feet 4 inches	--	--	19	6.2	0.4	19	0
(4) End Post #1-2	6 feet 6 inches	--	--	19	6.7	0.3	5	14
(5) End Post #2-3	6 feet 6 inches	--	--	19	6.6	0.3	7	12
(6) End Post #3-4	6 feet 6 inches	--	--	19	6.4	0.3	12	7
Median Slope Conditions (inches per foot)								
(1) Pre-Concrete Pad (near)	--	4:1 or 6:1 (b)	4:1 or 6:1 (b)	36	4/5	5/7	35	1
(2) Concrete Pad (near)	4:1 or 6:1 (b)	4:1 or 6:1 (b)	4:1 or 6:1 (b)	36	1 1/3	4/7	36	0
Rope Height from Ground (c) (inches)								
(1) Bottom Rope	18.5 inches	18.8 inches	--	36	19.7	0.9	19	17
(2) 2nd Rope	24.5 inches	24.8 inches	--	36	25.6	0.7	22	14
(3) 3rd Rope	30.5 inches	30.7 inches	--	36	31.7	1.0	16	20
(4) Top Rope	36.5 inches	36.6 inches	--	36	37.5	0.6	35	1
Offset Distances (feet)								
(1) CMB to Near Travel Lane	--	4 ft max (4:1)	Varies (e)	35	10.9	1.4	30	5
(2) CMB to Ditchline	See (d) below	10 ft min (4:1)	Varies (e)	34	20.4	4.1	34	0
Post Vertical Angle (degrees)								
(1) End Post #1	79 degrees (f)	--	--	19	75.5	3.0	10	9
(2) In-Line Post #1	90 degrees (f)	--	--	17	88.4	1.1	15	2
(3) In-Line Post #2	90 degrees (f)	--	--	17	88.2	1.4	15	2
End Post Weakening Cuts								
(1) End Post #1	See (g) below	See (g) below	--	24	NA	NA	14	5
(2) End Post #2	See (g) below	See (g) below	--	24	NA	NA	9	10
(3) End Post #3	See (g) below	See (g) below	--	24	NA	NA	8	11
(4) End Post #4	See (g) below	See (g) below	--	24	NA	NA	7	12

Table 15: Summary of CMB Site Survey Results (Brifen)

The research team assessed the as-built conditions using applicable criteria for each condition. In most cases, this meant comparing the as-built condition to the KYTC proposal requirement. However, some criteria relied on the manufacturer's guideline or FHWA acceptance letter criteria in the absence of definitive KYTC proposal guidance. The applicable source for each metric used to grade installation conditions is shown in the bullets below:

Post Spacing*
- In-Line Post #1: FHWA Standards (same as KYTC proposal)
- In-Line Post #1: FHWA Standards (same as KYTC proposal)
- Anchor-End Post #1: Manufacturer's Guidelines
- End Post #1-End Post #2: Manufacturer's Guidelines
- End Post #2-End Post #3: Manufacturer's Guidelines
- End Post #3-End Post #4: Manufacturer's Guidelines

Median Slope Conditions
- Pre-Concrete Pad: KYTC Proposal (based on FHWA conditions)
- Concrete Pad: KYTC Proposal (based on FHWA conditions)

Rope Height from Ground
- Bottom Rope: Manufacturer's Guidelines
- 2nd Rope: Manufacturer's Guidelines
- 3rd Rope: Manufacturer's Guidelines
- Top Rope: Manufacturer's Guidelines

Offset Distances*
- CMB to Near Travel Lane: KYTC Proposal (see footnote e below)
- CMB to Ditchline: FHWA Standard (same as KYTC proposal)

Post Vertical Angle
- End Post #1: Manufacturer's Guidelines
- In-Line Post #1: Manufacturer's Guidelines
- In-Line Post #2: Manufacturer's Guidelines

End Post Weakening Cuts*
- End Post #1: FHWA Standards
- End Post #2: FHWA Standards
- End Post #3: FHWA Standards
- End Post #4: FHWA Standards

* Engineering tolerances were not specified for this feature of the CMB.

In the Brifen cable survey summary table, the definitions for the listed footnotes are described below:

(a) The recommended Brifen spacing for in-line posts is determined by the state DOT (but no more than 21 feet); measured from post center to post center.

(b) A maximum 4:1 slope is allowed on a TL-3 design, and a maximum 6:1 slope is allowed on a TL-4 design.

(c) The maximum deviation from the required rope height is 1 inch, and the rope heights are measured from the edge of pavement when placed less than 2 feet to edge of pavement.

(d) The recommended offset distance from the CMB to the slope break (e.g., ditch line) is 10 feet; however, the minimum offset distance is one foot.

(e) The offset distance for the CMB location to the edge of the adjacent traveled lane vary by proposal (and given site conditions). The FHWA offset distance to the adjacent lane slope break was not assessed (although it is shown here for reference purposes).

(f) The post vertical angle tolerances are > = 2 degrees for a TL-3 design and > = 4 degrees for a TL-4 design.

(g) Each end post should have a weakening cut on the side facing the anchor (near the ground line). Per the FHWA 2007-01-05 acceptance letter, each post notch should be cut to 12.5-mm x 3-mm dimensions. Category ratings include: (1) satisfactory-present with no deficiencies, (2) inadequate-present with deficiencies (e.g., improper placement, non-perforated notch, improper cut size), or (3) absent.

Cable Median Barrier Installation Criteria	Gibraltar Guidelines	FHWA Standards	KYTC Proposals	Sample Size Per Row	Average Value	Standard Deviation	Site Surveys within Tolerance	Site Surveys outside of Tolerance
Site Survey:								
(1) Route	--	--	--	NA	NA	NA	NA	NA
(2) Milepoint	--	--	--	NA	NA	NA	NA	NA
(3) Latitude	--	--	--	NA	NA	NA	NA	NA
(4) Longitude	--	--	--	NA	NA	NA	NA	NA
(5) Date	--	--	--	NA	NA	NA	NA	NA
(6) End or In-Line Posts	--	--	--	NA	NA	NA	NA	NA
(7) District	--	--	--	NA	NA	NA	NA	NA
Post Spacing (feet, inches)								
(1) In-Line Post #1	10-20 feet	10-30 feet	10.5 feet	19	10.3	0.2	16	3
(2) In-Line Post #2	10-20 feet	10-30 feet	10.5 feet	19	10.3	0.8	11	8
(3) Anchor-End Post #1	6 feet 3 inches	6 feet 3 inches	--	20	6.1	0.4	16	4
(4) End Post #1-2	6 feet 3 inches	6 feet 3 inches	--	20	6.3	0.3	10	10
(5) End Post #2-3	7 feet 6 inches	7 feet 6 inches	--	20	7.4	0.4	13	7
(6) End Post #3-4	7 feet 6 inches	7 feet 6 inches	--	20	7.5	0.3	12	8
Median Slope Conditions (inches per foot)								
(1) Pre-Concrete Pad (near)	--	4:1 or 6:1 (a)	4:1 or 6:1 (a)	36	2/3	1/3	36	0
(2) Concrete Pad (near)	4:1 or 6:1 (a)	4:1 or 6:1 (a)	4:1 or 6:1 (a)	36	1 1/5	4/7	36	0
Rope Height from Ground (b) (inches)								
(1) Bottom Rope	20 inches	20 inches	--	36	20.4	0.5	33	3
(2) 2nd Rope	25 inches	25 inches	--	36	25.4	0.5	33	3
(3) 3rd Rope	30 inches	30 inches	--	36	30.4	0.5	34	2
(4) Top Rope	39 inches	39 inches	--	36	39.4	0.5	34	2
Offset Distances (feet)								
(1) CMB to Near Travel Lane	4 feet max (c)	4 feet max (c)	8 feet min (d)	35	10.3	1.8	34	1
(2) CMB to Slope Break	8 feet min (c)	8 feet min (c)	10 feet min (d)	33	21.4	5.3	33	0
Post Vertical Angle (e) (degrees)								
(1) End Post #1	84.1 degrees	--	--	20.0	77.4	8.0	7	13.0
(2) In-Line Post #1	85.9-90 deg	--	--	19	88.4	0.9	19	0
(3) In-Line Post #2	85.9-90 deg	--	--	19	88.7	1.0	19	0
End Post Holes								
(1) End Post #1	See (f) below	--	--	20	NA	NA	20	0
(2) End Post #2	See (f) below	--	--	20	NA	NA	20	0

Table 16: Summary of CMB Site Surveys (Gibraltar)

In the second system evaluation, the same methodology for evaluating the individual site installation practices was used. The applicable source for each metric used to grade installation conditions for Gibraltar is shown in the bullets below:

Post Spacing*
- In-Line Post #1: KYTC Proposal
- In-Line Post #1: KYTC Proposal
- Anchor-End Post #1: Manufacturer's Guidelines
- End Post #1-End Post #2: Manufacturer's Guidelines
- End Post #2-End Post #3: Manufacturer's Guidelines
- End Post #3-End Post #4: Manufacturer's Guidelines

Median Slope Conditions*
- Pre-Concrete Pad: KYTC Proposal (based on FHWA conditions)
- Concrete Pad: KYTC Proposal (based on FHWA conditions)

Rope Height from Ground
- Bottom Rope: Manufacturer's Guidelines
- 2nd Rope: Manufacturer's Guidelines
- 3rd Rope: Manufacturer's Guidelines
- Top Rope: Manufacturer's Guidelines

Offset Distances*
- CMB to Near Travel Lane: KYTC Proposal (see footnote (d) below)
- CMB to Ditchline: KYTC Proposal (see footnote (d) below)

Post Vertical Angle
- End Post #1: Manufacturer's Guidelines
- In-Line Post #1: Manufacturer's Guidelines
- In-Line Post #2: Manufacturer's Guidelines

End Post Weakening Cuts*
- End Post #1: Manufacturer's Guidelines
- End Post #2: Manufacturer's Guidelines

* Engineering tolerances were not specified for this feature of the CMB.

In the Gibraltar cable survey summary table, the definitions for the listed footnotes are described below:

(a) The Gibraltar TL-4 CMB is acceptable as a TL-3 barrier when placed no farther than 4 feet down a 4:1 slope and no closer than 8 feet from the ditch bottom.

(b) The maximum tolerance for the required rope height is +/- 1 inch.

(c) These are the recommended offset distances on a 4:1 slope with 4-feet from edge of pavement (fore-slope) and 8-feet from ditch bottom; no recommendations on 6:1 slope.

(d) The KYTC standard is a minimum 8-feet from the edge of the travel way and a minimum 10-feet from the ditch line, respectively. The FHWA offset distance to the adjacent lane slope break was not assessed (although it is shown here for reference purposes). The KYTC ditch line minimum offset distance of 10-feet is the most stringent standard between the three, and was used for criteria evaluation.

(e) The end post vertical angle requirement is 1 1/4 inches out of 12 inches from plumb (84.1 degrees), while the in-line post vertical angle requirements are no more than 3 inches out of plumb (85.9 degrees).

(f) Circular holes are required at the bottom of the first two end posts and act as weakening cuts for crashes.

4.2.2 Discussion of Installation Evaluation Results

As noted, researchers conducted site surveys, or cable barrier inspections, across 100 locations in every KYTC district with cable barrier installation. This included 47 surveys for Brifen, 39 surveys for Gibraltar, and 14 surveys for Trinity. Upon further review, KTC researchers decided to exclude Trinity CASS from a more detailed installation evaluation for the reasons previously discussed in section 4.2.1. Nevertheless, the Brifen and Gibraltar cable system installation summary results revealed several concerns. Those concerns were represented by the percentages of CMB installations that fell outside of installation specifications.

The following proportion of site surveys were within tolerance for Brifen installation inspections.

In-line post spacing	59 percent
End post spacing	57 percent
Median slope	99 percent
Rope height	64 percent
Offset distance	93 percent
End post angle	75 percent
End post weakening cut	50 percent

The following proportion of site surveys were within tolerance for Gibraltar installation inspections.

In-line post spacing	74 percent
End post spacing	58 percent
Median slope	100 percent
Rope height	93 percent
Offset distance	99 percent

End post angle	78 percent
End post holes	100 percent

While there were differences in the installed values and installation criteria, there were no major variations. In summary, the primary CMB installation deficiencies by brand include:

Brifen:
- Insufficient post spacing for in-line posts (greater than 10.5 feet)
- Insufficient post spacing for end posts (greater than specification)
- Rope heights exceed tolerance
- End post vertical angles out of tolerance
- Insufficient weakening cuts for the end treatment posts

Gibraltar:
- Insufficient post spacing for in-line posts (greater than 10.5 feet)
- Insufficient post spacing for end posts (greater than specification)
- End post vertical angles out of tolerance

The figures below illustrate several common deficiencies identified above. Example figures are provided for both Brifen and Gibraltar CMB systems.

Figure I: Excessive Rope Heights (due to lack of vertical restraint, Brifen)

Figure J: Brifen End Post with sufficient weakening cut

Figure K: Brifen End Post with insufficient weakening cut (not cut all the way through)

Figure L: Gibraltar End Post vertical angle out of tolerance (less than 84.1 degrees)

4.3 Maintenance Evaluation

In the next phase, the research team evaluated CMB maintenance issues across Kentucky. For the purposes of this report, the term maintenance is synonymous with repairs related to damaged systems following crash impacts. This process involved three separate, yet related, investigations that each built upon another. First, researchers interviewed multiple KYTC officials and state-sanctioned contractors to understand the concerns and issues surrounding CMB performance among the three brands. Next, the research team analyzed the statewide repair invoice database (see section 3.4.2) and developed a list of relevant questions to identify cost trends. This process led to the development of cost summary tables, organized by vendor and district, and shaped several findings for this study. Finally, there was a focus on potential problem areas discovered during the interview process. Statistical analyses were conducted on the relevant cost data, which validated issues that were initially highlighted during those interviews.

4.3.1 Interviews

Prior to data collection and analysis, KTC researchers began their initial CMB evaluation through interviews with KYTC and contract personnel. This consisted of three distinct groups, including one KYTC district and two private-sector contract companies charged with maintaining the systems across the state. All three groups had many years of experience handling repairs and maintenance of CMB systems. Two of the three groups had experience with all three brands, while the third group had experience with Brifen and Gibraltar systems only. All three groups offered increased understanding of the primary CMB maintenance concerns and provided a first-hand perspective on which systems seem to perform better. All three groups had different perspectives, but shared some common themes.

In addition, KTC researchers investigated CMB infrastructure component issues, primarily cable rope and the CMB base support. This involved receiving feedback from the three original interview groups, as well as soliciting feedback from multiple KYTC district offices during the course of site visits. The policies and performance issues surrounding these components are discussed in this section. Ultimately, the combined formal interviews coupled with KYTC district discussions provided valuable insights from CMB field practitioners and further assisted in identifying specific, potentially problematic CMB areas for further analysis.

4.3.1.1 Brifen Feedback

When questioned about the Brifen CMB, interview participants touted the system's ability to better withstand impacts and hold minimum tension; the end anchor in particular held up well upon impact. Two of the three interview groups listed Brifen as their preferred choice amongst the brands. Primarily, the rationale was that this system performed as intended and held up better in terms of durability. All three groups stated that the Brifen end terminal treatment displayed superior performance upon impact, compared to the other two brands. Primarily, its performance is shown through its ability to maintain tension following crashes that occur within the vicinity of the end terminal. The Brifen cable release mechanism is less susceptible to accidental release from a nearby impact and complete tension loss. The groups noted that the other brands more often experienced complete tension loss (or cable ropes laying on the ground) when crashes impacted their end terminals. As a result, the Brifen CMB typically requires less frequent re-tensioning repairs for end terminal impacts. One interview group cited an advantage of Brifen: its ability to maintain tension when an increased number of posts are damaged, as well as fewer lateral deflections upon impact.

Figure M: Brifen Interwoven Ropes

Despite these advantages, the Brifen system was not without its limitations. All three groups stated that the interwoven nature of the system made it more difficult to repair. Brifen cable barrier systems require cable rope to be weaved around the posts. Therefore, any repairs to this system require a special tool and several maintenance personnel to properly weave the cable ropes back into configuration, requiring more repair time than other cable barrier systems. Thus, replacing the damaged posts on the Brifen system after vehicle impacts is more difficult than the other systems. One interview participant mentioned that vehicles penetrating the Brifen cable system are the most difficult to extract following a crash. Cable rope vertical incongruities from the required rope heights present another challenge. One interview group stated that this system lacks components to vertically constrain the cable rope movement. Three cable strands rest on pegs attached to the side of a post while the top cable strand rests inside a partition found in the top center position of the post. Therefore, wire strands frequently leave their originally placed position upon impact and require additional effort to reposition during repairs.

4.3.1.2 Gibraltar Feedback

Figure N: Gibraltar Hairpin & Lockplate Components

Interview participants gave the Gibraltar system the high marks for ease of maintenance. Two of the three groups touted Gibraltar as the easiest to repair due to its straight-line cable rope installation and lower system tension after vehicle impacts. In addition, one participant stated that vehicle penetrations into these systems are typically the easiest to remove.

Conversely, interview participants expressed concerns with the Gibraltar design because of the additional post components and the cable release mechanism on its end anchor. Two of the three groups claim that additional post components add both complexity and cost. The Gibraltar system slides lock-plates and hairpins into each post to secure cable ropes (Figure I). The other manufacturer's cable systems utilize a single-integrated post which can be replaced with another post in the event of a crash. However, lock-plates and hairpins attach to the Gibraltar post and must be replaced each time a post is damaged. These components are itemized as separate line items from the post for district maintenance contracts, and consequently lead to increased maintenance costs per post. One interview participant also believed that the additional components presented a safety hazard as the metal pieces tend to break upon impact and may become an airborne hazard. The metal pieces are often not picked up after repairs, remain in the median, and have reportedly been hit and flung by mowers during mowing operations.

The second Gibraltar concern stemmed from its end anchor's release mechanism. All three interview groups stated that crashes on or near the end terminal triggered the cable release mechanism, leading to tension loss in the system. In fact, multiple participants said the tension loss often occurred over significant longitudinal portions of the system and often resulted in complete tension loss. Such incidents required maintenance personnel to re-tension the cable ropes across long sections or from anchor to anchor. Interview participants stated these repairs were time consuming and might span over several hours.

4.3.1.3 Trinity Feedback

The Trinity CASS (3-cable) system received high marks from several interview participants due to its relatively low cost and ease of installation. However, maintenance concerns differed between the two interview groups, with one stating it had the highest number of maintenance issues and another expressing a sense of overall ease of maintenance. The research team only interviewed two maintenance groups for this system since the third group from the previous sessions did not actively maintain any Trinity CASS systems.

One interview group expressed an overall high level of satisfaction with Trinity, stating that the system had an advantage over Brifen (and comparable to Gibraltar) due to its ease of repair. Cable ropes along the Trinity system are installed in a straight line configuration, which makes repairs faster and easier. The same group also cited this system as the least expensive to install compared to the other brands, due to reduced materials (one less cable rope and wider post spacing) and labor efforts.

Figure O: Trinity CASS with spacers

Conversely, the second interview group had an unfavorable view of the Trinity CASS system, stemming from maintenance concerns. The cable barrier rope often experiences complete loss of tension (i.e., cable on ground) once two or more cable posts have been knocked down. This group cited numerous instances when this cable system required repairs due to complete loss of tension following most crash impacts. A second maintenance concern revolved around the Trinity CASS system's use of strong posts. As the name implies, strong posts offer increased strength over other cable barrier models that adopt weak posts, which yield and bend easily upon impact. The CASS posts increased structural strength allows for greater transfer of force or energy from the vehicle to the concrete foundation during crash impacts. As a result, the CASS foundations typically require more frequent and extensive repairs than weak post system foundations. Finally, the CASS three-cable strand configuration presents additional opportunities for vehicles to penetrate the barrier via underrides or overrides due to a reduced capture area. The current Trinity CASS system is now available in a four-rope configuration. The CASS four-rope configuration was not available at the time this system was originally installed.

Both interview groups expressed reservation about Trinity's end terminal performance. Like Gibraltar, the CASS end anchor's cable release mechanism triggers when crashes impact on or near the end terminal, causing a loss of tension across this system's cable wire ropes.

4.3.1.4 CMB Tension Feedback

Tension levels are the most critical component for ensuring a high-tension CMB system operates as intended. All the CMB manufacturers stress the importance of maintaining minimum required tension levels, as stated within their installation and maintenance manuals. High-tension cable barrier systems rely on minimum tension levels in their cable ropes to adequately absorb crash impacts and deter excessive deflection distances. Therefore, KTC researchers identified this issue as critical and consulted with various KYTC districts on their maintenance procedures involving tension levels.

