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IN-SERVICE PERFORMANCE EVALUATION OF KDOT'S CABLE MEDIAN BARRIER

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16. Abstract

Kansas Department of Transportation (KDOT) installed approximately 7.9 total miles of cable median barrier (CMB) along K-10, K-96, and US-75 highways in 2011 and 2012. In January 2020, KDOT funded a study to evaluate Kansas CMB performance by analyzing cross-median crashes (CMCs) and cross-median events (CMEs).

All crashes which occurred on these roadways within the longitudinal length of the CMBs were reviewed and crashes which involved a CMB were noted. Researchers analyzed the number of injuries, barrier damage (when available), vehicle damage, and crash outcome in each of the cable median barrier crashes. Researchers identified two CMB penetrations with CMEs, one which resulted in a CMC. Overall, eight penetrations (3.1%) and one rollover (0.4%) result were identified. Although the KDOT dataset was small, rates of penetration and rollover were lower than other state DOT averages. The average CMB crash rate in Kansas was 26.99 crashes per hundred-million vehicle-miles traveled. Approximately 31% of CMB crashes in Kansas were associated with adverse weather conditions (rain, fog, snow, sleet, icy conditions), although the injury rate was significantly higher for non-adverse weather crashes. CMB crash rates were significantly higher between December and February, accounting for 36% of all annual CMB crashes. Overall, the performance of the CMB in Kansas was determined to perform acceptably and comparably to other states.

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in.	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short ton (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela per square meter	cd/m^2
		FORCE & PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in.
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yard	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliter	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or “metric ton”)	1.103	short ton (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela per square meter	0.2919	foot-Lamberts	fl
		FORCE & PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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GLOSSARY

AASHTO: American Association of State Highway and Transportation Officials

ADT: Average Daily Traffic

AADT: Annualized Average Daily Traffic

CMB: Cable Median Barrier

CME: Cross-Median Event or Cross-Median Encroachment

CMC: Cross-Median Crash

ISPE: In-Service Performance Evaluation

KDOT: Kansas Department of Transportation

KABCO: Injury scale used to evaluate crash severity; K – Killed; A –Incapacitating Injury; B – Moderate Injury; C – Minor/Possible Injury; O – Property Damage Only

VSL: Value of a Statistical Life

FHWA: Federal Highway Administration

RDG: Roadside Design Guide

VMT: Vehicle-Miles Traveled

MVMT: Million Vehicle-Miles Traveled

HVMT: Hundred-Million Vehicle-Miles Traveled

Penetration: Vehicle passes from one side of the cable median barrier to the opposite side of the barrier system, with no cables remaining on the impact side to capture or contain the vehicle

Rollover: Vehicle performs a minimum of 90-degree roll displacement with left or right side of vehicle leading

Capture: Vehicle came to rest in median and in contact with cable median barrier, either due to (a) entanglement with cables; (b) significant friction or vehicle sliding; or (c) low-speed impact at the end of the vehicle’s trajectory

Redirection: Vehicle impacted the cable median barrier and exited contact with the barrier toward the same-direction travel lanes

Serious Injury: Killed (K) or Incapacitating Injury (A) with hospitalization

Serious Crash Result: Maximum injury severity sustained by an occupant of vehicle involved in the crash was consistent with Serious Injury

1 INTRODUCTION

1.1 Background

In 2009, the Midwest Roadside Safety Facility (MwRSF) performed a review of median barrier guidelines for the Kansas Department of Transportation (KDOT) [1-2]. This study included a literature review of American Association of State Highway and Transportation Officials (AASHTO) warrants for the installation of median barriers, a review of policy and freeway construction practice and state right-of-way, as well as a summary of the median barrier warrants and guidelines used by other state DOTs. To determine the cost-effectiveness of median barrier shielding guidelines for Kansas, all crashes on Kansas freeways were reviewed and cross-median events (CMEs) were identified. The cost-effectiveness of installing barriers in medians was evaluated based on median width and annual average daily traffic (AADT). The study resulted in newer guidelines for the installation of median barriers in medians up to 70 ft wide, and supported revision to median barrier installation guidelines described in the AASHTO *Roadside Design Guide* (RDG) [3].

Many state DOTs have determined that cable median barriers (CMBs) successfully prevented many cross-median crashes, with cross-median crash reduction factors often exceeding 80% in before-and-after studies. Nonetheless, some cross-median crashes still occur after installing median barriers. Stolle determined that CMBs can contribute to additional severe crash outcomes such as vehicle rollovers, occupant interaction with median barrier elements, and rapid decelerations or snagging on barriers [4]. Moreover, installing cable median barriers has been shown to increase the overall number of median crashes, and many of those crashes would not have occurred at all if a median barrier was not present. Therefore, it is essential to determine the cost-effectiveness of these barrier systems and warrants for installing systems to maximize the safety benefit and value of investments in safer infrastructure.

1.2 Problem Statement

The objective of this research effort is to perform an in-service performance evaluation of KDOT's CMBs to determine if they are performing acceptably.

1.3 Scope

Phase 1 of the in-service performance evaluation (ISPE) for KDOT's cable median barriers was conducted using a sequence of steps. First, a literature review was completed to collect findings from other state DOTs and research organizations regarding cable median barrier ISPEs. Second, KDOT supplied 1,723 crash reports from roads within regions corresponding to cable median barrier installations between January 2010 and June 2019. MwRSF staff reviewed each crash report and identified characteristics of each crash: if a left- or right-side departure occurred, if a CMB was impacted, and the outcome of the CMB crash (e.g., penetration, rollover, capture). Additionally, researchers attempted to determine, based on barrier and vehicle damage, impact vector angle, and crash circumstances, whether a cross-median event (CME) could have occurred. Results were tabulated and determined recommendations and conclusions. Next, KDOT's CMB crash data was evaluated based on published data from other state DOTs regarding CMBs. Although number of CMB crashes in Kansas were not statistically significant to evaluate injury, crash outcome, or cost comparisons with other states, trends from other states were evaluated and compared with KDOT data. Finally, a research report was prepared to discuss results. Recommendations were made to identify critical features for a following Phase 2 study to evaluate median encroachments.

2 LITERATURE REVIEW

2.1 Multi-State and International Experience with Crash Data

2.1.1 Roadsafe LLC, 2009

Ray, Silvestri, Conron, and Mongiardini published a review of cable median barrier data in 2009 [5]. The authors identified more than 2,600 miles of cable median barrier that had been installed in 23 different states, resulting in an overall reduction in cross-median crashes (CMCs) and serious and fatal injuries. Ray also noted the number of crashes which resulted in CMCs and compared those crashes to the total number of recorded crashes, which was deemed the "effectiveness" of the system. Of the 11 states with pertinent data, the average effectiveness ranged between 88.9% (Utah) to 100% (Iowa and Rhode Island) in terms of preventing cross-median crashes after CMB installation. Ray concluded that there were significant benefits obtained by installing CMBs in appropriate locations, such as reduced cross-median fatal and severe injury rates, though the guidelines and limitations for the installation of cable median barriers were not discussed.

2.1.2 Midwest Roadside Safety Facility, 2013

Stolle completed a review of cable median barrier crashes in 2013 spanning 12 states and which included more than 12,000 cable median barrier crashes [4]. Stolle identified factors which contributed to unsuccessful CMB performance, including vehicular penetrations, rollovers, and severe injuries or fatalities. The study included analysis of the effects of weather and road conditions, time of day, vehicle type involved in the impact, vehicle orientation ("attitude") at the time of impact and at the point of departure with the roadway, barrier type (proprietary and non-proprietary designs), median slopes, and crash outcome (penetration, rollover, severe injury, or no bad outcome).

High-tension CMBs were found to exhibit fewer penetrations and rollover than low-tension, non-proprietary cable barrier designs, although the overall severe injury rates were lower for non-proprietary CMBs than for proprietary CMBs. Of the proprietary CMB designs considered, the Brifen Wire Rope Safety Fence (WRSF), consistent with the National Cooperative Highway Research Program (NCHRP) Report No. 350 design approved for use anywhere on slopes as steep as 6:1 [6-8], exhibited the fewest number of penetrations and rollovers, but the dataset was limited, as shown in Table 1.

Table 1. Summary of Cable Median Barrier Performance in 12 States, 2005-2009 [4]

Weather Conditions at Time of Crash	Low-Tension 3-Cable			Brifen WRSF			Nucor NU-CABLE			Trinity CASS		
	Crashes	Penetrations	Frequency	Crashes	Penetrations	Frequency	Crashes	Penetrations	Frequency	Crashes	Penetrations	Frequency
No Adverse Effects	3020	224	7.4%	56	3	5.4%	333	40	12.0%	1134	112	9.9%
Rain	969	59	6.1%	29	2	6.9%	131	8	6.1%	189	26	13.8%
Snow or Sleet	243	13	5.3%	33	3	9.1%	213	15	7.0%	652	33	5.1%
Fog or Mist	28	6	21.4%	0	0	-	7	2	28.6%	16	2	12.5%
Strong Crosswind	0	0	-	1	0	-	0	0	-	6	0	-
Unknown or Other	8	0	-	0	0	-	8	2	25.0%	5	0	-
Total	**4268**	**302**	**7.1%**	**119**	**8**	**6.7%**	**692**	**67**	**9.7%**	**2002**	**173**	**8.6%**

Overall, clear or cloudy weather was correlated with the highest likelihood of penetration, rollover, and severe injury outcomes compared with all other weather (mist, drizzle, fog, snow, sleet, high wind, etc). Likewise, dry road conditions were correlated with more adverse vehicle interactions with CMBs than wet, icy, slick, snowy, or muddy roads. A summary of the effect of travel conditions on CMB crash outcomes is shown in Table 2.

Table 2. Effect of Weather and Road Condition on CMB Performance [4]

Weather Condition	Penetration	Rollover
No Adverse Effects	9.8%	6.7%
Rain	6.9%	2.1%
Snow or Sleet	6.7%	2.1%
Average Failure Rate	**9.3%**	**5.1%**

Road Condition	Penetration	Rollover
No Adverse Effects	11.5%	6.8%
Wet or Pooling Water	9.9%	2.5%
Snow, Slush, or Ice	6.1%	3.8%
Average Failure Rate	**9.3%**	**5.1%**

Stolle also determined that winter weather conditions were associated with significant increases in the average number of crashes with CMBs. An annualized distribution of crashes by occurrence (normalized week number out of 52) indicated that crash rates more than doubled between November and March, but that the total number of severe crashes per week actually declined during the same time period, as shown in Figure 1.

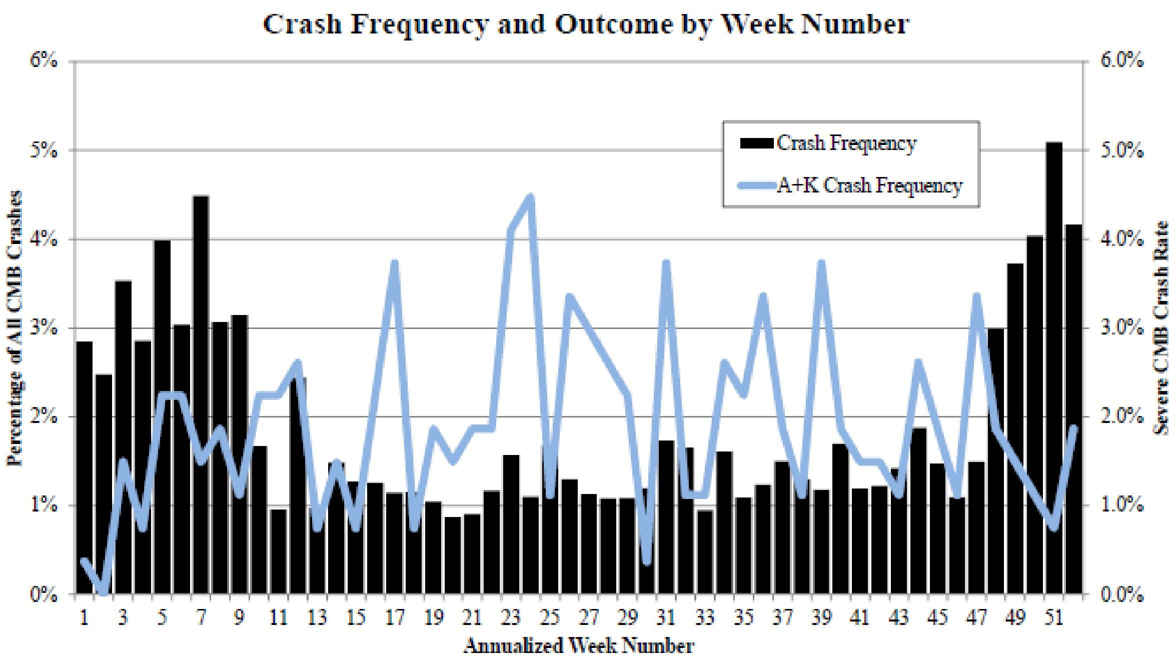


Figure 1. CMB Crashes by Normalized Week Number [4]

Lastly, Stolle examined barrier installation location and correlation to median slopes for Ohio DOT crash data. Barriers installed within 4 ft of the median center resulted in a higher number of penetration outcomes on average, but were also correlated with the lowest risk of severe injury and rollover outcomes, as shown in Table 3. Barriers installed on slopes of V-ditch medians, corresponding to either foreslope or backslope locations, were associated with reduced penetration rates but increased rollover and severe injury rates. Surprisingly, barriers installed adjacent to shoulders (generally within 6 ft of the travelway) resulted in the highest overall rate of penetration, rollover, and severe injury crashes. The dataset for barriers installed on roadway shoulders was too small to be statistically significant, and further research is needed to verify if installations on shoulders pose a statistically higher risk to impacting vehicles compared to other locations.

Table 3. Summary of Barrier Installation Location and Crash Outcome in Ohio [4]

Barrier Location	Crashes	Penetrations	Rollovers	A+K Injuries
Shoulders (Either Side)	20	20.0%	5.0%	15.0%
Traffic-Side Slope	485	8.5%	4.3%	4.5%
Within 4 ft of Ditch Bottom	*123*	*13.8%*	*2.4%*	*0.8%*
Opposite-Side Slope	229	8.3%	4.4%	3.5%
All Traffic-Side Crashes	494	8.7%	4.5%	4.9%
All Opposite-Side Crashes	240	8.8%	4.2%	3.8%
All Crashes Not in Ditch Center	734	8.7%	4.4%	4.5%
All Crashes	857	9.5%	4.1%	4.0%

2.1.3 VHB and Persaud & Lyon, Inc, 2017

Srinivasan et al. evaluated CMB crash data for roads with and without rumble strips from the states of Illinois, Kentucky, and Missouri in 2017 [9]. Researchers evaluated the benefits of adding CMB to roads with existing rumble strips in place, as well as adding a combination of both CMBs and rumble strips at the same time during roadway improvement projects. Results indicated approximately the same safety benefit by installing CMBs: a 27-percent increase in crashes, 22 to 24-percent decrease in fatal and injury crashes; and a 48-percent decrease in opposite-direction crashes. Benefits in Missouri were similar overall, but a larger decrease in opposite-direction crashes was observed. It was concluded that it was beneficial to install CMBs in combination with rumble strips to improve the effectiveness of the safety treatments.

2.2 Recent State and Province Experience with CMBs

2.2.1 Alberta, 2013

Maintenance, operation, and performance results were discussed by representatives of EBA in Alberta, Canada, at the 2013 Annual Conference of the Transportation Association of Canada [10]. Approximately 122 km (75.8 miles) of Gibraltar cable median barrier was installed in driven sockets between 2009 and 2011 on roads with annualized average daily traffic (AADT) up to 80,000. Contractors averaged the maintenance costs over the course of two years, consisting of barrier repairs, maintenance (tensioning), mowing, and vehicle extraction, which averaged to $4,135/km ($6,650/mile). Although cross-median crashes were reduced in the shielded region and the barriers were well-received by maintenance staff due to ease and speed of maintenance, some additional problems were noted. Specifically, maintenance workers reported that vehicles which encroached into the work zones made avoidance difficult, leaving to greater apprehension while performing maintenance activities. In addition, installations at roadside shoulders made maintenance much more difficult because vehicles could no longer park in the divided medians to execute barrier maintenance, and workers were required to cross all travel lanes to access the barriers. First responders and maintenance workers developed a maintenance plan to extract vehicles entrapped in the cables, including cutting cables to release tension to extract the vehicles.

2.2.2 Florida, 2012

In January 2013, researchers at Florida International University (FIU) presented a conference paper describing Florida DOT's (FLDOT's) experiences with cable median barriers at the 92nd Meeting of the Transportation Research Board [11-12]. The authors reviewed 8,818 crashes between the years of 2003 and 2010 in locations which utilized CMBs and identified all CME events. It was observed that 2.6% of crashes with CMBs in Florida resulted in a CME, corresponding to 98.1% containment of passenger cars and 95.5% containment for light trucks (e.g., pickup trucks, sport utility vehicles (SUVs), compact utility vehicles (CUVs), and vans). A total of 16.4% of vehicles were determined to have penetrated through the barrier, but most remained within the median. The authors concluded that the Trinity CASS system outperformed the Gibraltar cable barrier in terms of preventing penetrations and CMEs.

The net reduction in serious injuries and fatalities per hundred-million vehicle-miles traveled (HVMT) after CMB installation was approximately 64%. Cross-median crash rates declined by 61% after CMB installation, although overall number of annual median-related crashes increased by 161%. The CMB ISPE results from Florida are shown in Tables 4 and 5.

Table 4. Cable Median Barrier Penetration Crashes in Florida [12]

Vehicle Type	Barrier Crossover Crashes					Barrier Non-Crossover Crashes			Total Crashes (i) = (e)+(h)	Percent of Barrier Non-Crossover Crashes (h)/(i)
	Under-ride (a)	Over-ride (b)	Penetration (c)	Unknown Crossover (d)	Total Crossover (e) = (a)+(b)+(c)+(d)	Redirected (f)	Contained (g)	Total Non-Crossover (h) = (f)+(g)		
Car	2	16	18	18	54	193	122	315	369	85.4%
Light Truck[1]	0	17	7	7	31	81	42	123	154	79.9%
Medium Truck[2]	0	0	1	0	1	0	1	1	2	50.0%
Heavy Truck[3]	0	1	3	0	4	3	5	8	12	66.7%
Motorcycle	0	0	0	0	0	1	1	2	2	100.0%
Unknown	0	0	0	0	0	4	1	5	5	100.0%
Other	0	0	0	0	0	3	2	5	5	100.0%
Total	**2**	**34**	**29**	**25**	**90**	**285**	**174**	**459**	**549**	**83.6%**

[1] Light Trucks include vans and pickup trucks with two or four rear tires.
[2] Medium Trucks are vehicles with four rear tires.
[3] Heavy Trucks include truck tractors.

Table 5. Cross-Median Events at CMB Locations in Florida [12]

Vehicle Type	Median Crossover Crashes					Median Non-Crossover Crashes (f)	Total Crashes (g) = (e)+(f)	Percent of Median Non-Crossover Crashes (f)/(g)
	Under-ride (a)	Over-ride (b)	Penetration (c)	Unknown Crossover (d)	Total Crossover (e) = (a)+(b)+(c)+(d)			
Car	0	4	2	1	7	362	369	98.1%
Light Truck[1]	0	4	1	2	7	147	154	95.5%
Medium Truck[2]	0	0	0	0	0	2	2	100.0%
Heavy Truck[3]	0	0	0	0	0	12	12	100.0%
Motorcycle	0	0	0	0	0	2	2	100.0%
Unknown	0	0	0	0	0	5	5	100.0%
Other	0	0	0	0	0	5	5	100.0%
Total	**0**	**8**	**3**	**3**	**14**	**535**	**549**	**97.4%**

[1] Light Trucks include vans and pickup trucks with two or four rear tires.
[2] Medium Trucks are vehicles with four rear tires.
[3] Heavy Trucks include truck tractors.

2.2.3 Indiana, 2013-2014

Researchers at Purdue University teamed up with representatives of the Indiana DOT (INDOT) to evaluate the performance of INDOT's high-tension CMB [13]. The study evaluated impacts on a 21-km (13-mile) stretch of flat, predominantly straight highway. The medians in the study section were approximately 60 ft wide and the roads had good measured friction overall, although some traffic-polished sections were observed. The distribution of injuries involving CMB impacts was comparable to impacts involving W-beam ("steel guardrail"), and it was concluded that the average cost of repairs and crash cost for CMB systems were less than the comparable repair and crash cost of the W-beam systems. In addition, majority of the repair costs associated with CMB systems were associated with labor, not materials or equipment use. Statistical evaluations indicated a reduction in the severity and variability of injuries associated with sites in which CMBs were installed compared to control sites without CMBs. An alternative median barrier effectiveness study, published in 2014, indicated that CMB impacts reduced the risk of injury by 78 to 85 percent compared to no barrier, whereas concrete barriers and W-beam barriers reduced injury occurrence by 39 and 65 percent, respectively [14]. Results were statistically significant and suggested significant value in the use of CMBs for median protection.

Researchers at Purdue University also conducted a study on behalf of INDOT to compare the injury outcome risk for fixed objects, including barriers and non-barrier hazards [15]. It was determined that cable barriers posed the lowest risk of injury of all roadside barrier types when feasible (e.g., sufficiently wide median). Impacts on the "near side" (or adjacent to traffic) resulted in less overall injuries and risk than impacts on the "far side" (opposite median slope or shoulder), but still resulted in fewer overall injuries than W-beam guardrail or a concrete median barrier.

2.2.4 Iowa, 2018

Researchers at the Center for Transportation Research and Education (CTRE), located at Iowa State University (ISU), evaluated CMB crashes in the state of Iowa [16]. Crash outcomes were reviewed on roads with CMB and control roads with similar attributes to compare crash costs and the number of cross-median crashes. Statistical models were used to generate benefit-to-cost models for installing CMBs compared to a "do nothing" treatment option. The B/C ratio associated with installing CMBs was 16.08 despite the significant increase in non-severe crashes and additional median crashes related to CMBs over a 20-year design life. The primary high-tension cable median barrier system selected appeared to be a Gibraltar 4-cable barrier design, although researchers did not identify the manufacturer or barrier design. Results of the CTRE evaluation are shown in Table 6.

Table 6. Summary of CMB Effectiveness in Injury Prevention in Iowa [16]

	Before Installation		After Installation		
Severity Level	Crashes per HMVMT	Percentage of Total Crashes	Crashes per HMVMT	Percentage of Total Crashes	Percent Change
K (Fatal)	0.32	2.37%	0.11	0.46%	-65.63%
A (Incapacitating)	0.65	4.81%	0.40	1.68%	-38.46%
B (Non-incapacitating)	1.69	12.52%	1.37	5.77%	-18.93%
C (Possible Injury)	2.03	15.04%	2.27	9.55%	11.82%
O (No Injury)	8.81	65.26%	19.61	82.53%	122.59%
Total Crashes	13.50	100.00%	23.76	100.00%	76.00%

CCTRE researchers also investigated the cost-effectiveness of installing CMB based on AADT and median width. Negative binomial regression modeling was used resulting in natural logarithmic distributions of crash rates and injury outcomes correlated to ADT and median widths. Statistical model results indicated relatively low cost-effectiveness for installing CMB in narrow medians or at low traffic volumes, but diminishing return as median widths increased beyond 50 ft. Using the assumed distribution of injuries in before-and-after CMB impact analysis, researchers identified the benefit-to-cost ratios of installing CMB based on median width and ADT. Results are shown in Figure 2. The assumed distribution of crash rate by median width is shown in Figure 3.

