Potential Effect of Cable Median Barriers on Commercial Vehicle Crossover Crashes

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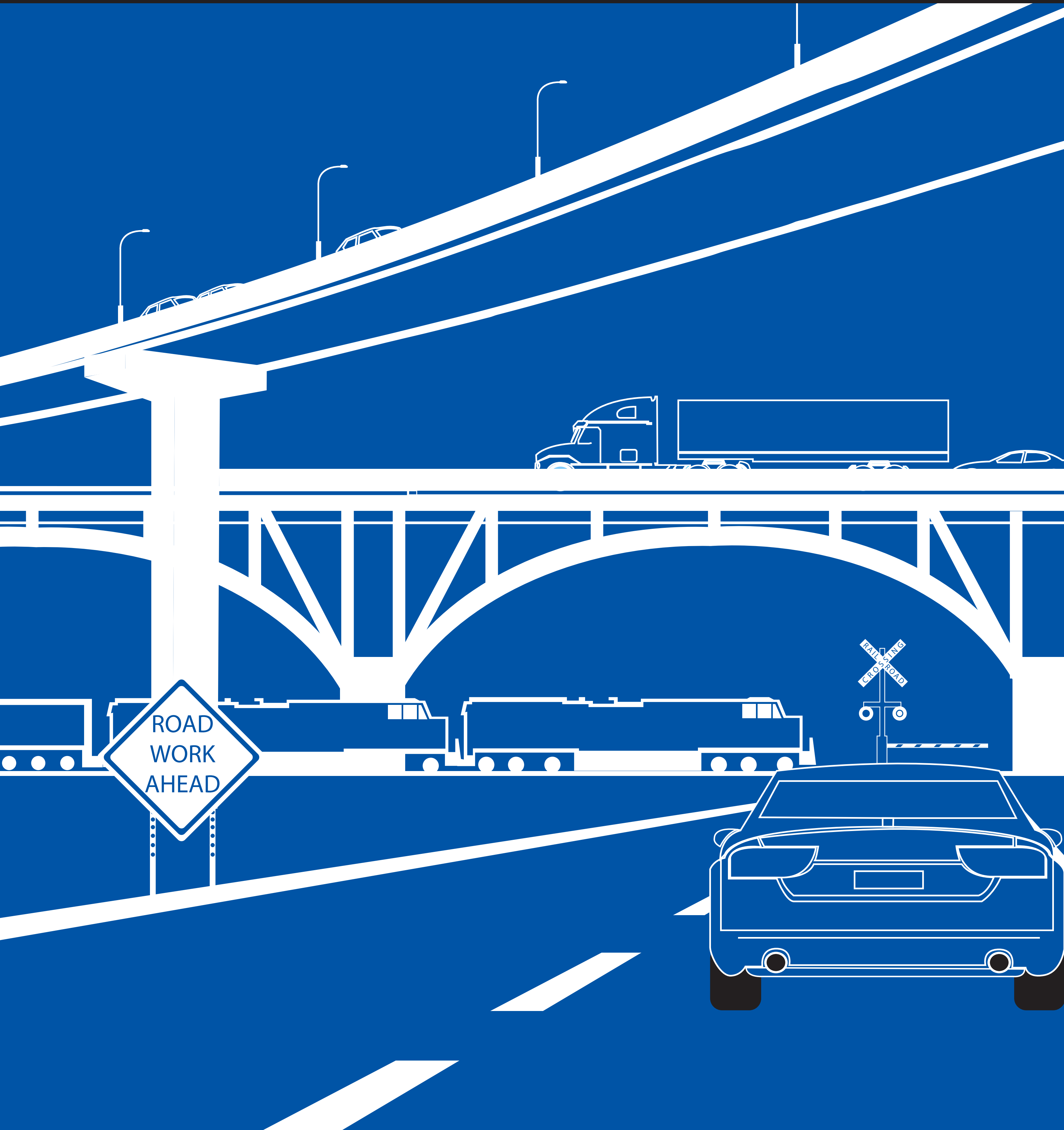

Kentucky Transportation Center
College of Engineering, University of Kentucky, Lexington, Kentucky

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- This document replaces the original version published in June 2020. No content has been altered. The formatting has been corrected and updated to fix errors that arose when the Word document was converted to a PDF.