The inspection and maintenance of cable rope tension levels is inconsistent across the districts. Only District 7 has a routine maintenance program in place to monitor cable rope tension levels. Annually, this district checks cable tension along its CMB system installed on KY 4 (New Circle Road). This 8.2-mile Brifen CMB segment was installed in 2007. District 7 last conducted routine tension inspections and maintenance on this system in 2016, at a cost of $22,432. This process requires the contractor to check each of the four cable ropes for tension at given intervals along the 8.2-mile stretch. The contractor increases the tension at each location if there are deviations from required tension levels. The manufacturer provides tension-temperature matrix charts that specify the required tension level needed for a given temperature. Additionally, a Brifen representative reported "Tension should not be adjusted in any case without first checking the complete run, calculating the average tension per turnbuckle so as to determine if the tension is within the +/- 20% tolerance. If necessary then tension can be adjusted." Brifen recommends annual maintenance checks. District 7's 2016 tension inspections also provided the district with an opportunity to repair 102 rusted posts, at a cost of $25,500 (with a unit cost of $250 per post). All other districts only check the tension levels following a crash repair. Per the terms of all KYTC district maintenance contracts, the repair contractor is responsible for measuring tension levels following any CMB repairs after a crash. According to the Brifen representative, checking after repairs is optional, but suggested if a significant number of posts has been damaged or large vehicle has impacted the system.

4.3.1.5 In-line Post Support Base Feedback

Early on, KYTC adopted a robust support base foundation for its CMB infrastructure, in the form of a mow pad. The mow pad consists of a continuously poured concrete foundation at a four-foot width along the installation of the individual CMB in-line post bases. The pad resembles a sidewalk placed parallel to the roadside, is used to alleviate the need for mowing, and provides the foundation for CMB. The earliest CMB systems used individual concrete cylindrical footers for the in-line posts' support base. However, KYTC maintenance personnel soon experienced challenges with their repairs. A frequent complaint involved excessive repairs required for individual in-line posts' base footers. For example, the cylindrical footer might shift upon a particularly forceful vehicle impact. When this occurred, the footer would need to be replaced to bring it back into vertical alignment (plumb). The reconstruction of the concrete footer imposed additional labor and material costs. Use of the mow pad provided additional concrete supporting the lateral direction, which reinforced foundational strength and reduced steel post movement.

KTC received favorable feedback from the three interview groups on the mow pad's maintenance performance. One group stated that the continuous concrete mow pad is easier to maintain after crash impacts than individual concrete posts because the individual sockets were more prone to lateral movement within the ground and required more frequent repair. The second group never observed mow pad concrete foundation damages at socketed locations. However, they did observe foundation damages in early CMB installations that used the individual socket foundations. The third group of interviewees confirmed these observations. Maintenance personnel have noticed the concrete mow pads perform significantly better and require less repair work than the individual concrete post anchors, which failed more frequently. Because mow pads have performed so favorably, KTC recommends using them in future CMB installations.

4.3.2 Repair Costs

To better understand the data and identify repair cost trends, summary tables for repair costs were compiled, sorted by cost per crash and cost per mile. Each individual CMB repair cost invoice was treated as a single crash event, although in some cases, multiple vehicles may have been involved. This effort sought to identify the costs KYTC was paying for CMB vendor repairs. The team identified several critical questions, including:

- What is the average repair cost per crash by district by year by vendor?
- What is the average repair cost per crash statewide by year by vendor?
- What is the average repair cost per crash by district across all years by vendor?
- What is the average repair cost per crash statewide across all years by vendor?
- What is the average repair cost per mile by district by year by vendor?
- What is the average repair cost per mile statewide by year by vendor?
- What is the average repair cost per mile by district across all years by vendor?
- What is the average repair cost per mile statewide across all years by vendor?

The summary sheets excluded data (crashes, costs) for a roadway segment during the year a CMB was constructed, or in some cases removed. The average repair cost summary by district is shown in Appendix C, while the average repair cost summary statewide is shown in Table 17. A more detailed examination of the potential reasons for the discrepancies in repair costs is discussed further in section 4.3.2.

Vendor	Calendar Year[a]	Total Miles	Total Crashes	Total Costs	Average Repair Costs			
					Per Crash By Year	Per Crash (All Yrs)	Per Mile By Year	Per Mile (All Yrs)
Brifen	2010	17.5	71.0	$64,625	$910		$3,693	
	2011	53.7	302.0	$320,980	$1,063		$5,977	
	2012	75.9	350.0	$516,620	$1,476		$6,807	
	2013	116.2	482.0	$787,670	$1,634		$6,779	
	2014	140.3	601.0	$1,072,160	$1,784		$7,642	
	2015	166.0	612.0	$1,364,301	$2,229		$8,219	
	2010-15					$1,516		$6,519
Gibraltar	2010	10.5	22.0	$11,200	$509		$1,067	
	2011	26.2	137.0	$172,600	$1,260		$6,588	
	2012	26.2	99.0	$144,500	$1,460		$5,515	
	2013	37.4	173.0	$356,196	$2,059		$9,524	
	2014	37.4	203.0	$441,235	$2,174		$11,798	
	2015	37.4	172.0	$463,636	$2,696		$12,397	
	2010-15					$1,693		$7,815
Trinity	2011	12.9	63.0	$54,300	$862		$4,209	
	2012	12.9	43.0	$50,000	$1,163		$3,876	
	2013	12.9	50.0	$41,900	$838		$3,248	
	2014	12.9	56.0	$64,414	$1,150		$4,993	
	2015	12.9	75.0	$72,838	$971		$5,646	
	2011-15					$997		$4,395

Table 17: Average Cable Median Barrier Repair Costs, Statewide (2010-2015)

4.3.2.1 Vendor Discussion

As seen in the summary table, the average repair costs vary among the vendors on a per crash and per mile basis. There seem to be several reasons for these differences. First, the Trinity CASS system appears to offer the lowest maintenance costs on both a per crash and per mile basis at $997 per crash and $4,395 per mile, respectively. This may be due to the post spacing configuration of Trinity CASS, which places in-line posts at approximately 20-foot offsets. Consequently, each crash into this system will typically damage half the number of in-line posts in proportion to Brifen and Gibraltar systems. A review of the CMB repair invoice database revealed that damaged posts account for the highest costs to KYTC on an annual basis. It makes sense that a reduction in the overall number of damaged posts results in a comparable reduction in the overall costs incurred over time. However, the small sample size for Trinity CASS installations in Kentucky (12.9 miles) and the distinct geometric conditions of its site location (e.g., wide median) limits the ability to state unequivocally that this system has the lowest maintenance costs. Additional Trinity CASS sites in other states would need to be evaluated to reinforce this data.

The Brifen system placed second in terms of overall maintenance costs. Maintenance costs were extracted from years 2010 through 2015 over 225.4 miles of Kentucky state maintained roadways. The Brifen system displayed maintenance costs that averaged $1,516 per crash and $6,519 per mile. This seems reasonable considering post spacing requirements of approximately 10.5 feet. The closer spacing increased the average number of posts damaged per crash. In addition, interview participants stated that vehicle extractions often take more effort with Brifen systems. The number of vehicle extractions, however, was not readily available from invoice data so this hypothesis could not be investigated.

The Gibraltar system exhibited the highest overall maintenance costs among the three brands from the years 2010 through 2015, where it was installed across 47.9 miles of state-maintained roadways, at average maintenance costs of $1,693 per crash and $7,815. There are several reasons for the higher cost. First, KYTC established additional itemized repair costs specifically for the lock-plate and hairpin components used within Gibraltar posts. These necessary components and their additional costs per post increased the overall cost for this brand. It makes sense that in-line post repairs for this system cost slightly more over time than the other two brands, which have self-contained posts. Second, several interview participants mentioned that the end terminals frequently disengage tension when impacts occur close to but not necessarily at the terminal. Thus, the whole CMB from end-to-end loses cable rope tension. Any such tension loss leads to additional repairs to re-tension the cable line to the required levels and thereby increases repair costs.

4.3.2.2 Maintenance and Repair Contract Discussion

On average, repair costs have trended upward since 2010. This trend line is consistent across both a Per Crash by Year and Per Mile by Year basis (see Table 17). This trend cannot be explained by increases in raw material costs since steel prices have generally trended downward since 2011.[19]

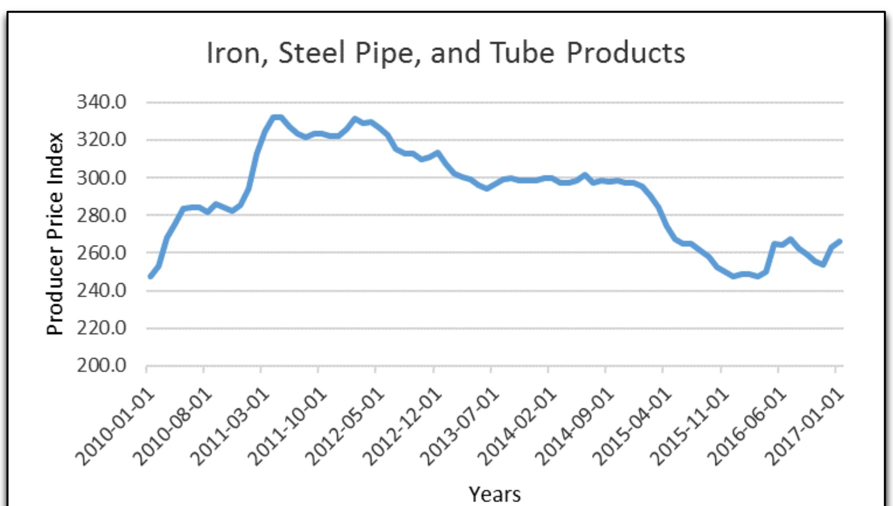


Figure P: Iron, Steel Pipe, and Tube Products (2010-2017)

The previous vendor section (4.3.2.1) compared repair costs between brands, but it did not address the overall trend of increasing costs over this study period. In-line steel posts represent the number one cost driver for maintenance repairs. In fact, in-line posts represented nearly 89% of KYTC costs for all CMB-related repairs over the study period. Therefore, reducing in-line post repair costs could result in considerable savings to KYTC. The research team decided to focus their efforts on opportunities for cost savings by examining maintenance contracts.

Each district specifies unit line item costs for CMB repairs per the terms of the maintenance contract. The yearly itemized costs by district are shown in Appendix B. KYTC maintenance contracts provide two options to replace damaged in-line posts—"furnished by department" and "furnished by vendor". As the name implies, the first option requires that the District maintain an in-line post stock and provide them to the contractor, as needed, for repairs. This contract cost includes the District responsible for material cost (the posts, shipping, and handling), while the contractor is responsible for labor (post transport to the job site and installation). The second option leaves the entire process—both steel post resupply and labor—entirely up to the maintenance contractor. In this scenario, the contractor negotiates prices and obtains steel posts directly from the manufacturer. Consequently, the two itemized repair costs differ between the two options.

The research team collected itemized maintenance costs for every district with CMB, and then analyzed the price differences between the two options. In every case, maintenance contracts over the length of this study proved itemized costs for "furnished by vendor" exceeded those for "furnished by department". Quite often, the itemized cost differences were significant, and ranged between a 28 percent to a 113 percent increase (after taking into account the steel post material costs). The research team decided to investigate the in-line post repair costs over the study period (2010-2015). Specifically, the team determined actual in-line post repair costs, estimated total repair costs if every post was furnished by the department, and compared the differences (see Table 18).

Additional table footnote explanations should be clarified prior to any review of the following table. In footnote (a), the District 1 cost invoices did not provide an itemized cost figure for posts furnished by the department. Therefore, the research team decided to estimate (or assume) this cost type would be $50 per in-line post, a similar figure to other districts. The second set of footnotes (b, c, d, and e) represents individual years where the maintenance contract changed. Typically, the itemized costs increased, on average, from the old to the new contract. The research team decided to estimate approximate costs for those years by averaging the costs between the old and new contract itemized cost values.

District	Calendar Year	Contract Post Cost (Furnished by Depart.) (a)	Contract Post Cost (Furnished by Vendor) (b)	Posts Damaged (Furnished by Depart.) (c)	Posts Damaged (Furnished by Vendor) (d)	Actual Post Costs Paid by District (e)	Potential Post Costs (if Furnished by Depart.) (f)	Potential Savings (if Furnished by Depart.) (g)
1	2015 (a)	$50	$150	0	318	$47,700	$37,365	$10,335
2	2015	$50	$150	0	493	$73,950	$57,928	$16,023
4	2010	$50	$150	817	35	$101,248	$100,110	$1,138
	2011	$50	$150	1,495	0	$175,663	$175,663	$0
	2012	$50	$150	1,025	142	$141,738	$137,123	$4,615
	2013	$50	$150	129	1,046	$172,058	$138,063	$33,995
	2014	$50	$150	16	819	$124,730	$98,113	$26,618
	2015	$50	$150	0	953	$142,950	$111,978	$30,973
	2010-15					$858,385	$761,048	$97,338
5	2011	$40	$150	11	2,627	$395,233	$283,585	$111,648
	2012	$40	$150	0	2,913	$436,950	$313,148	$123,803
	2013 (b)	$45	$150	11	2,644	$397,838	$298,688	$99,150
	2014	$50	$150	57	3,063	$466,148	$366,600	$99,548
	2015	$50	$150	157	3,538	$549,148	$434,163	$114,985
	2011-15					$2,245,315	$1,696,183	$549,133
6	2013	$50	$250	1	921	$230,368	$108,335	$122,033
	2014	$50	$250	0	1,083	$270,750	$127,253	$143,498
	2015	$50	$250	0	1,289	$322,250	$151,458	$170,793
	2013-15					$823,368	$387,045	$436,323
7	2012	$175	$200	0	675	$135,000	$163,688	-$28,688
	2013 (c)	$113	$225	7	534	$121,410	$97,380	$24,030
	2014	$50	$250	0	685	$171,250	$80,488	$90,763
	2015	$50	$250	0	521	$130,250	$61,218	$69,033
	2012-15					$557,910	$402,773	$155,138
8	2011	$175	$240	0	381	$91,440	$92,393	-$953
	2012	$175	$240	0	367	$88,080	$88,998	-$918
	2013 (d)	$175	$245	0	299	$73,255	$72,508	$748
	2014	$175	$250	0	588	$147,000	$142,590	$4,410
	2015	$175	$250	0	843	$210,750	$204,428	$6,323
	2011-15					$610,525	$600,915	$9,610
11	2013 (e)	$50	$240	0	701	$168,240	$82,368	$85,873
	2014	$50	$250	0	1,052	$263,000	$123,610	$139,390
	2015	$50	$250	0	1,361	$340,250	$159,918	$180,333
	2013-15					$771,490	$365,895	$405,595
			Statewide Totals =	**3,726**	**29,891**	**$5,988,643**	**$4,309,150**	**$1,679,493**

Table 18: Furnished by Department Post Savings (2010–2015)

(e) = [(a)+67.5]*(c)+[(d)*(b)]
(f) = [(c)+(d)]*[(a)+67.5)]
(g) = (e)-(f)

In the 2010-2012 period, CMBs were not yet installed in several districts (e.g., Districts 1, 2, 6, 11). Furthermore, some Districts (primarily District 4) provided their own posts for CMB repair. These two factors led to reduced overall post maintenance costs in the early years. However, in recent years, the installation of additional CMB systems coupled with districts relying extensively on posts furnished by the vendor have led to increasing costs for in-line post repairs. If KYTC were to furnish posts, there could be a potential savings opportunity.

The cost analysis shown in Table 18 presents a hypothetical scenario whereby KYTC only uses the "furnished by department" itemized cost for CMB post repairs. Selecting this line-item option, additional costs would be borne by KYTC including the cost of purchasing the steel posts directly from the manufacturer. The research team investigated steel posts material costs and discovered the three vendors' post prices ranged anywhere from $45 to $90 per post. Therefore, an average post cost $67.50 was used for all posts and applied to the cost savings analysis. This figure represents a conservative estimate of the average post cost. The research team did not evaluate the KYTC resource and staffing requirements needed for purchasing, storage and handling, storage space requirements, and inventory issues. Current KYTC policies regarding contractor access to Commonwealth property and materials will also need to be considered. Those costs and concerns should be internally investigated by KYTC prior to any policy changes on contract maintenance.

In this scenario, all eight districts showed cost savings over the study period. Under the assumptions stated above, District 5 could have saved nearly $500,000 from 2011-2015 had it relied exclusively upon the furnished by department clause. Applying the assumptions across all districts and years, the potential cost savings was nearly $1.7 million. Over the six-year period, this averaged nearly $279,000 in annual cost savings. However, this number is not indicative of more recent annual trends associated with higher maintenance costs. The average potential savings by year rose from 2010 through 2015 (see Table 19). Therefore, KYTC can expect increasing annual post repair costs in the future.

Average Potential Savings by Year (F by D)					
2010	2011	2012	2013	2014	2015
$1,138	$110,695	$98,813	$365,828	$504,225	$598,795

Table 19: Average Post Potential Savings by Year (2010-2015)

4.3.3 Statistical Analysis

During the interviews, contractors and KYTC personnel raised concerns about discrepancies in performance among the three CMB brands, specifically, that a certain system's end terminal performed better. Some CMB systems experience a higher frequency of end treatment damage and cable rope tension loss following hits on or near the end terminal.

The research team used statistical analysis to investigate end terminal impact crashes in more detail. Cost invoice data were collected and analyzed with two statistical tests. First, a chi-square test was used to determine the relationship between end terminal hits and specific cable rope repairs. Second, any statistically significant relationship was further examined through use of a z-test, which assessed the differences in performance between the brands.

4.3.3.1 Chi-Square Test

In the first test, the Brifen system was assessed with cost repair invoice data from 2006 through 2015. This involved the use of itemized cost data for three categories, including end post, cable tension, and cable repair/replace. End posts were defined as the first four posts found directly adjacent to the end terminal. Cable tension represented the need to re-tension a cable rope system due to loss of tension, frequently observed when ropes rested on the ground. Finally, the cable repair/replace category represented the need to repair or replace an existing cable rope due to crash damage.

In this study, damaged end posts were used as a proxy for end terminal crashes since crashes impacting the end terminal vicinity would likely result in damage to one or more end posts. The end posts for all three cable barrier systems are the four posts located directly adjacent to the terminal (i.e., anchor). The chi-square test attempts to analyze the relationship between damage occurring to end posts and the occurrence of cable rope-related damages. In this case, the end post repair represents the independent variable (x1), while cable tension (y1) and cable repair/replace (y2) represents the dependent variables. Two separate chi-square test were run for each one-to-one relationship to assess the statistical significance in their relationship.

The chi-square test uses a null hypothesis and alternate hypothesis as a basis for its determination. For all three brands, the same null and alternate hypotheses were used. The null hypothesis (Ho) stated that the cable tension damage was independent of end post damage. Conversely, the alternate hypothesis (Ha) stated the cable tension damage was not independent of end post damage. The chi-square test attempts to reject the null hypothesis and thereby, by default, accept the alternate hypothesis. Accepting the alternate hypothesis provides confidence that a statistically significant relationship does exist between the two examined variables. In all cases, normal distribution with a 95 percent confidence interval was used.

The chi-square test compares the actual frequencies that occurred for categorical variables versus the frequencies expected to occur. The expected frequencies are found through the following equation:

$$\boldsymbol{Er, c = \frac{(nr * nc)}{n}}$$

Where[20]

- *Er, c* is the expected count frequency
- *nr* is the total number of sample observations for variable A at level *r*
- *nc* is the total number of sample observations for variable B at level *c*
- *n* is the total sample size

Comparing the actual frequency count with the expected frequency count, the chi-square test determines the presence of relationship, if any, between the variables. The chi-square test statistic is found through the following equation:

$$x^2 = \Sigma\, [Or,c - Er,c)^2\,)/\,Er,c]$$

Where[21]

- x^2 is the chi-square test statistic
- *Or, c* is the observed (actual) frequency count for variable A at level *r*
- *Er, c* is the expected frequency count for variable A at level *r*

The final chi-square test statistic is compared to the p-value of 0.05 (for a 95 percent confidence interval) to determine the significance of the relationship. If the test statistic is less than the p-value (or more extreme), then we can reject the null hypothesis and accept the alternate hypothesis. In other words, we can state that there is a statistically significant relationship between the frequency of end posts damaged and a cable requiring re-tensioning or repair/replacement, as applicable.

The following tables display the results of the chi-square test for each brand. In all cases, the chi-square test revealed a statistically significant relationship between the assessed variables. Accompanying p-values are displayed between each set of tables to demonstrate the results and validate the rejection of the null hypothesis. The first four tables display results from the Brifen tests, the second four tables display the results from the Gibraltar tests, and the final four display the results from the Trinity tests.