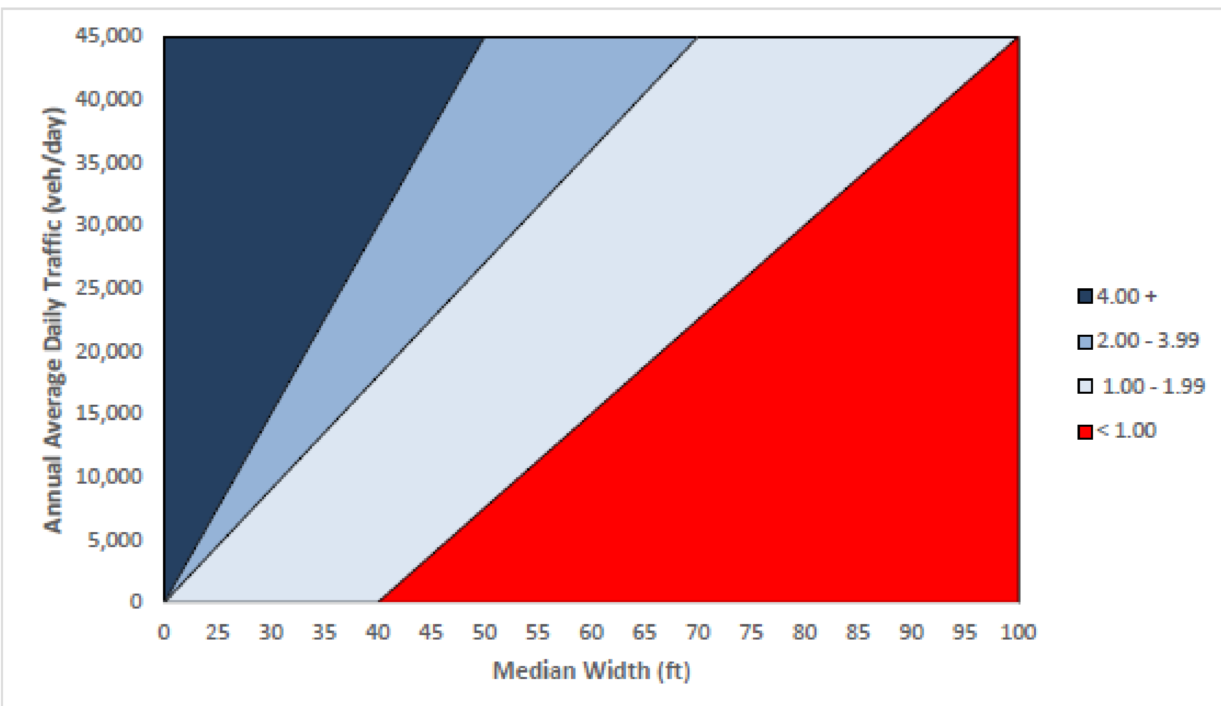


Figure 2. Benefit-to-Cost Ratio for Installing CMB in Iowa Based on AADT and Median Width [16]

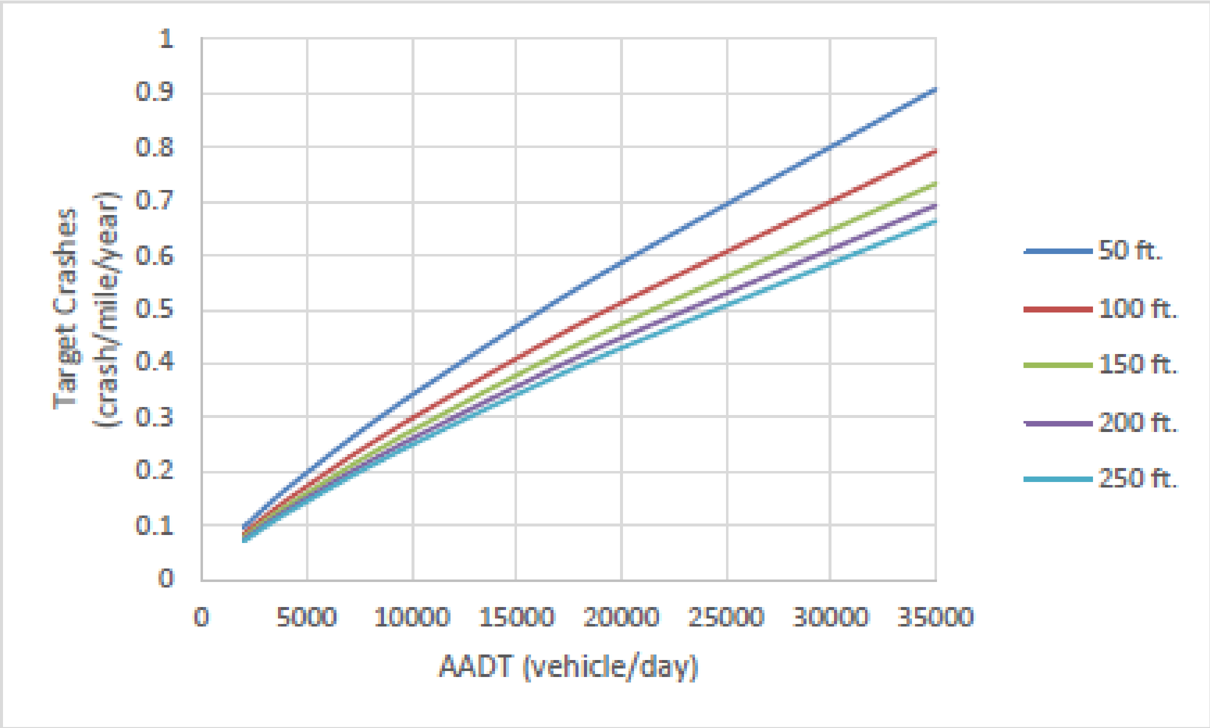


Figure 3. Negative Binomial Regression Estimate of Crash Rates by AADT and Median Width [16]

2.2.5 Kentucky, 2017

Agent et al. at the Kentucky Transportation Center (KTC) at the University of Kentucky evaluated crash data involving CMBs for Kentucky DOT [17]. Three different high-tension CMB systems, consisting of 4-cable Brifen, 3-cable Trinity, and 4-cable Gibraltar systems, were evaluated in seven discrete installation locations. Note that few crashes were observed in locations with the Trinity CASS system installed. Researchers conducted interviews with maintenance and repair technicians, tabulated crashes involving the CMB, estimated crash costs for each CMB crash, and compared results. By equating probable cross-median crashes before and after installing CMBs using three- and five-year evaluation periods, it was estimated that hundreds of cross-median crashes were prevented by the CMBs, resulting in millions of dollars in economic benefits from reduced crash costs and travel disruptions. Results are tabulated and shown in Table 7. Overall, the Brifen system was observed to perform the best in terms of crash cost, sustained cable tension after impact, impact performance near end anchorages, and in terms of repair costs and maintenance.

Table 7. Summary of Estimated Economic Benefits Resulting from CMB Installation in Kentucky [17]

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

2.2.6 Michigan, 2014

Savolainen et al. at Wayne State University evaluated CMB crashes in Michigan to determine if there was warrant to install additional CMBs to prevent cross-median crashes [18]. A survey of installers and maintenance technicians was conducted regarding the effectiveness and use of CMBs, crashes and crash costs were evaluated, and a statistical evaluation of the barriers' effectiveness in preventing CMCs and rollovers was performed. Most of the cable barrier systems considered were 3-cable Gibraltar high-tension CMBs, but some 4-cable Brifen and 3-cable CASS systems were also investigated. After installing CMBs, fatal and incapacitating injury crashes were reduced by 33 percent and CMC crash rates were reduced by 86.8 percent. Rollover crashes were also reduced by 50.4 percent. Detailed review of some of the crash reports indicated that the net CMB penetration rate was approximately 3.1%. Changes in the injury distributions before and after CMB installation, in terms of 100 million vehicle-miles traveled (100 MVMT or HVMT), are shown in Table 8.

Table 8. Before-and-After Injury Outcomes for CMB Installation in Michigan [18]

Crash Severity/Type	Average Annual Crash Rate (crashes per 100 MVMT)		
	Before Period	After Period	Percent Change
All Target Crashes	15.60	34.88	123.6%
Target PDO & C Crashes	12.90	32.85	154.7%
Target B Crashes	1.85	1.33	-28.1%
Target K & A Crashes	1.15	0.58	-49.6%
Median Crossover Crashes	2.66	0.35	-86.8%
Target Rollover Crashes	4.88	2.42	-50.4%

2.3 Historical State Data

Significant changes in vehicle fleet, travel patterns, road design and safety measures, traffic volumes, full-scale crash testing standards and roadside device crash testing, and safety improvement projects have occurred in the last 15 to 20 years. As a result, publications and presentations older than 2005 were included for discussion but not considered in detail.

2.3.1 Colorado, 2004

Colorado DOT performed an ISPE of their CMB systems in 2004 [19]. Colorado installed Brifen WRSF on three different roads as a pilot project. Most of the barrier installations were placed adjacent to the road shoulder, but approximately half the total mileage on Interstate 25 was located in the median behind two W-beams. Most of the investigated impacts with the CMB resulted in good performance, but one vehicle impacted the end of a W-beam system, passed beneath the cable barrier system, and impacted a vehicle in the opposing lanes. Representatives also noted that barriers placed on shoulders experienced increased numbers of impacts, including unreported crashes and damage from snowplows and snow removal efforts. Overall performance of the CMBs was believed to be good and beneficial at preventing cross-median crashes.

2.3.2 Oklahoma DOT, 2003

Oklahoma installed approximately 7.2 miles of Brifen CMB in 2000 and 2001 [20], as shown in Figure 4. CMB installations were placed in narrow, flat, divided medians. The Oklahoma DOT (ODOT) noted a decrease in fatal crashes after installing CMBs from 6 fatal crashes in 2001 to 1 in 2006. The average barrier damage during the impacts was approximately 5 posts. ODOT reported good success overall with the CMB performance, with 430 impacts with the CMBs identified through 2006. Overall maintenance, repairs, and installation were noted to be relatively easy and inexpensive. One particular crash resulted in a large truck being captured in the median, which was potentially above the design conditions for this median barrier system, as shown in Figure 5. However, no statistics were available to conclusively analyze the effectiveness of preventing cross-median crashes or the likelihood of other undesirable outcomes (barrier penetration, rollover, or barrier-related severe injuries or fatalities).

Figure 4. ODOT’s CMB [20]

Figure 5. Large Truck Stopped by Cable Median Barrier System in Oklahoma [20]

2.3.3 Oregon DOT, 2003

Oregon DOT installed CMBs in the late 1990s as a means of preventing cross-median crashes [21]. The CMB systems installed in the 1990s were low-tension, three-cable median barrier designs. The construction details for the ODOT CMB system are shown in Figure 6. Although the dataset was limited, a total of 11 CMCs were noted between 1994 and 1996, but after the completion of the CMBs, no CMCs were reported in the areas with CMBs installed out of the 231 identified CMB impacts for December 1996 through April 2002. Nonetheless, seven cable median barrier penetrations were identified in this timeframe, five related to underride and two related to override. ODOT sought to estimate the number of potential CMEs prevented by designating all crashes which damaged more than four CMB posts as “potential” CMEs. A total of 105 potential CMEs were identified, corresponding to 45% of all CMB crashes.

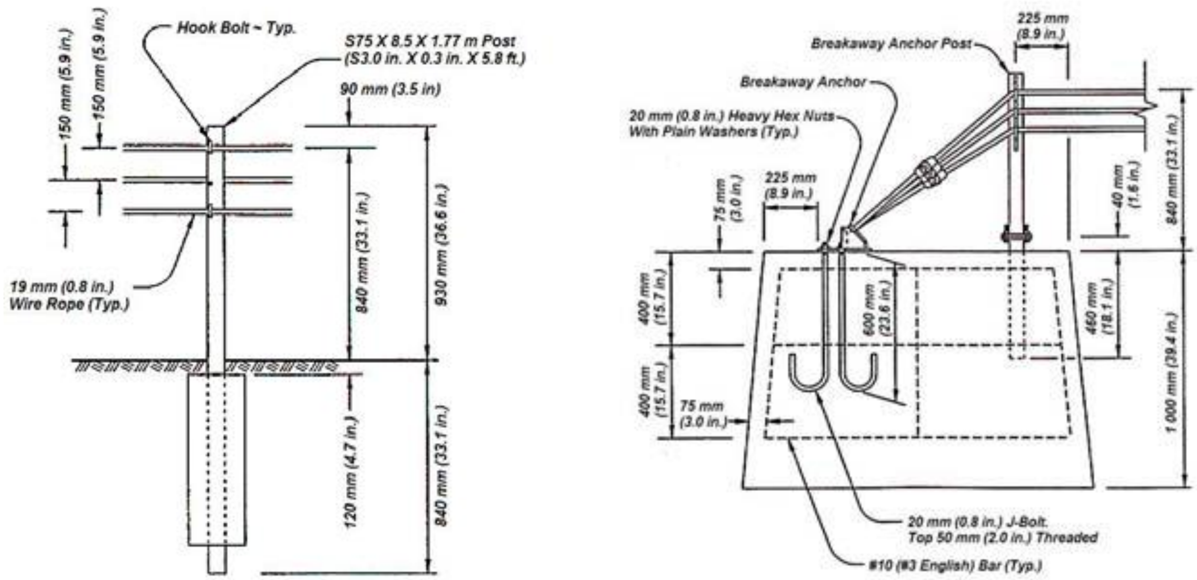


Figure 6. ODOT CMB Assembly and Construction Details [21]

2.4 Motorcyclist Safety

Several studies were conducted evaluating the risk of injury for motorcyclists in New South Wales, Australia, by examining medial data and reported crashes [22]. The Transport and Road Safety (TARS) center from the University of New South Wales investigated 1,364 motorcycle crash reports and associated injury classifications between 2001 and 2009. It was observed that non-barrier elements including trees, poles, and other fixed infrastructure was significantly more hazardous than barrier systems, including CMBs. Further analysis revealed that the predominant fatal injury mechanism for motorcyclists impacting roadside barriers was trauma to the torso (abdomen and thorax) followed by head injuries, which was unique compared to vehicle-to-vehicle crashes in which head injury predominates [23]. Sliding impacts with roadside barriers were also determined to result in more injuries to the pelvis and thorax, although injury profiles for riders who slid into the barrier vs. collided with the barrier while upright were similar.

It should be noted that barrier systems included all roadside barriers. Previous research has indicated that cable median barriers fare slightly better than W-beam and concrete barriers overall for preventing fatal injuries to motorcyclists [24]. However, CMBs are typically spaced farther from the roadway and therefore are impacted by motorcyclists less often, leading to fewer bad outcomes than barriers which were installed closer to the roadway.

3 METHODOLOGY

3.1 CMB Construction

KDOT identified approximately 7.95 miles of highway in which cable median barrier was installed in a divided median. Before analyzing crash data, KDOT maintenance records were evaluated which indicated the start and completion of the construction of CMB systems. Only CMB crashes which occurred after the KDOT-indicated date of CMB completion were considered when evaluating the CMB ISPE. The timelines of the CMB installations are shown below.

- K-10: Construction started August 2012, completed November 2012
- K-96: Construction started May 2011, completed December 2011
- US-75: Construction started April 2011, completed July 2011

The location of the CMB installations and mileage of the systems are shown Table 9. The CMB segments were also located on maps using Google Earth™ [25] and are shown in Figures 7 through 10.

Table 9. CMB Mileage in Kansas

Road Name	Nearby City	Total CMB Mileage	CMB Construction Started	CMB Construction Finished
K-10 (Douglas County)	Eudora	2.30 mi	August 2012	November 2012
K-10 (Johnson County)	Olathe	2.03 mi	August 2012	November 2012
US-75 (Shawnee County)	Topeka	0.51 mi	April 2011	July 2011
K-96 (Sedgwick County)	Wichita	3.11 mi	May 2011	December 2011
TOTAL		**7.95 mi**		

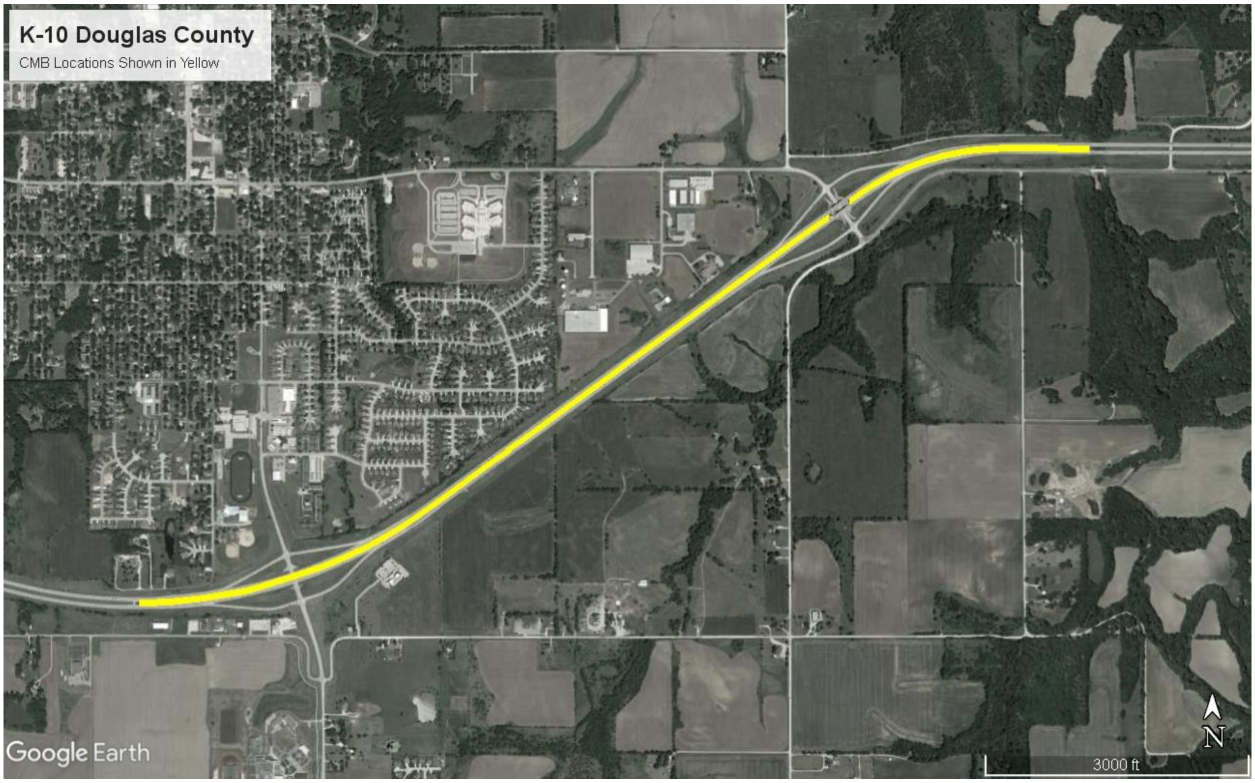


Figure 7. CMB Installations: K-10 in Douglas County (2.30 mi)

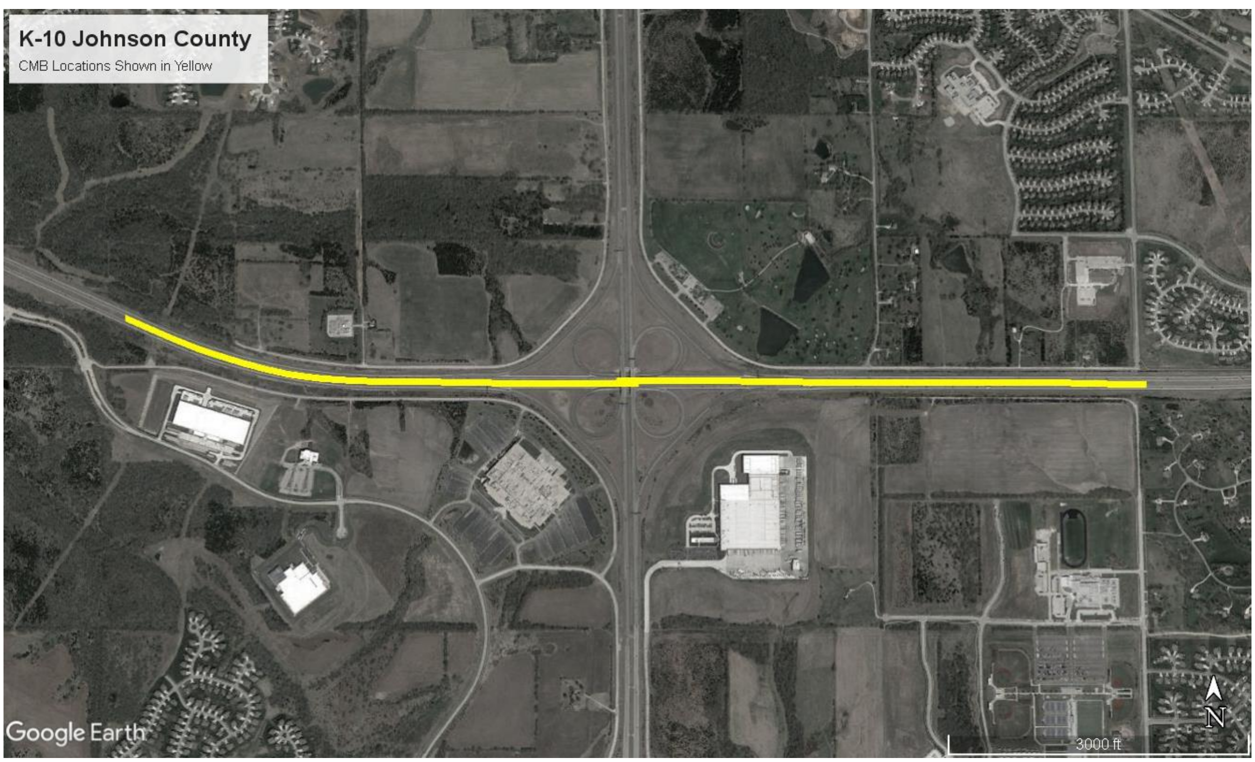


Figure 8. CMB Installations: K-10 in Johnson County (2.00 mi)

Figure 9. CMB Installation: US-75 (0.51 mi)

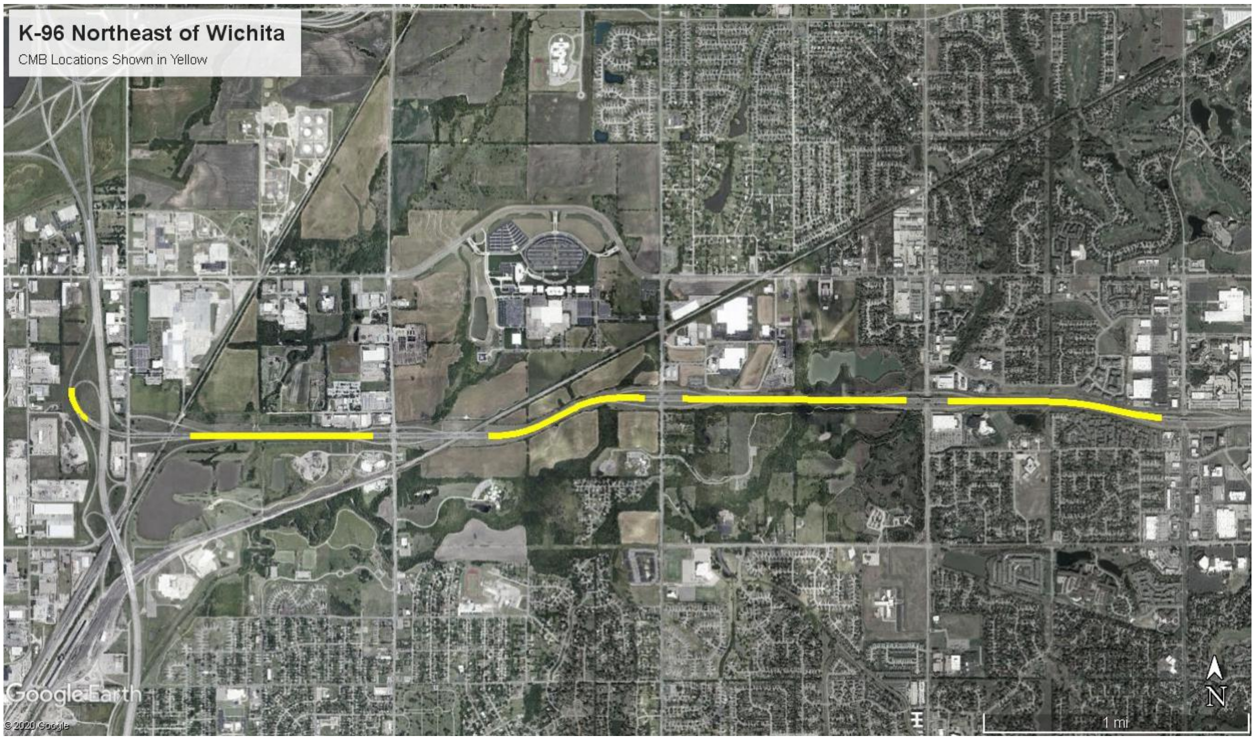


Figure 10. CMB Installations: K-96 (3.11 mi)

Several crashes occurred near the CMB construction locations during barrier installation; one crash involved impacting the barrier system before construction was completed and before cables were fully established and tensioned. These crashes were excluded from the analysis of the barrier performance.