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Potential Effect of Cable Median Barriers on Commercial Vehicle Crossover Crashes

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16. Abstract
In 2016, commercial motor vehicles (CMVs) were involved in 4,079 fatal crashes in the U.S., representing 11.8 percent of all fatal crashes. State of Kentucky crash data for 2015-2016 show that per capita crash rates and increases in crash-related fatalities exceeded the national average. Crossover crashes occur when a vehicle leaves its intended path and veers into the path of oncoming traffic, typically resulting in head-on or sideswipe opposite direction crashes. Cable median barriers are a countermeasure which can potentially be used to mitigate crossover crashes. This research investigated the potential effectiveness of cable median barriers on CMV crashes. Analysis relied on an expert panel approach that evaluated the potential effects of cable barriers on altering the crash severity for fatal and incapacitating injuries (K and A in the KABCO severity index) and developed safety performance functions (SPFs) that resulted in crash prediction models that can be used to develop crash modification factors (CMFs) for estimating how the presence of cable median barriers can potentially affect crash occurrence and severity. The expert panel analysis concluded that safety gains are possible by installing cable median barriers and that their effectiveness is greater for fatalities. The average score of over 2 from the panel (on a scale from 0-5) indicates a moderate effect on crash outcomes. SPFs developed also supported the overall expert panel assessment. Analysis found that CMV crash outcomes benefit from installing cable median barriers, although only interstate routes were examined. The results indicate that CMV crashes will indeed be mitigated by installing cable median barriers. Both analyses supported this finding, and the overall conclusion is one of a positive impact. Benefits may be greater on divided roadways, since installations on two-lane roads may be more problematic due to space limitations. Additional research is recommended to evaluate this finding in light of which vehicle is the errant vehicle, since there could be significant implications for assessing the effectiveness of the cable median barrier if the CMV is the crossing-over vehicle.

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Chapter 1 Introduction

According to World Health Organization (WHO), every year 1.25 million people die in road traffic crashes, while at least 20 million are involved in non-fatal crashes (WHO 2018). In the United States (U.S.), road traffic crashes are a leading cause of death. Crash data from the Kentucky Transportation Center (KTC) indicate that fatalities increased from 761 to 834 between 2015 and 2016 reflecting an increase of 10 percent, which was higher than the national average (KTC 2016). In addition, Kentucky has a higher overall crash rate per population than the national average. In 2016, the National Highway Traffic Safety Administration (NHTSA) estimated 22.5 crashes per 1,000 persons at the national level, while Kentucky had a rate of 37.3. NHTSA also estimated the value of societal harm — which includes economic impacts and a valuation for lost quality of life — for all traffic crashes in 2010 at $836 billion (NHTSA 2015). An increasing trend has been observed for commercial truck crashes since 2009. During the 2009-2016 period, commercial vehicle (CMV) crashes increased 27 percent in Kentucky (KSP 2016).

Of the 269 million registered vehicles in the U.S. in 2016, approximately 11.5 million were CMVs according to the Federal Motor Carrier Safety Administration (FMCSA 2018). CMVs include trucks and busses. Approximately 6.1 million drivers hold a Commercial Driver License, comprising only 3 percent of all licensed drivers. In 2016, CMVs were involved in 4,079 fatal crashes in the U.S. — this represented 11.8 percent of all fatal crashes and 7.4 percent of non-fatal crashes. Even though CMVs typically drive longer distances, their crash involvement could be considered somewhat proportional to their exposure. In 2016, CMVs were responsible for 9.1 percent of all vehicle miles traveled (VMT) in the U.S. (FMCSA 2018). However, the number of CMV crashes has increased continually since 2009. In 2017, the number of people who died in large truck crashes was 30 percent higher than in 2009, according to the Insurance Institute for Highway Safety (IIHS 2017). Most deaths in crashes involving CMVs are passenger vehicle occupants, which is mainly attributed to the vulnerability of people traveling in smaller vehicles.