Matrix #1 (Actual)	End Post Repair		Grand Total
	Yes (1)	No (0)	
Cable Tension Repair - Yes (1)	7	13	20
Cable Tension Repair - No (0)	65	2631	2696
Grand Total =	72	2644	2716

Table 20: Chi-Square Test for End Post Repair and Cable Tension, Brifen (Actual Results)

Matrix #1 (Expected)	End Post Repair		Grand Total
	Yes (1)	No (0)	
Cable Tension Repair -Yes (1)	1	19	20
Cable Tension Repair - No (0)	71	2625	2696
Grand Total =	72	2644	2716

Table 21: Chi-Square Test for End Post Repair and Cable Tension, Brifen (Expected Results)

Chi-Square Test for End Post Repair and Cable Tension, Brifen

p-value = 1.58E-19

- Since the p-value is less than 0.05 (for the 95% confidence interval), we can reject the null hypothesis and accept the alternative hypothesis, cable tension damage was not independent of end post damage.

Matrix #2 (Actual)	End Post Repair		Grand Total
	Yes (1)	No (0)	
Cable Repair/Replace - Yes (1)	14	41	55
Cable Repair/Replace - No (0)	58	2603	2661
Grand Total =	72	2644	2716

Table 22: Chi-Square Test for End Post Repair and Cable Repair/Replace, Brifen (Actual Results)

Matrix #2 (Expected)	End Post Repair		Grand Total
	Yes (1)	No (0)	
Cable Tension Repair -Yes (1)	1	54	55
Cable Tension Repair - No (0)	71	2590	2661
Grand Total =	72	2644	2716

Table 23: Chi-Square Test for End Post Repair and Cable Repair/Replace, Brifen (Expected Results)

Chi-Square Test for End Post Repair and Cable Repair/Replace, Brifen

p-value = 2.04E-26

- Since the p-value is less than 0.05 (for the 95% confidence interval), we can reject the null hypothesis and accept the alternative hypothesis, cable repair/replacement was not independent of end post damage.

Matrix #1 (Actual)	End Post Repair		Grand Total
	Yes (1)	No (0)	
Cable Tension Repair -Yes (1)	8	8	16
Cable Tension Repair - No (0)	15	848	863
Grand Total =	23	856	879

Table 24: Chi-Square Test for End Post Repair and Cable Tension, Gibraltar (Actual Results)

Matrix #1 (Expected)	End Post Repair		Grand Total
	Yes (1)	No (0)	
Cable Tension Repair -Yes (1)	0	16	16
Cable Tension Repair - No (0)	23	840	863
Grand Total =	23	856	879

Table 25: Chi-Square Test for End Post Repair and Cable Tension, Gibraltar (Expected Results)

Chi-Square Test for End Post Repair and Cable Tension, Gibraltar

p-value = 4.36584E-33

- Since the p-value is less than 0.05 (for the 95% confidence interval), we can reject the null hypothesis and accept the alternative hypothesis, cable tension damage was not independent of end post damage.

Matrix #2 (Actual)	End Post Repair		Grand Total
	Yes (1)	No (0)	
Cable Repair/Replace -Yes (1)	9	19	28
Cable Repair/Replace - No (0)	14	837	851
Grand Total =	23	856	879

Table 26: Chi-Square Test for End Post Repair and Cable Repair/Replace, Gibraltar (Actual Results)

Matrix #2 (Expected)	End Post Repair		Grand Total
	Yes (1)	No (0)	
Cable Repair/Replace -Yes (1)	1	27	28
Cable Repair/Replace - No (0)	22	829	851
Grand Total =	23	856	879

Table 27: Chi-Square Test for End Post Repair and Cable Repair/Replace, Gibraltar (Expected Results)

Chi-Square Test for End Post Repair and Cable Repair/Replace, Gibraltar

p-value = 2.5913E-23

- Since the p-value is less than 0.05 (for the 95% confidence interval), we can reject the null hypothesis and accept the alternative hypothesis, cable repair/replacement was not independent of end post damage.

Matrix #1 (Actual)	End Post Repair		Grand Total
	Yes (1)	No (0)	
Cable Tension Repair -Yes (1)	3	3	6
Cable Tension Repair - No (0)	6	306	312
Grand Total =	9	309	318

Table 28: Chi-Square Test for End Post Repair and Cable Tension, Trinity (Actual Results)

Matrix #1 (Expected)	End Post Repair		Grand Total
	Yes (1)	No (0)	
Cable Tension Repair -Yes (1)	0	6	6
Cable Tension Repair - No (0)	9	303	312
Grand Total =	9	309	318

Table 29: Chi-Square Test for End Post Repair and Cable Tension, Trinity (Expected Results)

Chi-Square Test for End Post Repair and Cable Tension, Trinity

p-value = 2.00688E-12

- Since the p-value is less than 0.05 (for the 95% confidence interval), we can reject the null hypothesis and accept the alternative hypothesis, cable tension damage was not independent of end post damage.

Matrix #2 (Actual)	End Post Repair		Grand Total
	Yes (1)	No (0)	
Cable Repair/Replace -Yes (1)	2	13	15
Cable Repair/Replace - No (0)	7	296	303
Grand Total =	9	309	318

Table 30: Chi-Square Test for End Post Repair and Cable Repair/Replace, Trinity (Actual Results)

Matrix #2 (Expected)	End Post Repair		Grand Total
	Yes (1)	No (0)	
Cable Tension Repair -Yes (1)	0	15	15
Cable Tension Repair - No (0)	9	294	303
Grand Total =	9	309	318

Table 31: Chi-Square Test for End Post Repair and Cable Repair/Replace, Trinity (Expected Results)

Chi-Square Test for End Post Repair and Cable Repair/Replace, Trinity

p-value = 0.01197263

- Since the p-value is less than 0.05 (for the 95% confidence interval), we can reject the null hypothesis and accept the alternative hypothesis, cable repair/replacement was not independent of end post damage.

4.3.3.2 Two-Proportion Z-Test

In the second test, the research team wanted to further assess the relationship between end terminal crashes and the need to re-tension, repair, or replace cable ropes. The original chi-square test established that a relationship did exist between end post damages and corresponding re-tension or repair/replace efforts, as applicable. This relationship existed for all three CMB systems tested. The two-proportion z-test used a statistical analysis to assess the strength of the relationship among the brands. In essence, this test allowed researchers to compare performance among individual brands when crashes impacted an end terminal.

Testing a null hypothesis measures the difference in two population proportions. Two null hypotheses were used in this evaluation including:

- Re-tension Hypothesis: the probability of cable requiring re-tensioning once end post damage occurs for p1 (brand #1) is greater than or equal to the corresponding proportion for p2 (brand #2)

- Repair/Replace Hypothesis: the probability of cable requiring repair or replacement once end damage occurs for p1 (brand #1) is greater than or equal to the corresponding proportion for p2 (brand #2)

In both cases, a rejection of the null hypothesis leads acceptance of the alternate hypothesis meaning brand #1 requires less re-tensioning or repair/replacement following end-line post impacts. This essentially means that brand #1 performs better in the event of end terminal crashes.

The test statistic for this test is as follows:[22]

$$\boldsymbol{z} = [(\boldsymbol{p1} - \boldsymbol{p2}) - \boldsymbol{0}]/[\boldsymbol{p}(\boldsymbol{1} - \boldsymbol{p})\left(\frac{\boldsymbol{1}}{\boldsymbol{n1}} + \frac{\boldsymbol{1}}{\boldsymbol{n2}}\right)]\hat{}\boldsymbol{0.5}$$

Where p is represented as:

$$\boldsymbol{p} = \frac{(\boldsymbol{y1} + \boldsymbol{y2})}{(\boldsymbol{n1} + \boldsymbol{n2})}$$

Where

- $y1$ is the number of positive occurrences in group 1
- $y2$ is the number of positive occurrences in group 2
- $n1$ is the total sample size of group 2
- $n2$ is the total sample size of group 2

All tests are conducted using an upper tail test with a confidence interval of 95% (p = 0.05 for one tail). The full array of z-tests comparing all brands against each other for each condition tested are shown on the following pages.

Comparing End Post Repairs and Cable Retensioning	
Brifen	**Gibraltar**
n1 = 72	n2 = 23
y1 = 7 (yes for retension)	y2 = 8 (yes for retension)
p1 = 7/72 = 0.10	p2 = 8/23 = 0.35
Pooled Sample Proportion: p = (y1 + y2) / (n1 + n2)	
p = 0.15789	
Z Statistic: z = (p1-p2) / [p * (1 - p)*((1/n1) + (1/n2))]^0.5	
z = -2.84714	

Table 32: Tension Z-Test, Brifen & Gibraltar

Null Hypothesis: Ho: p1 >= p2
The probability of cable requiring re-tensioning once end post damage occurs for p1 (Brifen) is greater than or equal to the corresponding proportion for p2 (Gibraltar).

Alternate Hypothesis: Ha: p1 < p2
The probability of cable requiring re-tensioning once end post damage occurs for p1 (Brifen) is less than the corresponding proportion for p2 (Gibraltar).

The z-value is -2.84714. This corresponds to a p-value of 0.00221 (less than significance level of 0.05), meaning we can reject the null hypothesis.

Comparing End Post Repairs and Cable Retensioning	
Brifen	**Trinity**
n1 = 72	n2 = 9
y1 = 7 (yes for retension)	y2 = 3 (yes for retension)
p1 = 7/72 = 0.10	p2 = 3/9 = 0.33
Pooled Sample Proportion: p = (y1 + y2) / (n1 + n2)	
p = 0.12346	
Z Statistic: z = (p1-p2) / [p * (1 - p)*((1/n1) + (1/n2))]^0.5	
z = -2.00189	

Table 33: Tension Z-Test, Brifen & Trinity

Null Hypothesis: Ho: p1 >= p2
The probability of cable requiring re-tensioning once end post damage occurs for p1 (Brifen) is greater than or equal to the corresponding proportion for p2 (Trinity).

Alternate Hypothesis: Ha: p1 < p2
The probability of cable requiring re-tensioning once end post damage occurs for p1 (Brifen) is less than the corresponding proportion for p2 (Trinity).

The z-value is -2.00189. This corresponds to a p-value of 0.02265 (less than significance level of 0.05), meaning we can reject the null hypothesis.

Comparing End Post Repairs and Cable Retensioning	
Gibraltar	**Trinity**
n1 = 23	n2 = 9
y1 = 8 (yes for retension)	y2 = 3 (yes for retension)
p1 = 8/23 = 0.35	p2 = 3/9 = 0.33
Pooled Sample Proportion: p = (y1 + y2) / (n1 + n2)	
p = 0.34375	
Z Statistic: z = (p1-p2) / [p * (1 - p)*((1/n1) + (1/n2))]^0.5	
z = 0.10738	

Table 34: Tension Z-Test, Gibraltar & Trinity

Null Hypothesis: Ho: p1 >= p2
The probability of cable requiring re-tensioning once end post damage occurs for p1 (Gibraltar) is greater than or equal to the corresponding proportion for p2 (Trinity).

Alternate Hypothesis: Ha: p1 < p2
The probability of cable requiring re-tensioning once end post damage occurs for p1 (Gibraltar) is less than the corresponding proportion for p2 (Trinity).

The z-value is 0.10738. This corresponds to a p-value of 0.54276 (greater than significance level of 0.05), meaning we cannot reject the null hypothesis.

Comparing End Post Repairs and Cable Repair or Replacement (R&R)	
Brifen	**Gibraltar**
n1 = 72	n2 = 23
y1 = 14 (yes for R&R)	y2 = 9 (yes for R&R)
p1 = 14/72 = 0.20	p2 = 9/23 = 0.39
Pooled Sample Proportion: p = (y1 + y2) / (n1 + n2)	
p = 0.24211	
Z Statistic: z = (p1-p2) / [p * (1 - p)*((1/n1) + (1/n2))]^0.5	
z = -1.85742	

Table 35: Repair/Replace Z-Test, Brifen & Gibraltar

Null Hypothesis: Ho: p1 >= p2
The probability of cable requiring repair or replacement once end post damage occurs for p1 (Brifen) is greater than or equal to the corresponding proportion for p2 (Gibraltar).

Alternate Hypothesis: Ha: p1 < p2
The probability of cable requiring repair or replacement once end post damage occurs for p1 (Brifen) is less than the corresponding proportion for p2 (Gibraltar).

The z-value is -1.85742. This corresponds to a p-value of 0.03163 (less than significance level of 0.05), meaning we can reject the null hypothesis.

Comparing End Post Repairs and Cable Repair or Replacement (R&R)	
Brifen	**Trinity**
n1 = 72	n2 = 9
y1 = 14 (yes for R&R)	y2 = 2 (yes for R&R)
p1 = 14/72 = 0.20	p2 = 2/9 = 0.22
Pooled Sample Proportion: p = (y1 + y2) / (n1 + n2)	
p = 0.19753	
Z Statistic: z = (p1-p2) / [p * (1 - p)*((1/n1) + (1/n2))]^0.5	
z = -0.14209	

Table 36: Repair/Replace Z-Test, Brifen & Trinity

Null Hypothesis: Ho: p1 >= p2
The probability of cable requiring repair or replacement once end post damage occurs for p1 (Brifen) is greater than or equal to the corresponding proportion for p2 (Trinity).

Alternate Hypothesis: Ha: p1 < p2
The probability of cable requiring repair or replacement once end post damage occurs for p1 (Brifen) is less than the corresponding proportion for p2 (Trinity).

The z-value is -0.14209. This corresponds to a p-value of 0.44350 (greater than significance level of 0.05), meaning we cannot reject the null hypothesis.

Comparing End Post Repairs and Cable Repair or Replacement (R&R)	
Gibraltar	**Trinity**
n1 = 23	n2 = 9
y1 = 9 (yes for R&R)	y2 = 2 (yes for R&R)
p1 = 9/23 = 0.39	p2 = 2/9 = 0.22
Pooled Sample Proportion: p = (y1 + y2) / (n1 + n2)	
p = 0.34375	
Z Statistic: z = (p1-p2) / [p * (1 - p)*((1/n1) + (1/n2))]^0.5	
z = 0.91274	

Table 37: Repair/Replace Z-Test, Gibraltar & Trinity

Null Hypothesis: Ho: p1 >= p2
The probability of cable requiring repair or replacement once end post damage occurs for p1 (Gibraltar) is greater than or equal to the corresponding proportion for p2 (Trinity).

Alternate Hypothesis: Ha: p1 < p2
The probability of cable requiring repair or replacement once end post damage occurs for p1 (Gibraltar) is less than the corresponding proportion for p2 (Trinity).

The z-value is 0.91274. This corresponds to a p-value of 0.8193 (greater than significance level of 0.05), meaning we cannot reject the null hypothesis.

In summary, the Brifen system outperformed the other two systems, on average, in terms of resiliency upon crash impacts with its end terminal. The final results from the chi-square and two-proportion, z-tests are as follows:

Cable Retensioning
- Brifen outperforms Gibraltar
- Brifen outperforms Trinity
- Gibraltar and Trinity have no statistical difference between performance

Cable Repair or Replacement
- Brifen outperforms Gibraltar

- Brifen and Trinity have no statistical difference between performance
- Gibraltar and Trinity have no statistical difference between performance

CHAPTER 5
Crash Analysis

Brifen CMB System

Chapter 5: Crash Analysis

5.1 Summary of Crash Data

In the project's final phase, KTC researchers conducted a comprehensive crash analysis on vehicles impacting CMB, as well as provided multiple case studies to discuss crash analysis scenarios. The research team used the Kentucky Open Portal Solution (KyOPS) state police database to collect the crash analysis data through listed crash reports. Crash reports contain multiple codes and a narrative that indicate the type and description of the crash, respectively. One crash report code provides information describing the collision type and struck object. This code designates one category as crashes involving a cable barrier. The crash database was analyzed to determine any instances where a vehicle involved in a crash impacted a CMB as a first, second, third, or fourth order event in a crash sequence. The research team reviewed crash data from 2008 through 2016. Using these criteria, 4,350 crashes were identified, which included 729 injury crashes and 20 fatal crashes. Considering all of the identified crashes, 74.5 percent were coded as a first event crash and 22.9 percent as a second event crash. For injury crashes, 54.6 percent were coded as a first event crash and 35.9 percent as a second event crash.

The following summary table provides crash types and event order by year across the examined CMB crash data from 2008 through 2016.

	First Event			Second Event			Third Event			Fourth Event		
Year	Total	Fatal Crash	Injury Crash	Total	Fatal Crash	Injury Crash	Total	Fatal Crash	Injury Crash	Total	Fatal Crash	Injury Crash
2008	29	0	5	12	1	2	0	0	0	0	0	0
2009	173	0	21	48	0	9	0	0	0	0	0	0
2010	258	1	30	69	1	19	0	0	0	0	0	0
2011	406	3	59	118	1	30	6	0	3	3	0	2
2012	385	3	50	144	0	37	15	1	8	2	0	1
2013	400	0	51	128	0	34	21	1	10	2	0	1
2014	455	2	49	136	0	36	14	0	9	7	0	4
2015	539	2	62	156	1	43	24	0	13	6	2	1
2016	584	1	71	184	0	52	26	0	17	0	0	0
Total	3,229	12	398	995	4	262	106	2	60	20	2	9

Table 38: CMB Crash Events, 2008-2016

In the table, approximately 17 percent of crashes were identified as injury crashes and among those, nearly 0.5 percent involved a fatal crash. Using these percentages, injury and fatal crashes were compared to all rural crashes involving a fixed object. This analysis provided a means to relate crash severity among CMB crashes to those crashes involving impacts with other fixed objects. For rural crashes, researchers discovered that about 29 percent and 1.7 percent of those fixed object impact crashes resulted in injuries or fatalities, respectively. The comparison shows that cable barrier crashes resulted in less severe outcomes than rural fixed object crashes.

A review of the crash data found 16 motorcycle crashes and 245 large truck crashes in which there was a collision with cable barrier. Of the motorcycle crashes, there were 11 injury crashes and 3 fatal crashes; of the large truck crashes, there were 49 injury crashes and 4 fatal crashes. These results reveal that an impact between a motorcycle and the cable barrier can result in serious injuries (which is the case for motorcycle crashes involving any type of barrier). The data showed that the overall severity of a large truck impact with the cable barrier was less than for all rural fixed object crashes involving trucks.

CMB frequently experiences minor impacts (involving damage to very few posts) where no crash report is filed. These instances are known as nuisance hits. Unreported crashes present a financial burden to many state DOTs since these organizations frequently submit reimbursement claims to the insurance companies of at-fault drivers who damage roadside CMB structures. Reported crashes often provide a mechanism to fund the repairs of damaged CMB infrastructure, while unreported crashes introduce additional fiscal demands on the state DOT's general fund. The research team investigated the number of reported crashes versus unreported crashes. As a method to estimate the number of unreported crashes, repair data and crash data were compared (using the locations and time period for the available repair data). Repair data were gathered through the individual billing invoices from each of the districts using CMB. The repair data (for the routes and time periods where data were analyzed) contained information on 3,916 repairs; however, a review of the crash data found 2,794 crashes (for those same routes and times). This indicated that reported crashes accounted for 71 percent of the repairs—or, about 30 percent of the total impacts were nuisance hits and did not result in a crash report. The lowest percentage of reported crashes compared to repairs was in District 5 (Jefferson, Bullitt, and Oldham Counties) with reported crashes totaling 64 percent of repairs. This percentage was also 64 percent in Fayette County and 69 percent in District 6 (Boone, Kenton, Campbell, Gallatin, and Carroll Counties). These locations are typically urban interstates. On the other hand, Districts 8 and 11 (rural interstate in Laurel, Rockcastle, and Whitley Counties) demonstrated the highest percentage of reported crashes, at 89 percent of total repairs.

KTC researchers conducted numerous field investigations during the course of this study. Several inspections revealed instances where posts had begun rusting underneath the ground line. This was the result of water runoff accumulating in the post base, resulting in a prolonged exposure between the steel and water. The research team speculated that many of these same posts had not been replaced since their initial installation, leaving them more susceptible to rusting. It was also noted that these posts sometimes split—rather than bend—during the crash event. However, the site surveys did not provide any evidence of physical post separation (e.g., projectile motion) at these locations. If separation should occur, there could be a potential for the post to impact another secondary vehicle. Two different post configurations with sub-surface rusting conditions are displayed in the figures below.

Figure Q: Gibraltar post with rust due to water intrusion

Figure R: Brifen post with rust due to water intrusion

5.2 Analysis of Fatal Crashes

Transportation measures are often instituted to reduce traffic fatalities. Therefore, the research team investigated the occurrence of fatal crashes involving CMB in Kentucky by analyzing crash reports. The 20 fatal crashes were categorized as a first, second, third, or fourth event depending on the order in which the vehicle impacted the CMB. For instance, if the vehicle struck the CMB initially, this event would be a first event. However, if the vehicle struck another vehicle and then struck the CMB, this event would be a second event. The list of events involving fatalities are shown below:

- First Event: 12 crashes
- Second Event: 4 crashes
- Third Event: 2 crashes
- Fourth Event: 2 crashes

A detailed review of the crash reports revealed that 10 incidents did not involve any technical or performance issue with the cable barrier. In these instances, the cause of the fatality was primarily due to other crash events or circumstances. For example, several crash events involved a vehicle either coming to rest against the cable barrier after a major collision or a vehicle occupant ejected during the crash sequence.