3.2 Crash Data Collection

KDOT provided crash records from between January 1, 2009, and June 30, 2019. The crash dataset was partitioned into three parts: pre-CMB construction (before start of CMB construction), during construction, and post-construction. Crashes which occurred during the CMB construction were not included in the analysis. Baseline crash data considered all crashes which occurred before the start of the construction, and the post-construction dataset consisted of all data involving crash dates after the CMB construction was completed.

All crashes which occurred on the roads within the milepoints provided by KDOT and up to a half-mile away on either side of the reference mileposts were provided to MwRSF. KDOT also supplied geotags which supplied additional information, including the ADT of the roadway segments. University of Nebraska-Lincoln (UNL) researchers were tasked with reviewing the crash outcomes and identifying the subset of crashes which involved CMBs.

3.3 Analysis Procedure

Each scene diagram and crash narrative were reviewed to identify characteristics of the crash. Additional notes which were pertinent to the crash were also identified. Depending on the sequence of events which occurred during the crash, binary data were identified which were useful for classifying and evaluating CMB performance. A flow chart describing the evaluation of the crash sequence of events is shown in Figure 11. Right-side RORs were noted but the analysis primarily examined outcomes of left-side RORs. Right-side and left-side run-off-road (ROR) departures were not mutually exclusive.

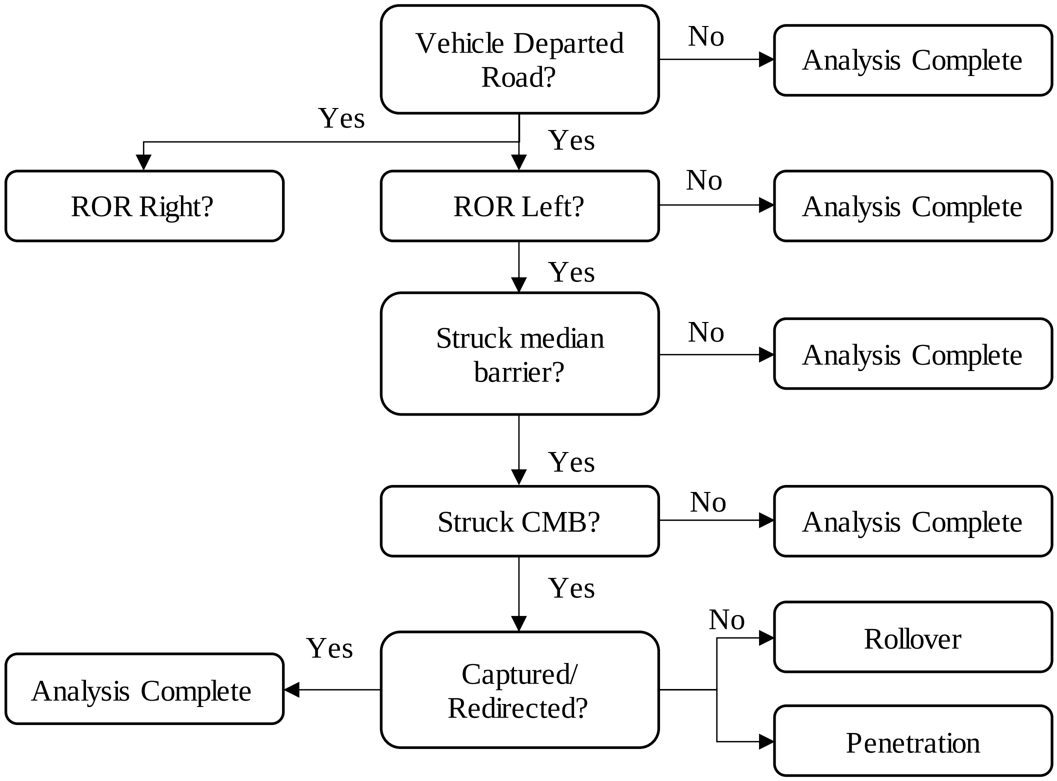


Figure 11. Flow Chart for Analyzing CMB Impact Data

The percentage of vehicle capture and/or redirection events as a percent of total events was also desired. The following terms were defined for use in this study:

- **Redirection** occurred when a vehicle rebounded away from the CMB after an impact.
- **Capture** was defined as a vehicle-to-CMB crash resulting in the barrier system stopping the vehicle while in contact with the system. Captures could include:
    - *Entanglement*, in which the vehicle had cables on both the left and right sides of the vehicle;
    - *Arrests*, in which the vehicle's forward progress was stopped with at least one cable located on the impact side of the vehicle; and
    - *Incidentals* in which the barrier absorbed a very small amount of energy from a low-speed impact with minimal damage to the vehicle or barrier system.
- **Penetration** was defined as a crash in which the vehicle passed completely from one side of the barrier to the other with no cables remaining in capture position; therefore, an outcome in which the vehicle came to rest on top of or beneath every cable of the barrier was considered a penetration crash.
- **Rollover** was defined as a vehicle trajectory resulting in a minimum of 90-degree roll rotation of the impacting vehicle on either its left or right side.

The injuries sustained in the crash were examined to determine the average crash severity and identify severe crashes, which could be compared to other state DOTs. **Severe crashes** were defined as crashes in which disabling or fatal injuries occurred to one or more occupants of the vehicle involved in the CMB impact.

3.4 Reference Data Sets & Comparisons

3.4.1 "Before-and-After"

Left-side departure crashes into unobstructed, grassy or paved medians do not always result in a crash event, and few – if any – non-crash events are reported to public safety departments or the DOT. Therefore, researchers sought to identify if the addition of cable median barrier increased the amount of reported left-side departure crashes compared to left-side departure crashes before the CMB was installed. The "baseline" median encroachment rate was estimated by comparing the number of *right-side departure crashes only* for yearly records before and following CMB installation. The number of on-road crashes only (no departures to the left or right side) were also identified and compared. The left-side encroachments and CMB impacts were compared to the total number of left-side encroachments before CMBs to estimate the crash increase factor. However, it was expected that some impact events would result in minimal damage and a "drive-away" response from drivers. Thus, not every left-side departure or crash would be reported, and thus the left-side departure rate would still be underrepresented.

3.4.2 Total Median Crash Rates

Many state DOTs reported a total percent increase in reported left-side departure crashes and total crashes after installing CMBs. The crash rate amplification factor found during the "before-and-after" analysis was compared to crash rate increases reported by other states after installing CMBs.

3.4.3 CMB Crash Outcomes

Crash outcomes were critical for determining the ISPE of KDOT's CMBs. Penetration and rollover crash rates were compared to similar rates reported for other states. The distribution of maximum injury sustained by any occupant of the vehicle which impacted the CMB was examined. Unfortunately, several concerns were raised during this project which affected the distribution of crash outcomes and serious injury rates:

- For one fatal crash in Kansas, the fatality was not in a vehicle affected by the CMB; nonetheless, the presence of the CMB and the CMB impact still likely contributed to the fatal crash outcome. It is uncertain whether the fatality would have occurred or not if the CMB was not installed; is it also uncertain if the CMB prevented a potentially more-serious CMC as a result.
- KDOT does not differentiate crash injury levels using a "KABCO" scale (K-Killed, A-Incapacitating Injury; B-Non-Incapacitating Injury; C-Minor/Possible Injury; O-Property Damage Only). The KDOT injury scale consisted of "Fatal," "Injury," and "Property Damage Only;" some responding officers provided additional classification for injury levels including "N" (not injured) and "P" (possible injury). However, collection was not consistent. It was not known how many serious/disabling ("A") injuries occurred which were related to CMB crashes. This could affect the estimation of the benefit-to-cost of CMBs as well as their overall effectiveness, which often utilizes either an MAIS or KABCO scale to estimate societal costs resulting from crashes of

different severities, such as using the Federal Highway Administration (FHWA) "Value of a Statistical Life" [26].

- For this study, every crash on roadways with CMB installed were reviewed individually to determine which crashes involved the CMB. It is difficult to compare this data with data from other state DOTs, which often tabulate CMB impacts based on First Harmful Event (FHE), Most Harmful Event (MHE), or Fixed Object Struck = Cable Median Barrier. Outcomes vary because in a sequence of impact events if a CMB was neither the most severe nor first object struck, and particularly if other fixed objects besides a CMB were struck, it is not clear whether the CMB impact was correctly identified. The total number of crashes which are attributable to, or correlated with, CMBs will change due to variations in how crashes are classified and the difference in distributions may affect injury percentage estimation. Researchers attempted to relate KDOT CMB outcomes with the most similar datasets from other states. In addition, some states do not track data including penetrations or rollovers.
- It is known, based on analysis of full-scale crash testing, that impact speed has a strong effect on vehicle stability, dynamic deflection of the system, vehicle and occupant accelerations, and barrier performance. In general, lower impact speeds are correlated with fewer undesirable crash outcomes and better overall barrier performance. Although impact speeds were not known for any of the CMB crashes in the available dataset, all of the divided median roadways with cable median barrier considered for KDOT were "commuter routes" which had disproportionately-high traffic volumes during peak travel hours, with significantly reduced traffic volumes at off-peak hours. During "rush hour," typical travel speeds are greatly reduced compared to the posted speed limit due to roadway congestion. Many CMB crashes were associated with conditions described as "bumper to bumper" or "stop-and-go" traffic. As such, results of this study may not be comparable to scenarios with significantly different traffic characteristics, such as rural freeways where traffic volumes do not have such sharp transitions between peak hours and non-peak hours.

The attributes of the datasets were considered in other states when making state-to-state data comparisons.

4 CMB IN-SERVICE PERFORMANCE EVALUATION RESULTS

The MwRSF research team at UNL reviewed each of the crash reports supplied by KDOT and identified crashes which involved a CMB. KDOT provided crash data and crash reports spanning between 2011 and 2019 on highways K-10, K-96, and US-75 near the CMB locations. A total of 1,723 candidate crashes were identified; note that some crashes were removed from consideration which were noted to correspond to the freeways, but which were either (a) confined to an exit or entrance ramp to one of the roadways (and hence did not interact with the highway or highway traffic); or (b) involved a different roadway but was misclassified. A summary of all crash data collected from KDOT is shown in Table 10.

Table 10. Summary of KDOT Crash Data: January 1, 2009 – June 30, 2019

Road	All Crashes*		RS Departures		LS Departures		RS + LS Departures		On-Road Only		Crash Years w/ CMB
K-10 DG County	144	8.4%	35	24.3%	55	38.2%	8	5.6%	62	43.1%	**6.6**
K-10 JO County	515	29.9%	116	22.5%	179	34.8%	2	0.4%	222	43.1%	**6.6**
US-75	44	2.6%	17	38.6%	16	36.4%	7	15.9%	18	40.9%	**7.9**
K-96	1020	59.2%	114	11.2%	218	21.4%	23	2.3%	711	69.7%	**7.5**
TOTAL	**1723**		**282**	**16.4%**	**468**	**27.2%**	**40**	**2.3%**	**1013**	**58.8%**	**-**

*Crash records do not include crashes which were not related to noted highway segments
RS – Vehicle c.g. crossed over road edge on Right Side
LS – Vehicle c.g. crossed over road edge on Left-Side
RS + LS – Vehicle c.g. crossed over road edge on both Right and Left Sides
On-Road Only: Total Crashes – {Right + Left – (Right and Left) Departures}
Crash Years with CMB: Total number of years CMB was installed during 2009-2019 data range

4.1 CMB Crash Summary

Within the available dataset, a total of 409 crashes occurred before CMB construction began and 1,220 crashes occurred after CMB construction was completed. Note that because crashes which occurred during construction may not be representative of the effectiveness of the CMB, they were omitted from before-and-after analysis and determination of CMB performance. A total of 150 crashes occurred during construction, six of which involved a CMB; however, those CMB crashes were not considered. When evidence was not sufficient to identify if the CMB was impacted, the crash result was excluded. Examples of excluded crashes included minimalized narratives, no scene diagrams, or inconclusive language which did not denote impacts or roadside barriers. Crashes which did enter the median (left-side departure) and which impacted barriers other than CMB were also denoted. Note that for several crashes, best estimates were applied for crash outcomes as it was unclear from narratives or scene diagrams which barrier was impacted. The flow chart assignment method shown in Figure 11 was used to evaluate the crash outcomes, and results are shown in Tables 11 through 12.

Table 11. Baseline Crash Data Before Start of CMB Construction in Kansas

Road	All Crashes*		RS Departures		LS Departures		RS + LS Departures		On-Road Only		Hit Median Barrier	
K-10 DG County	64	5%	15	23%	17	27%	5	8%	37	58%	1	2%
K-10 JO County	160	13%	35	22%	44	28%	0	0%	81	51%	44	28%
US-75	11	1%	4	36%	3	27%	2	18%	6	55%	3	27%
K-96	174	14%	32	18%	30	17%	4	2%	116	67%	30	17%
OVERALL	**409**		**86**	**21%**	**94**	**23%**	**11**	**2.7%**	**240**	**59%**	**78**	**19%**

Table 12. Crash Data After CMB Construction was Completed in Kansas

Road	All Crashes*		RS Departures		LS Departures		RS + LS Departures		On-Road Only		Hit Median Barrier		Hit CMB	
K-10 DG County	75	6%	18	24%	36	48%	2	3%	23	31%	31	41%	27	36%
K-10 JO County	340	28%	77	23%	131	39%	2	1%	134	39%	131	39%	106	31%
US-75	32	3%	13	41%	13	41%	5	16%	11	34%	13	41%	5	16%
K-96	773	63%	74	10%	173	22%	15	2%	541	70%	173	22%	116	15%
OVERALL	**1220**		**182**	**15%**	**353**	**29%**	**24**	**2.0%**	**709**	**58%**	**348**	**29%**	**254**	**21%**

Some events, including weather and crash severity, are highly correlated with crash dates. For these crashes, the datasets were extracted such that only full calendar years for *all* available roadways were considered. The first CMB construction began in 2011 (Kansas Highway US-75) and the final CMB construction was finished in November 2012 (Kansas Highway K-10). Therefore, when appropriate, researchers considered these extracted datasets and excluded crash data which fell outside of the following calendar ranges:

- Pre-CMB Construction: January 2009 through December 2010
- Post-CMB Construction: January 2013 through December 2018

The full calendar year datasets were subsets of the pre- and post-CMB construction datasets. As the size of the dataset decreased, the significance and confidence in the conclusions likewise decreased. Therefore, attempts were made to delineate differences in conclusions based on which datasets were used for each analysis. The baseline and CMB data for the calendar year extraction is shown in Tables 13 and 14.

Table 13. Baseline Full-Calendar Year Crash Data Before Start of CMB Construction in Kansas (2009-2010)

Road	All Crashes* (2009-2010)		RS Departures		LS Departures		RS + LS Departures		On-Road Only		Hit Median Barrier	
K-10 DG County	40	3%	15	38%	17	43%	5	13%	13	33%	0	0%
K-10 JO County	92	8%	35	38%	44	48%	0	0%	13	14%	8	9%
US-75	11	1%	4	36%	3	27%	2	18%	6	55%	1	9%
K-96	135	11%	32	24%	30	22%	4	3%	77	57%	12	9%
OVERALL	**278**		**86**	**31%**	**94**	**34%**	**11**	**4.0%**	**109**	**39%**	**21**	**8%**

Table 14. Full-Calendar Year Crash Data After CMB Construction was Completed in Kansas (2013-2018)

Road	All Crashes* (2013-2018)		RS Departures		LS Departures		RS + LS Departures		On-Road Only		Hit Median Barrier		Hit CMB	
K-10 DG County	70	6%	17	24%	33	47%	2	3%	22	31%	29	41%	25	10%
K-10 JO County	307	25%	73	24%	119	39%	1	0%	116	38%	104	34%	97	38%
US-75	24	2%	10	42%	8	33%	4	17%	10	42%	6	25%	3	1%
K-96	624	51%	60	10%	138	22%	12	2%	438	70%	132	21%	94	37%
OVERALL	**1025**		**160**	**16%**	**298**	**29%**	**19**	**1.9%**	**586**	**57%**	**271**	**26%**	**219**	**21%**

4.1.1 CMB Crash Locations

Each crash had an associated “crash location” denoted using GNSS coordinates in latitude and longitude assigned by KDOT. However, crashes occur over broad longitudinal areas; it was unclear whether this geospatial position indicated start of vehicle instability, point of impact, approximate “centerpoint” of vehicle trajectory, vehicle final rest, or a different reference point. As such, the crash locations are considered as approximations of the locations of the crashes. A graphical summary of CMB crashes shown with respect to CMBs are provided in Figures 12 through 15.

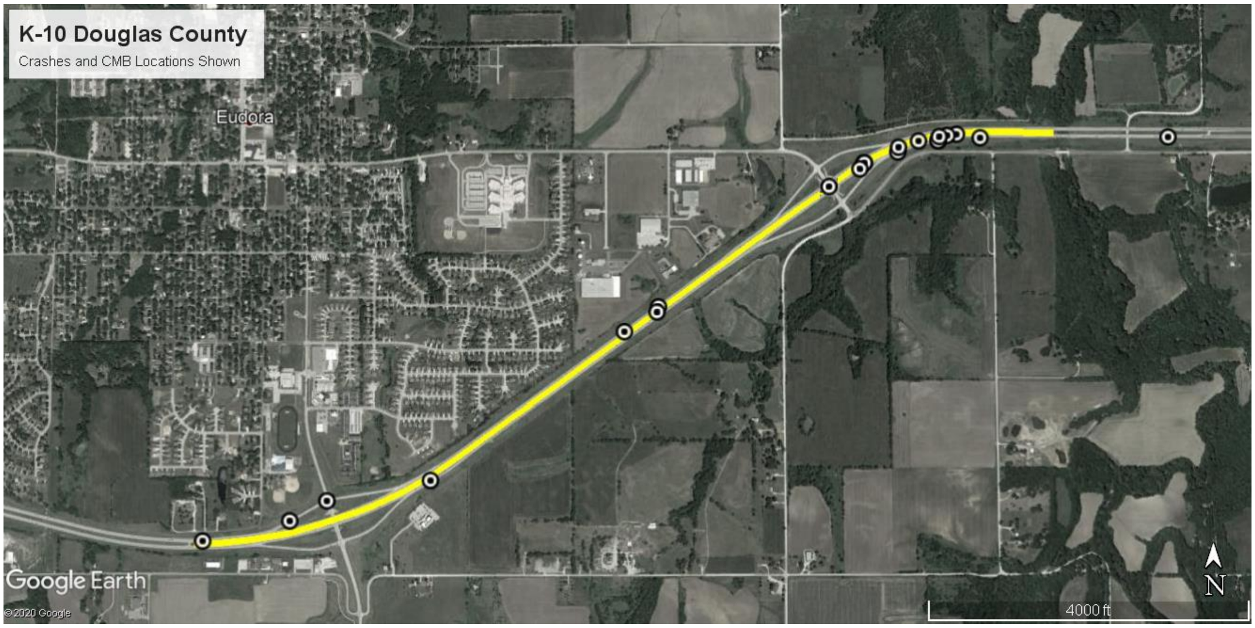


Figure 12. CMB Crashes on Kansas K-10 Roadway in Douglas County

Figure 13. CMB Crashes on Kansas K-10 Roadway in Johnson County

Figure 14. CMB Crashes on Kansas K-96 Highway

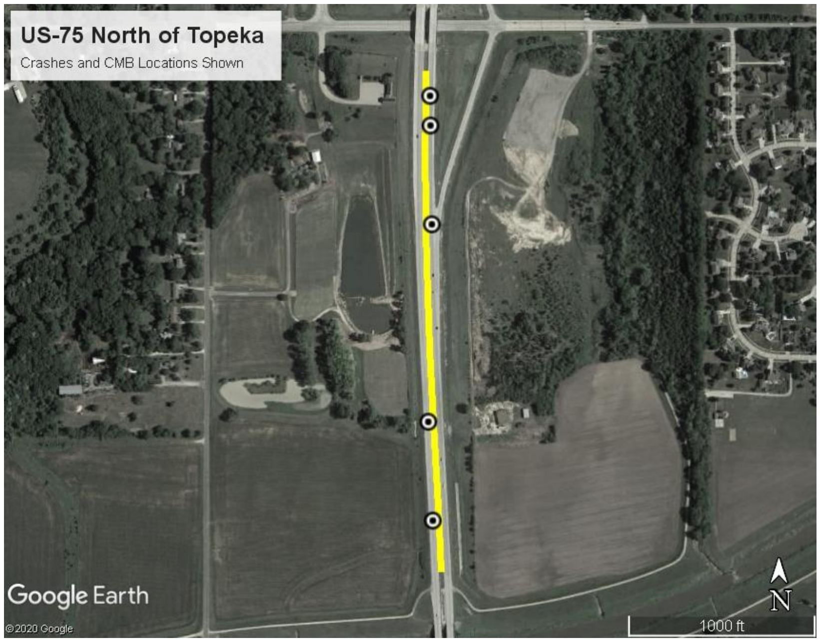


Figure 15. CMB Crashes on Kansas US-75 Highway

4.1.2 CMB Exposure

Daily and annual traffic volumes on roads in Kansas varied through the range of crash data provided, which spanned from 2009 to 2019. During the recession between 2007 and 2013 in the United States, unemployment increased and vehicle-miles traveled (VMT) decreased, although the extent of traffic volume reductions varied geographically. Likewise, there was a significant reduction in overall traffic-related deaths during the same time period [27]. There has been evidence that VMT declines alone do not account for the reduction in traffic deaths, but that groups with the highest rates of traffic fatality, namely younger drivers, were disproportionately affected during the financial crisis [28]. Reduced traffic from high-risk drivers may have been the greatest contributor to the reduction in deaths through 2012.

All CMBs installed in Kansas were completed between 2011 and 2012. The VMT and number of national travel deaths both increased starting in 2012, and while traffic deaths stabilized, VMT has continued to increase. Therefore, the data corresponding to the non-CMB "baseline" may have suppressed exposure compared to CMBs after the recession had ended.

Exposure was calculated using hundred-million vehicle-miles traveled (HVMT) based on the length of each CMB system and the AADT, as well as crashes per mile (total and per year). A summary of the exposure of the CMB systems based on total number of CMB impacts is shown in Tables 15 and 16.