Crossover crashes are those where a vehicle leaves its intended path and veers into the path of oncoming traffic. In crash records, these crashes appear as head on or sideswipe opposite direction. Head-on crashes on divided highways accounted for approximately 8 percent of fatalities (NHTSA 2017). In 2017, the crash rate for heavy trucks was 1.56 crashes per 100 million VMT, while that of passenger cars was 1.48 crashes per 100 million VMT. A potential countermeasure for addressing crossover crashes is median barriers. Among the types of median barriers that can be used, cable barriers are considered more forgiving than others. Moreover, they have a lower installation and replacement costs compared to concrete and beam barriers. It has been estimated that median barriers have been effective in reducing 97 percent of crossover crashes after installation (Graham et al. 2014).

It is apparent that installing cable median barriers could positively affect crash outcomes (i.e., occurrence and severity). It is therefore critical to analyze and determine their potential effects on CMV crossover crashes. Identifying factors which may contribute to crashes could aid in understanding the circumstances leading up to them and provide a foundation for determining the potential remedial impact of the barrier.

The primary goal of this research is to investigate the potential effectiveness of cable median barriers on CMV crashes. The study investigates factors which contribute to CMV crashes — on roadways without a cable median barrier — and evaluates the potential effectiveness of barriers for either averting the crossover or reducing crash severity. The findings of this work will help identify areas where cable barriers could potentially affect CMV crash outcomes and thus improve overall safety.

Chapter 2 Literature Review

Significant research has been conducted globally to investigate how vehicle, roadway, and driver factors influence CMV crash severity and occurrence. The following sections discuss CMV-related safety issues to better understand what roles they play crashes and identify potential occupational characteristics that would support the crash analysis described in later chapters.

2.1 Commercial Vehicle Driver Issues

Considerable research has been done around the world to investigate the effects of vehicle, roadway, and driver characteristics on crash severity and occurrence. Notably, the role of alcohol and drug use has become a topic of interest, especially in relation to CMV drivers. Some analysis has focused on the prevalence of drug use among CMV drivers and related contributing factors, while other research has sought to determine the correlation between substance use and crash occurrence and severity. Prior research that examined factors which contribute to CMV crashes, and specifically the role that alcohol and drug use plays in those crashes, is presented here.

Several research efforts have focused on the factors that contribute to CMV drivers using some form of impairing substances, regardless of their effects on crash occurrence or severity. Girotto et al. (2014) and Knauth et al. (2012) examined the factors that contribute to CMV driver drug usage. Girotto et al. (2014) looked specifically into factors influencing the intake of psychoactive substances by synthesizing cross-sectional studies across multiple countries, with most of the data sourced from self-reporting surveys. They found that even though methodologies varied between studies, the intake of psychoactive substances is a relatively frequent occurrence — 19.3 percent of drivers admitted to having used marijuana during their lifetimes. They also concluded that poor working conditions, such as resting time, trip length, and night shifts, tended to increase the frequency of drug intake. Knauth et al. (2012) also relied heavily on survey data to analyze the factors affecting substance use among truck drivers in Brazil. The study focused on substances used with the intent of staying awake and used a Poisson regression to analyze the data. They found that approximately 23 percent of drivers used some substance to stay awake, with the majority using some form of amphetamines, while the consumption of alcohol on a weekly basis was reported by 45 percent of drivers. They also noted that longer trips along with younger age, higher income, and alcohol consumption were all associated with more frequent use of substances to stay awake. Like Girotto et al. (2014), they theorized that working conditions and the inherent physical and emotional stress of truck driving are major factors which lead to more frequent substance use.

Souza et al. (2005) focused primarily on the prevalence of sleep disorders and sleeping habits among truck drivers, but were able to discover through questionnaires that substance use is frequent among Brazilian truck drivers, with 95 percent reporting alcohol use and 11 percent reporting amphetamine use, of which 77 percent used more than six times a week. Similarly, Mir et al. (2013) interviewed 857 truck drivers in Pakistan about socioeconomics, sleep habits, drug use, and crash involvement. They discovered that 23 percent admitted to smoking marijuana while driving, 6 percent reported drinking alcohol right before driving, and 8 percent reported using stimulant pills. However, using multivariate logistic regression, only alcohol was found to have a significant effect on crash occurrence. It is important to note that all of these studies have been primarily based on self-reported data, and that introduces implicit bias into data on substance use frequency and the crash frequency.