Out of the remaining 10 fatal crashes, there were four crashes where a vehicle went through (penetration) or over (override) the cable and struck a vehicle traveling in the opposing direction. In three of those four crashes, the vehicle was a large truck. Another three fatal crashes involved a vehicle going through or over the cable barrier into the median (with one involving a single unit truck). In a third group, there were three fatal crashes involving a motorcycle impacting the cable barrier.

The following event codes provide narrative descriptions of the fatal crashes over the designated time period, along with dates, locations, and CMB brands. Each narrative discusses the impacted vehicle and crash sequence.

5.2.1 First Event Code

Date	County	Route	Mile Point	Vendor

- January 14, 2016 | Fayette | KY 4 | 16.8 | Brifen
  Description: A Chevrolet Tahoe hit the guardrail on the right side of the road. The driver overcorrected resulting in impact with the cable barrier. The vehicle rolled over the cable with the driver ejected.

- September 8, 2015 | Rockcastle | I-75 | 64.0 | Brifen
  Description: A Toyota 4Runner contacted the cable barrier adjacent to its lane of travel and then overturned into the median.

- July 9, 2015 Jefferson I-64 7 Brifen
  Description: A Ford Escort contacted the adjacent cable barrier and went through two of the bottom cables. The vehicle then crossed the median resulting in a head-on collision with a vehicle in the opposing direction.

- December 25, 2014 Whitley I-75 15.2 Brifen
  Description: A large recreation vehicle came to a final rest position adjacent to the cable barrier (the older aged driver was unbelted).

- September 22, 2014 Rockcastle I-75 68 Brifen
  Description: A motorcycle contacted the adjacent cable barrier.

- November 14, 2012 Jefferson I-71 7.6 Brifen
  Description: A Ford Ranger hit the adjacent cable barrier and overturned into the road.

- November 12, 2012 Jefferson I-265 30.2 Brifen
  Description: A Ford F150 pickup contacted the adjacent cable barrier and then veered across both lanes and overturned with the driver ejected.

- May 13, 2012 Hart I-65 54.5 Gibraltar
  Description: A tractor-trailer traveled through the grass median and then through the cable barrier resulting in a head-on collision with a vehicle traveling in the opposing direction.

- July 22, 2011 Hardin I-65 86.9 Brifen
  Description: A Cadillac Escalade crossed the median and contacted the cable barrier. The vehicle overturned with a passenger ejected.

- July 13, 2011 Hardin I-65 86.2 Brifen
  Description: A Ford F650 truck contacted and went through the adjacent cable barrier and overturned in the median.

- April 21, 2011 Fayette KY 4 15.7 Brifen
  Description: A motorcycle contacted the adjacent cable barrier.

- March 26, 2010 Hart I-65 61.4 Gibraltar
  Description: A tractor-trailer traveled through the grass median and then through the cable barrier resulting in a head-on collision with the vehicle traveling in the opposing direction.

5.2.2 Second Event Code

Date	County	Route	Mile Point	Vendor

- August 26, 2015 Carroll I-71 44.0 Brifen
  Description: A Lexus ES300 traveled through the median and contacted the cable barrier with the vehicle overturning in the median (with the passenger ejected).

- January 6, 2011 Jefferson I-71 10.9 Brifen
  Description: After an initial collision with another vehicle, a tractor trailer traveled through the adjacent cable barrier resulting in a head-on collision with the vehicle traveling in the opposing direction.

- October 23, 2010 Jefferson KY 841 2.3 Gibraltar
  Description: After an initial collision with another vehicle, a motorcycle contacted the cable barrier adjacent to its lane of travel.

- November 25, 2008 Jefferson I-265 11.0 Trinity
  Description: A fatal collision resulted from an impact between the passenger side of the vehicle and the end of a guardrail. The vehicle then crossed the median with its final rest at the cable barrier.

5.2.3 Third Event Code

Date	County	Route	Mile Point	Vendor

- December 6, 2013 Hardin I-65 96.9 Brifen
  Description: The driver was ejected after an impact with a guardrail and then the Pontiac Montana contacted the cable barrier.

- September 20, 2012 Jefferson I-71 8.1 Brifen
  Description: The driver was ejected when the Chevrolet Tahoe overturned and then the vehicle contacted cable barrier.

5.2.4 Fourth Event Code

Date	County	Route	Mile Point	Vendor

- December 22, 2015 Hardin I-65 96.9 Brifen
  Description: A Chevrolet Trailblazer overturned and was hit by another vehicle before its final rest position against the cable barrier.

- November 1, 2015 Laurel I-75 47 Gibraltar
  Description: A previous accident involved a pedestrian fatality and then a Volkswagen Jetta came to a final rest position at the cable barrier.

The review of the fatal crashes did not find a common issue or noticeable trend. The majority of vehicle head-on collisions involved large trucks going through the cable into the opposing lane. The TL-3 and TL-4 cable barrier used in Kentucky was not designed to prevent a large truck striking the cable at a substantial angle from going through the cable.

5.3 Case Studies

5.3.1 Site Inspections

KTC conducted inspections on CMB crash sites as another method to evaluate brand performance and to possibly identify concerns or trends. First, researchers continuously monitored the KyOPS crash database during the study period to rapidly identify when a CMB crash report appeared. Next, site visits were made to several locations before repairs to the cable barrier were completed, and a concerted effort was made to review the more severe crashes. In many instances, the maintenance contractors made repairs before an inspection could be conducted. This site survey and inspection process revealed that repairs were typically completed within a few days of the crash. In select instances, the contractor required additional CMB hardware to complete the repairs, which prolonged the repair time.

Each site survey gathered information on the number of posts damaged, evidence of the pre-impact and post-impact travel path of the vehicle, and the condition of the cable system after the crash. Where crashes impacted only a few posts, the cables typically maintained their tension levels. When numerous posts were damaged, the CMB might experience severe or complete loss of tension as evidenced by cable rope/s that have fallen on the ground. For instance, researchers noticed several instances where the Gibraltar system was hit on or near the end terminal, resulting in loss of tension over long cable distances.

Additional site visit information and crash details can be found in Appendix E. Repair costs and the date of repair are also provided where available.

5.3.2 Repair Date and Costs

Repair data were used to analyze the number of days from the date of the crash to the repair date and to find the cost of each repair. The team reviewed crash reports so the crash could be assigned to the individual repair invoice, typically through examination of its repair date and location. The following case studies provide crash descriptions, along with repair dates and costs. Several crashes involved many damaged posts. Among the 30 case studies, repair time exceeded 5 days in 12 cases. On average, these crashes required replacement of 43 posts.

- The crash occurred on December 5, 2015, on I-75 in Whitley County near mile point 0.1. A Kenworth tractor trailer was involved with no injury reported. The repair was conducted on December 10, with 84 posts (Brifen) replaced at a cost of $23,400.

- The crash occurred on November 19, 2015, on I-75 in Whitley County near mile point 8.9. A Kenworth tractor trailer traveled through the barrier after sideswipe contact with another vehicle. There was no injury to the truck driver. The repair was conducted on December 3, with 42 posts (Brifen) replaced and the cable re-tensioned. The cost was $17,500.

- The crash occurred on January 28, 2013, on I-75 in Whitley County near mile point 24.5. A Freightliner tractor trailer was involved with no injury reported. The repair was conducted on February 19, with 39 posts (Brifen) replaced at a cost of $10,120.

- The crash occurred on November 14, 2015, on I-75 in Whitley County near mile point 11.6. A Mercury Grand Marquis was involved with no injury reported. The repair was conducted on November 14, with 26 posts (Brifen) replaced and a cost of $6,900.

- The crash occurred on August 2, 2015, on I-75 in Whitley County near mile point 5.8. A Peterbilt tractor trailer was involved with no injury reported. The repair was conducted on September 9, with 70 posts (Brifen) replaced at a cost of $19,900.

- The crash occurred on March 28, 2014, on I-65 in Larue County near mile point 76.3. A Nissan Pathfinder was involved with no injury reported. The repair was conducted on April 1, with 27 posts (Brifen) replaced at a cost of $4,050.

- The crash occurred on August 9, 2015, on I-275 in Campbell County on I-275 near mile point 76. A Chevrolet Prizm was involved with no injury reported. The repair was conducted on August 14 with 12 in-line posts and four end posts (Brifen) replaced (with tension restored) at a cost of $5,799.

- The crash occurred on September 7, 2015, on I-275 in Campbell County on I-275 near mile point 76.2. A Dodge Dakota pickup was involved with no injury reported. The repair was conducted on September 10, with 64 posts (Brifen) replaced at a cost of $16,010.

- The crash occurred on July 18, 2015, on I-24 in Christian County on I-24 near mile point 87.7. A Chevrolet Trail Blazer was involved with no injury reported. The repair was conducted on July 27, with four posts (Brifen) replaced at a cost of $625.

- The crash occurred on November 5, 2014, in Christian County on I-24 near mile point 76.1. A GMC Envoy was involved with no injury reported. The repair was conducted on January 9, 2015, with 67 posts (Briden) replaced at a cost of $10,075.

- The crash occurred on November 9, 2015, in McCracken County on I-24 near mile point 15.7. A Dodge Nitro was involved with no injury reported. The repair was conducted on November 10, with 18 posts (Brifen) replaced at a cost of $3,100.

- The crash occurred on March 27, 2015, in McCracken County on I-24 near mile point 13. A Freightliner tractor trailer collided with an adjacent cable and then overturned in the road. There were three injuries in a pickup that collided with the overturned truck. The repair was conducted on April 21, with 61 posts (Brifen) replaced (and tension restored) at a cost of $17,250.

- The crash occurred on August 1, 2014, in Larue County on I-65 near mile point 75.5. A Saturn SL was involved with no injury reported. The repair was conducted on August 5, with 23 posts (Brifen) replaced at a cost of $3,450.

- The crash occurred on May 13, 2012, in Hart County on I-65 near mile point 54.5. A Volvo tractor trailer traveled through the median then through the cable barrier adjacent to the opposing lanes where a fatal head-on collision occurred. The repair was conducted on May 22, with 41 posts (Gibraltar) replaced at a cost of $4,575.

- The crash occurred on March 9, 2013, on I-65 in Larue County near mile point 77.1. A Ford Ranger was involved with one injury reported. The repair was conducted on March 15, with 12 posts (Brifen) replaced at a cost of $1,800.

- The crash occurred on June 20, 2014, in Larue County on I-65 near mile point 75.2. An International tractor trailer was involved with no injury reported. The repair was conducted on June 24, with 51 posts (Brifen) replaced at a cost of $8,050.

- The crash occurred on January 25, 2013, in Larue County on I-65 near mile point 78.2. A Freightliner tractor trailer was involved with no injury reported. The repair was conducted on February 3, with 53 posts (Brifen) replaced at a cost of $7,950.

- The crash occurred on February 9, 2014, in Jefferson County on I-265 near mile point 23.0. A Chevrolet Silverado extended cab pickup was involved with no injury reported. The repair was conducted on February 11, with nine in-line and two end posts (Trinity) replaced at a cost of $1,650.

- The crash occurred on May 13, 2012, in Hart County on I-65 near mile point 54.5. A Volvo tractor trailer crossed the median and traveled over the cable adjacent for the opposing lane resulting in a fatal head-on collision. The repair was conducted on May 22, with 42 posts (Gibraltar) replaced (with cable repair) at a cost of $4,575.

- The crash occurred on December 7, 2013, in Jefferson County on I-265 near mile point 23.6. A Hyundai Sonata contacted the cable after a sideswipe contact with another vehicle. No injury was reported for the Sonata driver. The repair was conducted on December 9 with, 21 posts (Brifen) replaced at a cost of $1,800.

- The crash occurred on September 23, 2014, in Bullitt County on I-65 near mile point 120.8. A Pontiac Transport van was involved with no injury reported. The repair was conducted on September 24, with seven posts (Gibraltar) replaced at a cost of $1,050.

- The crash occurred on May 4, 2014, in Jefferson County on I-71 near mile point 11. A Mercury Montego was involved with no injury reported. The repair was conducted on May 8, with 41 posts (Brifen) replaced at a cost of $6,150.

- The crash occurred on May 24, 2014, in Bullitt County on I-65 near mile point 111. A Pontiac Vibe was involved with no injury reported. The repair was conducted on June 3, with 33 posts (Gibraltar) replaced at a cost of $4,950.

- The crash occurred on June 21, 2014, in Jefferson County on I-265 near mile point 29. A Chevrolet pickup was involved with no injury reported. The repair was conducted on June 27, with 50 posts (Brifen) replaced at a cost of $7,500.

- The crash occurred on September 4, 2014, in Jefferson County on I-265 near mile point 12.8. A Chrysler PT Cruiser was involved with no injury reported. The repair was conducted on September 5, with nine in-line and eight end posts (Trinity) replaced. There was also re-tensioning of the cable. The repair cost was $4,950.

- The crash occurred on August 6, 2014, in Jefferson County on I-265 near mile point 29.5. A Ford Escape was involved with one reported injury. The repair was conducted on August 11, with 18 posts (Brifen) replaced at a cost of $2,700.

- The crash occurred on September 20, 2014, in Jefferson County on KY 851 near mile point 3. A Toyota Highlander was involved with two reported injuries. The repair was conducted on September 23, with 20 posts (Gibraltar) replaced at a cost of $3,000.

- The crash occurred on September 30, 2014, in Bullitt County on I-65 near mile point 120. A Chevrolet S10 was involved with no injury reported. The repair was conducted on September 30, with 18 posts (Brifen) replaced at a cost of $2,700.

- The crash occurred on April 30, 2014, in Jefferson County on I-265 near mile point 19.6. A Nissan Maxima was involved with no injury reported. The repair was conducted on May 1, with eight posts (Trinity) replaced. There was re-tensioning of the cable. The cost was $9,203.

- The crash occurred on August 10, 2014, in Hardin County on I-65 near mile point 97.9. A Dodge Ram was involved with one injury reported. The repair was conducted on August 11, with 61 posts (Brifen) replaced at a cost of $9,150.

CHAPTER 6
Conclusion

Trinity CMB System

Chapter 6: Conclusion

This KYTC-sponsored research study examined many aspects of cable median barrier (CMB) systems installed across Kentucky. The research team collected both field data and district-provided cost data to identify safety, performance, and cost trends across all KYTC approved vendors. In addition, the research team conducted multiple interviews and consultations with KYTC personnel and private-sector maintenance contract personnel to better identify concerns and issues. The study examined and assessed five main topics related to cable barrier: (1) literature review on cable median barrier best practices, (2) crash effectiveness, (3) product evaluation of installation method, (4) product evaluation of maintenance, and (5) crash analysis. Although discussed in separate chapters within the report, there are many similarities and overlap among the findings for crash effectiveness and crash analysis. Therefore, they are discussed here jointly. The research study's main findings and recommendations are meant to provide guidance for KYTC decision makers.

6.1 Findings

The following summary lists the findings derived from the investigation and from analysis of the data, categorized by topic area.

Literature Review

- Most state DOTs (36) check cable median barrier rope tension following major or minor repairs (NCHRP Report 493).
- All CMB vendor systems experienced increased deflection distances as post spacing and anchor spacing increased (NCHRP Report 711).
- Brifen cable median barrier experienced a reduced rate of increase in lateral deflections at increased post spacing and anchor spacing distances, compared to Gibraltar, Trinity CASS, and the other brands (NCHRP Report 711).

Crash Effectiveness/Analysis

- The crash data and benefits analysis showed that cable median barriers have been an effective method of reducing median crossover crashes.
- A comparison of repair data and crash reports found that approximately 30 percent of all cable median barrier crash impacts would be classified as nuisance hits which have not been reported in the KyOPS data base, thereby restricting the ability of KYTC to collect reimbursements for those damages.
- Vehicles rarely penetrated cable median barrier systems. However, the few instances in which a vehicle traveled through the cable barrier system usually involved a large truck. (CMB was not designed to redirect large trucks).
- When passenger vehicles traveled over or through the cable median barrier, these penetrations often occurred where the cable barrier was installed at a lower elevation than where the vehicle exited its travel lane.
- Multiple crash site inspections found rust on some underground portions of the posts (i.e., the bottom of the posts inserted into the sleeve of the concrete base), regardless of vendor product. Rusted posts may split upon impact. Since the posts

were made to yield upon impact, the rusting of the posts will most probably not hinder the operation of the cable barrier.
- Cable median barrier typically maintained required tension levels when few posts were damaged; however, crashes resulting in excessive post damages frequently led to tension losses.
- Crashes on or near Gibraltar and Trinity CASS end treatments sometimes led to tension losses along the whole distance of the cable rope system.
- The benefit cost analysis demonstrated that cable median barrier installations have resulted in high value in both economic and comprehensive terms.

Product Evaluation (Installation)
- KYTC contract proposal specifications for cable median barrier systems have met FHWA crashworthy acceptance letter conditions and manufacturing guidelines as listed.
- Cable barrier inspections revealed the following issues related to installation on Brifen cable median barrier systems: (1) in-line post spacing greater than the specified distance, (2) end post spacing greater than the specified distance, (3) cable rope strands outside vertical height tolerances, (4) end post vertical angles out of tolerance, and (5) insufficient weakening cuts on end posts.
- Cable barrier inspections through site surveys revealed the following issues related to installation on Gibraltar cable median barrier systems: (1) in-line post spacing greater than the specified distance, (2) end post spacing greater than the specified distance, and (3) end post vertical angles out of tolerance.

Product Evaluation (Maintenance)
- Field observations and interviews found that contractors typically completed cable median barrier repairs within the time frame specified in the district maintenance contracts.
- Damaged in-line posts accounted for nearly 89 percent of the total maintenance costs for cable median barrier between 2010 through 2015.
- The Trinity system had the lowest maintenance costs on both a per crash and per mile basis, which may be due to the increased post spacing. The Brifen system was second in terms of overall maintenance costs. Gibraltar had the highest maintenance costs.
- The repair cost per crash for the Brifen and Gibraltar systems nearly doubled from 2010 through 2015. This seemed to result from two main factors: (a) the inclusion of Gibraltar's post hardware components as separate, add-on costs into the original maintenance contract and (b) district offices' increased reliance on the maintenance contractor to provide post materials.
- The higher maintenance costs for the Gibraltar system may be attributed to: (1) the costs for the lock-plate and hairpin components and (2) the higher probability of cable re-tensioning efforts, particularly for impacts on or near the end anchor.
- Interviews with KYTC district and contract repair personnel revealed both positive and negative attributes associated with each cable median barrier vendor:

    - Brifen maintained its tension best after crash impacts and after collisions on or near the end treatment. However, the higher tension and the interwoven nature of the system made maintenance more complex, particularly for vehicle extractions. In addition, the cable ropes were more prone to movement in the absence of vertical restraints.
    - Gibraltar was the easiest overall to maintain and repair. However, there were concerns with its ability to maintain tension due to collisions on or near the end treatment, and the need for additional post components complicated repair.
    - Trinity had relatively low maintenance costs relative to the other brands. However, there were differences of opinion concerning the ease of maintenance. Also, there were concerns with its ability to maintain tension after collisions on or near the end treatment and whether the 3-cable design is sufficient to prevent crossover crashes.
- KYTC district and contract repair personnel were in general agreement over the concrete mow pads installed on the majority of Kentucky's cable median barrier systems; the mow pad outperforms individual, cylindrical concrete post foundations. Improvements cited were increased strength, less lateral deflection, and fewer additional repairs and maintenance.
- Both research studies and manufacturers touted the critical importance of maintaining required tension levels for cable median barrier to perform properly. However, only District 7 has instituted a tension inspection program. This district asks the maintenance contract provider to perform tension level readings across the entire cable median barrier system at scheduled intervals and then adjust tensions at any locations not meeting the specification.
- Tension levels after CMB repairs do not appear to be recorded in tension logs and provided to district offices per the terms of the maintenance contract.
- Statistical analysis of cable median barrier re-tensioning repairs after impacts on or near the end treatment demonstrated the following: (1) Brifen outperformed Gibraltar and Trinity, and (2) there was no statistical difference between Gibraltar and Trinity.
- Statistical analysis of cable median barrier rope repairs or replacements after impacts on or near the end treatment demonstrated the following: (1) Brifen outperformed Gibraltar, (2) there was no statistical difference between Brifen and Trinity CASS, and (3) there was no statistical difference between Gibraltar and Trinity CASS.

6.2 Recommendations

The study resulted in the following recommendations.

- Cable median barrier installations greatly reduced the number of median crossover crashes when compared to roadways with no median barrier. Cable median barrier effectiveness justifies continued use and additional installations at appropriate locations.