Table 15. CMB Exposure Calculations in Kansas: All Crashes After CMB Construction Completed

Road	Years CMB Installed	Hit CMB		Miles CMB	HVMT at CMB/year	Total HVMT with CMB	Crashes/HVMT	Crashes/ Mile CMB	Crashes/Mile CMB per year
K-10 DG	**6.58**	27	36%	2.30	0.254	1.673	16.14	11.74	1.79
K-10 JO	**6.58**	106	31%	2.03	0.373	2.451	43.25	52.22	7.94
US-75	**7.91**	5	16%	0.51	0.049	0.385	12.98	9.80	1.24
K-96	**7.49**	116	15%	3.11	0.654	4.902	23.67	37.30	4.98
TOTAL	**-**	**254**	**21%**	**7.95**	**1.330**	**9.410**	**26.99**	**31.95**	**3.99**

Table 16. CMB Exposure Calculations in Kansas: Crashes After CMB Construction Completed with Full Calendar Year Data (2013-2018)

Road	Crash Years 2013-2018	Hit CMB		Miles CMB	HVMT at CMB/year	Total HVMT with CMB	Crashes/HVMT	Crashes/ Mile CMB	Crashes/Mile CMB per year
K-10 DG	**6.00**	25	36%	2.30	0.254	1.526	16.38	10.87	1.81
K-10 JO	**6.00**	97	32%	2.03	0.373	2.236	43.38	47.78	7.96
US-75	**6.00**	3	13%	0.51	0.049	0.292	10.27	5.88	0.98
K-96	**6.00**	94	15%	3.11	0.654	3.925	23.95	30.23	5.04
TOTAL	**-**	**219**	**21%**	**7.95**	**1.330**	**7.979**	**27.45**	**27.55**	**3.95**

The CMB installed on K-10 in Johnson County and K-96 experienced significantly more crashes per year, per mile, and per HVMT compared to K-10 in Douglas County and US-75 highway. The HVMT with CMB in Douglas county was 0.254, compared to 0.373 in Johnson county (46% increase), but the crash rate per HVMT was 43.4 in Johnson County compared to 16.4 in Douglas county (168% increase).

The concentration of crashes appeared to be associated with two features: (a) roadway curves and (b) urban interchanges. Both K-10 in Douglas County and US-75 were primarily suburban/rural routes with few interchanges; approximately half of the crashes on K-10 in Douglas County occurred on the north-most curve, as in Figure 12. In comparison, crashes on K-96 (urban with many interchanges) and K-10 in Johnson County at the interchange of K-10 and K-7 interstates were disproportionately high. The highest crash rates per HVMT occurred in conjunction with K-10 in Johnson County and K-96.

Due to the limited number of installations and mileage of barriers, limited conclusions could be drawn regarding the CMB exposure. However, for the high-traffic roadways it was observed that median barrier crash rates, and hence median encroachments, were significantly higher around interchanges and near curves than on straight-line roads with few interchanges.

4.1.3 Weather & Road Conditions at Time of Crash

Weather events have a strong effect on crash rates due to decreased tire-pavement friction, reduced visibility, and reduced vehicle control. Therefore, it is important to determine whether weather-related effects had a strong influence on CMB impact likelihood by comparing weather effects before and after CMB installations. Results are shown in Figure 16. It should be noted a total of 409, 94, and 1,220 crashes occurred before, during, and after construction of the CMBs, respectively.

Results overall were very similar for before, after, and all crashes. Results indicated that a higher percentage of "winter-weather" crashes occurred before CMB construction which is likely because the construction start dates were all in summer and fall timelines, resulting in "undersampled" warm, dry weather conditions. Likewise, the number of rainy- and winter-weather crashes were very similar for post-CMB installation and all crashes because 1,220 of the 1,723 crashes in the database occurred after CMBs were installed. Despite these observations and differences, it was concluded that the weather patterns before and after CMB installations were not significantly different and likely did not result in statistical differences in crash severity or frequency.

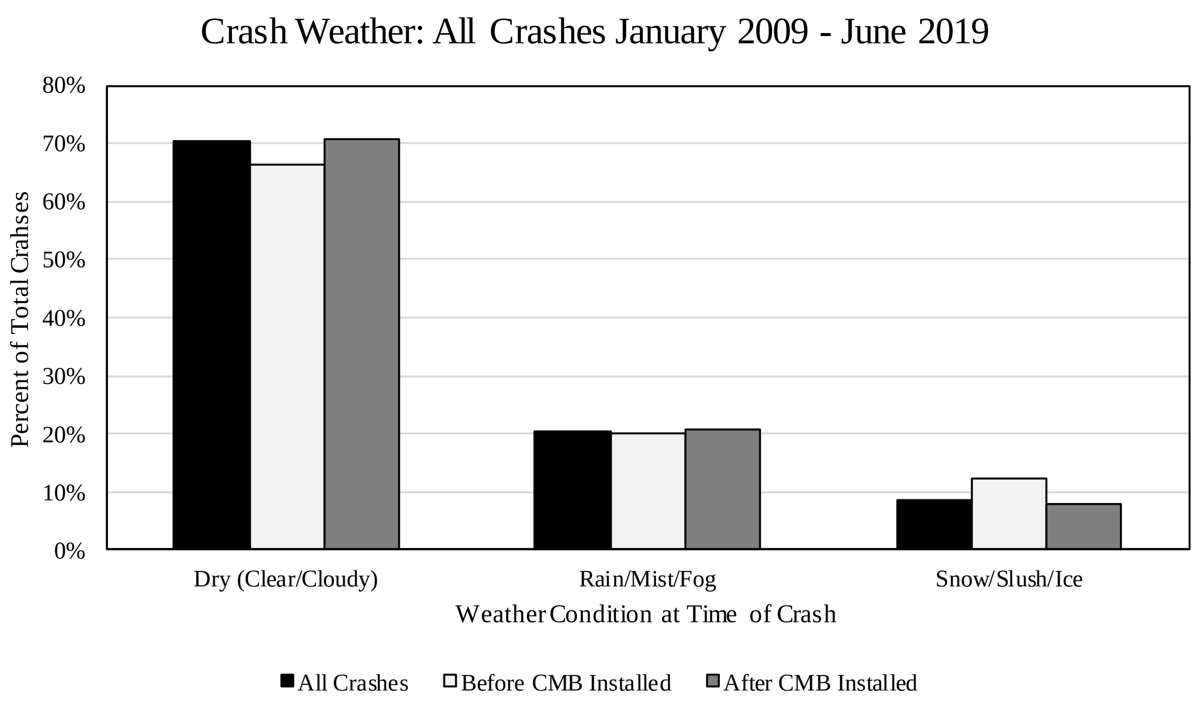


Figure 16. Weather at Crash Time, KDOT Data Summary

Next, the distribution of weather effects for CMB-related and non-CMB crashes was compared, as shown in Figure 17. Recall, CMB crashes had only one common characteristic: a left-side departure resulting in contact with the cable median barrier. Non-CMB crashes consisted of left-side departure crashes not impacting CMBs, on-road only, and right-side only ROR crashes.

Note that all CMB impacts were evaluated equally, as severity indicators such as speed and angle were not known for any CMB crash.

The weather patterns of non-CMB crashes were consistent with the distribution of all post-CMB installed crashes, largely because the number of CMB crashes (254) was vastly lower than non-CMB crashes (966) for the same time period. Still, CMB crashes exhibited significantly higher percentages of “adverse” weather (rain, snow, sleet, hail, etc) than non-CMB crashes. This observation was further explored by examining the distribution of all ROR and non-ROR outcomes, as shown in Figure 18. Crashes involving CMB were more likely to be associated with rain and snow outcomes than any other ROR outcome, including left-side non-CMB, right-side, and no departure (on-road only) crashes.

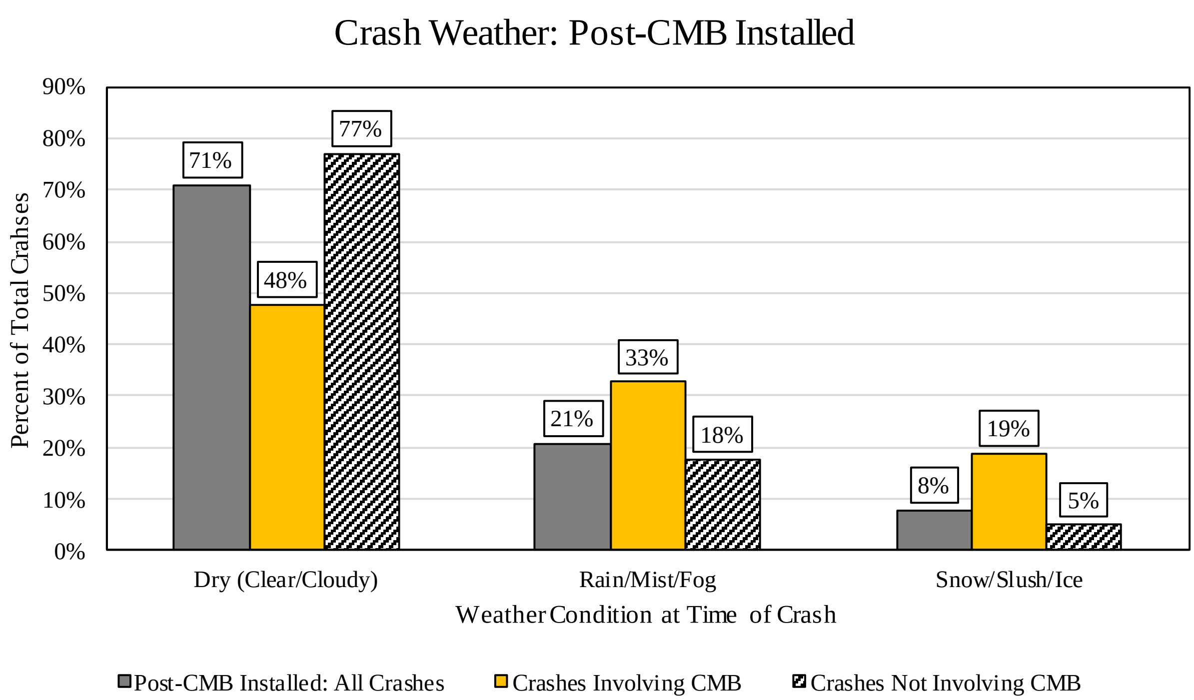


Figure 17. Crash Weather After CMB Installed: CMB vs Non-CMB Crashes

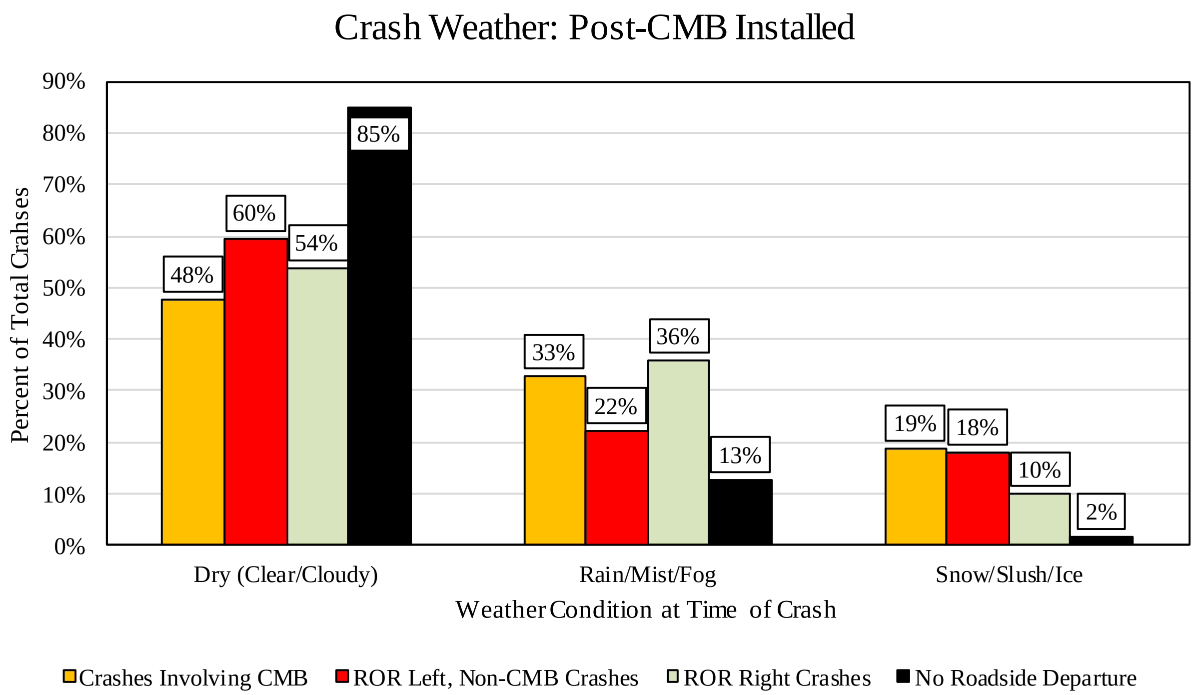


Figure 18. Crash Weather After CMB Installed: ROR Distribution

Results suggested that the lateral offset of the vehicle into the median or the roadside may be strongly related to the weather condition and tire-ground friction. During wet or icy weather, friction capacity on paved roads is known to drop by 30 to 80% (peak dry friction ranging 0.8-1.2 for asphalt and concrete, wet asphalt and concrete 0.6-0.8, icy asphalt and concrete 0.1-0.4). Although less is known about roadsides and grassy conditions under adverse weather, the peak dry-weather friction on grass or dirt medians is approximately 0.4-0.6 [29]. Therefore, road departures during adverse weather may be associated with larger lateral offsets. The increase in lateral offset for left-side departure crashes associated with adverse weather was also identified during a previous crash study to investigate CMB warrants in Kansas [1-2].

As previously noted, potential differences in distributions or crash outcomes may occur when including or excluding data from partial calendar years. These differences may be attributable to weather differences or crash rate differences on different road segments at CMB locations. The weather-related results for only calendar years 2013 through 2018 was plotted, in which all CMB construction was completed and full calendar year data was available for every road. Minor differences were noted, but the overall behavior was unchanged compared to results without the calendar year subset, as shown in Figures 19 and 20.

Odds ratios were calculated for CMB weather-related contributions. Results indicated that snowy, slushy, or icy conditions increased the risk of CMB crashes by approximately 2.4 times in comparison with all crashes. Moreover, the risk of CMB crash during snowy, slushy, or icy weather was 3.9 times more likely than non-CMB crashes and by approximately 9.5 times compared to non-ROR crashes for the same weather conditions. CMB crash rates also increased by factors of 1.5, 1.8, and 2.5 for wet, rainy, or foggy conditions compared to all crashes, non-CMB crashes, and non-ROR crashes, respectively.

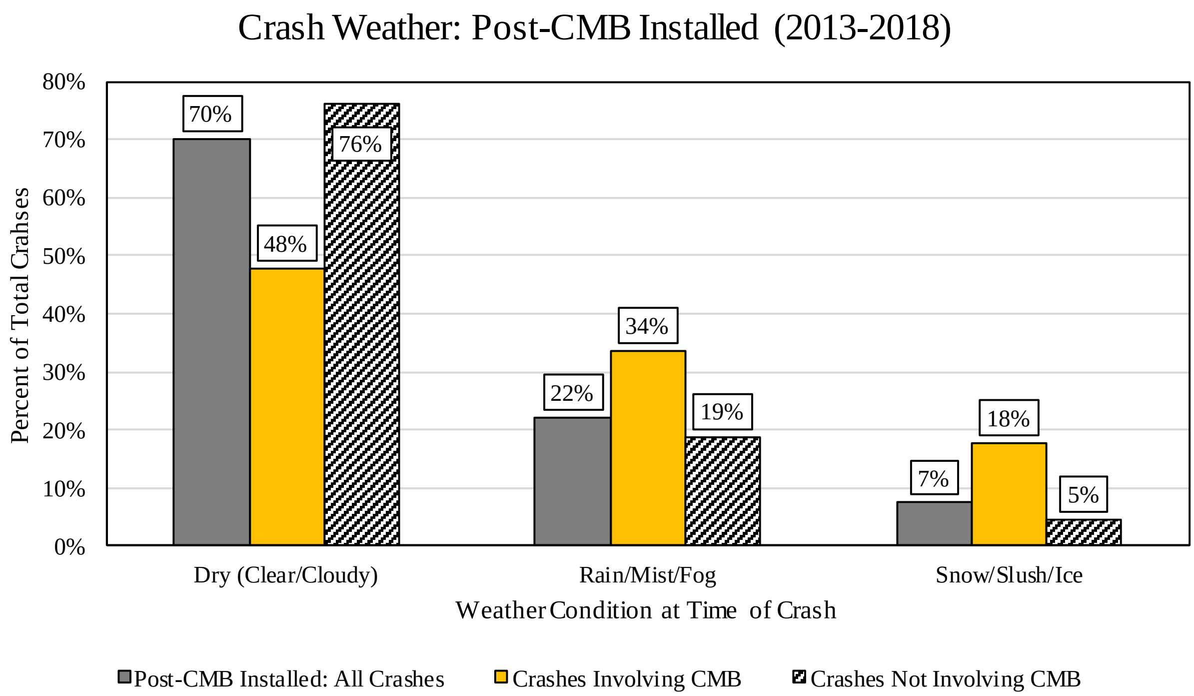


Figure 19. Crash Weather After CMB Installed: CMB vs Non-CMB Crashes (2013-2018)

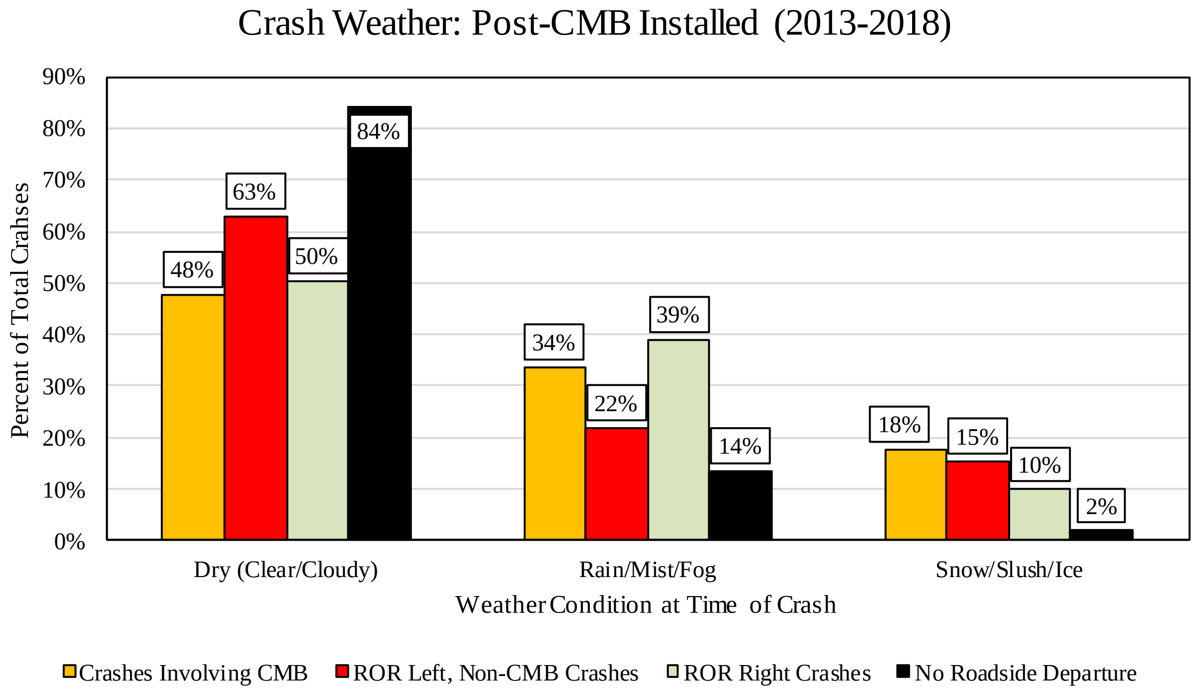


Figure 20. Crash Weather After CMB Installed: ROR Distribution (2013-2018)

4.1.4 Crash Time of Day

The reported time of the crash was also plotted using a "radar plot," as shown in Figure 21. For both crashes involving CMB and non-CMB crashes, the number of crashes declined significantly after 7 pm, and peaked between 7 and 9 am and 5 to 7 pm. Approximately 67% of all crashes involving CMBs occurred between the hours of 7 am and 5 pm, compared to 56% for non-CMB crashes. Moreover, non-CMB crashes peaked between 7 and 9 am (18.2%) and 5 to 7 pm (21.8%); approximately 35% of all non-CMB crashes occurred between 3 and 7 pm and approximately a sixth (16%) of all non-CMB crashes occurred between 5 and 6 pm. Results indicate that during peak traffic hours, crashes were more likely to occur and fatigued drivers in the late afternoon were more likely to be involved in a crash.

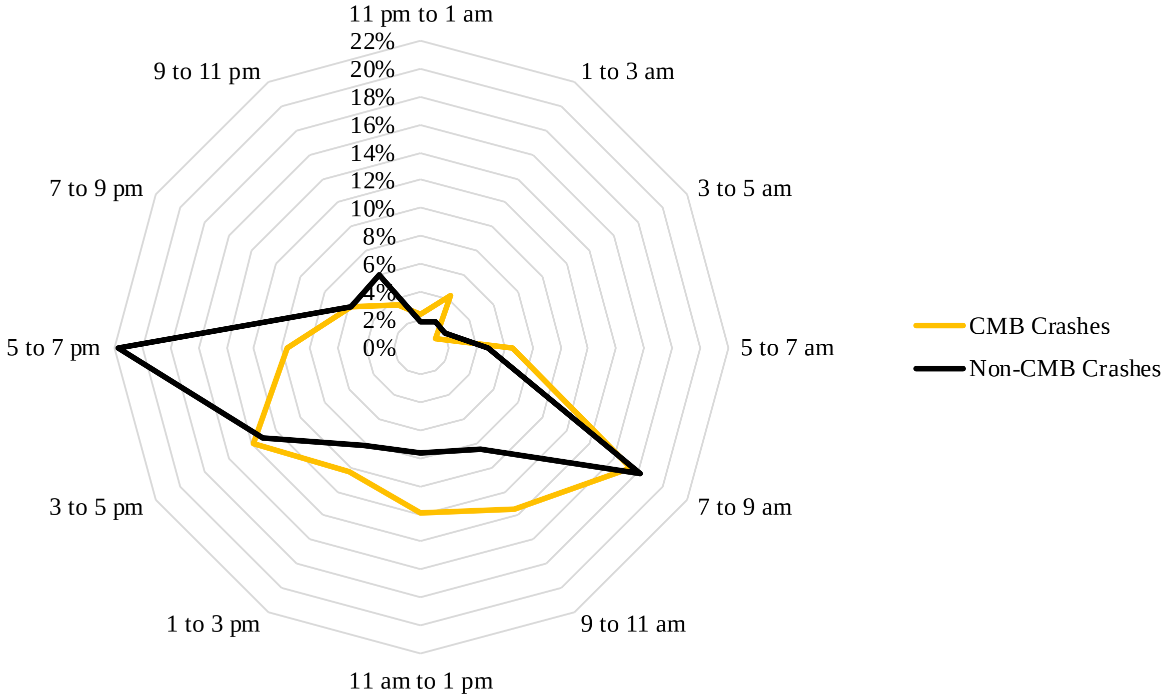
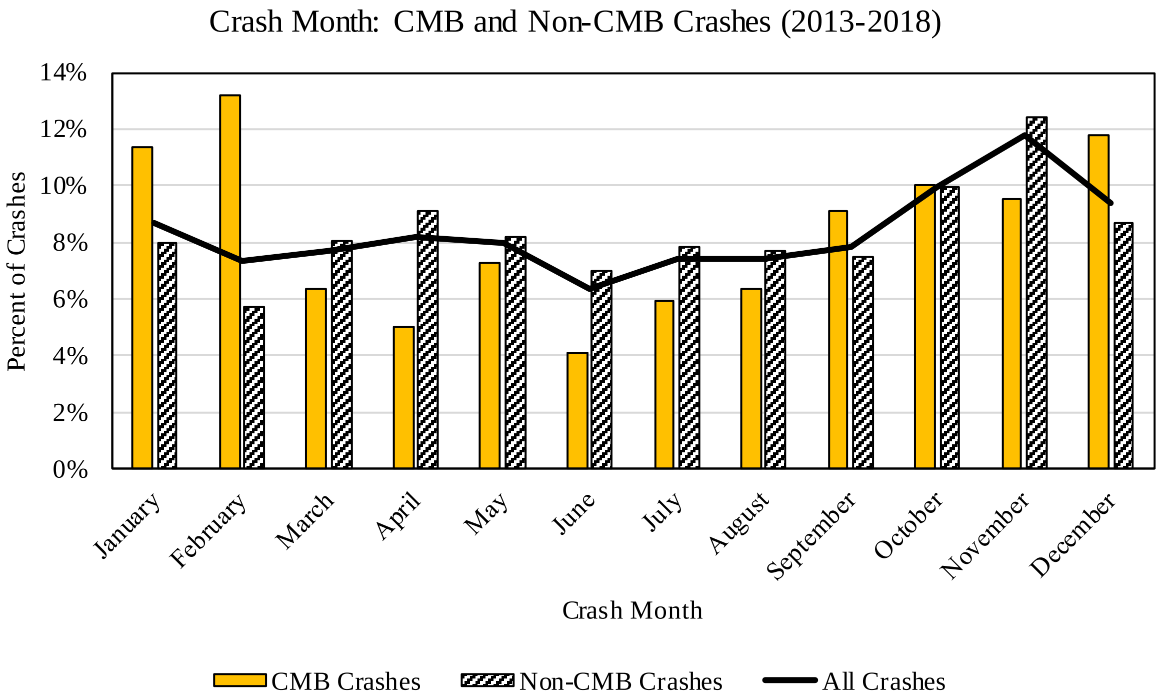


Figure 21. Crash Time: Crashes Involving CMB and Non-CMB Crashes

4.1.5 Crash Date

Next, the reported date of the crash was examined to determine if crashes involving CMBs were comparable to crashes not involving CMBs, as shown in Figure 22 and Table 17. Researchers only considered the time between January 1, 2013, and December 31, 2018 to ensure full calendar years of data were available and that all CMB construction was finished. Non-CMB crashes were more distributed, with a peak in October and November. CMB crashes were less common from March through August, more frequent between September and November, and more than 36% of CMB crashes occurred between in the months of December, January, and February ("winter months"). More CMB crashes occurred in December, January, and February than the six months between March and August.