To counter this, many researchers have conducted crash analyses using historical crash records and instances of drug and alcohol use recorded therein. The National Transportation Safety Board (NTSB; 1990) attempted to examine and identify the contributing factors to crashes looking only at crashes which were fatal to truck drivers. This approach resulted in a much higher reporting rate for toxicological samples indicating alcohol and drug use. The NTSB studied fatal crashes across eight states for 1988 using FARS crash data and contracted with these states to obtain consistent toxicological tests for these fatal crashes. Alcohol and marijuana were both involved in 13 percent of fatal truck driver crashes. In addition, caffeine was involved in 35 percent, with other drugs and amphetamines less common. While this information indicates the presence of substance use, it only does so for drivers involved in fatal crashes, reducing the sample size significantly and possibly underestimating the level of use.

Chen et al. (2015) analyzed crashes on a slightly larger scale, considering two years of crash data for injury or fatal CMV crashes. This study used a Bayesian random intercept model and discovered that along with factors such as road grade, number of vehicles, and seatbelt usage, the presence of alcohol or drugs positively correlated with crash severity. However, crash severity does not necessarily indicate whether the truck drivers are driving less safely due to the presence of drugs. Gates et al. (2013) attempted to quantify this in relation to stimulant (e.g., amphetamines, cocaine) use by analyzing unsafe driving actions (UDAs) recorded in the FARS database. Drivers in this analysis were only included when their blood alcohol level tests were available. A logistic regression was used to calculate odds ratios and results indicated that stimulant-positive drivers had 78 percent greater odds of committing a UDA compared to drivers who were stimulant-negative. Khorashadi et al. (2005) also found that alcohol or drug use was the prominent causal factor in 4 percent of crash events for rural road truck crashes and the probability for severe/fatal injury increased 246 percent compared to crashes not involving alcohol or drugs. Conversely, Lemp et al. (2011) found that truck drivers under the influence of illegal drugs were most commonly involved in minor injury crashes as opposed to major injury or fatality crashes. While these studies elaborate on the relation between truck crashes and drug/alcohol use, they also rely on crash reports for information on drivers under the influence, which can result in problems such as sample size and collection bias. To adjust for a small sample size of vehicles actually tested for drugs (in this case marijuana), Chen et al. (2018) developed a multiple imputation procedure for estimating marijuana positivity among drivers with missing marijuana test results, using a Bayesian multilevel model that allows a nonlinear association with blood alcohol concentrations (BACs), accounts for correlations among drivers in the same states, and includes both individual-level and state-level covariates. The resulting adjusted marijuana positivity rate of 11.7 percent was lower than the observed rate of 14.8 percent among drivers involved in fatal motor vehicle crashes. Chen suggested that the multiple imputation model can reduce bias and improve efficiency in estimating positivity rates of marijuana.

The research presented thus far has primarily shown that truck drivers are at risk for alcohol and drug use, both during their lifetimes and on the job, and that substance use seems to correlate positively with both truck driver injury severity and crash occurrence. This does not however assess the risk to other drivers. Several researchers have investigated both the occurrence of truck driver fault in crashes and the differences in truck driver single crashes versus multi-vehicle crashes. Vachal (2016) investigated the difference in contributing crash factors as they differ among single and multivehicle truck crashes, finding that non-truck drivers who were involved in injury crashes with trucks had the highest rate of alcohol or drug usage at 16.6 percent, compared to 12.5 percent for drivers in non-truck related injury crashes, and only 1.3 percent for truck drivers involved in injury crashes. In addition, for multivehicle truck crashes involving alcohol or drugs, the risk of serious injury was twice as likely for the driver of the passenger vehicle compared to the truck driver. This research seems to indicate that while drugs and alcohol are potentially a contributing factor for truck drivers, substance use is more common and more dangerous for drivers of passenger vehicles. Chen et al. (2011) also separated crash analysis into single and multivehicle truck crashes. Using Highway Safety Information System (HSIS) data and multinomial logit models, they discovered that drivers influenced by drugs or alcohol were more likely to experience of injury or fatality according to the multivehicle model, but this relation was not significant in the single vehicle model. This indicates that truck drivers under the influence of alcohol or drugs are the most dangerous when combined with the presence of other vehicles.