- The concrete mow pad has performed well, increasing the overall strength of the cable barrier systems. The mow pad has resulted in reduced maintenance issues compared to cable barrier with no mow pad. Mow pads should continue to be used in cable barrier installations.
- Quality assurance during installation is needed to ensure cable median barrier meets all applicable standards and guidelines, most notably, appropriate post spacing, post vertical angles, and end post weakening cuts. Additional training and/or guidelines should be provided to KYTC inspectors to aid construction inspection during CMB projects.
- New cable median barrier installations should be installed on the high-elevation side of divided median roadways when the difference in elevation is significant.
- KYTC district offices should institute and enforce tension-monitoring programs, as applicable, for both annual inspections and after repairs. The contract repair personnel should maintain a tension log and document tension readings for cable median barrier sites at set distance intervals (as determined by the district). This should occur approximately 72 hours following repairs.
- In recent years, the installation of additional CMB systems coupled with districts relying extensively on posts described by "furnished by vendor" have led to increasing costs for in-line post repairs. If KYTC were to furnish posts, there could be a potential savings opportunity.
- Additional CMB specifications and requirements, especially tolerances in the specifications, should be provided in future KYTC district installation and maintenance contracts.
- KYTC could consult manufacturers to inquire about improved end treatments or methods to mitigate system tension loss when crashes occur near the end treatment.
- If KYTC is interested in studying the performance of CMB systems following crashes, consideration should be given to collecting tension data prior to repairs of CMB systems.

Appendix A – Benefits Methodology

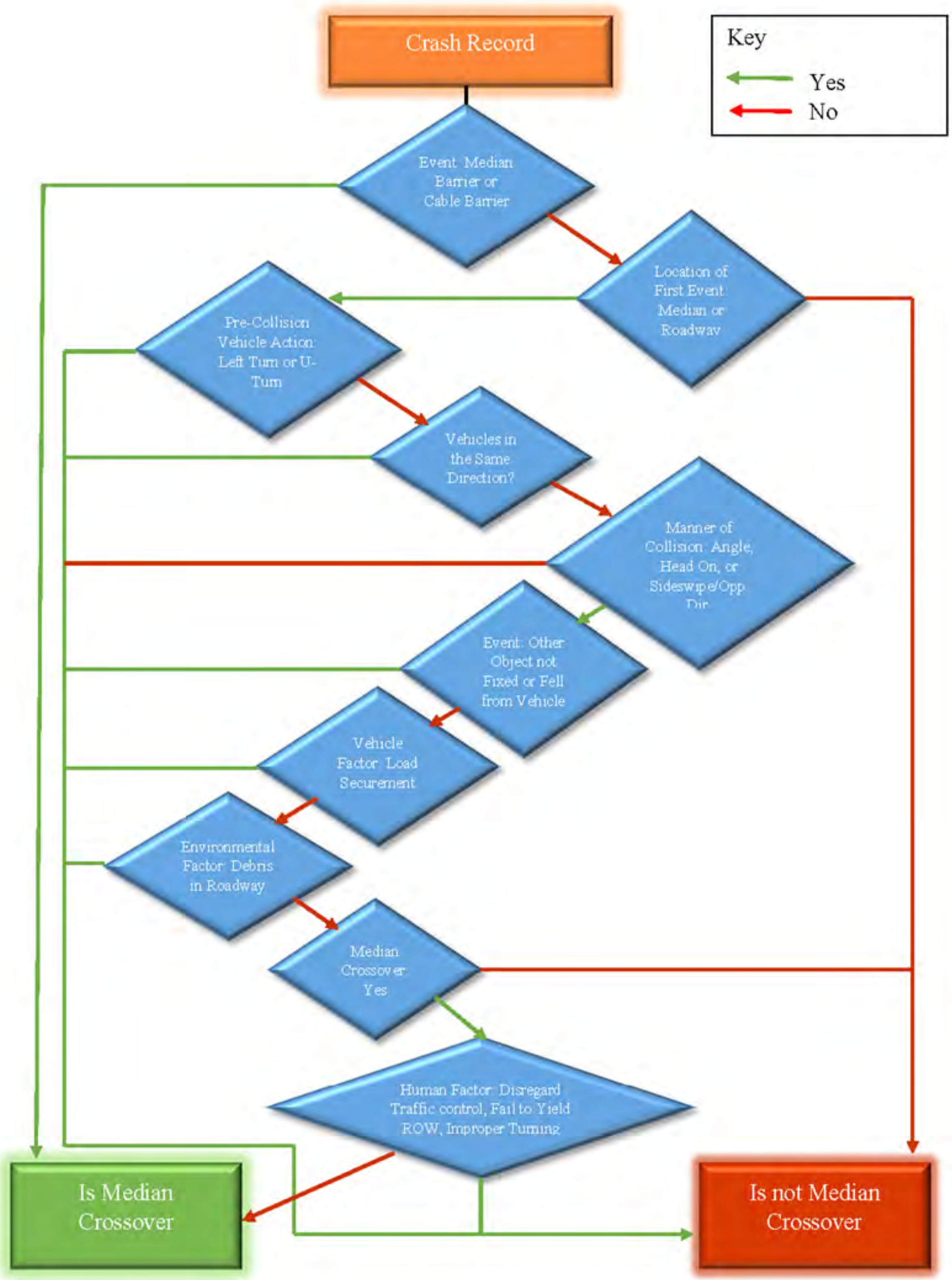


Figure S: Pre-CMB Installation Median Crossover Query Logic[15]

Appendix B – Itemized Costs by District

Year	Cable Tension (LF)	Cable Repair or Replace (LF)	In-Line Post (EA) (F by D)	In-Line Post (EA) (F by V)	End-Line Post (EA) (F by D)	End-Line Post (EA) (F by V)	Post Base (EA)	Lane Closure (EA)	Shoulder Closure (EA)	End Anchor (EA)	Post Hardware (EA)	Other Item (List)
2014	$ 0.50	$ 10.00	$ -	$ 150.00	$ -	$ 150.00	$ -	$ 400.00	$ 25.00	$ -	$ -	a
2015	$ 0.50	$ 10.00	$ -	$ 150.00	$ -	$ 150.00	$ -	$ 400.00	$ 25.00	$ -	$ -	$ -

Table 39: District 1 Itemized Costs

Year	Cable Tension (LF)	Cable Repair or Replace (LF)	In-Line Post (EA) (F by D)	In-Line Post (EA) (F by V)	End-Line Post (EA) (F by D)	End-Line Post (EA) (F by V)	Post Base (EA)	Lane Closure (EA)	Shoulder Closure (EA)	End Anchor (EA)	Post Hardware (EA)	Other Item (List)
2014	$ -	$ 20.00	$ 50.00	$ 150.00	$ 50.00	$ 150.00	$ 75.00	b	$ 25.00	$ -	$ 75.00	$ -
2015	$ -	$ 20.00	$ 50.00	$ 150.00	$ 50.00	$ 150.00	$ 75.00	b	$ 25.00	$ -	$ 75.00	$ -

Table 40: District 2 Itemized Costs

Year	Cable Tension (LF)	Cable Repair or Replace (LF)	In-Line Post (EA) (F by D)	In-Line Post (EA) (F by V)	End-Line Post (EA) (F by D)	End-Line Post (EA) (F by V)	Post Base (EA)	Lane Closure (EA)	Shoulder Closure (EA)	End Anchor (EA)	Post Hardware (EA)	Other Item (List)
2010	$ 0.50	$ 500.00	$ 50.00	$ 150.00	$ 50.00	$ 150.00	$ 75.00	c	$ -	$ -	$ 75.00	$ -
2011	$ 0.50	$ 500.00	$ 50.00	$ 150.00	$ 50.00	$ 150.00	$ 75.00	c	$ -	$ -	$ 75.00	$ -
2012	$ 0.50	$ 500.00	$ 50.00	$ 150.00	$ 50.00	$ 150.00	$ 75.00	c	$ -	$ -	$ 75.00	$ -
2013	$ 0.50	$ 500.00	$ 50.00	$ 150.00	$ 50.00	$ 150.00	$ 75.00	c	$ -	$ -	$ 75.00	$ -
2014	$ 0.50	$ 500.00	$ 50.00	$ 150.00	$ 50.00	$ 150.00	$ 75.00	c	$ -	$ -	$ 75.00	$ -
2015	$ 0.50	$ 500.00	$ 50.00	$ 150.00	$ 50.00	$ 150.00	$ 75.00	c	$ -	$ -	$ 75.00	$ -

Table 41: District 4 Itemized Costs

a - Replace and repair (R&R) turnbuckle @ $1,000 EA
b - Daytime lane closure @ $350 and nighttime lane closure @ $25
c - Daytime lane closure @ $400 and nighttime lane closure @ $25

Appendix B – Itemized Costs by District

Year	Cable Tension (LF)	Cable Repair or Replace (LF)	In-Line Post (EA) (F by D)	In-Line Post (EA) (F by V)	End-Line Post (EA) (F by D)	End-Line Post (EA) (F by V)	Post Base (EA)	Lane Closure (EA)	Shoulder Closure (EA)	End Anchor (EA)	Post Hardware (EA)	Other Item (List)
2010	$ 0.50	$ 400.00	$ 40.00	$ 150.00	$ 50.00	$ 150.00	$ 75.00	$ 400.00	$ 25.00	$ 2,000.00	$ 75.00	$ -
2011	$ 0.50	$ 400.00	$ 40.00	$ 150.00	$ 50.00	$ 150.00	$ 75.00	$ 400.00	$ 25.00	$ 2,000.00	$ 75.00	$ -
2012	$ 0.50	$ 400.00	$ 40.00	$ 150.00	$ 50.00	$ 150.00	$ 75.00	$ 400.00	$ 25.00	$ 2,000.00	$ 75.00	$ -
2013 (a)	$ 0.50	$ 400.00	$ 40.00	$ 150.00	$ 50.00	$ 150.00	$ 75.00	$ 400.00	$ 25.00	$ 2,000.00	$ 75.00	$ -
2013 (b)	$ 0.50	$ 400.00	$ 50.00	$ 150.00	$ 50.00	$ 150.00	$ 75.00	$ 400.00	$ 25.00	$ 1,500.00	$ 75.00	$ -
2014	$ 0.50	$ 400.00	$ 50.00	$ 150.00	$ 50.00	$ 150.00	$ 75.00	$ 400.00	$ 25.00	$ 1,500.00	$ 75.00	$ -
2015	$ 0.50	$ 400.00	$ 50.00	$ 150.00	$ 50.00	$ 150.00	$ 75.00	$ 400.00	$ 25.00	$ 1,500.00	$ 75.00	$ -

Table 42: District 5 Itemized Costs

Year	Cable Tension (LF)	Cable Repair or Replace (LF)	In-Line Post (EA) (F by D)	In-Line Post (EA) (F by V)	End-Line Post (EA) (F by D)	End-Line Post (EA) (F by V)	Post Base (EA)	Lane Closure (EA)	Shoulder Closure (EA)	End Anchor (EA)	Post Hardware (EA)	Other Item (List)
2013 (c)	$ -	$ 500.00	$ -	$ 250.00	$ -	$ 20.00	$ 200.00	e	$ 10.00	$ 1,200.00	$ -	$ -
2013 (d)	$ 0.50	$ 500.00	$ 50.00	$ 250.00	$ 20.00	$ 300.00	$ 200.00	f	$ 10.00	$ 1,000.00	$ 50.00	$ -
2014	$ 0.50	$ 500.00	$ 50.00	$ 250.00	$ 20.00	$ 300.00	$ 200.00	f	$ 10.00	$ 1,000.00	$ 50.00	$ -
2015	$ 0.50	$ 500.00	$ 50.00	$ 250.00	$ 20.00	$ 300.00	$ 200.00	f	$ 10.00	$ 1,000.00	$ 50.00	$ -

Table 43: District 6 Itemized Costs

a - Contract rates from January 1 through April 10 in 2013
b - Contract rates from April 11 through December 31 in 2013
c -Contract rates from January 1 through February 28, 2013
d - Contract rates from March 1 through December 31 in 2013
e - Daytime lane closure @ $500 and nighttime lane closure @ $700
f - Daytime lane closure @ $500 and nighttime lane closure @ $550

Appendix B – Itemized Costs by District

Year	Cable Tension (LF)	Cable Repair or Replace (LF)	In-Line Post (EA) (F by D)	In-Line Post (EA) (F by V)	End-Line Post (EA) (F by D)	End-Line Post (EA) (F by V)	Post Base (EA)	Lane Closure (EA)	Shoulder Closure (EA)	End Anchor (EA)	Post Hardware (EA)	Other Item (List)
2011	$ -	$ 200.00	$ 175.00	$ 200.00	$ 240.00	$ 300.00	$ 100.00	$ 400.00	$ 10.00	$ 1,200.00	$ -	$ -
2012	$ -	$ 200.00	$ 175.00	$ 200.00	$ 240.00	$ 300.00	$ 100.00	$ 400.00	$ 10.00	$ 1,200.00	$ -	$ -
2013 (a)	$ -	$ 200.00	$ 175.00	$ 200.00	$ 240.00	$ 300.00	$ 100.00	$ 400.00	$ 10.00	$ 1,200.00	$ -	$ -
2013 (b)	$ 0.50	$ 500.00	$ 50.00	$ 250.00	$ 20.00	$ 300.00	$ 200.00	$ 400.00	$ 10.00	$ 1,000.00	$ -	$ -
2014	$ 0.50	$ 500.00	$ 50.00	$ 250.00	$ 20.00	$ 300.00	$ 200.00	$ 400.00	$ 10.00	$ 1,000.00	$ -	$ -
2015	$ 0.50	$ 500.00	$ 50.00	$ 250.00	$ 20.00	$ 300.00	$ 200.00	$ 400.00	$ 10.00	$ 1,000.00	$ -	$ -

Table 44: District 7 Itemized Costs

Year	Cable Tension (LF)	Cable Repair or Replace (LF)	In-Line Post (EA) (F by D)	In-Line Post (EA) (F by V)	End-Line Post (EA) (F by D)	End-Line Post (EA) (F by V)	Post Base (EA)	Lane Closure (EA)	Shoulder Closure (EA)	End Anchor (EA)	Post Hardware (EA)	Other Item (List)
2010	$ 0.50	$ -	$ 175.00	$ 240.00	$ -	$ 300.00	$ -	$ 400.00	$ 30.00	$ -	$ -	$ -
2011	$ 0.50	$ -	$ 175.00	$ 240.00	$ -	$ 300.00	$ -	$ 400.00	$ 30.00	$ -	$ -	$ -
2012	$ 0.50	$ -	$ 175.00	$ 240.00	$ -	$ 300.00	$ -	$ 400.00	$ 30.00	$ -	$ -	$ -
2013 (c)	$ 0.50	$ -	$ 175.00	$ 240.00	$ -	$ 300.00	$ -	$ 400.00	$ 30.00	$ -	$ -	$ -
2013 (d)	$ 0.50	$ -	$ 175.00	$ 250.00	$ -	$ 300.00	$ -	$ 600.00	$ 50.00	$ -	$ -	$ -
2014	$ 0.50	$ -	$ 175.00	$ 250.00	$ -	$ 300.00	$ -	$ 600.00	$ 50.00	$ -	$ -	$ -
2015	$ 0.50	$ -	$ 175.00	$ 250.00	$ -	$ 300.00	$ -	$ 600.00	$ 50.00	$ -	$ -	$ -

Table 45: District 8 Itemized Costs

Year	Cable Tension (LF)	Cable Repair or Replace (LF)	In-Line Post (EA) (F by D)	In-Line Post (EA) (F by V)	End-Line Post (EA) (F by D)	End-Line Post (EA) (F by V)	Post Base (EA)	Lane Closure (EA)	Shoulder Closure (EA)	End Anchor (EA)	Post Hardware (EA)	Other Item (List)
2013 (e)	$ -	$ 250.00	$ -	$ 230.00	$ -	$ -	$ -	$ 400.00	$ -	$ -	$ -	$ -
2013 (f)	$ 0.50	$ 400.00	$ 50.00	$ 250.00	$ 50.00	$ 300.00	$ 100.00	$ 400.00	$ 20.00	$ 1,000.00	$ 50.00	$ -
2014	$ 0.50	$ 400.00	$ 50.00	$ 250.00	$ 50.00	$ 300.00	$ 100.00	$ 400.00	$ 20.00	$ 1,000.00	$ 50.00	$ -
2015	$ 0.50	$ 400.00	$ 50.00	$ 250.00	$ 50.00	$ 300.00	$ 100.00	$ 400.00	$ 20.00	$ 1,000.00	$ 50.00	$ -

Table 46: District 11 Itemized Costs

a - Contract rates from January 1 through March 31 in 2013
b - Contract rates from April 1 through December 31 in 2013
c - Contract rates from January 1 through March 31 in 2013
d - Contract rates from April 1 through December 31 in 2013
e - Contract rates from January 1 through March 31 in 2013
f - Contract rates from April 1 through December 31 in 2013

Appendix C – Maintenance Costs by District

District	Calendar Year[a]	Vendor	Total Miles	Total Crashes	Total Costs	Average Repair Costs			
						Per Crash By Year	Per Crash (All Yrs)	Per Mile By Year	Per Mile (All Yrs)
1	2015	Brifen	16.0	47	$68,375	$1,455	$1,455	$4,273	$4,273
2	2015	Brifen	23.4	24	$76,400	$3,183	$3,183	$3,265	$3,265
4	2010	Brifen	17.5	71	$64,625	$910		$3,693	
	2011	Brifen	17.5	125	$69,150	$553		$3,951	
	2012	Brifen	17.5	67	$48,750	$728		$2,786	
	2013	Brifen	23.4	106	$162,850	$1,536		$6,959	
	2014	Brifen	23.4	99	$127,536	$1,288		$5,450	
	2015	Brifen	9.7	60	$98,141	$1,636		$10,118	
	2010-15	Brifen					$1,109		$5,493
	2010	Gibraltar	10.5	22	$11,200	$509		$1,067	
	2011	Gibraltar	10.5	35	$10,350	$296		$986	
	2012	Gibraltar	10.5	24	$14,375	$599		$1,369	
	2010-12	Gibraltar					$468		$1,140
5	2011	Brifen	27.1	147	$157,990	$1,075		$5,830	
	2012	Brifen	34.8	141	$236,100	$1,674		$6,784	
	2013	Brifen	41.8	180	$216,000	$1,200		$5,167	
	2014	Brifen	44.6	208	$292,088	$1,404		$6,549	
	2015	Brifen	44.6	189	$332,156	$1,757		$7,447	
	2011-15	Brifen					$1,422		$6,356
	2011	Gibraltar	15.7	102	$162,250	$1,591		$10,334	
	2012	Gibraltar	15.7	75	$130,125	$1,735		$8,288	
	2013	Gibraltar	15.7	83	$135,425	$1,632		$8,626	
	2014	Gibraltar	15.7	92	$165,516	$1,799		$10,542	
	2015	Gibraltar	15.7	90	$211,907	$2,355		$13,497	
	2011-15	Gibraltar					$1,822		$10,258
	2011	Trinity	12.9	63	$54,300	$862		$4,209	
	2012	Trinity	12.9	43	$50,000	$1,163		$3,876	
	2013	Trinity	12.9	50	$41,900	$838		$3,248	
	2014	Trinity	12.9	56	$64,414	$1,150		$4,993	
	2015	Trinity	12.9	75	$72,838	$971		$5,646	
	2011-15	Trinity					$997		$4,395

Table 47: Maintenance Costs by District (1, 2, 4, 5)

a - Calendar Year does not count the year during which the cable median barrier was either initially constructed (or removed)

Appendix C – Maintenance Costs by District

District	Calendar Year[a]	Vendor	Total Miles	Total Crashes	Total Costs	Average Repair Costs Per Crash By Year	Per Crash (All Yrs)	Per Mile By Year	Per Mile (All Yrs)
6	2013	Brifen	7.8	31	$75,810	$2,445		$9,719	
	2014	Brifen	15.6	64	$102,091	$1,595		$6,544	
	2015	Brifen	15.6	70	$159,219	$2,275		$10,206	
	2013-15	Brifen					$2,105		$8,823
	2013	Gibraltar	12.6	71	$175,091	$2,466		$13,896	
	2014	Gibraltar	12.6	87	$222,419	$2,557		$17,652	
	2015	Gibraltar	12.6	57	$154,974	$2,719		$12,300	
	2013-15	Gibraltar					$2,580		$14,616
7	2012	Brifen	14.5	114	$142,110	$1,247		$9,801	
	2013	Brifen	14.5	99	$134,700	$1,361		$9,290	
	2014	Brifen	14.5	113	$177,520	$1,571		$12,243	
	2015	Brifen	14.5	91	$133,060	$1,462		$9,177	
	2012-15	Brifen					$1,410		$10,127
8	2011	Brifen	9.1	30	$93,840	$3,128		$10,312	
	2012	Brifen	9.1	28	$89,660	$3,202		$9,853	
	2013	Brifen	9.1	18	$71,280	$3,960		$7,833	
	2014	Brifen	13.3	48	$150,650	$3,139		$11,327	
	2015	Brifen	13.3	71	$222,000	$3,127		$16,692	
	2011-15	Brifen					$3,311		$11,203
11	2013	Brifen	19.6	48	$127,030	$2,646		$6,481	
	2014	Brifen	28.9	69	$222,275	$3,221		$7,691	
	2015	Brifen	28.9	60	$274,950	$4,583		$9,514	
	2013-15	Brifen					$3,483		$7,895
	2013	Gibraltar	9.1	19	$45,680	$2,404		$5,020	
	2014	Gibraltar	9.1	24	$53,300	$2,221		$5,857	
	2015	Gibraltar	9.1	25	$96,755	$3,870		$10,632	
	2013-15	Gibraltar					$2,832		$7,170