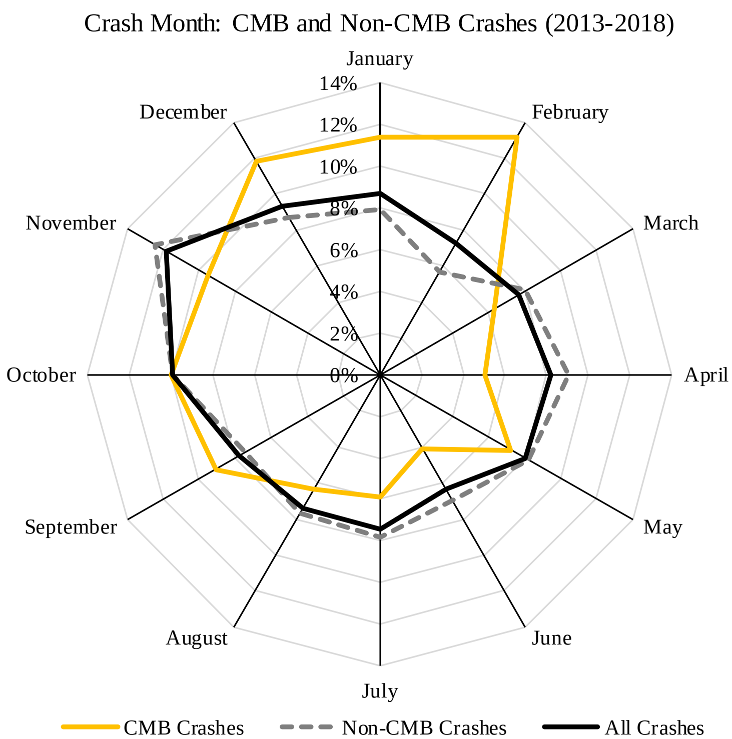


Figure 22. Crash Month: Crashes Involving CMB, Non-CMB Crashes, and All Crashes (2012-2018)

Table 17. Crash Month Summary: Calendar Years 2013-2018

Crash Month	**ALL CRASHES**		**CMB Crashes**		**Non-CMB Crashes**		**ROR Left Crashes**		**ROR Right Crashes**		**Non-ROR Crashes**	
	No.	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**
January	89	8.7%	25	11.4%	64	8.0%	32	10.7%	18	11.3%	42	7.2%
February	75	7.3%	29	13.2%	46	5.7%	36	12.1%	11	6.9%	29	4.9%
March	79	7.7%	14	6.4%	65	8.1%	22	7.4%	13	8.1%	46	7.8%
April	84	8.2%	11	5.0%	73	9.1%	17	5.7%	10	6.3%	57	9.7%
May	82	8.0%	16	7.3%	66	8.2%	24	8.1%	16	10.0%	44	7.5%
June	65	6.3%	9	4.1%	56	7.0%	13	4.4%	16	10.0%	38	6.5%
July	76	7.4%	13	5.9%	63	7.8%	17	5.7%	11	6.9%	50	8.5%
August	76	7.4%	14	6.4%	62	7.7%	21	7.0%	5	3.1%	51	8.7%
September	80	7.8%	20	9.1%	60	7.5%	24	8.1%	10	6.3%	48	8.2%
October	102	10.0%	22	10.0%	80	9.9%	29	9.7%	14	8.8%	60	10.2%
November	121	11.8%	21	9.5%	100	12.4%	27	9.1%	17	10.6%	79	13.5%
December	96	9.4%	26	11.8%	70	8.7%	36	12.1%	19	11.9%	42	7.2%
TOTAL (2013-2018)	**1,025**		**220**		**805**		**298**		**160**		**586**	
Annual Average	**170.8**		**36.7**		**134.2**		**49.7**		**26.7**		**97.7**	
Monthly Average	**14.24**		**3.06**		**11.18**		**4.14**		**2.22**		**8.14**	
Distribution	**-**		**21.5%**		**78.5%**		**29.1%**		**15.6%**		**57.2%**	

NOTE: CMB and Non-CMB crashes are mutually exclusive groupings. ROR left and ROR right crashes are not mutually exclusive, but neither are included in Non-ROR crash grouping.

The data were normalized by dividing the monthly crashes by the number of days per month and multiplying the total crashes by the annual average days per month (30.4). (Note, because 2012 and 2016 were leap years, the average days in February for the analysis timeframe was 28.29). Again, results indicated that CMB crashes were much more likely during the winter months of December, January, and February compared to non-CMB crashes; approximately 37% of all CMB crashes occurred during these months, as shown in Figure 23. In general, after normalization the non-CMB crash months were generally similar to the “expected” value of 8.5% (1/12) except for October (10.0%) and November (12.4%).

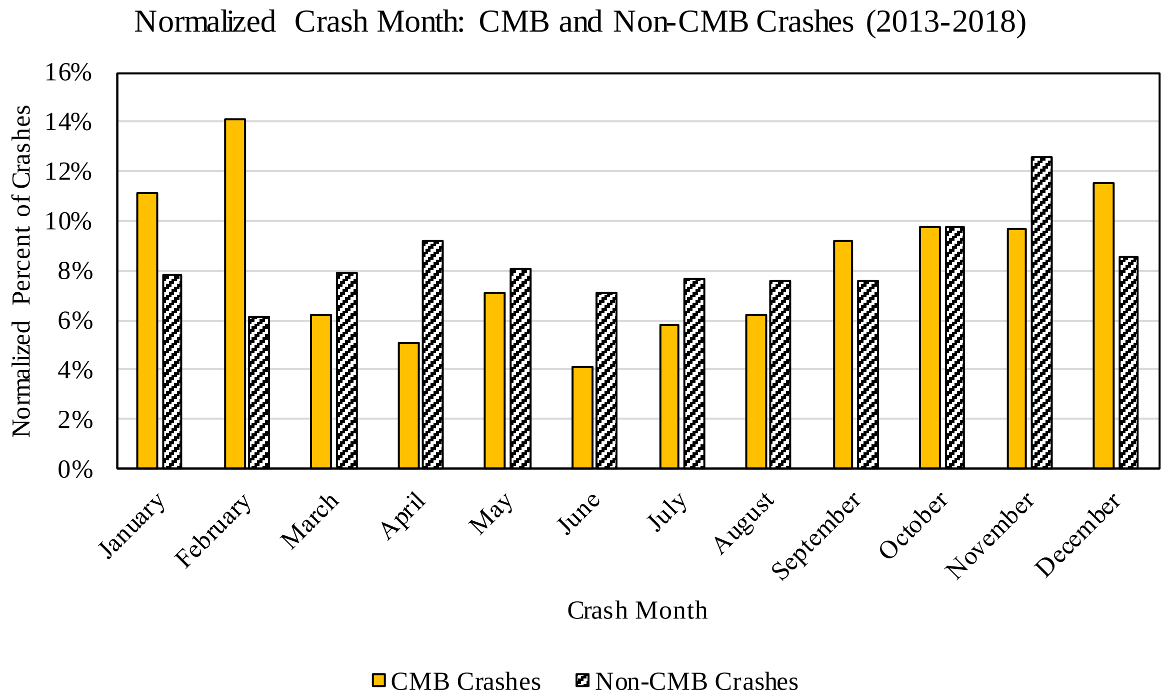
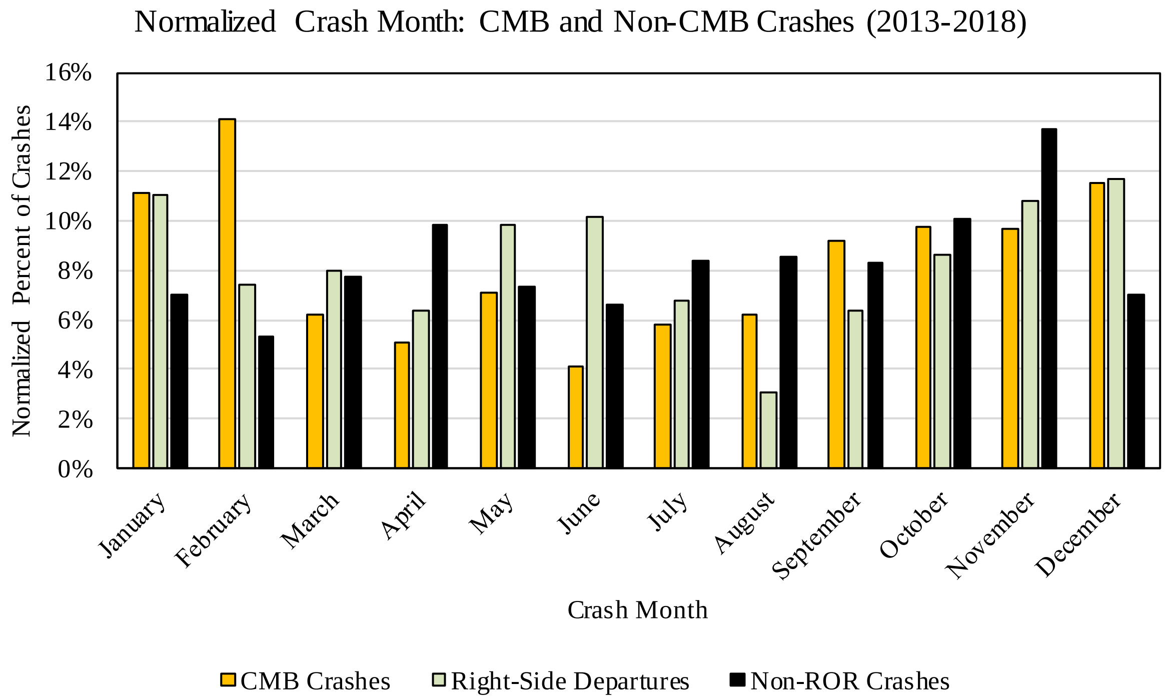


Figure 23. Crash Month: CMB and Non-CMB Crashes

To further examine if the crashes involving CMBs were unique compared to other ROR crashes, the distributions of crash months for CMB crashes, right-side ROR crashes, and non-ROR (on-road only) crashes were compared. Results indicated that ROR crashes were much higher for both right- and left-side departures during December and January and were similar to left-side ROR, CMB crashes. Surprisingly, right-side ROR crashes were significantly less common during the months of August and September. The non-ROR crashes were again highest during October and November, with another peak in April. Non-ROR crashes (as a percent of total) were also surprisingly low for winter months of December, January, and February, even as the total number of crashes during that time period increased. No other major patterns or observations with respect to crash date were identified.



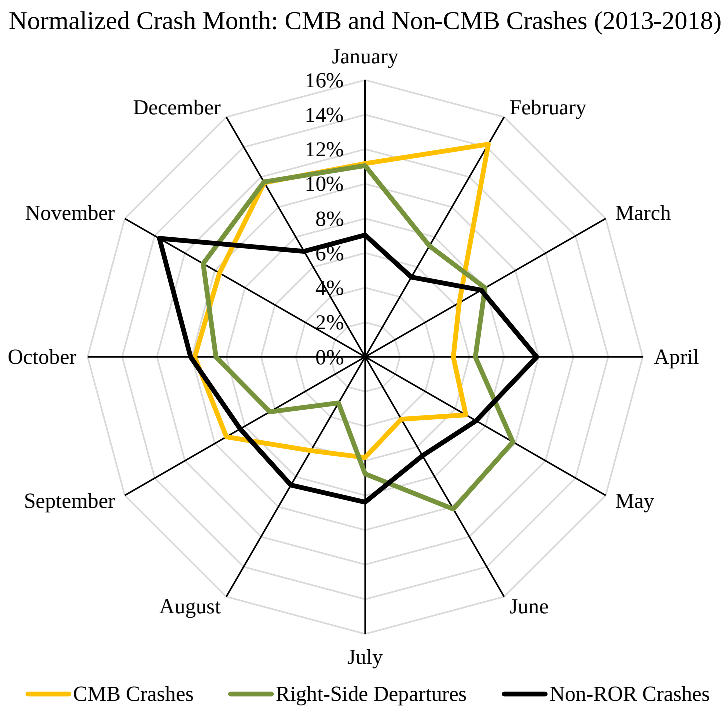


Figure 24. Crash Month: CMB Crashes, Right-Side Departure, and Non-ROR Crashes

Finally, the crash dates for the "baseline" period prior to the installation and completion of the CMBs were plotted to compare with crash dates after installing CMBs. As the baseline dataset was much smaller than the post-CMB crash dataset, only the full calendar-year data were evaluated to avoid discrepancies associated with weather- and date-related phenomena. Results are shown in Table 20 and plotted in Figure 25.

Table 18. Baseline Data Crash by Month: 2009-2010

Crash Month	ALL CRASHES		ROR Left Crashes		ROR Right Crashes		Non-ROR Crashes	
	No.	%	No.	%	No.	%	No.	%
January	22	7.9%	4	7.0%	5	9.6%	13	7.3%
February	22	7.9%	3	5.3%	5	9.6%	14	7.9%
March	18	6.5%	5	8.8%	3	5.8%	10	5.6%
April	8	2.9%	3	5.3%	1	1.9%	4	2.2%
May	30	10.8%	6	10.5%	3	5.8%	23	12.9%
June	16	5.8%	0	0.0%	1	1.9%	15	8.4%
July	23	8.3%	5	8.8%	3	5.8%	16	9.0%
August	18	6.5%	0	0.0%	7	13.5%	11	6.2%
September	26	9.4%	6	10.5%	5	9.6%	16	9.0%
October	35	12.6%	8	14.0%	4	7.7%	25	14.0%
November	34	12.2%	6	10.5%	6	11.5%	22	12.4%
December	26	9.4%	11	19.3%	9	17.3%	9	5.1%
TOTAL (2009-2010)	**278**		**57**		**52**		**178**	
Annual Average	**139.0**		**28.5**		**26.0**		**89.0**	
Monthly Average	**11.58**		**2.38**		**2.17**		**7.42**	
Distribution	**-**		**20.5%**		**18.7%**		**64.0%**	

NOTE: ROR left and ROR right crashes are not mutually exclusive, but neither are included in Non-ROR crash grouping.

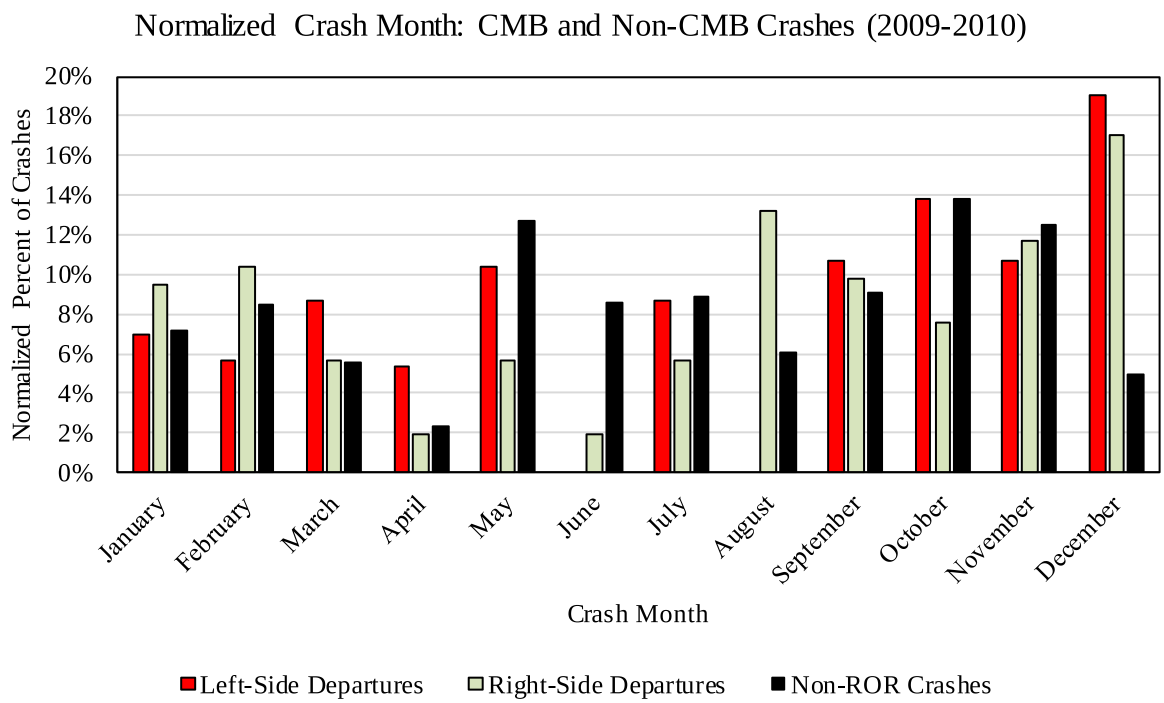


Figure 25. Crash Month: Baseline Data (2009-2010)

Although the available data was limited to only two years, a similar pattern of increased crashes and run-off-road departures was observed in the "wintery" months of November and December. Surprisingly, January, February, and March had a reduced overall number of crashes and left-side ROR crashes compared to the annual average.

4.1.6 Additional Crash Factors Not Considered

Many other factors that also affect the impact performance of cable median barriers were not addressed here. Vehicle types (make, model year) and safety features affect both barrier performance and occupant survivability in events including rollover, vehicle-to-vehicle crashes, and interactions with roadside fixed objects. Additional occupant and/or driver factors (intoxication, blood alcohol concentration (BAC), influence of controlled substances or medications, occupant age, demographics, health condition, etc.) also influence the injury and severity outcome of a crash.

Unfortunately, these factors were not addressed in this project. Based on the time and budget constraints, researchers focused primarily on vehicle-barrier interaction, stability, and crash outcomes. These other factors may be valuable to include with regard to estimation of crash modification factors (CMCs), statistical modeling, and targeted improvements for benefit-to-cost analyses.

In addition, KDOT provided an itemized coded database of crash summaries. The year, make, and model of the vehicle which impacted the CMB during the crash was not included in the dataset. Due to time and budget constraints and scope of the research effort, vehicle information was only extracted from selected reports and therefore no vehicle-specific analyses were conducted to identify CMB-impacting vehicle demographics, body style, age, etc.

4.2 Median Crash Rate Amplification Factor

Based on the review of the “baseline” data set (crashes before CMB was installed), it was concluded that the attributes of crashes which occurred prior to and after the CMBs were installed were sufficiently similar that the “before-and-after” crash rates involving cable median barriers could be compared. Annual left- and right-side ROR crashes and total crash rates per year were considered.

The effect of CMB on median-related and total crash rates was explored. As a percent of all crashes, left-side departure crashes increased by 7% after CMB installation (from date of completion to June 2019) compared to crash rates before CMBs were installed (January 2009 to construction start date). However, it was observed that left-side departure (78 crashes, 22%) and right-side departure (71 crashes, 20%) crashes were very similar before CMBs were installed, with 11 crashes involving departure on both left and right sides of the roadway. After CMBs were installed, surprisingly, the left-side crash rate was nearly double the right-side crash rate; moreover, the number of left- and right-side departures dropped from 3.1% (11/353 crashes) to 2.0% (24/1,220 crashes).

Further analysis considered only full calendar years of data for the period 2009-2010 (before CMB construction) and 2013-2018 (after CMB construction). Between 2009 and 2010, a total of 57 ROR-left crashes were identified, and 52 ROR-right crashes were identified. After CMB construction was finished, there were 298 reported left-side ROR crashes between 2013 and 2018 compared to only 160 right-side ROR crashes. For these same periods, the number of annual non-ROR crashes in the vicinity of CMBs rose by 9.7%. The annual number of non-ROR crashes was explored as a “control group” to scale the rate of left- and right-side ROR crashes per year, based on the assumption that the construction of CMBs would not affect non-ROR crash rates. Results of the comparison are shown in Table 20.

Table 19. Crash Rates Comparison: Before and After CMB Construction

Parameter	2009-2010 Before CMB Construction		2013-2018 After CMB Construction		Scaled % Change Due to CMB*
	No. Crashes	Crashes/ Year	No. Crashes	Crashes/ Year	
All Left ROR Crashes (Includes left + right)	57	28.5	298	49.7	+58.8%
Left ROR Only	48	24.0	279	46.5	+76.6%
All Right ROR Crashes (Includes left + right)	52	26.0	160	26.7	-6.5%
Right ROR Only	43	21.5	141	23.5	-0.4%
Left & Right ROR Crashes	9	4.5	19	3.2	-36%**
Non-ROR Crashes	178	89.0	586	97.7	-

*NOTE: It was assumed the annual rate of on-road crashes would not be affected by CMB, thus the before-and-after crash rates for right- and left-side ROR crashes were scaled by changes in non-ROR crashes.
** Due to small dataset for left- & right-side departure crashes, the uncertainty in the change resulting from CMB installation is significant.

The installation of CMBs was observed to have minimal effect on right-side ROR departures. By scaling the results based on the number of on-road crashes only, the annual number of right-side-only ROR crashes was essentially unchanged at roughly 23 right-side ROR/year. This result indicated crashes in which the vehicle only exited on the right side of the road was essentially unchanged by the presence of CMBs, which matched expectations.

However, all left-side ROR crash rates and left-side-only ROR crash rates increased significantly after installing CMBs, by 59 and 77%, respectively. It was not believed that the installation of CMBs resulted in *additional* left-side departures which would not have otherwise occurred in the absence of CMBs. Therefore, the increase in left-side crash rates strongly suggests that prior to CMB installation, many vehicles had previously entered the median but had not been involved in a crash, and were therefore not reported to first responders or documented using crash reports. Results suggest that there were an additional 15 to 16 left-side ROR departures per year in the 7.95-mile long segments of road with CMBs installed, which were not previously being documented or reported before CMB installation.

The rate of crashes in which vehicles exited the road on one side, then crossed over the entire road during the crash event (ROR on both right and left sides) decreased after installing CMBs. A total of 24 left- and right-side road departures occurred between the end of the CMB installations until June 2019; of these, only 10 involved CMB, and six of those ten crashes involved a right-side departure first before the left-side departure and CMB impact. The remainder of the CMB crashes did not cross over travel lanes to the right side. During this period, 182 right-side departure crashes occurred, meaning that 10/182 (5.5%) were both ROR-right and ROR-left; in comparison, 254 left-side departure crashes which impacted CMBs occurred, meaning that 10/254 (3.9%) were both CMB-impact left and ROR-right, and only 4/254 (1.6%) consisted of impacting a CMB *before* crossing travel lanes to the right side of the road.