Finally, Spainhour et al. (2005) performed an in-depth analysis of fatal truck crashes by utilizing crash records, video logs, photographs and site visits. They found that drugs and alcohol use was much more common among truck drivers that were considered at-fault in fatal crashes. However, truck drivers were only at fault for approximately 30 percent of the crashes they had been involved in.

2.2 Cable Median Barriers as Countermeasures

Against the backdrop of impaired driving among passenger vehicle and truck drivers, it is appropriate to consider roadway countermeasures that may decrease fatalities and injuries. Many countermeasures have been studied by researchers, including rumble strips, chevrons, post-mounted delineators, and placing rigid or flexible barriers on the roadside or median. Researchers have explored the influence of cable median barrier installations on crash rates and crash severity, including their safety effectiveness for all crashes, by vehicle type, injury severity, and other categories. Little research has been conducted on the effectiveness of cable median barriers for mitigating CMV crashes. Most previous studies have considered overall safety improvements provided by cable median barriers for median and cross-median crashes for *all* vehicle types. Other research has developed Crash Modification Factors (CMF) and Safety Performance Functions (SPF) to predict the safety effectiveness of barrier installation. Researchers have studied the effectiveness of cable median barriers using before-and-after studies, the Empirical Bayes (EB) method, and other methods.

Previous research has generated a range of crash decreases/increases, as well as a range of safety effectiveness estimates. However, most studies have generally shown that installing cable median barriers prevents cars and CMVs from crossing into opposing traffic lanes (thereby reducing crossover crashes), lessens crash severity, but increases the number of crashes overall. Graham et al. (2014) studied median barriers across six states, using at least five years of crash data from each state. While total crashes increased an average of 277 percent following the installation of cable median barriers on four-lane roads, crossover crashes fell 96 percent, and fatal/injury crossover crashes declined 92 percent. Coulter and Ksaibati (2013) found that critical median and cross-median crashes in Wyoming fell 44 percent during their analysis period, including a reduction of nearly 79 percent in critical cross-median crashes and of 43 percent in critical rollover crashes in the median. The number of serious crashes in fell by about 12 percent, while the number of property damage only (PDO) crashes increased by only 53 percent. Srinivasan et al. (2017) considered the safety effectiveness of cable median barriers, in combination with inside shoulder rumble strips, on divided roads in Illinois, Kentucky, and Missouri. Combined results for Illinois and Kentucky showed a 24 percent decrease in fatal and injury crashes and a 27 percent increase in overall crashes, with very similar results for Missouri.

Reviewing cable median barrier crashes in 23 states, Ray et al. (2009) found that cable barrier installations reduced crossover fatalities by 95 percent, while increasing PDO crashes. Agent and Pigman (2008) studied crashes involving cable median barrier systems on major highways in Kentucky over two years, finding a crossover prevention rate of up to 48 percent. In a study of the statewide installation of cable median barriers in Missouri, Chandler (2007) found they prevented 95 percent of vehicles which entered the median from crossing into opposing travel lanes. Olson et al. (2013) reported on the evolution and accomplishments of the Washington State Department of Transportation's (WSDOT's) cable median barrier program, where cable median barriers prevented cars or CMVs from entering the opposing traffic in a number of crashes.