Table 48: Maintenance Costs by District (6, 7, 8, 11)

a - Calendar Year does not count the year during which the cable median barrier was either initially constructed (or removed)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	I-24	I-24	I-24	I-24	I-24	I-24	
(2) Milepoint	69	66	61	17.3	15	13	
(3) Latitude	36°51'3" N	36°52'24" N	36°55'15" N	36°59'40" N	36°59'37" N	37°0'18" N	
(4) Longitude	87°41'36" W	87°43'11" W	87°47'53" W	88°28'39" W	88°31'37" W	88°33'32" W	
(5) Date	1/27/2017	1/27/2017	1/27/2017	1/27/2017	1/27/2017	1/27/2017	
(6) End or In-Line Posts	In-Line	End	In-Line	End	Middle	Middle	
Post Spacing (feet, inches)							
(1) In-Line Post #1	11' 3"	--	10' 7"	--	10' 3"	10' 5"	
(2) In-Line Post #2	8' 9"	--	11' 5"	--	9' 8"	10' 7"	
(3) Anchor-End Post #1	--	6' 6"	--	5' 9"	--	--	
(4) End Post #1-2	--	6' 4"	--	6' 8"	--	--	
(5) End Post #2-3	--	6' 9"	--	6' 7"	--	--	
(6) End Post #3-4	--	6' 2"	--	6' 7"	--	--	
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	1/8	7/8	3/8	3/4	3/4	1/2	
(2) Concrete Pad (near)	1 1/4	1 1/8	1 1/2	1 1/8	2	2	
Rope Height from Ground (c) (inches)							
(1) Bottom Rope	20.5"	19.5"	20.5"	19"	19.5"	20"	
(2) 2nd Rope	26.5"	25.5"	26"	25"	25"	25"	
(3) 3rd Rope	32.5"	31.5"	32.5"	29"	31.5"	32"	
(4) Top Rope	38"	37.5"	38"	36.5"	37"	37.5"	
Offset Distances (#1 - feet, inches; #2 - feet)							
(1) CMB to Near Travel Lane	8' 9"	9' 2"	8' 11"	10' 8"	11' 0"	10' 9"	
(2) CMB to Slope Break	23'	22'	22'	38'	18'	18'	
Post Vertical Angle (degrees)							
(1) End Post #1	--	75.8°	--	76.1°	--	--	
(2) In-Line Post #1	88.5°	--	88.6°	--	87.1°	87.2°	
(3) In-Line Post #2	89.0°	--	88.1°	--	87.4°	88.3°	
End Post Weakening Cuts							
(1) End Post #1	--	Satisfactory	--	Satisfactory	--	--	
(2) End Post #2	--	Inadequate	--	Satisfactory	--	--	
(3) End Post #3	--	Inadequate	--	Satisfactory	--	--	
(4) End Post #4	--	Satisfactory	--	Satisfactory	--	--	

Table 49: District 1, Survey #1 (Brifen)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	I-24	I-24	I-24	I-24	I-24	I-24	I-24
(2) Milepoint	56	54.8 (X-ing #1)	54.8 (X-ing #2)	93.3	92.5	91	86
(3) Latitude	36°57'57" N	36°58'19" N	36°55'15" N	36°38'32" N	36°38'57" N	36°39'41" N	36°42'5" N
(4) Longitude	87°52'18" W	87°53'17" W	87°47'53" W	87°20'23" W	87°21'9" W	87°22'30" W	87°27'1" W
(5) Date	1/27/2017	1/27/2017	1/27/2017	1/27/2017	1/27/2017	1/27/2017	1/27/2017
(6) End or In-Line Posts	In-Line	End	End	End	End	In-Line	End
Post Spacing (feet, inches)							
(1) In-Line Post #1	10'1"	--	--	--	--	10' 3"	--
(2) In-Line Post #2	11'1"	--	--	--	--	10' 2"	--
(3) Anchor-End Post #1	--	6' 5"	6' 5"	6' 1"	6' 2"	--	6' 3"
(4) End Post #1-2	--	7'0"	6' 4"	7' 2"	7'0"	--	6' 11"
(5) End Post #2-3	--	6' 3"	6' 8"	6' 6"	6' 7"	--	6'10"
(6) End Post #3-4	--	6' 3"	6' 4"	6' 2"	5' 10"	--	6' 6"
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	3/8	1/2	7/8	5/8	1/2	1/2	3/8
(2) Concrete Pad (near)	1 1/2	1 1/8	3/4	1 1/4	2	1 3/8	1 1/8
Rope Height from Ground (c) (inches)							
(1) Bottom Rope	19.5"	21"	18.5"	20.5"	20.5"	19"	20.5"
(2) 2nd Rope	25.5"	26"	25.5"	26.5"	25"	25.5"	25"
(3) 3rd Rope	31.5"	32.5"	28.5"	31.5"	31.5"	31"	31.5"
(4) Top Rope	37.5"	38"	37"	38"	37"	37"	38"
Offset Distances (#1 - feet, inches; #2 - feet)							
(1) CMB to Near Travel Lane	8' 11"	9' 1"	10' 4"	11' 0"	12' 0"	10' 9"	10' 9"
(2) CMB to Slope Break	21'	20'	21'	21'	18'	19'	21'
Post Vertical Angle (degrees)							
(1) End Post #1	--	72.2°	76.0°	78.3°	77.9°	--	73.1°
(2) In-Line Post #1	89.7°	--	--	--	--	88.4°	--
(3) In-Line Post #2	88.9°	--	--	--	--	87.8°	--
End Post Weakening Cuts							
(1) End Post #1	--	Satisfactory	Inadequate	Inadequate	Satisfactory	--	Satisfactory
(2) End Post #2	--	Inadequate	Inadequate	Inadequate	Satisfactory	--	Satisfactory
(3) End Post #3	--	Inadequate	Inadequate	Inadequate	Inadequate	--	Inadequate
(4) End Post #4	--	Inadequate	Inadequate	Absent	Satisfactory	--	Absent

Table 50: District 2, Survey #1 (Brifen)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	I-24	I-24	I-24	I-24			
(2) Milepoint	83	79	75	72			
(3) Latitude	36°43'40" N	36°45'50" N	36°47'46" N	36°49'16" N			
(4) Longitude	87°29'19" W	87°32'41" W	87°36'15" W	87°38'48" W			
(5) Date	1/27/2017	1/27/2017	1/27/2017	1/27/2017			
(6) End or In-Line Posts	End	End	In-Line	In-Line			
Post Spacing (feet, inches)							
(1) In-Line Post #1	--	--	10' 5"	10' 3"			
(2) In-Line Post #2	--	--	10' 3"	10' 5"			
(3) Anchor-End Post #1	6' 7"	6' 8"	--	--			
(4) End Post #1-2	6' 3"	6' 11"	--	--			
(5) End Post #2-3	6' 11"	6' 3"	--	--			
(6) End Post #3-4	6' 3"	6' 11"	--	--			
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	7/8	1/8	1/2	1/2			
(2) Concrete Pad (near)	5/8	1 1/4	1 3/4	1 1/8			
Rope Height from Ground (c) (inches)							
(1) Bottom Rope	19.5"	19"	19.5"	19"			
(2) 2nd Rope	26"	25"	25.5"	25"			
(3) 3rd Rope	32"	31"	31.5"	32"			
(4) Top Rope	37.5"	37"	37.5"	37"			
Offset Distances (#1 - feet, inches; #2 - feet)							
(1) CMB to Near Travel Lane	10' 10"	11' 5"	11' 0"	10' 11"			
(2) CMB to Slope Break	19'	13'	19'	19'			
Post Vertical Angle (degrees)							
(1) End Post #1	73.5°	82.4°	--	--			
(2) In-Line Post #1	--	--	89.9°	88.2°			
(3) In-Line Post #2	--	--	89.3°	89.1°			
End Post Weakening Cuts							
(1) End Post #1	Satisfactory	Satisfactory	--	--			
(2) End Post #2	Inadequate	Inadequate	--	--			
(3) End Post #3	Inadequate	Satisfactory	--	--			
(4) End Post #4	Absent	Satisfactory	--	--			

Table 51: District 2, Survey #2 (Brifen)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	I-65	I-65	I-65	I-65			
(2) Milepoint	102	95	98	100			
(3) Latitude	37°47'47" N	37°43'51" N	37°45'6" N	37°47'2" N			
(4) Longitude	85°45'12" W	85°49'0" W	85°47'46" W	85°46'22" W			
(5) Date	12/19/2016	12/19/2016	12/19/2016	12/19/2016			
(6) End or In-Line Posts	In-Line	End	End	End			
Post Spacing (feet, inches)							
(1) In-Line Post #1	10' 10"	--	--	--			
(2) In-Line Post #2	10' 3"	--	--	--			
(3) Anchor-End Post #1	--	5' 8"	5' 9"	6' 1"			
(4) End Post #1-2	--	7'1"	6' 11"	6' 3"			
(5) End Post #2-3	--	6' 5"	6' 3"	6' 7"			
(6) End Post #3-4	--	6' 3"	6' 5"	6' 8"			
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	3/8	1/4	1/2	1/8			
(2) Concrete Pad (near)	1 1/2	1 1/8	2	0			
Rope Height from Ground (c) (inches)							
(1) Bottom Rope	18.5"	21"	21"	18.5"			
(2) 2nd Rope	25.5"	26"	27"	26.5"			
(3) 3rd Rope	31.5"	31.5"	33"	32.5"			
(4) Top Rope	37.5"	38"	39"	38.5"			
Offset Distances (#1 - feet, inches; #2 - feet)							
(1) CMB to Near Travel Lane	11' 10"	12' 1"	12' 0"	13' 6"			
(2) CMB to Slope Break	20'	17'	20'	26'			
Post Vertical Angle (degrees)							
(1) End Post #1	--	73.4°	72.3°	76.9°			
(2) In-Line Post #1	88.2°	--	--	--			
(3) In-Line Post #2	89.7°	--	--	--			
End Post Weakening Cuts							
(1) End Post #1	--	Satisfactory	Satisfactory	Satisfactory			
(2) End Post #2	--	Satisfactory	Inadequate	Satisfactory			
(3) End Post #3	--	Satisfactory	Satisfactory	Satisfactory			
(4) End Post #4	--	Absent	Absent	Absent			

Table 52: District 4, Survey #1 (Brifen)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	I-65	I-65	I-71	I-71	I-71	I-71	I-71
(2) Milepoint	109	108	11 (X-ing #1)	11 (X-ing #2)	9	7	6
(3) Latitude	37°53'52" N	37°52'54" N	38°19'38" N	38°19'38" N	38°18'28" N	38°18'3" N	38°17'41" N
(4) Longitude	85°41'58" W	85°42'5" W	85°32'52" W	85°32'52" W	85°35'47" W	85°36'50" W	85°37'50" W
(5) Date	12/7/2016	12/7/2016	1/25/2017	1/25/2017	1/25/2017	1/25/2017	1/25/2017
(6) End or In-Line Posts	End	In-Line	End	End	In-Line	In-Line	In-Line
Post Spacing (feet, inches)							
(1) In-Line Post #1	--	10' 7"	--	--	10' 5"	11' 3"	10' 11"
(2) In-Line Post #2	--	10' 2"	--	--	10' 4"	10' 4"	10'6"
(3) Anchor-End Post #1	6' 11"	--	6' 1"	6'0"	--	--	--
(4) End Post #1-2	6' 10"	--	6' 7"	6' 6"	--	--	--
(5) End Post #2-3	5' 10"	--	6' 6"	NA - Damaged	--	--	--
(6) End Post #3-4	6' 10"	--	7'0"	NA - Damaged	--	--	--
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	3/4	5/8	5/8	1/2	5/8	1 1/8	3/4
(2) Concrete Pad (near)	1 3/8	1	1 3/8	2	3 1/8	3 5/8	1 3/4
Rope Height from Ground (c) (inches)							
(1) Bottom Rope	19.5"	19.5"	20"	20"	18"	19"	20"
(2) 2nd Rope	25.5"	25.5"	22.5"	26.5"	24"	23.5"	25.5"
(3) 3rd Rope	30.0"	31.5"	26.5"	27.5"	30.5"	31.5"	32"
(4) Top Rope	37.5"	37.5"	29"	29"	36"	37"	38"
Offset Distances (#1 - feet, inches; #2 - feet)							
(1) CMB to Near Travel Lane	12' 8"	11' 9"	10' 9"	11' 3"	9' 2"	8' 8"	7' 8"
(2) CMB to Slope Break	18'	18'	16'	20'	20'	20'	24'
Post Vertical Angle (degrees)							
(1) End Post #1	80.2°	--	81.3°	85.4°	--	--	--
(2) In-Line Post #1	--	89.6°	--	--	89.7°	85.1°	89.3°
(3) In-Line Post #2	--	89.5°	--	--	89.8°	86.4°	89.5°
End Post Weakening Cuts							
(1) End Post #1	Satisfactory	--	Absent	Absent	--	--	--
(2) End Post #2	Inadequate	--	Absent	Absent	--	--	--
(3) End Post #3	Inadequate	--	Absent	Absent	--	--	--
(4) End Post #4	Inadequate	--	Absent	Absent	--	--	--

Table 53: District 5, Survey #1 (Brifen)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	KY 841	KY 841	KY 841	KY 841	KY 841	KY 841	KY 841
(2) Milepoint	10	9	8	7	5	3	2
(3) Latitude	38°6'56" N	38°6'49" N	38°7'1" N	38°7'4" N	38°6'51" N	38°5'56" N	38°5'25" N
(4) Longitude	85°42'21" W	85°43'13" W	85°43'58" W	85°45'45" W	85°47'40" W	85°49'32" W	85°50'25" W
(5) Date	12/7/2016	12/7/2016	12/7/2016	12/7/2016	1/25/2017	1/25/2017	1/25/2017
(6) End or In-Line Posts	End	In-Line	End	In-Line	In-Line	End	In-Line
Post Spacing (feet, inches)							
(1) In-Line Post #1	--	10' 7"	--	10' 5"	10' 4"	--	10' 4"
(2) In-Line Post #2	--	10'1"	--	10' 8"	11'0"	--	10' 6"
(3) Anchor-End Post #1	6' 10"	--	6'1"	--	--	5' 8"	--
(4) End Post #1-2	6' 4"	--	5' 3"	--	--	6' 11"	--
(5) End Post #2-3	7' 9"	--	7' 3"	--	--	7' 6"	--
(6) End Post #3-4	7' 11"	--	7' 2"	--	--	7' 5"	--
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	7/8	1	1/2	1/2	3/4	3/8	3/8
(2) Concrete Pad (near)	1 1/4	3/4	1 3/8	1 1/4	1 1/2	1 5/8	1 5/8
Rope Height from Ground (b) (inches)							
(1) Bottom Rope	20"	20.5"	20.5"	20"	20.5"	20"	20"
(2) 2nd Rope	25.5"	26"	25.5"	25"	25.5"	25"	25"
(3) 3rd Rope	30.5"	31"	30"	30"	30.5"	30"	30"
(4) Top Rope	39.5"	40"	39"	39"	39"	39"	39"
Offset Distances (#1 - feet, inches; #2 - feet)							
(1) CMB to Near Travel Lane	10' 7"	10' 7"	10' 1"	10' 3"	10'	10'	10'
(2) CMB to Slope Break	31'	33'	18'	20'	21'	NA	21'
Post Vertical Angle (d) (degrees)							
(1) End Post #1	75.3°	--	81.1°	--	--	71.4o	--
(2) In-Line Post #1	--	87.9°	--	88.6°	89.1°	--	88.7°
(3) In-Line Post #2	--	89.0°	--	89.1°	89.9°	--	89.7°
End Post Holes							
(1) End Post #1	Yes	--	Yes	--	--	Yes	--
(2) End Post #2	Yes	--	Yes	--	--	Yes	--

Table 54: District 5, Survey #2 (Gibraltar)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	KY 841	KY 841	I-65	I-65	I-65	I-65	
(2) Milepoint	1	0	111	110	113	112	
(3) Latitude	38°5'18" N	38°5'34" N	37°54'50" N	37°54'24" N	37°56'49" N	37°55'52"	
(4) Longitude	85°51'26" W	85°52'26" W	85°41'16" W	85°41'30" W	85°41'24" W	85°41'18"	
(5) Date	1/25/2017	1/25/2017	12/7/2016	12/7/2016	12/7/2016	12/7/2016	
(6) End or In-Line Posts	In-Line	End	In-Line	End	In-Line	End	
Post Spacing (feet, inches)							
(1) In-Line Post #1	10' 5"	--	10' 7"	--	10' 5"	--	
(2) In-Line Post #2	10' 9"	--	10' 4"	--	10' 5"	--	
(3) Anchor-End Post #1	--	5' 8"	--	5' 3"	--	5' 10"	
(4) End Post #1-2	--	5' 11"	--	6' 6"	--	6' 1"	
(5) End Post #2-3	--	8' 0"	--	7' 1"	--	7' 6"	
(6) End Post #3-4	--	7' 1"	--	7' 11"	--	7' 7"	
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	3/4	5/8	5/8	3/8	1/2	3/8	
(2) Concrete Pad (near)	1 1/4	1 3/8	5/8	3/8	1/2	3/8	
Rope Height from Ground (b) (inches)							
(1) Bottom Rope	19.5"	20.5"	20.5"	20"	20.5"	21"	
(2) 2nd Rope	24.5"	25.5"	25.5"	25"	25.5"	26"	
(3) 3rd Rope	29.5"	30.5"	30.5"	30"	30.5"	31"	
(4) Top Rope	38.5"	39.5"	39.5"	39"	39.5"	40"	
Offset Distances (feet)							
(1) CMB to Near Travel Lane	10'	10'	10'	10'	10'	10'	
(2) CMB to Slope Break	32'	NA	22'	21'	21'	20'	
Post Vertical Angle (d) (degrees)							
(1) End Post #1	--	75.0°	--	84.2°	--	79.7°	
(2) In-Line Post #1	87.9°	--	88.6°	--	87.4°	--	
(3) In-Line Post #2	89.0°	--	86.8°	--	88.8°	--	
End Post Holes							
(1) End Post #1	--	Yes	--	Yes	--	Yes	
(2) End Post #2	--	Yes	--	Yes	--	Yes	

Table 55: District 5, Survey #3 (Gibraltar)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	I-265	I-265	I-265	I-265	I-265	I-265	I-265
(2) Milepoint	23	22	21	20	19	18	17
(3) Latitude	38°11'14" N	38°10'27" N	38°9'36" N	38°9'6" N	38°8'42" N	38°8'30" N	38°8'29" N
(4) Longitude	85°30'33" W	85°30'58" W	85°31'35" W	85°32'14" W	85°33'12" W	85°34'16" W	85°35'5" W
(5) Date	1/25/2017	1/25/2017	1/25/2017	1/25/2017	1/25/2017	1/25/2017	1/25/2017
(6) End or In-Line Posts	End	In-Line	In-Line	End	In-Line	In-Line	End
Post Spacing (feet, inches)							
(1) In-Line Post #1	--	19' 10"	19' 10"	--	20' 9"	20' 1"	--
(2) In-Line Post #2	--	20' 1"	19' 8"	--	19' 9"	20' 5"	--
(3) End Post #1-2	5' 9"	--	--	5' 9"	--	--	5' 11"
(4) End Post #2-3	5' 10"	--	--	6' 5"	--	--	6' 6"
(5) End Post #3-4	6' 3"	--	--	5' 6"	--	--	5' 6"
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	1 1/4	1	1 1/8	1 1/8	1 5/8	2 5/8	2 5/8
(2) Concrete Pad (near)	1 3/8	2 1/4	1	1 3/8	1 1/2	1/2	1/2
Rope Height from Ground (b) (inches)							
(1) Bottom Rope @ >= #9 (In-Line)	--	21"	21.5"	--	22.5"	21"	--
(2) Middle Rope @ >= #9 (In-Line)	--	29.5"	30"	--	31"	29.5"	--
(3) Top Rope @ >= #9 (In-Line)	--	37.5"	38"	--	38.5"	38"	--
(4) Bottom Rope @ #4 (End)	22"	--	--	23"	--	--	13.5"
(5) Middle Rope @ #4 (End)	22"	--	--	23"	--	--	16"
(6) Top Rope @ #4 (End)	30.5"	--	--	31.5"	--	--	25.5"
Offset Distances (feet)							
(1) CMB to Near Travel Lane	17'	18'	18'	17'	18'	18'	18'
(2) CMB to Slope Break	16'	11'	14'	14'	13'	13'	18'
Angle to Surface (c) (degrees)							
(1) Top Cable	5.2°	--	--	8.2°	--	--	3.9°
(2) Middle Rope	5.5°	--	--	8.0°	--	--	3.0°
(3) Bottom Rope	9.8°	--	--	13.7°	--	--	4.7°
In-Line Post Vertical Angle (degrees)							
(1) In-Line Post #1	--	89.3°	88.8°	--	88.5°	87.7°	--
(2) In-Line Post #2	--	87.6°	89.4°	--	89.5°	87.4°	--
Offset of End Posts							
(1) End Posts placed near traffic	Yes	--	--	Yes	--	--	Yes
(2) End Post placed opposite traffic	Yes	--	--	Yes	--	--	Yes