This result strongly suggests that vehicles which encountered CMBs were less likely to cross over all travel lanes after impacting the median barriers. Stolle [4] observed that crashes in which an impacting vehicle rebounded away from the cable median barrier and returned to, or crossed over, the adjacent travel lanes were more commonly severe compared to crashes in which the impacting vehicle did not return to travel lanes. Due to the small dataset, the uncertainty of this calculation is high. Nonetheless, results indicate that CMBs reduced the frequency of ROR crashes with driver “over-corrections” causing vehicles to depart both sides of the roadway.

4.3 Crash Severity

The maximum injury severity sustained in a crash event was evaluated for all CMB crashes, non-CMB crashes, and ROR crashes before installing CMBs. Results are shown in Figure 26. Recall, KDOT tabulates injury data on a three-point injury scale: fatal (killed), injury, and property damage only.

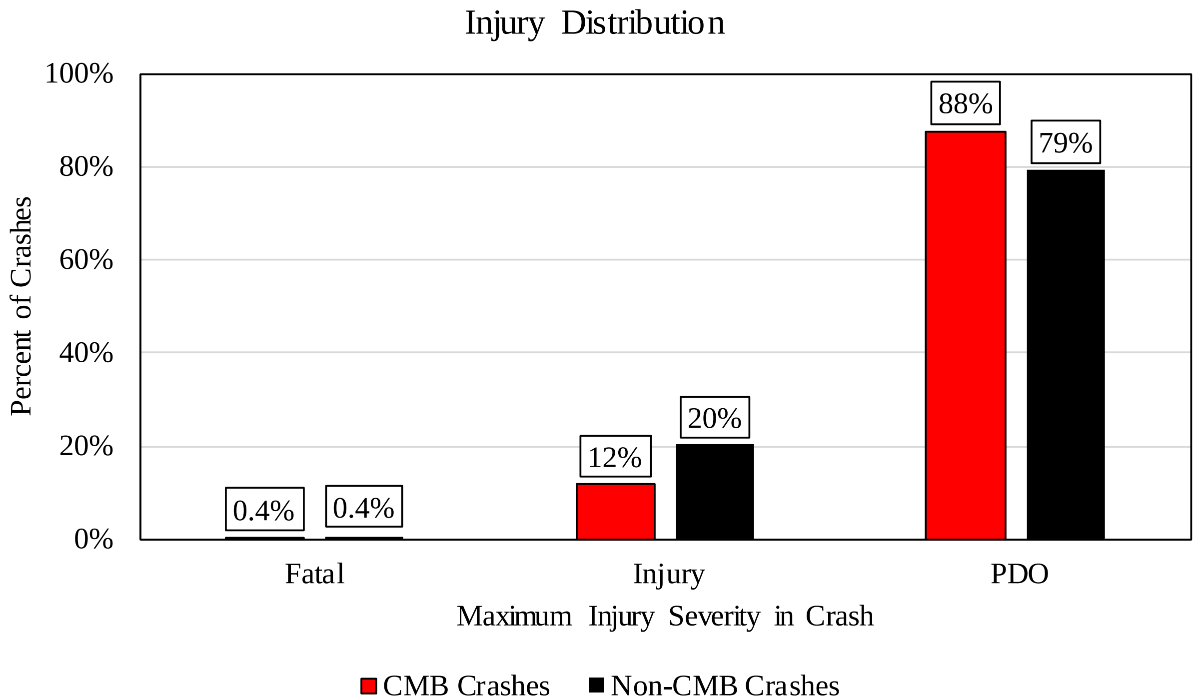


Figure 26. Injury Outcome Comparison: CMB and Non-CMB Crashes After CMB Construction

The distribution of crash injuries was further separated to consider CMB crashes, left-side departure and non-CMB crashes, right-side departure crashes, and non-ROR crashes, as shown in Figure 27. Results indicated that the CMB crashes were lower severity than other ROR crashes not involving CMBs. Non-ROR crashes were the least severe overall, with the greatest number of crashes yet no recorded fatalities and a comparable injury rate to CMB crashes.

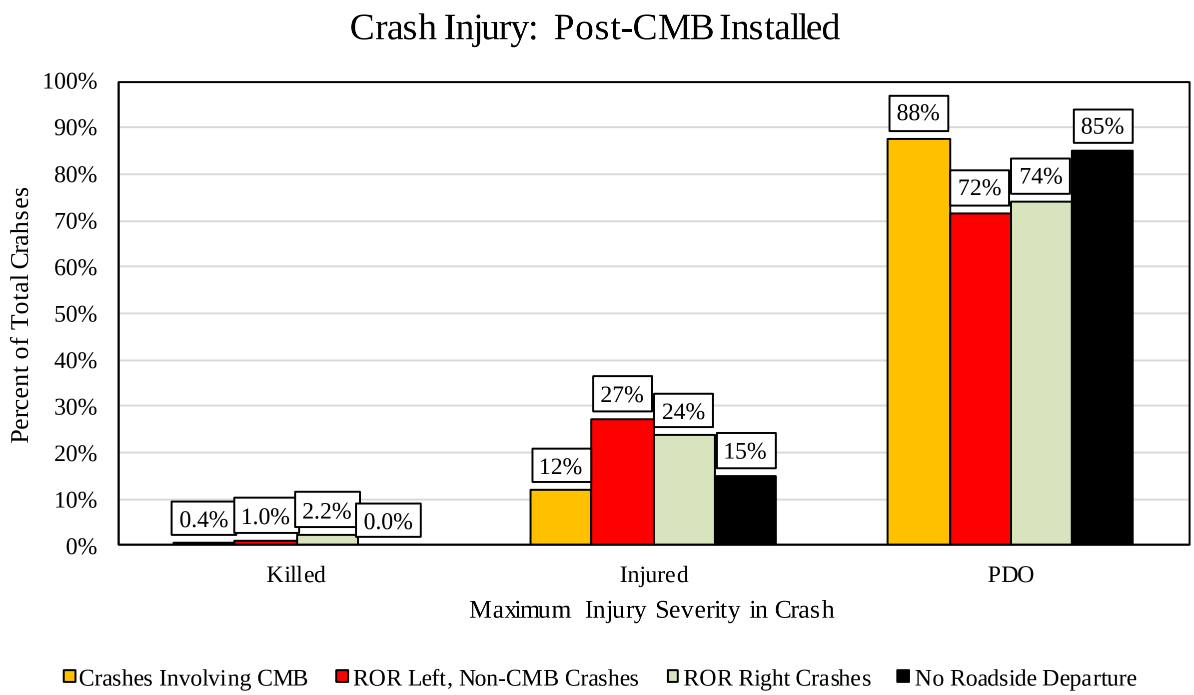


Figure 27. Maximum Injury Severity in Crash by Crash Designation

The distribution of crash outcomes for injury and PDO crashes was plotted based on weather conditions for CMB, right-side-only ROR, and non-ROR crashes, as shown in Figure 28. Injury crashes were disproportionately associated with dry, clear weather conditions, which is consistent with crash observations in literature [4,5,9,12]. However, a surprisingly high percentage of non-roadside departure PDO crashes were also associated with dry, clear weather conditions. In general, fewer injury crashes were observed during adverse weather conditions, both as a percentage of all injury crashes and as a percentage of all crashes with adverse weather. Only CMB crashes associated with wintery conditions (snow, slush, sleet, or icy conditions) incurred a higher proportion of injury crashes than PDO crashes in non-optimal driving conditions. Moreover, the composition ratio of PDO-to-injury crashes rose (up to twice as much) during adverse weather for other crash types indicating the benefit of reduced travel speeds on preventing injuries.

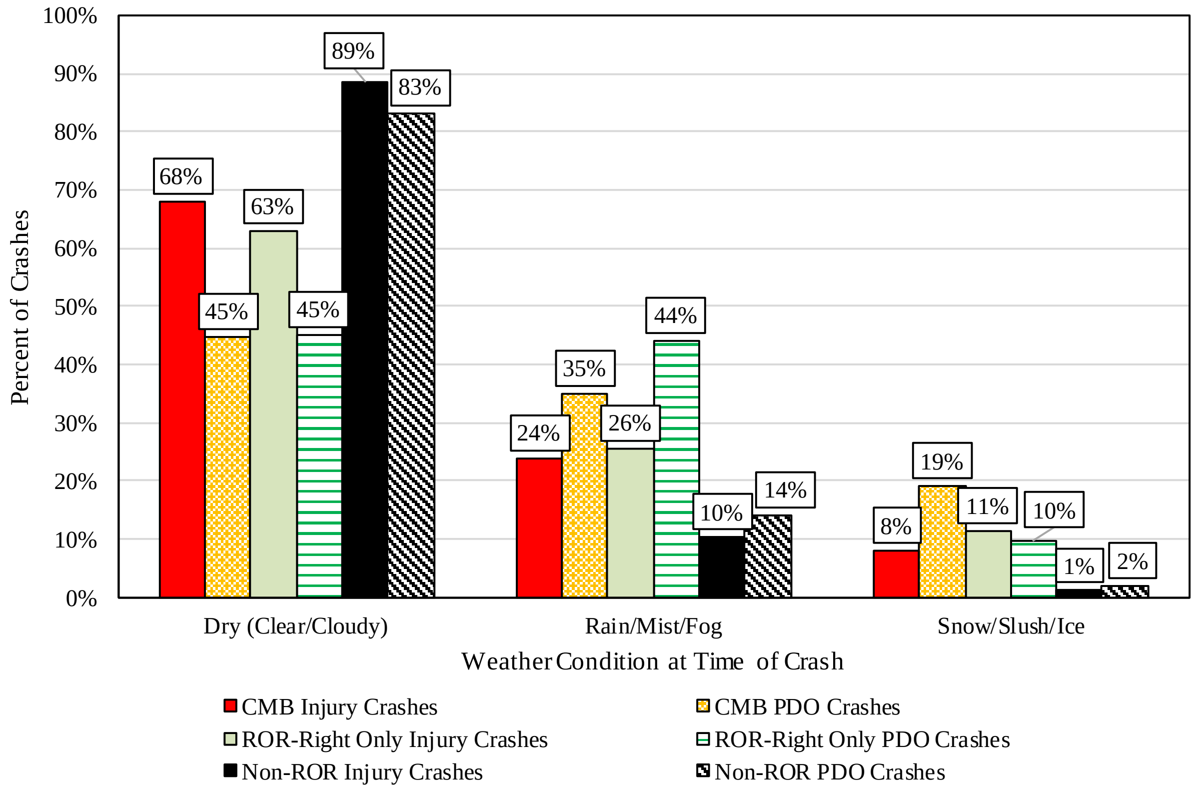


Figure 28. Comparison of Distribution of Injury Outcomes (2013-2018)

4.4 "Bad Outcome" Results

A critical parameter of CMB performance is related to the determination of "bad outcomes." For purposes of this analysis, a bad outcome is defined to be one of the following crash results: (1) penetration; (2) rollover; (3) severe injury/fatality. Recall that a penetration, which was mutually exclusive with capture or redirection results, was denoted any time the vehicle came to rest with zero cables between the vehicle and the opposing travel lanes. This definition is approximately consistent with *Manual for Assessing Safety Hardware* (MASH) evaluation criteria for longitudinal barrier performance [30]. A rollover was defined as at least one-quarter turn of the vehicle along the pitch or roll axes. A rollover could occur either during or shortly after engaging the CMB, such as during redirection. Rollover results which were not attributable to CMBs or vehicle-to-barrier interactions were not considered. If the crash outcome did not include a fatality and could not be identified as penetration or rollover with reasonable confidence based on available data it was not considered, which means that the actual "bad outcome" crash rates may be higher than what is shown.

When crashes resulted in one or more deaths, those crashes were noted with a "K" (Killed) classification. However, injuries were not subdivided by seriousness to differentiate incapacitating injuries (extended hospitalization, permanent or long-lasting physical or cognitive damage, disability, coma, etc.) from less serious injuries (broken bones not resulting in permanent damage, lacerations, cuts, concussions, bruising, etc.). Although the rates of such injuries may be assumed or estimated based on literature, they would not be tied to specific crash events. Therefore, during the analysis of serious injury crash outcomes only crashes which resulted in fatalities were examined.

Results of the "bad outcome" analysis are summarized in Table 20. Note that although weather events, time of year, and time of day have an effect on crash frequency and may influence crash injury risk, all crash results after CMB construction were analyzed to maximize the size and relevancy of the analysis database.

Table 20. CMB Crash Data Summary

Road	Hit CMB		CMB Penetrations		CMB Rollovers		Capture/ Redirect		CMB Fatal Crashes		CMB Injury Crashes		CMB PDO Crashes	
K-10 DG County	25	10%	0	0.0%	0	0.0%	25	100%	0	0.0%	1	4.0%	24	96%
K-10 JO County	97	38%	4	4.1%	1	1.0%	92	95%	0	0.0%	11	11.3%	86	89%
US-75	3	1%	0	0.0%	0	0.0%	3	100%	0	0.0%	0	0.0%	3	100%
K-96	94	37%	1	1.1%	0	0.0%	93	99%	1	1.1%	12	12.8%	81	86%
OVERALL	**219**	**21%**	**5**	**2.3%**	**1**	**0.5%**	**213**	**97%**	**1**	**0.5%**	**24**	**11.0%**	**194**	**89%**

Of the 254 CMB crashes identified, a total of 8 penetration results and 1 rollover result were observed. The corresponding penetration and rollover rates were therefore calculated to be 3.1% and 0.4%, respectively; this is very far below the national average collected for data in the 2000s [4] and reported by several other states [12,17]. One penetration crash resulted in entry into opposing travel lanes; another resulted in a CMC outcome. Results of both crashes are shown below.

4.4.1 Penetration Crash Resulting in CMC

One of the penetration crashes consisted of a vehicle passing behind a W-beam guardrail system, impacting the CMB near an end terminal, and passing to the opposing travel lanes, resulting in a CMC, as shown in Figure 29. This crash result is difficult to categorize as it is not clear whether this impact occurred outside of the Length-of-Need (LON) of the cable barrier system and downstream from the Critical Impact Point (CIP) in which the barrier behavior transitions from capturing or redirecting a vehicle to gating through the system to the opposing side. Further review using Google Earth [25] indicated that the W-beam system was located 12 ft laterally from the CMB, measured from cable-to-back side of post, and the length of overlap between the W-beam and CMB was approximately 83 ft.

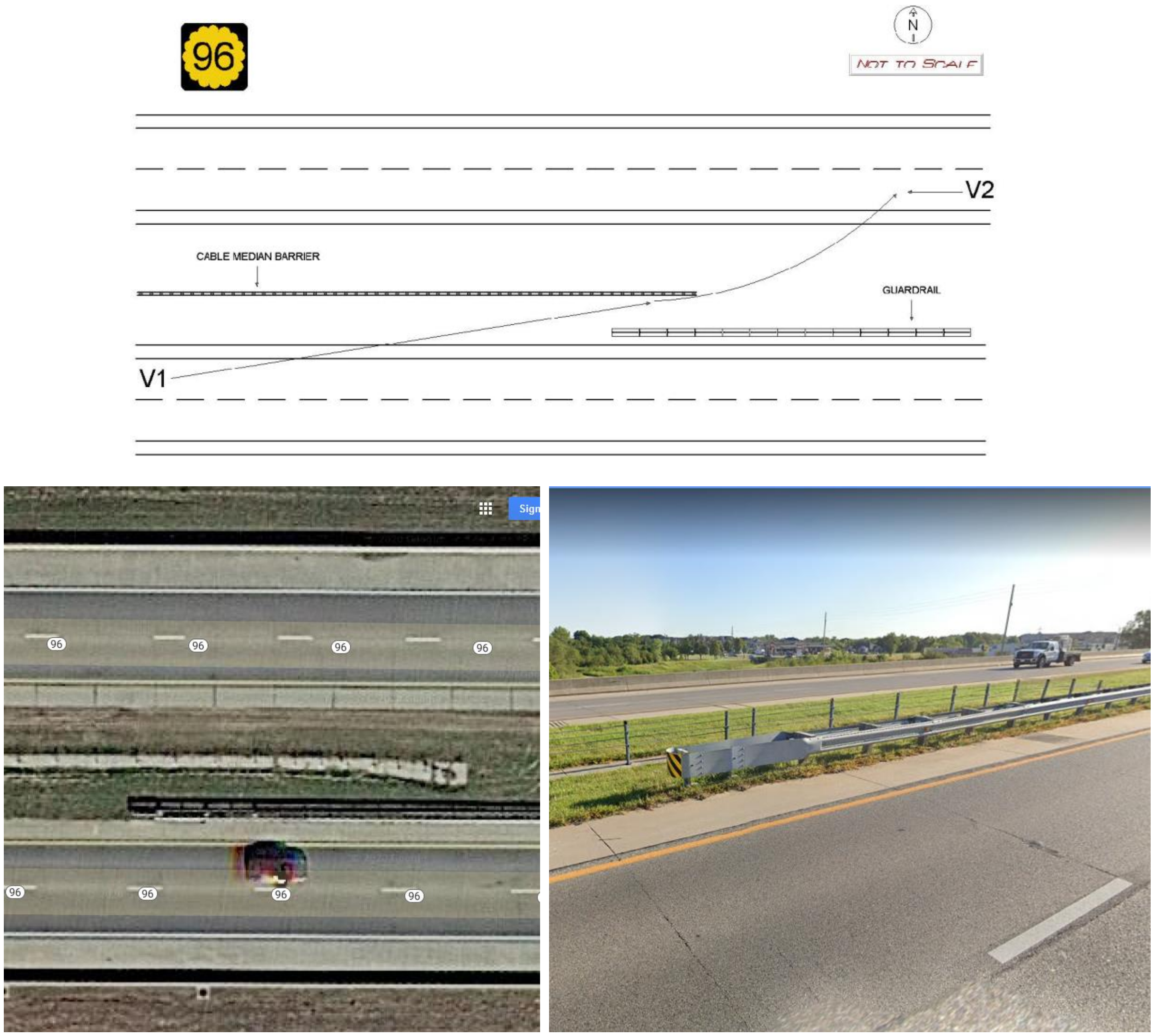


Figure 29. Penetration Crash Resulting in CMC [25]

Based on the crash narrative, it was concluded that a Ford F-150 pickup impacted and overrode the CMB at the downstream end of the system and started to yaw clockwise, with the front end of the truck rotating toward the original travel lanes. The vehicle proceeded through the relatively flat median and into opposing travel lanes where the pickup truck was impacted along the pickup's left (driver) side by a Chrysler Town and Country in the opposing lanes.

4.4.2 Penetration Crash Resulting in CME (Crash B)

The second CMB penetration crash resulting in intrusion into opposing travel lanes (Crash B) was not a typical CMB capture scenario. A tractor-trailer vehicle impacted the CMB, and very near to the time of impact the flatbed trailer disengaged from the tractor and passed over the CMB into the opposing travel lanes. No CMC occurred in this crash. CMBs are generally tested and approved using MASH evaluation criteria to Test Level 3 (TL-3) impact conditions [30], which consist of a light, subcompact car weighing approximately 2,425 lb and a heavy, ½-ton, quad cab pickup truck weighing approximately 5,000 lb each impacting a barrier system at 62.1 mph (100 km/h) and a 25-degree angle. Heavier vehicles, such as box trucks and tractors with van-body or tank-body trailers, are evaluated under higher service level conditions of TL-4, TL-5, and TL-6 impact conditions.

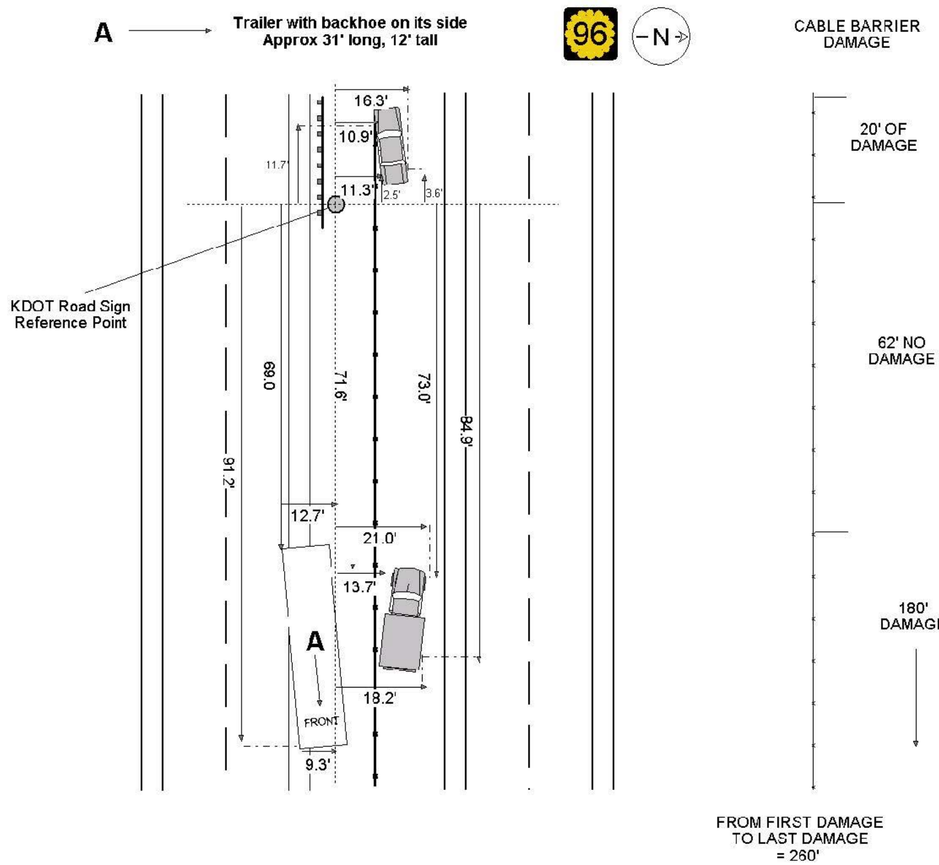


Figure 30. Penetration Crash with CME

Very few CMBs have been tested and shown to be crashworthy for impact conditions and vehicles consistent with TL-4 conditions, and no systems have been deemed crashworthy for containing and/or redirecting tractor-trailer combination vehicles. Nonetheless, there are many anecdotes of CMBs containing these types of vehicles [e.g., 31-33]. During this penetration crash, the tractor was contained, but the trailer overrode the CMB system. Although it is noted as a penetration crash for analysis purposes, it is generally not expected that CMBs can capture or redirect these vehicles.

4.4.3 Additional CMB Penetrations with Challenging Data

Identification of penetration and rollover events was very challenging because they required interpretation of the reported sequence of events and scene diagrams. Most scene diagrams were not to scale and some did not contain enough information to make an accurate determination of crash outcomes. Some examples of difficult scene diagrams which were correlated with penetration crashes based on the content of narratives and sequences of events and which could not be detected based on scene diagrams or fixed-object impact classification are shown in Figure 31.