Several previous studies included vehicle type as a variable. They found that crossover prevention was lower for trucks than for passenger vehicles, but the cable median barrier systems nonetheless improved safety. Gabauer (2012) looked at barrier crash and fatal crash involvement rates, along with performance of different barrier systems, for CMV crashes over nine years in the Fatal Analysis Reporting System (FARS), the General Estimates System, and the Large Truck Crash Causation Study. Using test-level categories, where the TL-4 systems included some high-tension cable barriers, the crossover rate for trucks was 17 percent, compared to 50 percent for lower test level categories. Alluri et al. (2015) evaluated the safety performance of cable median barriers on limited access facilities in Florida, which varied according to vehicle type. Medium and heavy trucks had a non-crossover rate of 50.0 percent and 66.7 percent, respectively, but the study only considered a small sample size (two crashes for medium trucks and 12 crashes for heavy CMVs). With a second look at median barrier crashes by vehicle type, Alluri et al. (2016) considered 101 miles of cable median barrier sections and six years of crash data, in Florida, arriving at similar results. Overall, 98.1 percent of cars and 95.5 percent of light trucks that hit the barrier were prevented from crossing the median.

Russo (2015) reviewed median-related crashes in Michigan, finding overall crash reductions of 86.8 percent following cable median barrier installation. Using the EB before-and-after method, statistical analysis showed that fatal and severe (KA-level) crashes decreased 33 percent, while low severity (CO-level) crashes increased 155 percent. Trucks and busses weighing over 10,000 pounds were over-represented in barrier penetrations, accounting for 0.2 percent of cable barrier strike crashes, while 6.7 percent resulted in penetration, a cross-median event, or a crash. Finally, Sheikh et al. (2008) reported on the state of the practice for cable barrier systems in the U.S., with some DOTs reporting cable median barriers prevent much larger vehicles from crossing into oncoming traffic (e.g., fire trucks, CMVs).

A number of studies have found that injury severity declines when cable median barriers are installed, while the number of PDO crashes goes up. A before-and-after study of cable median barriers using seven years of crash data from the Iowa DOT showed a reduction in fatality crashes of 51 percent (Nightingale (2017). A 118 percent increase in PDO crashes occurred over the same period. Almothaffar (2018) conducted a before-and-after study of 14 cable median barrier locations in Ohio and found that vehicles did not cross the barrier in 95.5 percent of crashes. Using the EB method, safety effectiveness was found to be 73.9 percent for all crashes and 80.4 percent for fatal and injury crashes combined. Savolainen et al. (2018) considered nine years of crash data for 251 miles of cable median barrier systems in Iowa. Using a naive before-after comparison, they found that cable median barrier installations reduced K, A, and B-level crashes by 68.7 percent, 36.8 percent, and 23.9 percent, respectively. On the other hand, C and O-level crashes increased by 5.7 percent and 95.4 percent, respectively.

Some researchers have considered the relative safety benefits of different median barriers, including cable barriers, guardrail, and concrete barriers. Zou et al. (2014) reported a reduction in the odds of injury at 85 percent for near-side cable median barriers (offset between 10 ft and 29 ft), and 78 percent for far-side cable median barriers (offset at least 30 ft). Results showed that with respect to injury reduction, a cable barrier is preferred over a guardrail or concrete barrier if road and traffic conditions allow. Alluri et al. (2015) found that guardrail prevented more vehicles from crossing over the median than cable barrier — 95 percent and 84 percent, respectively. Cable barrier, however, was more effective than guardrail at reducing injury. The odds of severe injury in crossing a cable barrier were 0.386 times lower than crossing a guardrail. Likewise, the odds sustaining a severe injury after hitting a cable barrier were 0.556 times lower than after hitting a guardrail.

Finally, a number of research efforts have sought to develop predictive tools for understanding the implications of using cable median barrier as a countermeasure. Srinivasan et al. (2017) developed CMFs for the application of rumble strips and cable median barrier as a combined safety system. With a Benefit/Cost (B/C) ratio of 4.14, this combined system provided the following CMFs: total crashes (1.247), KABC crashes (0.745), KAB crashes (0.783), and cross-median crashes (0.119). Dissanayake and Galgamuwa (2017) considered the effectiveness of different lane departure countermeasures, including shoulder and center line rumble strips, chevrons and post-mounted delineators, and cable median barriers, among others. Researchers developed CMFs for these measures and determined the safety effectiveness of cable median barriers on divided 4-lane roads to be 50-65 percent.