Table 56: District 5, Survey #4 (Trinity)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	I-265	I-265	I-265	I-265	I-265	I-265	I-265
(2) Milepoint	16	15	14	13	13	11	11
(3) Latitude	38°7'42" N	38°7'27" N	38°7'10" N	38°6'59" N	38°6'57" N	38°6'47" N	38°6'48" N
(4) Longitude	85°36'21" W	85°36'58" W	85°38'9" W	85°39'20" W	85°39'29" W	85°41'37" W	85°41'43" W
(5) Date	1/25/2017	1/25/2017	1/25/2017	1/25/2017	1/25/2017	1/25/2017	1/25/2017
(6) End or In-Line Posts	In-Line	End	In-Line	End	End	End	In-Line
Post Spacing (feet, inches)							
(1) In-Line Post #1	20' 2"	--	20' 11"	--	--	--	20' 4"
(2) In-Line Post #2	20' 8"	--	20' 1"	--	--	--	20' 6"
(3) End Post #1-2	--	6' 1"	--	5' 4"	6' 2"	5' 6"	--
(4) End Post #2-3	--	5' 6"	--	6' 1"	5' 5"	6' 2"	--
(5) End Post #3-4	--	6' 8"	--	6' 8"	6' 1"	5' 7"	--
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	2 1/2	2 1/4	1 5/8	1 3/8	1 3/8	1	2
(2) Concrete Pad (near)	1/2	7/8	1 1/8	1 7/8	3/4	3/4	1 5/8
Rope Height from Ground (b) (inches)							
(1) Bottom Rope @ >= #9 (In-Line)	22"	--	21.5"	--	--	--	21"
(2) Middle Rope @ >= #9 (In-Line)	30"	--	30"	--	--	--	29"
(3) Top Rope @ >= #9 (In-Line)	38.5"	--	38"	--	--	--	37.5"
(4) Bottom Rope @ #4 (End)	--	23"	--	21"	13"	12"	--
(5) Middle Rope @ #4 (End)	--	23"	--	21"	20"	13"	--
(6) Top Rope @ #4 (End)	--	32"	--	30"	29"	21"	--
Offset Distances (feet)							
(1) CMB to Near Travel Lane	18'	18'	18'	18'	18'	18'	18'
(2) CMB to Slope Break	15'	19'	14'	24'	29'	NA	24'
Angle to Surface (c) (degrees)							
(1) Top Cable	--	5.5°	--	7.0°	4.7°	2.5°	--
(2) Middle Rope	--	6.3°	--	7.5°	4.2°	1.0°	--
(3) Bottom Rope	--	11.0°	--	11.8°	4.2°	3.8°	--
In-Line Post Vertical Angle (degrees)							
(1) In-Line Post #1	81.4°	--	88.7°	--	--	--	88.5°
(2) In-Line Post #2	88.8°	--	89.7°	--	--	--	87.5°
Offset of End Posts							
(1) End Posts placed near traffic	--	Yes	--	Yes	Yes	Yes	--
(2) End Post placed opposite traffic	--	Yes	--	Yes	Yes	Yes	--

Table 57: District 5, Survey #5 (Trinity)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	I-275	I-275	I-275	I-275			
(2) Milepoint	76	77	78	79			
(3) Latitude	39°1'40" N	39°1'23" N	39°1'21" N	39°1'33" N			
(4) Longitude	84°28'24" W	84°28'58" W	84°30'4" W	84°31'37" W			
(5) Date	1/19/2017	1/19/2017	1/19/2017	1/19/2017			
(6) End or In-Line Posts	In-Line	End	In-Line	End			
Post Spacing (feet, inches)							
(1) In-Line Post #1	10' 5"	--	10'1"	--			
(2) In-Line Post #2	10' 7"	--	10' 7"	--			
(3) Anchor-End Post #1	--	6' 3"	--	6' 6"			
(4) End Post #1-2	--	7'0"	--	6' 8"			
(5) End Post #2-3	--	6' 2"	--	6' 4"			
(6) End Post #3-4	--	6' 5"	--	6' 5"			
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	1/2	3/4	1/2	3/8			
(2) Concrete Pad (near)	1 7/8	7/8	3/4	5/8			
Rope Height from Ground (c) (inches)							
(1) Bottom Rope	19.5"	19.5"	19"	19"			
(2) 2nd Rope	25"	26"	27"	24.5"			
(3) 3rd Rope	32"	32"	33"	30.5"			
(4) Top Rope	37.5"	37.5"	37"	36.5"			
Offset Distances (#1 - feet, inches; #2 - feet)							
(1) CMB to Near Travel Lane	12'	12' 2"	11' 10"	12'			
(2) CMB to Slope Break	20'	NA	18'	NA			
Post Vertical Angle (degrees)							
(1) End Post #1	--	72.4°	--	74.4°			
(2) In-Line Post #1	85.8°	--	89.2°	--			
(3) In-Line Post #2	84.0°	--	88.2°	--			
End Post Weakening Cuts							
(1) End Post #1	--	Satisfactory	--	Absent			
(2) End Post #2	--	Inadequate	--	Satisfactory			
(3) End Post #3	--	Satisfactory	--	Satisfactory			
(4) End Post #4	--	Satisfactory	--	Inadequate			

Table 58: District 6, Survey #1 (Brifen)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	I-275	I-275	I-275	I-275	I-275	I-275	I-275
(2) Milepoint	1 (X-ing #1)	1 (X-ing #2)	4	5	6	7	8 (X-ing #1)
(3) Latitude	39°2'57" N	39°2'55" N	39°4'13" N	39°4'27" N	39°4'42" N	39°4'49" N	39°5'6" N
(4) Longitude	84°37'12" W	84°37'9" W	84°39'15" W	84°40'27" W	84°41'30" W	84°43'16" W	84°44'37" W
(5) Date	1/19/2017	1/19/2017	1/19/2017	1/19/2017	1/19/2017	1/19/2017	1/19/2017
(6) End or In-Line Posts	End	End	In-Line	In-Line	End	In-Line	End
Post Spacing (feet, inches)							
(1) In-Line Post #1	--	--	10' 0"	9' 11"	--	10' 2"	--
(2) In-Line Post #2	--	--	9' 1"	10' 1"	--	10' 9"	--
(3) Anchor-End Post #1	6' 3"	6' 1"	--	--	6' 1"	--	6' 0"
(4) End Post #1-2	6' 2"	6' 6"	--	--	6' 3"	--	6' 3"
(5) End Post #2-3	7' 2"	7' 2"	--	--	7' 5"	--	7' 2"
(6) End Post #3-4	7' 8"	8' 0"	--	--	7' 6"	--	7' 5"
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	1/2	DNR	5/8	5/8	5/8	5/8	5/8
(2) Concrete Pad (near)	3/4	DNR	1	1	5/8	7/8	1 1/8
Rope Height from Ground (b) (inches)							
(1) Bottom Rope	20.5"	DNR	21"	20.5"	21"	20"	21"
(2) 2nd Rope	25.5"	DNR	25.5"	25.5"	26"	25"	26"
(3) 3rd Rope	30.5"	DNR	30.5"	30.5"	31"	30"	31"
(4) Top Rope	39.5"	DNR	39.5"	39.5"	40"	39"	40"
Offset Distances (#1 - feet, inches; #2 - feet)							
(1) CMB to Near Travel Lane	11' 8"	DNR	11' 7"	12'	12'	12' 3"	8' 3"
(2) CMB to Slope Break	19'	DNR	19'	19'	19'	17'	23'
Post Vertical Angle (d) (degrees)							
(1) End Post #1	76.9°	80.5°	--	--	81.0°	--	63.3°
(2) In-Line Post #1	--	--	88.6°	89.9°	--	87.7°	--
(3) In-Line Post #2	--	--	88.9°	90.0°	--	87.5°	--
End Post Holes							
(1) End Post #1	Yes	Yes	--	--	Yes	--	Yes
(2) End Post #2	Yes	Yes	--	--	Yes	--	Yes

Table 59: District 6, Survey #2 (Gibraltar)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	I-275	I-275	I-275	I-275	I-275	I-275	I-275
(2) Milepoint	8 (X-ing #2)	9	10	11	11	12	13
(3) Latitude	39°5'6" N	39°5'9" N	39°5'19" N	39°5'14" N	39°5'20" N	39°5'29" N	39°5'48" N
(4) Longitude	84°44'38" W	84°44'59" W	84°46'22" W	84°47'18" W	84°47'48" W	84°48'20" W	84°49'11" W
(5) Date	1/19/2017	1/19/2017	1/19/2017	1/19/2017	1/19/2017	1/19/2017	1/19/2017
(6) End or In-Line Posts	End	In-Line	In-Line	End	In-Line	In-Line	End
Post Spacing (feet, inches)							
(1) In-Line Post #1	--	10' 9"	10' 2"	--	10' 6"	10' 4"	--
(2) In-Line Post #2	--	9' 7"	7' 7"	--	10' 4"	10' 10"	--
(3) Anchor-End Post #1	5' 11"	--	--	6' 0"	--	--	5' 10"
(4) End Post #1-2	6' 7"	--	--	5' 11"	--	--	6' 3"
(5) End Post #2-3	7' 3"	--	--	6' 11"	--	--	7' 7"
(6) End Post #3-4	7' 7"	--	--	7' 0"	--	--	7' 7"
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	DNR	3/4	5/8	1/2	5/8	5/8	1/2
(2) Concrete Pad (near)	DNR	1 1/8	1 3/8	7/8	1	1 3/8	1
Rope Height from Ground (b) (inches)							
(1) Bottom Rope	DNR	21.5"	20.5"	20.5"	20.5"	21"	21.5"
(2) 2nd Rope	DNR	26.5"	25.5"	25.5"	25.5"	26"	26.5"
(3) 3rd Rope	DNR	31.5"	30.5"	30.5"	30.5"	31"	31"
(4) Top Rope	DNR	40.5"	39.5"	39.5"	39.5"	39.5"	40"
Offset Distances (#1 - feet, inches; #2 - feet)							
(1) CMB to Near Travel Lane	DNR	8' 7"	8' 0"	8' 1"	8' 1"	7' 10"	8' 1"
(2) CMB to Slope Break	DNR	22'	23'	12'	24'	24'	11'
Post Vertical Angle (d) (degrees)							
(1) End Post #1	58.4°	--	--	82.0°	--	--	61.0°
(2) In-Line Post #1	--	87.6°	87.8°	--	88.4°	88.2°	--
(3) In-Line Post #2	--	88.0°	87.1°	--	87.5°	87.7°	--
End Post Holes							
(1) End Post #1	Yes	--	--	Yes	--	--	Yes
(2) End Post #2	Yes	--	--	Yes	--	--	Yes

Table 60: District 6, Survey #3 (Gibraltar)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	KY 4	KY 4	KY 4	KY 4	KY 4	KY 4	
(2) Milepoint	1	1	17	17	18	18	
(3) Latitude	38°0'13" N	38°0'7" N	37°59'31" N	37°59'32" N	37°59'36" N	37°59'35" N	
(4) Longitude	84°32'35" W	84°32'20" W	84°28'51" W	84°28'42" W	84°30'45" W	84°30'43" W	
(5) Date	12/1/2016	12/1/2016	12/1/2016	12/1/2016	12/1/2016	12/1/2016	
(6) End or In-Line Posts	End	In-Line	End	In-Line	End	In-Line	
Post Spacing (feet, inches)							
(1) In-Line Post #1	--	10' 8"	--	10' 4"	--	10' 5"	
(2) In-Line Post #2	--	10'1"	--	10' 4"	--	10' 6"	
(3) Anchor-End Post #1	7'0"	--	8' 1"	--	7' 7"	--	
(4) End Post #1-2	7'6"	--	6' 3"	--	7'0"	--	
(5) End Post #2-3	6' 3"	--	7' 3"	--	7' 2"	--	
(6) End Post #3-4	6' 6"	--	6'1"	--	5' 11"	--	
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	1 1/2	2 1/2	1 1/2	2 1/4	1 5/8	1 3/4	
(2) Concrete Pad (near)	1 3/4	2 1/8	1 3/8	1 5/8	7/8	1 1/2	
Rope Height from Ground (c) (inches)							
(1) Bottom Rope	19.5"	19.5"	20"	18.5"	18.5"	20"	
(2) 2nd Rope	25"	25"	26"	25"	25.5"	25"	
(3) 3rd Rope	31.5"	31"	32"	31"	26.5"	32"	
(4) Top Rope	37"	37.5"	37.5"	37"	36"	37"	
Offset Distances (#1 - feet, inches; #2 - feet)							
(1) CMB to Near Travel Lane	7' 11"	7' 10"	8' 7"	7' 11"	8' 3"	7' 11"	
(2) CMB to Slope Break	17'	11'	11'	11'	11'	10'	
Post Vertical Angle (degrees)							
(1) End Post #1	76.6°	--	74.6°	--	70.0°	--	
(2) In-Line Post #1	--	88.5°	--	89.3°	--	87.8°	
(3) In-Line Post #2	--	89.9°	--	88.3°	--	88.9°	
End Post Weakening Cuts							
(1) End Post #1	Satisfactory	--	Inadequate	--	Inadequate	--	
(2) End Post #2	Inadequate	--	Absent	--	Satisfactory	--	
(3) End Post #3	Inadequate	--	Inadequate	--	Inadequate	--	
(4) End Post #4	Satisfactory	--	Inadequate	--	Absent	--	

Table 61: District 7, Survey #1 (Brifen)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	I-75	I-75	I-75	I-75	I-75		
(2) Milepoint	56	57	58	60	61		
(3) Latitude	37°18'10" N	37°19'2" N	37°19'51" N	37°21'10" N	37°22'22" N		
(4) Longitude	84°16'57" W	84°17'36" W	84°18'15" W	84°18'29" W	84°19'19" W		
(5) Date	12/14/2016	12/14/2016	12/14/2016	12/14/2016	12/14/2016		
(6) End or In-Line Posts	In-Line	In-Line	End	End	In-Line		
Post Spacing (feet, inches)							
(1) In-Line Post #1	10' 9"	10' 2"	--	--	10' 11"		
(2) In-Line Post #2	10' 10"	10' 6"	--	--	10' 5"		
(3) Anchor-End Post #1	--	--	5' 10"	5' 8"	--		
(4) End Post #1-2	--	--	6' 7"	6' 9"	--		
(5) End Post #2-3	--	--	6' 8"	6'10"	--		
(6) End Post #3-4	--	--	6' 7"	6' 6"	--		
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	1 7/8	2 1/2	3 1/8	2 1/4	2 1/2		
(2) Concrete Pad (near)	1 3/8	2	1 5/8	1 3/4	1 7/8		
Rope Height from Ground (c) (inches)							
(1) Bottom Rope	19"	20"	17"	21"	20"		
(2) 2nd Rope	25"	25"	25"	27"	26"		
(3) 3rd Rope	31.5"	32"	32.5"	32.5"	32"		
(4) Top Rope	37"	37"	36.5"	38.5"	38"		
Offset Distances (#1 - feet, inches; #2 - feet)							
(1) CMB to Near Travel Lane	8' 8"	8' 7"	10'	11'	7' 9"		
(2) CMB to Slope Break	20'	20'	19'	20'	20'		
Post Vertical Angle (degrees)							
(1) End Post #1	--	--	77.3°	77.0°	--		
(2) In-Line Post #1	88.5°	88.9°	--	--	89.0°		
(3) In-Line Post #2	86.7°	88.4°	--	--	87.4°		
End Post Weakening Cuts							
(1) End Post #1	--	--	Satisfactory	Absent	--		
(2) End Post #2	--	--	Satisfactory	Inadequate	--		
(3) End Post #3	--	--	Satisfactory	Inadequate	--		
(4) End Post #4	--	--	Satisfactory	Inadequate	--		

Table 62: District 8, Survey #1 (Brifen)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	I-75	I-75	I-75	I-75			
(2) Milepoint	25	26	27	28			
(3) Latitude	36°55'9" N	36°55'35" N	36°56'57" N	36°57'36" N			
(4) Longitude	84°7'46" W	84°7'39" W	84°7'18" W	84°7'3" W			
(5) Date	1/18/2017	1/18/2017	1/18/2017	1/18/2017			
(6) End or In-Line Posts	End	In-Line	In-Line	End			
Post Spacing (feet, inches)							
(1) In-Line Post #1	--	10' 5"	9' 9"	--			
(2) In-Line Post #2	--	10' 10"	10' 5"	--			
(3) Anchor-End Post #1	5' 9"	--	--	6'1"			
(4) End Post #1-2	6' 5"	--	--	6' 6"			
(5) End Post #2-3	7' 3"	--	--	6' 8"			
(6) End Post #3-4	6' 2"	--	--	6' 2"			
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	3/4	3/8	5/8	7/8			
(2) Concrete Pad (near)	1/4	2 7/8	1 7/8	5/8			
Rope Height from Ground (c) (inches)							
(1) Bottom Rope	20"	20"	20"	21"			
(2) 2nd Rope	26"	26"	25.5"	25.5"			
(3) 3rd Rope	32"	32.5"	32.5"	31.5"			
(4) Top Rope	38"	38.5"	38"	37.5"			
Offset Distances (#1 - feet, inches; #2 - feet)							
(1) CMB to Near Travel Lane	12' 6"	11' 9"	11' 11"	38'			
(2) CMB to Slope Break	30'	19'	19'	18'			
Post Vertical Angle (degrees)							
(1) End Post #1	70.9°	--	--	74.8°			
(2) In-Line Post #1	--	87.3°	88.8°	--			
(3) In-Line Post #2	--	89.3°	88.6°	--			
End Post Weakening Cuts							
(1) End Post #1	Inadequate	--	--	Satisfactory			
(2) End Post #2	Satisfactory	--	--	Satisfactory			
(3) End Post #3	Inadequate	--	--	Inadequate			
(4) End Post #4	Inadequate	--	--	Satisfactory			

Table 63: District 11, Survey #1 (Brifen)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	I-75	I-75	I-75	I-75	I-75	I-75	I-75
(2) Milepoint	29	30 (X-ing #1)	30 (X-ing #2)	30	31	31	32
(3) Latitude	36°58'33" N	36°59'25" N	36°59'24" N	36°59'2" N	37°0'14" N	36°59'41" N	37°1'5" N
(4) Longitude	84°6'41" W	84°6'31" W	84°6'31" W	84°6'37" W	84°6'19" W	84°6'28" W	84°6'1" W
(5) Date	1/18/2017	1/18/2017	1/18/2017	1/18/2017	1/18/2017	1/18/2017	1/18/2017
(6) End or In-Line Posts	End	End	End	In-Line	End	In-Line	In-Line
Post Spacing (feet, inches)							
(1) In-Line Post #1	--	--	--	10' 6"	--	10' 3"	10' 6"
(2) In-Line Post #2	--	--	--	10' 7"	--	10' 11"	10' 5"
(3) Anchor-End Post #1	6' 6"	5' 11"	6' 3"	--	6' 5"	--	--
(4) End Post #1-2	6' 2"	6' 5"	6' 2"	--	6' 4"	--	--
(5) End Post #2-3	7' 11"	7' 9"	7' 7"	--	6' 6"	--	--
(6) End Post #3-4	7' 0"	7' 5"	7' 3"	--	7' 8"	--	--
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	1/4	1/2	DNR	3/8	1/4	1/2	1/8
(2) Concrete Pad (near)	3/4	1 7/8	DNR	2 1/8	1/4	2 1/8	2 5/8
Rope Height from Ground (b) (inches)							
(1) Bottom Rope	19.5"	20"	DNR	20.5"	20"	20"	20.5"
(2) 2nd Rope	24.5"	25"	DNR	25.5"	25"	25"	25.5"
(3) 3rd Rope	29.5"	30"	DNR	30.5"	30"	30"	30.5"
(4) Top Rope	38.5"	39"	DNR	39.5"	39"	39"	39.5"
Offset Distances (#1 - feet, inches; #2 - feet)							
(1) CMB to Near Travel Lane	10' 6"	10' 3"	DNR	10' 2"	15' 7"	10' 7"	10' 4"
(2) CMB to Slope Break	20'	21'	DNR	21'	13'	19'	23'
Post Vertical Angle (d) (degrees)							
(1) End Post #1	82.6°	83.3°	86.0°	--	82.5°	--	--
(2) In-Line Post #1	--	--	--	89.5°	--	89.0°	86.1°
(3) In-Line Post #2	--	--	--	89.7°	--	88.0°	89.6°
End Post Holes							
(1) End Post #1	Yes	Yes	Yes	--	Yes	--	--
(2) End Post #2	Yes	Yes	Yes	--	Yes	--	--