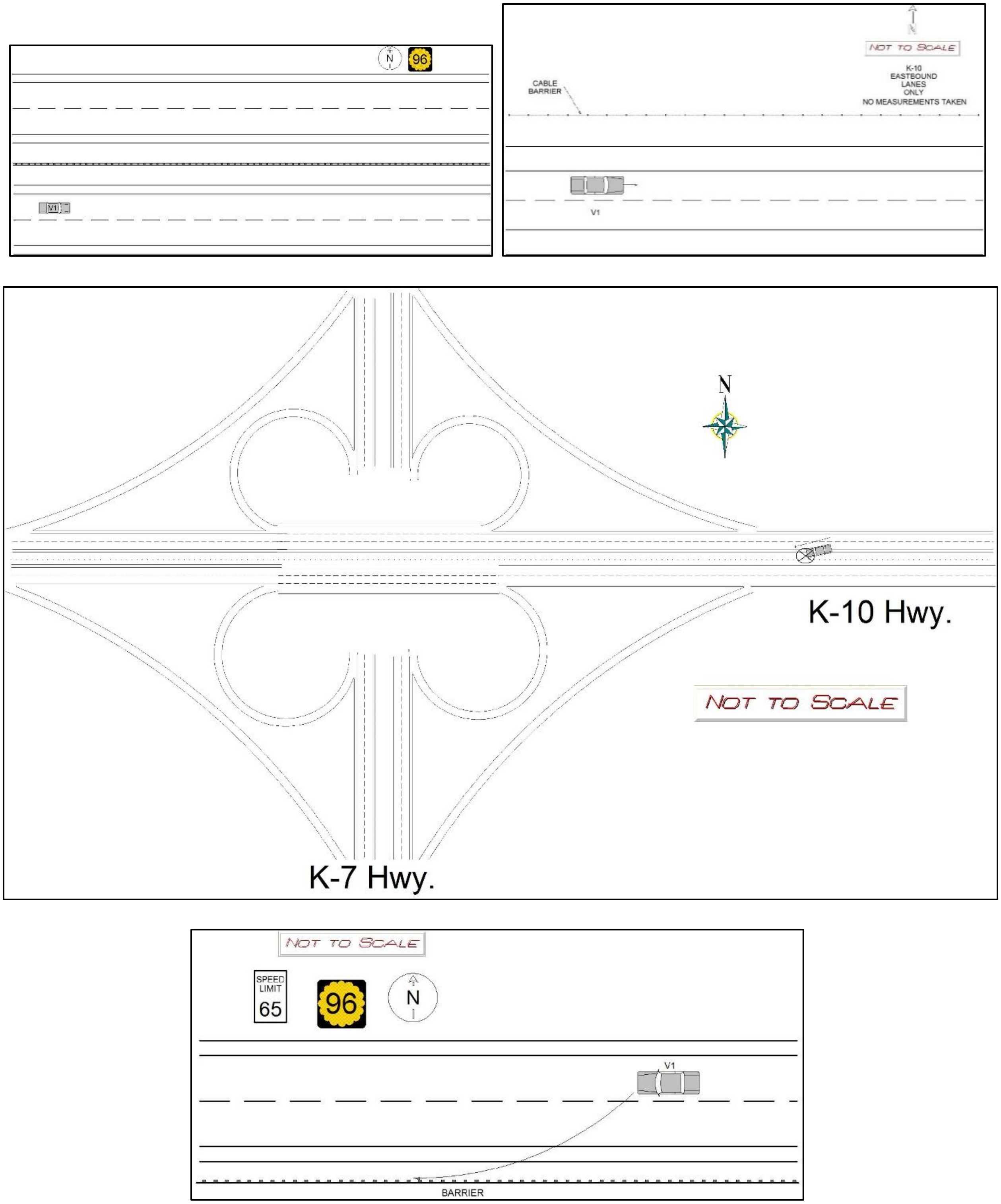


Figure 31. Challenging Scene Diagrams with Identified Penetration Crashes

4.4.4 Rollover Crash Result

One rollover crash outcome was observed. The scene diagram for the crash is shown in Figure 32. During the crash, the impacting vehicle, a 2003 Ford Focus, swerved to avoid another vehicle encroaching into the lane, but lost control and impacted the CMB. During redirection, the vehicle yawed sideways and was tripped and rolled. The scene diagram may also indicate a penetration crash result, but the crash narrative did not indicate that the vehicle had traveled to the opposite side of the cable barrier; therefore, it was not treated as a penetration crash.

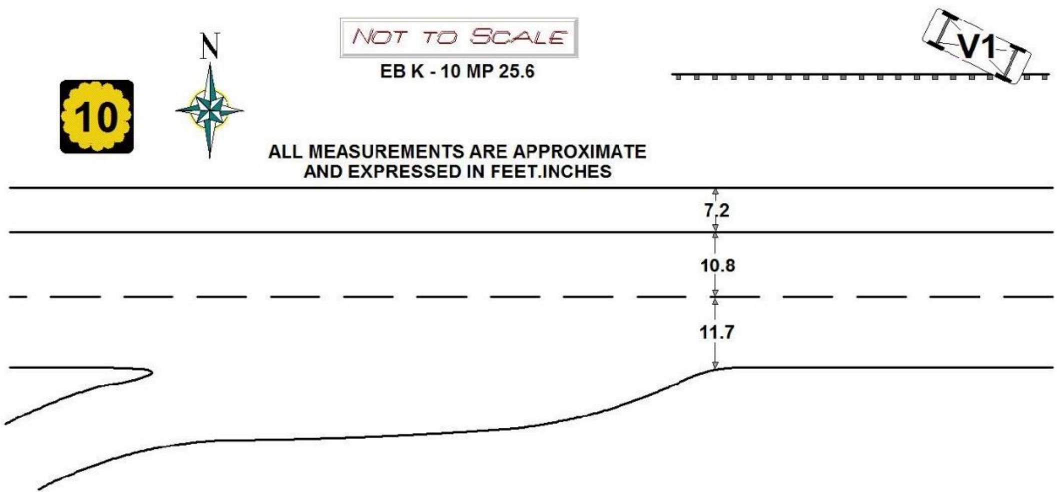


Figure 32. Rollover Crash Involving CMB

The median at the point of the crash was relatively flat (<10:1) and grassy. The CMB system utilized a narrow mow strip with posts located in sockets. At the point of impact, the CMB was flaring and tapered toward the impacting vehicle's lanes, but the taper appeared to be more gradual than 50:1. The approximate location of the rollover crash is shown in Figure 33. Researchers believed that excessive steering associated with an avoidance maneuver contributed to the rollover.

Figure 33. Location of CMB Rollover Crash [25]

4.4.5 Severe Crash Result

One severe crash outcome (fatality) was identified in the CMB results and included multiple non-contact vehicles. A Ford F-350 pickup truck carrying cargo in the bed abruptly lost part of the cargo in the roadway, and several adjacent trailing vehicles abruptly stopped and swerved to avoid the lost cargo. Some of the occupants of those vehicles exited the vehicles and intended to clean up the lost cargo to prevent subsequent crashes on K-96. A tractor-trailer vehicle came upon the lost cargo and stopped vehicles and made an avoidance maneuver to the left, toward the shoulder and median, striking one stopped vehicle and the cable median barrier. While slowing to a stop, the tractor-trailer also contacted and killed a pedestrian of a separate stopped vehicle. The crash location is shown in Figure 34, and the scene diagram is shown in Figure 35.

Figure 34. Severe Outcome Crash Location [25]

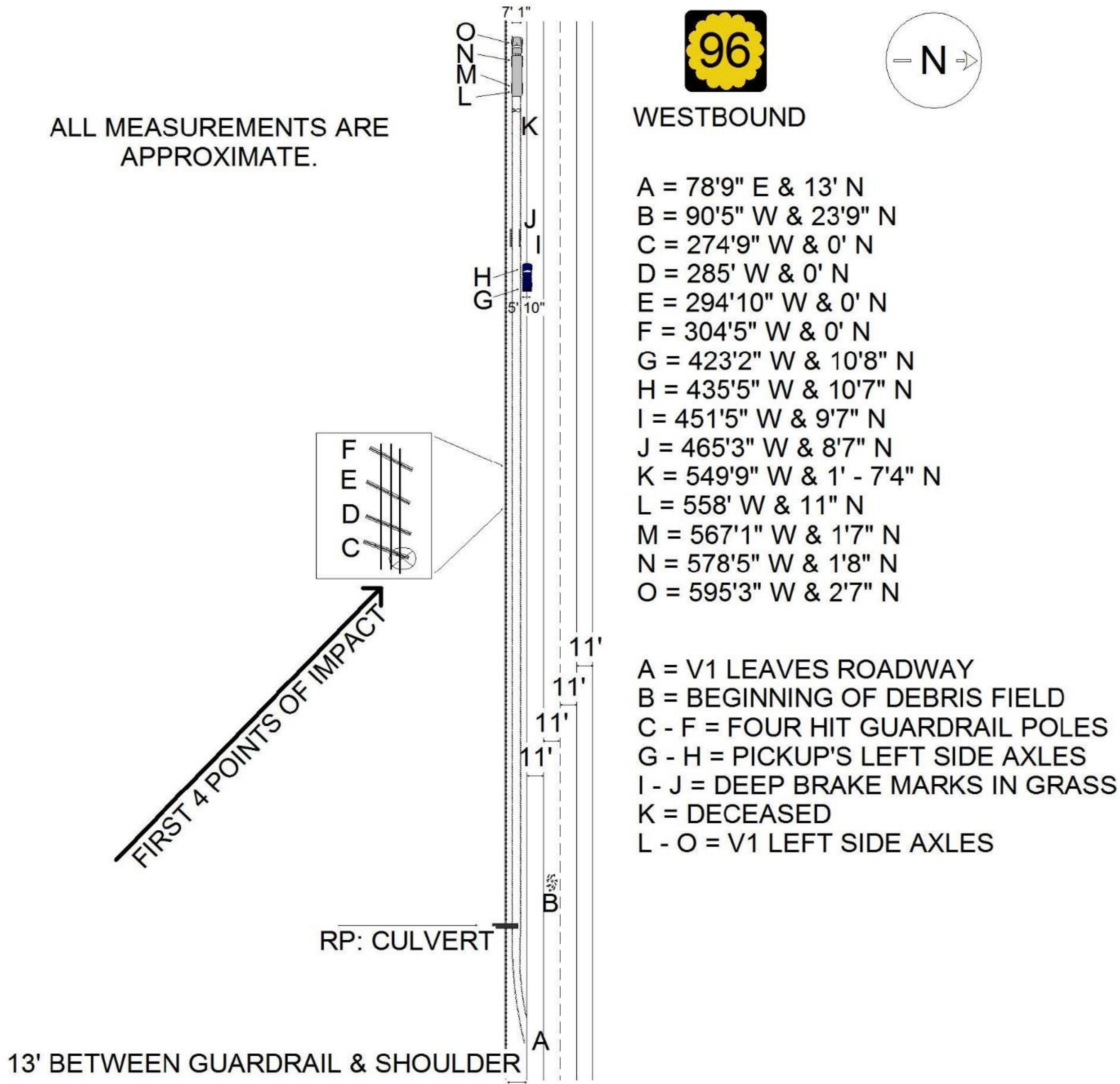


Figure 35. Scene Diagram, Fatal CMB Crash

The crash fatality was associated with the pedestrian and was not a product of the impact with the CMB; however, in the absence of the CMB, it is likely that the tractor-trailer would not have impacted either the pedestrian or the median barrier. As a result, the fatality associated with this CMB crash should not be interpreted as a failure of the CMB installation, design, or impact condition, but rather as an indirect consequence that can arise from the installation of a median barrier system.

4.4.6 "Bad Outcome" Analysis and Conclusions

Few "bad outcomes" were identified in conjunction with CMB crashes and when undesirable outcomes were identified, the severities were relatively minor. One CMC was associated with a penetration, although it was unclear whether the penetration was related to a change in the performance of the barrier when struck near the downstream end anchorage. One additional CME crash involved a vehicle impacting the CMB with impact conditions beyond the design constraints of the barrier. As a result, it was concluded that the CMB installed in Kansas performed well and the lack of identifiable bad outcomes indicates good overall barrier performance. A summary of bad outcome crashes is shown in Table 21.

Table 21. Summary of Bad Outcome Crashes in Kansas

Accident Key	Penetration	Rollover	Crash Severity	Weather Conditions	Light Condition	Time	Vehicle Struck CMB	Vehicle Body Type
20140095124	No	No	K	No adverse conditions	Daylight	1457	2006 Mack	Tractor-Trailer
20160124261	No	Yes	I	No adverse conditions	Daylight	1145	2003 Ford Focus	Sedan
20120102788	Yes	No	O	No adverse conditions	Daylight	1432	2009 Ford F-150	Pickup
20120108234	Yes	No	I	No adverse conditions	Daylight	1623	1992 International	Tractor-Trailer
20130108467	Yes	No	O	Rain, mist, or drizzle	Daylight	1351	2000 Toyota Camry	Sedan
20130118444	Yes	No	O	No adverse conditions	Daylight	1452	1997 Saturn Sedan	Sedan
20170104114	Yes	No	O	Fog	Dark: Street Lights On	2025	2016 Nissan 370	Sedan
20180014171	Yes	No	O	No adverse conditions	Daylight	819	2003 Ford F-150	Pickup
20180103165	Yes	No	O	No adverse conditions	Daylight	1321	2004 Toyota Camry	Sedan
20190110767	Yes	No	O	Fog	Dark: No Street Lights	220	2009 Ford Focus	Sedan

It was noted that most penetration crashes were passenger car, sedan body types. Traditionally, passenger car body types have been associated with the highest penetration rates [4,9]. However, recent research has shown that, nationally, new sales are overwhelmingly moving away from passenger cars to light truck vehicles such as CUVs [36-37]. Notably, none of the "bad outcome" crashes in Kansas involved CUVs or SUVs. Although researchers did not tabulate all CMB crashed vehicles, it is believed that CUVs and SUVs were involved in a significant number of crashes.

Lastly, it should be noted that only the most severe injury in a crash, regardless of the number of vehicles involved, was tabulated and summarized using a three-point scale. It is possible that in multi-vehicle crashes in which only one vehicle impacts the CMB, the maximum injury severity sustained by occupants of the vehicle colliding with the CMB was lower than the injury severity in other vehicle(s) not involved in a CMB impact. Due to the low injury resolution, an injury distribution correlated for each vehicle in a crash was not conducted.

4.5 Fixed-Object Classification and CMB Impact Identification

The last analysis conducted by researchers sought to identify how commonly CMB crashes were identified by first responders. This study was unique in that the crash dataset was not pre-filtered based on any criteria other than proximity to the location of the CMBs. Subsequently, researchers identified all CMB crashes based on crash scene diagrams and narratives on crash reports. This allowed researchers to review fields on the crash reports to identify how many CMB crashes would be identified if a selection filter had been applied.

The "Fixed Object Struck" field was reviewed for every CMB crash in the database to determine how crash reports were identifying CMB impacts. Note, some CMB impacts involved more than one fixed object and type of fixed object struck, but KDOT crash reports only indicated a single event in the Fixed Object Struck field. The distribution of declared fixed objects struck in CMB crashes are noted in Figure 39.

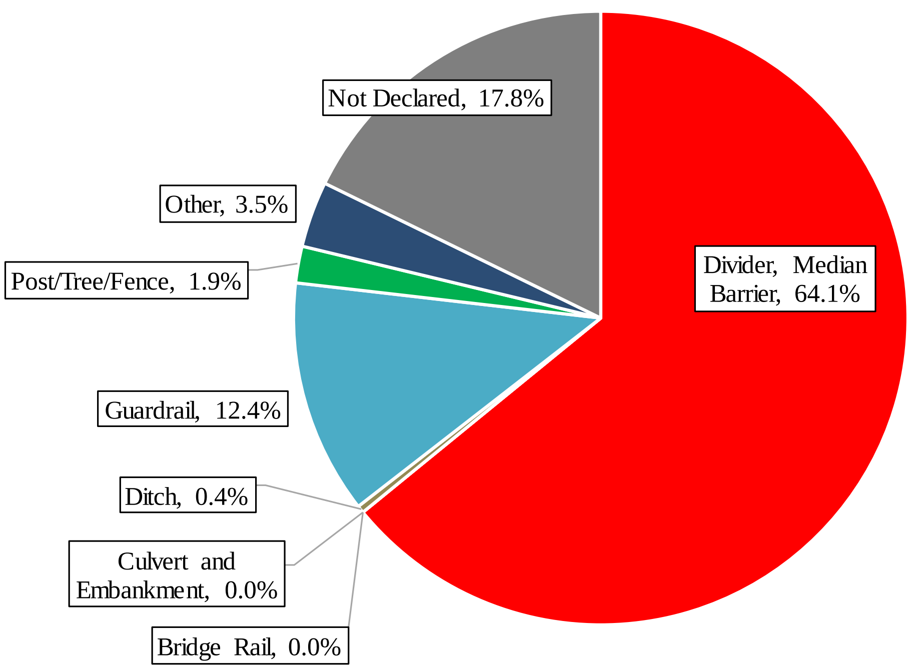


Figure 36. Distribution of Fixed Object Struck Assignments: All CMB Crashes in Kansas

Researchers conducted an analysis of the CMB crashes and identified as many impacts as could be determined based on scene diagrams and crash narratives. Researchers primarily reviewed the crash database summary provided by KDOT, which annotated the first fixed-object struck declared on crash report forms. Note that crash report forms allow up to two declared fixed objects struck. The following observations were made about the classification of cable barrier impacts:

- Approximately 46 (18%) of the identified CMB crashes did not denote a fixed object struck or provide a description of the barrier or any other object struck. Nearly all of these crash reports denoted only an impact with another vehicle. These crashes would not be identified using any fixed-object-based selection filter.

- Three errors were identified in the Fixed Object Struck field of KDOT's summary database. For each of these crashes, the crash report denoted "Guardrail" or "Divider, Median Barrier" for fixed object struck, but was coded as either "Embankment," "Ditch," or "Culvert" in the KDOT database. These errors were corrected in the analysis database.
- Crash reports indicate the fixed object struck using two fields. One field requires the respondent to select pre-established fields, shown in Figure 36. A second field allowed the respondent to write in a description of the object struck. The labels given to cable median barrier by officers ranged widely, including "Median Fence," "Wire Rope Barrier," and "Cable Barrier Post." The interpretation of the type object struck influenced the depiction of the fixed object type selected for classification (e.g., "Post/Tree/Fence" correlated with "Cable Barrier Post").
- Although a significant but non-tabulated number of crashes involved more than one event in the impact sequence (e.g., impacting bridge rail, delineator posts, and CMB), very rarely was more than one type of fixed-object struck in an impact sequence (2 crashes). Bridge rail was the most common other fixed object struck.

Next, the identified CMB crashes were filtered using only the criteria "Guardrail" or "Divider, Median Barrier" as Fixed Object Struck criteria and the results of the analysis were compared with the filtered dataset. A total of 191 of the CMB crashes were identified using these selection criteria, or 75%. It was observed that the distribution of weather events was statistically identical for the CMB crashes identified by MwRSF researchers compared to the filtered dataset of only CMB crashes denoted with guardrail or median barrier fixed object types, as shown in Figure 38. Likewise, the maximum injury severity in the crash was reduced when compared to all CMB impacts, as shown in Figure 39.

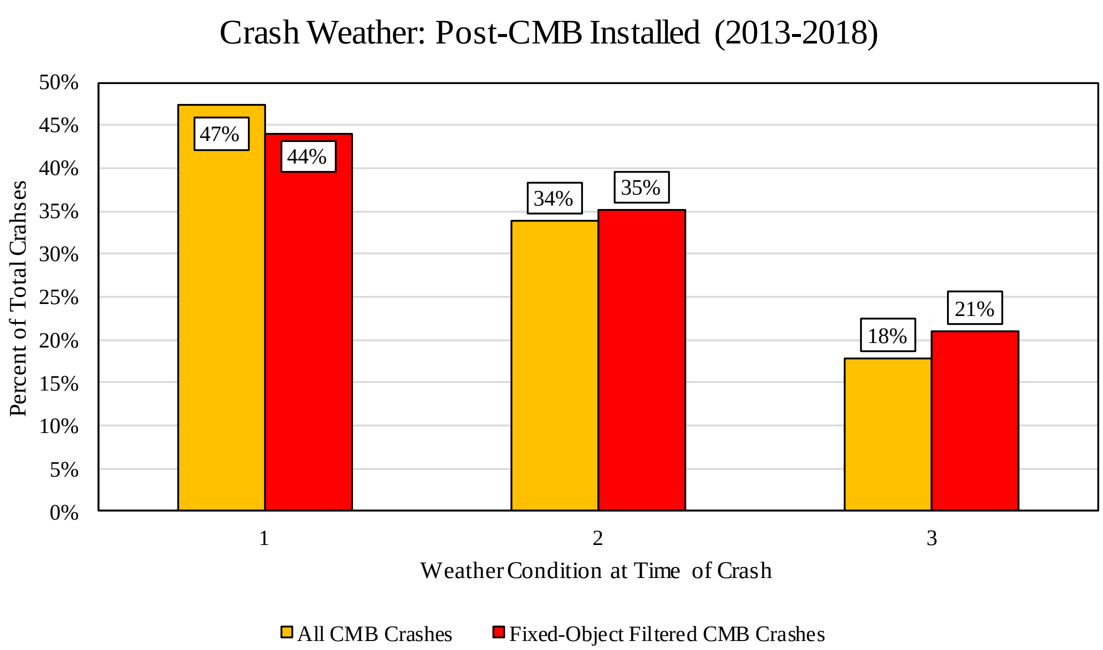


Figure 37. Comparison of Weather in Reported CMB Impacts

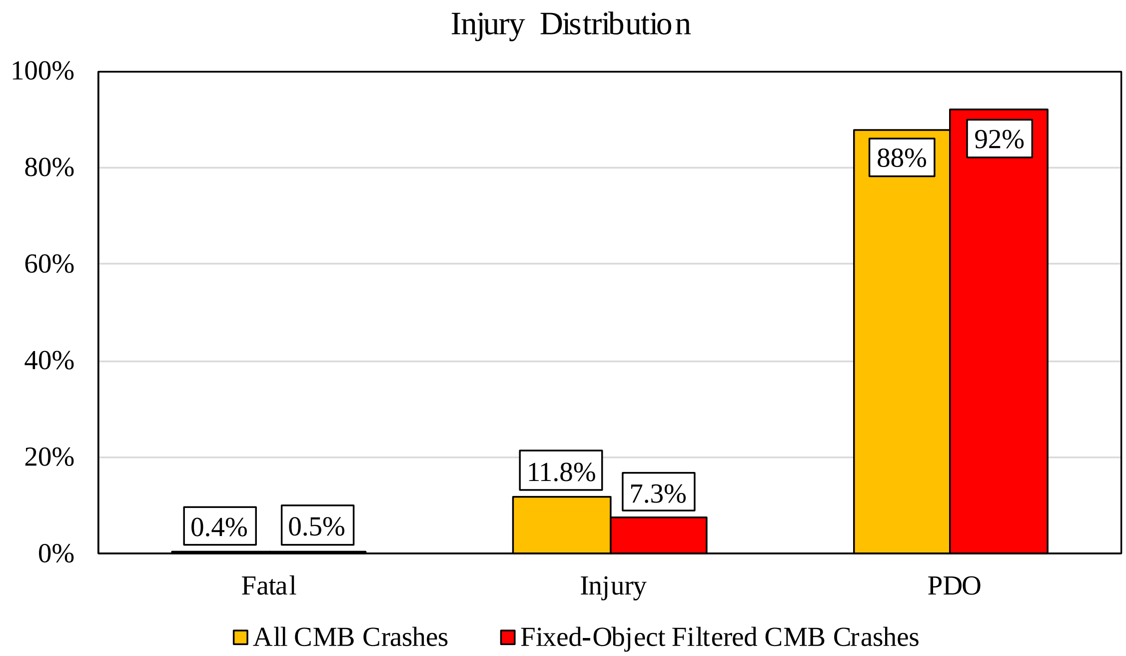


Figure 38. Comparison of Maximum Injury Severity in Reported CMB Impacts

However, after filtering, the number of identified "bad outcome" crashes changed. Seven of the 8 CMB penetration crashes were contained in the dataset filtered using fixed-object type for a composite penetration rate of 3.7% (7/191), but the rollover crash identified in the UNL CMB crash database was not located in the fixed-object filtered database. For that crash, the fixed-object struck had been listed as "Other" due to the rollover.

4.6 CMB Performance Summary

4.6.1 Review of Crash Results

Crashes with a "bad outcome" were those with undesirable results, such as vehicle penetration or rollover. Nonetheless, the primary objective of CMBs is to prevent cross-median crashes, or in certain applications, to prevent impact with a median feature, e.g., in Kansas, bridge piers were shielded by CMBs on Kansas Highway K-10, as shown in Figure 39. The evaluation of the performance of CMBs must therefore consider several factors:

- Were cross-median crashes prevented by CMBs?
- Did CMBs prevent other non-CMC bad outcomes from occurring?
- Did CMBs directly or indirectly contribute to bad outcomes which may not have otherwise occurred?
- What is the net benefit-to-cost (i.e., safety improvements and reduction in "societal cost" per state DOT dollar spent)?