Table 64: District 11, Survey #2 (Gibraltar)

Appendix D – District Installation Surveys

Cable Median Barrier Installation Criteria	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions	Site Survey Conditions
Site Survey:							
(1) Route	I-75	I-75	I-75	I-75	I-75		
(2) Milepoint	32	46	47	47	48		
(3) Latitude	37°1'14" N	37°12'19" N	37°12'41" N	37°12'50" N	37°12'58" N		
(4) Longitude	84°5'58" W	84°9'55" W	84°10'56" W	84°11'47" W	84°12'4" W		
(5) Date	1/18/2017	12/14/2016	12/14/2016	12/14/2016	12/14/2016		
(6) End or In-Line Posts	End	In-Line	In-Line	End	End		
Post Spacing (feet, inches)							
(1) In-Line Post #1	--	10' 1"	10' 2"	--	--		
(2) In-Line Post #2	--	10' 7"	10' 6"	--	--		
(3) Anchor-End Post #1	6' 7"	--	--	5' 10"	6' 3"		
(4) End Post #1-2	6' 5"	--	--	6' 5"	6' 5"		
(5) End Post #2-3	7' 4"	--	--	7' 7"	7' 3"		
(6) End Post #3-4	7' 3"	--	--	7' 4"	7' 6"		
Median Slope Conditions (inches per foot)							
(1) Pre-Concrete Pad (near)	2 1/8	1 1/4	1 3/8	7/8	5/8		
(2) Concrete Pad (near)	7/8	2 3/8	1 3/4	1 5/8	1/2		
Rope Height from Ground (b) (inches)							
(1) Bottom Rope	20"	20"	20"	20.5"	21.5"		
(2) 2nd Rope	25"	25"	25"	25"	26.5"		
(3) 3rd Rope	30"	30"	30"	30.5"	31.5"		
(4) Top Rope	39"	39"	39"	39.5"	40.5"		
Offset Distances (#1 - feet, inches; #2 - feet)							
(1) CMB to Near Travel Lane	16'	10' 1"	10' 9"	9' 6"	26'		
(2) CMB to Slope Break	36'	22'	20'	20'	NA		
Post Vertical Angle (d) (degrees)							
(1) End Post #1	85.1°	--	--	79.2°	80°		
(2) In-Line Post #1	--	89.0°	89.3°	--	--		
(3) In-Line Post #2	--	89.7°	89.6°	--	--		
End Post Holes							
(1) End Post #1	Yes	--	--	Yes	Yes		
(2) End Post #2	Yes	--	--	Yes	Yes		

Table 65: District 11, Survey #3 (Gibraltar)

Appendix E – Crash Site Inspections

The crash data file was monitored during the study to determine when a cable barrier involved in a traffic crash. To evaluate the performance of the cable barrier, site visits made to several locations before repairs were completed. An effort was made to review more severe types of crashes. The police report was also obtained. Following description of information obtained from some of these site visits and the review o crash report. Repair costs and the date of repair are provided where available.

Date	County	Route	Mile Point	Vendor
January 3, 2016	Rockcastle	I-75	67.7	Brifen

Description: Tire marks show that the BMW 325i impacted the cable barrier adjacent lane of travel at a shallow angle with eight posts down and the cable defection up to abo five feet. Two of the four cables were on the ground. The tire marks show that the ve was redirected back into the road. There was no reported injury for the unrestra driver.


Damaged Brifen CMB section


Damaged Brifen CMB section

Appendix E – Crash Site Inspections

Date	County	Route	Mile Point	Vendor
October 10, 2016	Jefferson	I-64	11.8	Brifen

Description: Tire marks show that a Ford Focus exited the road a shallow angle and crossed the depressed grass median (at an angle of about 50 degrees). After crossing the median the vehicle went through the cable barrier entering the opposing lane. This resulted in an angle impact with an opposing vehicle (Mercedez Benz E420). The impact to the passenger side of the Ford Focus resulted in major intrusion into the vehicle and injuries to both drivers. There was paint transfer to the three posts damaged as the car traveled through the cable. It was noted that the cable was installed at a lower elevation than the location where the vehicle entered the median and just past the lowest point in the median.

Damaged Brifen CMB section

Damaged Brifen CMB section

Vehicle that made impact with Brifen CMB section

Vehicle involved in crossover crash

Appendix E – Crash Site Inspections

Date	County	Route	Mile Point	Vendor
October 8, 2016	Fayette	KY 4	2.7	Brifen

Description: Tire marks show the driver of a Jeep Grand Cherokee oversteered with the vehicle entering and crossing the median at a substantial angle. There was damage to four posts as the vehicle traveled over the cable and overturned into the opposing lanes. There was no impact with another vehicle. The cable was installed at a lower elevation than the point where the vehicle entered the median. No injuries were reported.

Damaged Brifen CMB section

Damaged Brifen CMB section

Date	County	Route	Mile Point	Vendor
January 10, 2016	Fayette	KY 4	4.7	Brifen

Description: There were two impacts (Jaguar XJ6 and Chevrolet CK2500) within a few minutes where a vehicle lost control on an icy bridge and contacted the end portion of the cable barrier. There was no injury from either contact. The anchor remained intact with damage to the first four posts. Tension was maintained past the area of contact.

Damaged Brifen CMB section

Damaged Brifen CMB section

Appendix E – Crash Site Inspections

Date	County	Route	Mile Point	Vendor
August 26, 2015	Carroll	I-71	44.0	Brifen

Description: A Lexus ES300 traveled through the median and contacted the cable barrier with the vehicle overturning in the median. The unrestrained passenger sustained fatal injuries when ejected. There was damage to only two posts with tension maintained.

Damaged Brifen posts

Damaged Brifen posts

Date	County	Route	Mile Point	Vendor
October 12, 2016	Fayette	KY 4	1.7	Brifen

Description: A Ford Escape contacted the cable barrier adjacent to its lane of travel at a shallow angle. There was tire transfer on the posts and cable with a maximum deflection of about one foot. A total of 13 posts were damaged with the final rest position of the vehicle in the original lane of travel. Limited tension was maintained in the damaged area. No injury was reported.

Appendix E – Crash Site Inspections

Damaged Brifen post

Damaged Brifen post

Date	County	Route	Mile Point	Vendor
October 4, 2016	Fayette	KY 4	3.1	Brifen

Description: A Toyota Tundra struck the cable barrier adjacent to its lane of travel at a shallow angle and then, after rebounding into its original lane of travel, struck the barrier a second time. The first impact damaged 14 posts. After a gap of 22 posts, there was damage to 22 posts. Prior to the first damaged post, there were 14 posts where either the bottom or two bottom cables were out of position. For the 22 posts between the two contacts all of the four cables were in their original position on eight posts. There was no injury related to the collisions.

Damaged Brifen CMB section

Damaged Brifen CMB section

Appendix E – Crash Site Inspections

Date	County	Route	Mile Point	Vendor
October 7, 2016	Fayette	KY 4	11.9	Brifen

Description: A Ford Excursion had a tire failure with the cable barrier adjacent to the travel lanes contacted at a shallow angle. There was damage to 16 posts with a maximum deflection of about five feet. Tension was lost in the area of contact. There was no reported injury.

Damaged Brifen posts

Damaged Brifen posts

Date	County	Route	Mile Point	Vendor
March 13, 2016	Laurel	I-75	47.5	Gibraltar

Description: A Ford F150 crossed the grass median and struck the end of the cable barrier at a crossover. The truck continued past the crossover and struck the end of the cable barrier on other side of the crossover. The first impact damaged seven posts with the second damaging 16 posts. The cables became detached from both end anchors. There was a loss of tension for a substantial distance (up to about one mile). The truck overturned in the median with minor contact to the passenger side of an opposing vehicle. There were minor injuries reported.

_**Damaged Gibraltar CMB section**

Damaged Gibraltar CMB section

Date	County	Route	Mile Point	Vendor
March 27, 2016	Woodford	I-64	59.7	Brifen

Description: A Chevrolet Silverado crossed the grass median and struck the cable barrier. The vehicle contacted nine posts and then rotated around seven posts with damage to five additional posts where the pickup came to final rest. Tension was reduced in the first contact with tension maintained at the second location. There was no injury reported.

_Damaged Brifen posts

Damaged Brifen posts

Date	County	Route	Mile Point	Vendor
March 15, 2016	Rockcastle	I-75	68.1	Brifen

Description: A GMC Yukon struck the cable barrier adjacent to its lane of travel and rotated back into the road. It was struck with a Honda Accord with both vehicles hitting the cable. There was a total of 30 posts damaged divided in five sections (with undamaged posts between the damaged sections). The rotation of the vehicle in the initial impact and the second impacts explain the gaps in the post damage. Two injuries were reported.

Damaged Brifen posts

Damaged Brifen posts

Date	County	Route	Mile Point	Vendor
March 7, 2016	Woodford	I-64	61.3	Brifen

Description: A Peterbilt tractor traveled into the median after a sideswipe collision. The truck crossed the median and impacted the cable barrier resulting in damage to 10 posts. The truck was directed down the median where it traveled into the gap between two bridges and vaulted to the roadway below the interstate. One injury was reported.

Damaged Brifen posts

Damaged Brifen posts

Date	County	Route	Mile Point	Vendor
December 23, 2015	Laurel	I-75	43.9	Gibraltar

Description: A Chevrolet truck struck the cable near the end of a section of cable barrier. Five posts were damaged with contact at the fourth post from the end. The anchor became unattached with loss of tension for a substantial distance (and at splices a long distance from the impact area). There was no reported injury.

Damaged Gibraltar CMB Section

Damaged Gibraltar CMB Section

Appendix E – Crash Site Inspections

Date	County	Route	Mile Point	Vendor
November 13, 2015	Fayette	KY 4	2.7	Brifen

Description: A Suzuki SX4 passenger car rotated across the median (at a substantial angle) and impacted the cable barrier. Two posts were damaged with the car stopping in the median. There was no reported injury.

Damaged Brifen posts

Damaged Brifen posts

Date	County	Route	Mile Point	Vendor
November 14, 2016	Fayette	KY 4	16.5	Brifen

Description: A Ford Focus rotated into the cable barrier adjacent to the travel lane. There was damage to four posts with the vehicle rotating to final rest in its travel lane. There was no reported injury.

Damaged Brifen posts

Damaged Brifen posts

Appendix E – Crash Site Inspections

Date	County	Route	Mile Point	Vendor
September 4, 2015	Boone	I-275	5.6	Gibraltar

Description: A Ford Focus contacted the cable barrier within four posts of the trailing end anchor. The anchor became unattached with loss of tension in the complete 0.2-mile cable barrier section. The repair was conducted on September 11, 2015 with a cost of $1,785. There was no reported injury.

Damaged Gibraltar CMB section

Damaged Gibraltar CMB section

Date	County	Route	Mile Point	Vendor
February 10, 2016	Fayette	KY 4	0.3	Brifen

Description: A Lincoln LS passenger car slid on snow at a substance angle into the cable barrier adjacent to the direction of travel. There was damage to three posts with the car redirected back into the travel lanes. There was no reported injury.

Damaged Brifen CMB section

Damaged Brifen CMB section

Date	County	Route	Mile Point	Vendor
January 28, 2016	Jefferson	KY 861	6.8	Gibraltar

Description: A Mercury Mountaineer struck the cable barrier adjacent to the direction of travel at a moderate angle. There was damage to 10 posts with tension maintained. The vehicle was redirected in its travel lanes and overturned on its side. There was one reported injury.

Damaged Gibraltar CMB section

Damaged Gibraltar CMB section

Date	County	Route	Mile Point	Vendor
October 27, 2015	Jefferson	I-64	8.6	Brifen

Description: A Ford Explorer traveled from its lane across the median where it struck the cable barrier at a sharp angle. There is a drop in elevation as the vehicle traveled across the median to the cable barrier. The vehicle went through the cable stopping in the opposing lane (with no impact with an opposing vehicle). The repair records show nine posts were replaced. The repair was conducted on October 29, 2015 with a cost of $1,350. There was no reported injury.

Damaged Brifen posts

Damaged Brifen posts

Date	County	Route	Mile Point	Vendor
October 27, 2015	Jefferson	KY 841	5.4	Gibraltar

Description: A Nissan Sentra struck the cable barrier adjacent to its lane of travel and was redirected back across the road. There was damage to eight posts with the cable tension maintained. The repair was conducted on November 4, 2015 with a cost of $1,200. There was no reported injury.

Damaged Gibraltar posts

Damaged Gibraltar posts

Date	County	Route	Mile Point	Vendor
September 10, 2015	Boone	I-275	8.2	Gibraltar

Description: A Buick Park Avenue initially traveled on the right shoulder before crossing the road and impacting the cable barrier adjacent to its lane of travel at a sharp angle. The vehicle stopped in its direction of travel adjacent to the cable barrier. There was damage to eight posts with tension maintained. There was no reported injury. The repair was conducted on September 28, 2015 with a cost of $2,510.

Damaged Gibraltar posts

Damaged Gibraltar posts

Date	County	Route	Mile Point	Vendor
October 14, 2016	Jefferson	I-265	20.0	Trinity

Description: A Chrysler PT Cruiser left its lane of travel at a moderate angle (about 15 degrees) and contacted the cable barrier located in the median closer to its side. The vehicle damaged two posts and was redirected to its final rest position in the median. Tension was maintained. There was no reported injury.

Damaged Trinity posts

Damaged Trinity posts

Date	County	Route	Mile Point	Vendor
November 1, 2016	Jefferson	I-64	10.1	Brifen

Description: A Mitsubishi 3000GT was rotating at it exited its lane of travel (at an angle of about 30 degrees). The vehicle crossed the median and knocked down two posts on the cable barrier with tire marks showing its final rest position in the opposing lanes. Paint transfer to the top of the posts show where the car went over the cables. The cable remained in its original positions (with less tension). The height of the median is slightly higher on the side where the vehicle exited the lanes compared to the cable adjacent to the opposing lanes. There was no reported injury.

Damaged Brifen posts

Damaged Brifen posts

Date	County	Route	Mile Point	Vendor
November 2, 2016	McCracken	I-24	9.0	Brifen

Description: A Toyota Camry contacted a cable barrier adjacent to its lane of travel after a minor contact with a truck. The impact angle was about 20 degrees with 11 posts down. There was a loss in tension with two cables on the ground. There was no reported injury.

Damaged Brifen CMB section

Damaged Brifen CMB section

Date	County	Route	Mile Point	Vendor
February 2, 2017	Rockcastle	I-75	62.9	Brifen

Description: A tractor trailer impacted the rear of a Pontiac Sunfire with both vehicles crossing the median impacting the cable on the opposite side of the median. The initial contact was about 16 posts from the end. Four posts were pushed down with the vehicles entering the opposing lane contacting a Toyota Prius. There were seven posts damaged in the area of the second impact. There was a vehicle fire with cable strands burned to the point of separation. Tension was lost for several tenths of a mile. There were no reported injuries.

Damaged Brifen CMB section

Damaged Brifen CMB section

Date	County	Route	Mile Point	Vendor
November 3, 2015	Woodford	I-64	59.6	Brifen

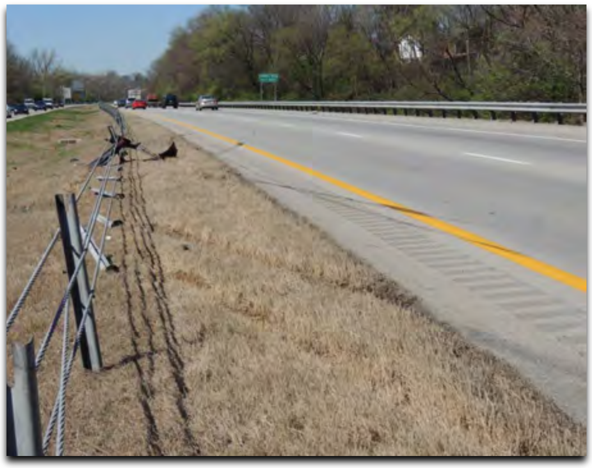
Description: A Toyota Avalon contacted the cable barrier adjacent to its travel lane at a shallow angle. There was damage to 11 posts and a deflection of seven feet. The repair was conducted on November 4, 2015 with a cost of $2,760. There was no reported injury.

Damaged Brifen posts

Damaged Brifen posts

Date	County	Route	Mile Point	Vendor
January 10, 2016	Jefferson	I-265	20.1	Brifen

Description: A Toyota Camry traveled at a moderate angle and contacted the cable barrier located closest to its direction of travel. The cable was deflected several feet and maintained tension. The tire tracks shows the vehicle rotated back into its lanes of travel. There was no reported injury.

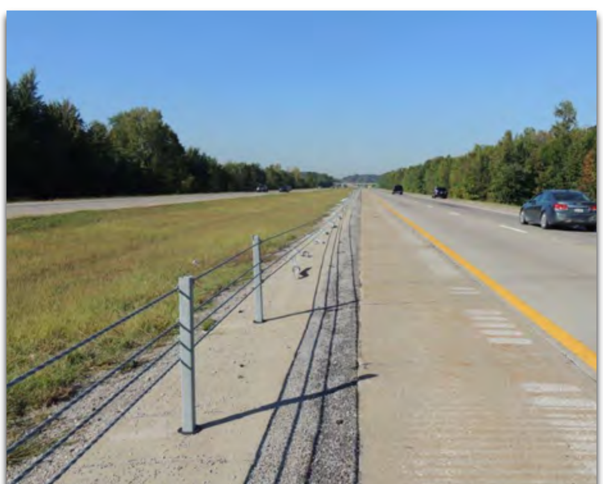


Damaged Brifen CMB section

Damaged Brifen CMB section

Date	County	Route	Mile Point	Vendor
September 21, 2015	Jefferson	KY 841	5.0	Gibraltar

Description: An Isuzu Rodeo contacted the adjacent cable barrier after a tire failure. There was damage to 25 posts. Tension was not maintained in the impact area. The repair was conducted on October 21, 2015 with a cost of $4,050. There was no reported injury.



Damaged Gibraltar posts

Damaged Gibraltar posts

Date	County	Route	Mile Point	Vendor
November 16, 2015	Fayette	KY 4	2.8	Brifen

Description: A Toyota Camry rotated across the median impacted the cable barrier with resulting damage to three posts. The final rest position of the vehicle was in the median. There was no reported injury.

Damaged Brifen posts

Damaged Brifen posts

Date	County	Route	Mile Point	Vendor
March 27, 2016	Jefferson	I-64	8.2	Brifen

Description: A Chevrolet Tahoe crossed the median and overturned over the cable into the opposing lane. The vehicle rotated into the median. There was damage to four posts. The vehicle traveled about 75 feet to the bottom of a slope where it started to roll and traveled over the cable. The cable was at a lower location than the lanes the vehicle exited. The unrestrained driver was ejected and injured.

Damaged Brifen CMB section

Damaged Brifen CMB section

Appendix E – Crash Site Inspections

Date	County	Route	Mile Point	Vendor
September 8, 2015	Rockcastle	I-75	64	Brifen

Description: A Toyota 4Runner collided with the cable barrier adjacent to its lane of travel. There was damage to 29 posts with the vehicle overturning into the median. The cable was pushed down to the turf with the vehicle traveling over the cable. The driver sustained fatal injuries. The repair was conducted on September 11 with a cost of $7,300.

Damaged Brifen CMB section

Damaged Brifen CMB section

Date	County	Route	Mile Point	Vendor
April 12, 2016	Whitley	I-75	8.8	Brifen

Description: A Chevrolet Blazer collided twice with the cable barrier adjacent to its lane of travel first after steering to avoid a truck and then after sideswiping the truck. There were three posts down and then, after no contact with three posts, the next six posts were down. The vehicle stopped adjacent to the cable barrier. There was no reported injury.

Damaged Brifen posts

Damaged Brifen posts

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