Figure 39. Bridge Pier Protection using CMB Barrier on Kansas Highway K-10 [25]

Because injury severity was not distributed using a KABCO scale, which includes incapacitating (“A”), moderate (“B”), and minor/possible (“C”) injuries, or an alternative scale such as the Modified Abbreviated Injury Scale (MAIS), the benefit-to-cost associated with the CMB installations could not be calculated. Additionally, the only fatal crash result was an indirect consequence of the CMB; while the presence of the CMB constrained the impacting tractor-trailer vehicle, it is not clear whether or not the pedestrian would have been struck if the CMB was not present and the fatal injury was unrelated to the performance of the barrier.

Instead of a traditional benefit-to-cost analysis, the propensity for CMEs was calculated based on available data from scene diagrams and crash narratives. Specifically, the reported extent of damage to the median barriers, pre-crash actions (including avoidance and/or panic steering into the median and overcorrecting from lane departures), and reported driver distractions or incapacitations (e.g., medical impairment, illness, diabetic shock, pre-crash cardiac event, or incapacitation from controlled substances) were reviewed. Using the collected data, a likelihood of crossing from the initial travel lanes across the median and either into opposing travel lanes (potential CME) or onto the opposing median shoulder was assigned. Crashes were deemed likely CMEs were labeled “Encroachments.” Approximately 16% of the identified CMB impacts were identified as potential Encroachments. Although it is unclear how many of the Encroachments would have resulted in CMEs, the CME rate was estimated at half of the Encroachments, or 8%

of CMB impacts. Thus, it was estimated that 21 CMEs would have occurred in the time period after the CMBs were installed.

In a previous study for KDOT investigating median encroachments, MwRSF researchers identified 525 CME crashes and 115 CMC crashes. A simple ratio indicated that approximately 22% of CMEs were also associated with CMC. Using this simplified estimate, it was estimated that approximately 5 CMCs were likely to have occurred on Kansas Highways K-10, US-75, and K-96 in the vicinity of the CMB locations during the evaluation period. After the CMBs were installed, one crash was identified with a CMC result; this suggests that approximately 80% of the potential CMCs on these road segments were prevented by installing CMBs. This correlates well with results identified by other state DOTs [5,11-12].

In contrast, approximately 58% of crashes were associated with either low impact speeds (minimal CMB damage) or low-angle impacts while under conscious driver control. These crashes were denoted as “Nuisance” crashes because the CMBs were not believed to have any helpful contribution to vehicle stability, capture, or occupant safety. Note that some of the “Nuisance” crashes would not have resulted in any crash outcome without the CMB present, although others were related to a low-speed impact after a previous impact event in the travel lanes.

4.6.2 Comparisons with Other State Data

Data from other state DOTs were reviewed and compared with KDOT CMB results. State geography had a very significant effect on the weather effects on crash outcomes, but Stolle identified a strong correlation was observed between adverse weather (rain, fog, snow, sleet, ice) and CMB crash rates [4]. As well, Stolle also observed a doubling in average weekly CMB crash rates beginning in December and extending through February; for KDOT, the crash rates with CMBs were significantly higher during this same time period.

Florida identified approximately 2.6% of CMB crashes resulted in cross-median events after installation [11-12]. Although the overall number of CMEs and CMCs was reduced after installing barriers in medians, FDOT determined that the penetration rate for crashes was deemed too high. With 254 identified CMB crashes in Kansas, the effective CME rate in this study was 0.8%; using only a fixed-object based classification, which may be more similar to other state data, the effective CME rate would be 1.0%.

KDOT’s crash rates were also compared with other states. Crashes per HVMT were calculated for each roadway in the KDOT study and results varied widely; thus, a low, high, and average crash per HVMT was compared with results from other states, as shown in Table 22. The average crash rates in Kansas per HVMT were higher than for Iowa or Michigan based on all crash data, but this was expected in part because the CMB locations in Kansas were only installed on high traffic volume commuter routes, whereas for Iowa and Michigan, a significant portion of the CMB installation was on primarily rural routes.

Table 22. Comparison of KDOT Crash Rates with Other State DOTs

Parameter	KDOT (All CMB Data)			IaDOT [16]	MDOT [18]
	Low	High	Composite		
CMB Crash Rate (HVMT)	12.98	43.25	26.99	-	-
Overall Crash Rate (HVMT)	44.83	157.70	129.64	23.76	34.88
Serious Crash Rate (HVMT)*	-	-	0.75 (CMB) 3.76 (All)	0.11 (All)	0.58 (All)
CME Crash Rate (HMVT)	-	-	1.50	-	0.35

MDOT Serious Crash Rate included both fatal and serious injuries (K+A), but Kansas and Iowa data only included fatal data (K).
Data marked “All” indicate all crashes on roadway segments with CMB present.

KDOT data overall compared well with Iowa and Michigan, although the small overall mileage and number of crashes limited the magnitude of the comparison and conclusions.

4.6.3 Conclusions

Based on these observations, researchers made the following conclusions:

- The CMBs installed in Kansas successfully prevented cross-median crashes on the selected roadways during the evaluation period.
- Cable median barriers are fixed objects which damage impacting vehicles. Thus, crash rates will increase after installing CMBs. Some non-reported median encroachments which would not result in a crash may subsequently result in a crash, requiring maintenance and potentially contributing to congestion in adjacent travel lanes.
- CMBs have been shown to reduce rollovers in divided medians by restraining vehicles with large yaw displacements [4]. However, the medians in Kansas are primarily flat and may not be prone to tripping yawed vehicles. It could not be determined if there was a noticeable change in rollover behavior before or after installation of the CMBs due to extremely small sample of crashes with rollover results.

4.7 Discussion

The KDOT CMB crash database was limited, with only 254 crashes identified between CMB construction completion in 2011 and 2012 and the end of the analysis period in 2019. CMB was also only installed on roadways with relatively high traffic volumes in near-urban areas, which were also denoted as “commuter routes” with heavy traffic primarily during morning and evening traffic commutes. Medians for all crash locations were predominantly flat and at least 40 ft wide. All roads were four lane, divided highways with speed limits of 65 mph. Thus, results may be limited by the constraints of the dataset.

5 DISCUSSION

5.1 Limitations on Conclusions

KDOT installed a total of 7.95 miles of CMB on principally commuter routes between 2011 and 2012. Analyzable data after the reported completion of the CMBs therefore ranged between 6.6 and 7.9 years of crash data, through June 2019. A total of 1,220 crashes occurred after the CMBs were reported to be completed, of which 254 involved impact with a CMB as at least one event in the crash sequence of events.

A valid method of evaluating crash rates, severities, ROR departure frequencies, and “black spot” identification is using suitable “control sites” for comparing crash histories. Such control sites were not evaluated in this study. Each of the CMB locations were associated with a median less than 70 ft wide, high daily traffic volumes, and 65-mph speed limits. Few segments of Kansas freeways have total median widths less than 70 ft in rural or suburban areas which did not already have median barrier present; these sites may possess significantly different attributes, traffic characteristics and crash rates. Control sites with different attributes (weather patterns, traffic volumes, number of lanes, freight or heavy truck transportation, road curvatures, median geometries) may not be well-suited for evaluating the before-and-after effectiveness of the CMBs. Lastly, the low number of miles of roadway with CMB installed (7.95) posed significant challenges for identifying similar sites with comparable lengths and attributes. Moreover, the attributes of the four sites in this study were each unique, with different crash rates and road geometrics. Although control site comparisons offer interesting insights into the data, they were not applicable for this study.

Before-and-after studies may be useful to estimate long-term effects of safety improvements projects, but changes in the behavior of drivers, state and national economic transitions, road improvement projects (including improved traffic control devices, surface friction treatments, and rumble strips), driver distractions (in-vehicle media, cell phones), and vehicle safety improvements (such as Advanced Driver Assistance Systems or ADAS) also affect the risk of crashes and crash severity [34-35]. Traffic patterns and crash histories before CMB installation were affected by the economic recession of 2007-2009, and most registered vehicles were passenger cars. As well, KDOT crash data prior to 2009 was archived prior to this study. Due to limited time and constraints on KDOT personnel, crash data before 2009 could not be accessed and provided to researchers. Thus only 409 total crashes and 94 left-side ROR crashes were identified before CMB installation in the 7.95-mile stretches of roadway considered. Between 2013 and 2019 (end of the study period), a much higher percentage of CUV, SUV, and pickup truck vehicles were sold compared to passenger cars, new driver ADAS warning features were implemented on many new vehicles, and traffic volumes grew significantly [36-37]. It was beyond the scope of this study to discern the variations in vehicle characteristics, registrations, weather patterns, and economic effects on run-off-road crash rates for before and after-CMB installation periods.

These factors were considered when determining the significance and applicability of conclusions.

5.2 Additional Considerations

Using KDOT crash data and experience from other research efforts, researchers also noted several supplementary aspects about CMB performance related to animal containment and motorcyclist interaction. Those observations are discussed below. Note that no analysis was performed to evaluate the significance of these observations.

5.2.1 CMB as Animal Crossing Deterrent

Kansas contains the geographical center of the continental United States, is primarily rural by land usage (mostly agricultural land), and has significant agricultural and forest areas. Researchers observed a significant number of crashes which were related to both domesticated animals and wildlife. Most crashes involving domesticated animals were related to drivers performing evasive maneuvers to avoid animals in the roadway; the presence or absence of CMBs was not believed to affect the number of domesticated animal incidents. However, prior to the installation of CMBs, a large number of crashes were attributed to avoidance maneuvers or post-impact trajectories related to deer, but the number of deer-related crashes fell sharply after installing CMBs. Very high numbers of deer crashes were also observed for rural highways in Kansas which did not have median barrier installed [1-2]. Although it was not confirmed in this study, it was believed that CMBs may contribute to changes in wildlife movement and/or migration patterns.

5.2.2 Motorcyclist Considerations

Motorcyclist advocacy groups are some of the most vocal opponents of CMBs [38-40]. Many motorcyclists refer to CMBs as “cheese cutters” due to a perceived risk of amputation or decapitation from impacting the longitudinal cables. However, as noted in Section 2.4, most motorcyclist safety studies have concluded that the cables are not strongly correlated with injuries, whereas the cable posts are strongly correlated with significant, disabling or fatal injuries for motorcyclists. Concrete barriers, though more expensive, showed a slight improvement in motorcyclist survivability by limiting contact with stiff post members, but W-beam barriers caused more serious or fatal injuries to motorcyclists due to short post spacing, stiff rail elements, and sharp post flanges.

Motorcyclist cross-median crashes are extremely rare, which indicate that few motorcyclists travel across divided medians into opposing travel lanes. To promote motorcyclist safety, the best safety treatment for CMBs is to maximize lateral recovery space. Motorcyclists who do not impact a barrier do not need any barrier modifications to improve survivability, which could be potentially expensive and may adversely affect the performance of the system designed for automobile impacts. It is recommended to maximize CMB offset from the travel lanes whenever practical to facilitate safety for motorcyclists.

6 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Crashes on three highways in Kansas were reviewed to identify CMB crashes: K-10, US-75, and K-96. Based on scene diagrams and crash narratives, 254 cable median barrier (CMB) crashes were identified after CMB construction was completed with crash data extending through June 2019. The rate of "bad outcome" crash results was very low for KDOT with 3.1% of crashes producing a penetration, 0.4% producing a rollover, and 0.4% producing a fatal injury.

Atmospheric weather and road conditions were found to strongly influence the likelihood of run-off-road crashes and CMB impact likelihood. Adverse weather or road conditions such as rain, fog, snow, ice, or sleet increased the likelihood of CMB impacts by between 1.5 and 9.5 times. Overall, adverse weather was associated with a larger number of crashes and a reduced number of injury or fatal crashes, particularly for CMB crashes.

Using observed ratios of cross-median encroachment (CME) and cross-median crash (CMC) for previous Kansas crash studies, it was estimated that 5 CMCs would likely have occurred if CMBs were not installed in 2011 and 2012. After CMBs were installed, one CMC crash occurred which was correlated with a CMB penetration, but that crash occurred near the downstream end terminal and it was unclear whether the crash result was affected by the impact location's proximity to the downstream anchorage. Therefore, it was estimated that approximately 80% of the possible CMCs which could have occurred on the selected roadways between 2013 and 2019 were prevented by the CMBs. Roadside departure crashes including CMB crashes were more commonly associated with adverse weather and/or road conditions, which were previously shown to be associated with increased rates of both CME and CMC.

CMBs are fixed objects installed in divided medians and can contribute to serious crash outcomes, some of which may not have occurred in the absence of a median barrier. A 59% increase in the reported number of all left-side ROR crashes and 77% increase in left-side-only ROR crashes occurred after installing CMBs.

Thus, the benefits provided by CMBs in terms of reduction of cross-median crashes should offset the additional expenses of CMB repairs and increased road congestion, emergency response, cleanup, crash reporting, and insurance claims associated with more median-related crashes which may not have occurred or been reported in the absence of a cable median barrier. Many state DOTs have also reported an increase in litigation related to CMB impacts. When tragic cross-median crashes occur in the absence of CMBs, state DOTs are sometimes accused of failing to take sufficient action to prevent CMCs. However, when bad outcomes occur in conjunction with CMBs, lawsuits may be filed related to claims of improper installation, placement in the median, or maintenance; or increased danger to potentially vulnerable occupants such as motorcyclists or occupants of convertibles. Motorcyclist advocacy groups are wary of cable median barriers due to both perceived and real risk of bodily injury or death associated with impacts with CMB posts [e.g., 38-40]. Additionally, a few CMCs will still occur due to vehicle penetration under, through, or over CMBs [e.g., 41] despite otherwise excellent CMB performance. Consideration must be given to the ramifications of selecting protective barrier systems and properly weighing safety benefits when committing to installation of roadside hardware.

In conclusion, researchers determined that the CMB installed in Kansas did not increase the number or rate of severe or injury crash outcomes, were generally less severe than non-CMB

ROR crash outcomes, and likely prevented potentially-severe CMC outcomes. Researchers at the University of Nebraska-Lincoln's (UNL's) Midwest Roadside Safety Facility (MwRSF) are conducting a separate median barrier warrants study to determine which conclusions from this in-service performance evaluation (ISPE) study, if any, may be useful for determining median barrier warrants on rural Kansas highways. Once that study is completed, it is anticipated that better guidance will be available to determine if additional median barriers, including CMB, are warranted and cost-effective for Kansas freeways.

7 REFERENCES

1. Sicking, D.L., de Albuquerque, F.D.B., Lechtenberg, K.A., and Stolle, C.S., *Guidelines for Implementation of Cable Median Barrier*, Journal of the Transportation Research Board No. 2120, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 82-90.

2. Sicking, D.L., de Albuquerque, F.D.B., and Lechtenberg, K.A., *Cable Median Barrier Guidelines*, Final Report to the Midwest States Regional Pooled Fund Program, Midwest Report No. TRP-03-206-08, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, March 2009 (revised).

3. *Roadside Design Guide (4th Edition)*, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2011.

4. Stolle, C.S., Sicking, D.L., Faller, R.K., and Reid, J.D., *Cable Median Barrier Failure Analysis and Remediation Phase II*, Final Report to the Midwest States Regional Pooled Fund Program, Midwest Report No. TRP-03-319-13, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, June 2013.

5. Ray, M.H., Silvestri, C., Conron, C.E., and Mongiardini, M., "Experience with Cable Median Barriers in the United States: Design Standards, Policies, and Performance," *Journal of Transportation Engineering*, Vol 135 No. 10, pp 711-720, October 2009.

6. HSA-10/B-82 Eligibility Letter for Brifen Wire Rope Safety Fence at TL-3 Impact Conditions (NCHRP Report No. 350), April 10, 2001. https://safety.fhwa.dot.gov/roadway_dept/countermeasures/docs/Cable_Sep2012Saferlogo.pdf.

7. HSA-10/B-82B, Eligibility Letter for Brifen Wire Rope Safety Fence at TL-4 Impact Conditions (NCHRP Report No. 350), March 27, 2005. https://safety.fhwa.dot.gov/roadway_dept/countermeasures/reduce_crash_severity/barriers/pdf/b82b.pdf

8. *Cable Barriers*, FHWA Informational and Eligibility Chart, Federal Highway Administration, September 12, 2012. https://safety.fhwa.dot.gov/roadway_dept/countermeasures/docs/Cable_Sep2012Saferlogo.pdf

9. Srinivasan, R., Lan, B., Carter, D., Persaud, B., and Eccles, K., *Safety Evaluation of Cable Median Barriers in Combination with Rumble Strips on Divided Roads*, Final Report to the U.S. Department of Transportation, Report No. FHWA-HRT-17-070, August 2017.

10. Churchill, A., Hassan, M., Ngo, B., Morison, C., Fischer, L., and Wilkie, K., "Operating and Maintaining Median High Tension Cable Barrier on Highway 2 in Alberta," Presented at the 2013 Annual Conference of the Transportation Association of Canada, Winnepeg, Manitoba, 2013.

11. Alluri, P., Haleem, K., Gan, A., and Mauthner, J., "Safety Performance Evaluation of Cable Median Barriers on Freeways in Florida," Presented at the 2013 Annual Meeting of the Transportation Research Board, Washington, D.C., January 2013.

12. Alluri, P., Haleem, K., and Gan, A., *In-Service Performance Evaluation (ISPE) for G4(1S) Type of Strong-Post W-beam Guardrail System and Cable Median Barrier: Volume II*, Final Report to the Florida Department of Transportation (FDOT), Florida International University, Miami, Florida, December 2012.

13. Li, S., Newbolds, S., Zhu, K., and Menne, H., *In-Service Performance Evaluation of a Cable Median Barrier System on Interstate Highways*, Journal of Performance of Constructed Facilities (ASCE), Issue 27 No. 2, pp. 163-170, 2013.

14. Zou, Tarko, Chen, and Romero, *Effectiveness of cable barriers, guardrail, and concrete barrier walls in reducing the risk of injury*, Accident Analysis and Prevention, Vol 72, pp.55-65, Purdue University, 2014.

15. Zou, Y., Tarko, A.P., Chen, E., and Romero, M.A., *Effectiveness of Cable Barriers, Guardrails, and Concrete Barrier Walls in Reducing the Risk of Injury*, Accident Analysis and Prevention Issue 72, 2014, pp. 55-65. doi: 10.1016/j.aap.2014.06.013

16. Savolainen, P.T. Kirsch, T.J., Hamzeie, R., Johari, M.U.M., and Nightingale, E., *In-Service Performance of Median Cable Barriers in Iowa*, Final Report to the Iowa Department of Transportation, Report No. InTrans Project 15-546, Center for Transportation Research and Education, Iowa State University, Ames, Iowa, May 2018.

17. Agent, K., Howell, B., Jasper, J., and Staats, W., *In-Service Evaluation of High Tension Cable Barrier Systems*, Final Report to the Kentucky Department of Transportation, Report No. KTC-17-17/SPR16-526-1F, Kentucky Transportation Center, University of Kentucky, Lexington, Kentucky, April 2017.

18. Savolainen, P.T., Gates, T.J., Russo, B.J., and Kay, J.J., *Study of High-Tension Cable Median Barriers on Michigan Roadways*, Final Report to the Michigan Department of Transportation, Report No. RC-1612, Wayne State University, Detroit, Michigan, October 2014.

19. Outcalt, W., *Cable Guardrail*, Report No. CDOT-DTD-R-2004-10, Colorado Department of Transportation, June 2004.

20. "Oklahoma's Experience with Wire Rope Safety Fence," Brifen USA, 2003.

21. Monsere, C.M., Sposito, B., and Johnston, S., "Safety Performance of Three-Cable Median Barrier on Interstate 5 in Oregon," Oregon DOT, 2003.

22. Bambach, M.R., Mitchell, R.J., and Grzebieta, R.H., *The Protective Effect of Roadside Barriers for Motorcyclists*, Traffic Injury Prevention Vol 14 Issue 7, 2013, pp. 756-765. doi: 10.1080/15389588.2012.752077

23. Bambach, M.R., Grzebieta, R.H., and McIntosh, A.S., *Injury Topology of Fatal Motorcycle Collisions with Roadside Barriers in Australia and New Zealand*, Accident Analysis and Prevention, Issue 49, Nov 2012, pp. 253-260. doi: 10.1016/j.aap.2011.06.016

24. Daniello, A., and Gabler, H.C., *The Effect of Barrier Type on Injury Severity in Motorcycle to Barrier Collisions in North Carolina, Texas, and New Jersey*, Transportation Research Record: Journal of the Transportation Research Board No. 2262, Washington, D.C., 2011, pp. 144-151.

25. "Google Earth," Google, Inc., https://earthengine.google.com/

26. "Economic Values Used in Analyses," Federal Highway Administration, December 2016. https://www.transportation.gov/regulations/economic-values-used-in-analysis

27. "National Statistics: Fatal Accident Reporting System," National Highway Traffic Safety Administration, 2019. https://www-fars.nhtsa.dot.gov/Main/index.aspx

28. Wegman, F., Allsop, R., Antoniou, C., Bergel-Hayat, R., Elvik, R., Lassarre, S., Lloyd, D., and Wijnen, W., *How did the economic recession (2008-2010) influence traffic fatalities in OECD-countries?*, Accident Analysis and Prevention, Vol 102, 2017, pp. 51–59. http://dx.doi.org/10.1016/j.aap.2017.01.022

29. Sweigard, M., *Development of a Novel Vehicle Guidance System: Vehicle Risk Mitigation and Control*, Master's Thesis, University of Nebraska-Lincoln, May 2020.

30. *Manual for Assessing Safety Hardware (MASH), Second Edition*, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.

31. "High-tension cable barriers test successfully following Highway 401 crash," CBC News (Canada), August 19, 2018. https://www.cbc.ca/news/canada/windsor/high-tension-cable-barriers-tested-highway-401-1.4790992

32. Torres, C., "High Tension Cable Barrier," Presented to the Michigan Traffic & Safety Summit, March 31, 2010, https://www.michigan.gov/documents/msp/Torres_318634_7.pdf

33. Chandler, B., *Eliminating Cross-Median Fatalities: Statewide Installation of Median Cable Barrier in Missouri*, TR News no. 248, January-February 2007. http://onlinepubs.trb.org/onlinepubs/trnews/trnews248rpo.pdf

34. Gancarczyk, S., "How Will Advanced Driver Assistance Systems Impact Collision Rates in the Future?", Insurance Auto Auctions, April 30, 2019. https://www.iaai.com/articles/how-will-advanced-driver-assistance-systems-impact-collision-rates-in-the-future/

35. Young, J., "Evidence Continues to Mount in Favor of Front Crash Prevention", Insurance Institute for Highway Safety and Highway Loss Data Institute, August 26, 2015. https://www.iihs.org/news/detail/evidence-continues-to-mount-in-favor-of-front-crash-prevention

36. Ronspies, K.B., Stolle, C.S., Faller, R.K., and Bielenberg, R.W., *NCHRP Task 20-07: MASH Test Vehicle Recommendations*, Presented to the 2020 Meeting of the Transportation Research Board, Washington, D.C., In Publication.

37. Stolle, C.S., Ronspies, K.B., Bielenberg, R.W., and Faller, R.K., *Evaluation and Update of MASH Test Vehicles*, Draft Report to the National Cooperative Highway Research Program, March 2020, In Publication.

38. *Vehicle Restraint Systems: Safety Fences, Crash Barriers, Motorcyclists*, Motorcycle Action Group, 2005. http://www.righttoride.co.uk/virtuallibrary/barriers/MAGcrashbarrier2005.pdf

39. Hinchliffe, M., *Are wire rope barriers "rider slicers"?*, Motorbike Writer, April 9, 2014. https://motorbikewriter.com/wire-rope-barriers-rider-slicers/

40. *Is cable barrier a special hazard to motorcyclists?*, Kitsap Sun Editorial (USA Today), September 5, 2006. http://pugetsoundblogs.com/roadwarrior/2006/09/05/is-cable-barrier-a-special-hazard-to-motorcyclists/

41. Stradling, R., *SHP: Car involved in fatal I-40 crash slid under median barrier into tractor-trailer*, The News & Observer, August 21, 2019. https://www.newsobserver.com/news/local/article234227427.html

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