Russo et al. (2015) considered 317 miles of cable median barrier systems in Michigan to ascertain the safety impacts of barrier installation. Using the EB method, CMFs for narrow and wide medians were developed by crash severity category, along with SPFs for CO-, B- and KA-level crashes. Using before-and-after comparisons and the EB method, Graham et al. (2014) developed CMFs for cable median barrier installations: 0.45 for all crossover crashes and 0.38 for fatality/injury cross-over crashes. Green and Fields (2015) developed an SPF to prioritize the locations under consideration for cable median barrier installation on Kentucky highways by identifying locations most likely to see a resulting safety benefit for all vehicle types. The new algorithm produced an estimated increase in crash data accuracy of 31 percent over the traditional method.

2.3 Analysis Methods

Over the past 30 years, researchers and practitioners have dedicated more and more resources to evaluating how changing various design elements influences safety. This has spurred the development of models which predict the crash rate or number of crashes as a function of different traffic conditions and geometric roadway elements. In the past 10 years most researchers have used negative binomial regression for modeling crashes. These models assume that unobserved crash variation across roadway segments follows a Gamma distribution, while crashes within sites follow a Poisson distribution (Washington et al. 2005). The Poisson, Poisson-Gamma (negative binomial), and other related models are collectively called generalized linear models (GLM). These models have the following general form:

$$E[N] = EXPO\ e^{b_0+b_1X_1+b_2X_2+\cdots+b_nX_n} \quad (1)$$

where: E[N]= predicted number of crashes per year for a roadway section, *EXPO* = exposure to crashes, $b_0 \ldots b_n$= regression coefficients, and $X_1 \ldots X_n$= predictor variables.

Models like the one above can identify the relationship between the number of crashes and the various elements under consideration. The exposure used in these prediction models could be either the traditional vehicle-miles, (i.e., length times, Average Annual Daily Traffic (AADT) volume, or length itself), while the AADT serves a predictor variable.

Negative binomial models are typically used to develop Crash Reduction Factors (CRF) or Crash Modification Factors (CMF). Even though these two terms are similar in concept, they have slightly different applications. A CRF is a value that represents the reduction in crashes expected at a site due to a safety improvement. These values represent the percentage improvement in the roadway and most often have a positive connotation (i.e., the safety intervention will have a net benefit). On the other hand, a CMF is a constant that represents the change in safety due to a change in a value of the segment. These factors are typically the ratio of the expected values of crashes with and without the change. CMFs are also used as multipliers for estimating the expected number of crashes. Values less than 1.0 indicate fewer crashes as a result of the change.

One method of estimating CMFs is to use baseline models and apply them to data that do not meet the nominal conditions (Washington et al. 2005). These models are developed using data that reflect nominal conditions commonly used by design engineers or could also reflect the average values for some input variables. These models usually only include traffic flow as the input variable. Examples of nominal conditions for rural four-lane undivided highways may include 12-foot lanes, 8-foot shoulder widths, and straight sections. It is anticipated that by controlling the input variables, the models will more accurately estimate the facility's safety performance for the given input conditions. However, an important drawback of developing baseline models is associated with the smaller sample size. Because the input data only include data meeting the nominal conditions, the sample size can be significantly reduced, which can affect model stability (especially if the sample mean value is low (Lord and Bonneson 2007)), increase model error (variance), and decrease the model's statistical power. Baseline models are currently the type of model used for the *Highway Safety Manual* (HSM) (AASHTO 2010)

However, there are several issues with using CMFs, such as the quality of a CMF; the proper application for the conditions examined, including volumes, geometry, and facility type, among others; and the crash types intended to be addressed and whether the CMF will actually impact them. All of these could lead to the inappropriate use of a CMF and provide an incorrect estimate of the safety gains or losses attributable to the treatment application. The CMF Clearing House contains several truck and lane departure-related CMFs. Included are median type (raised, flush, guardrail) and width, as well as truck lanes, restrictions, signage, and differential speed limits. However, none are specifically related to CMVs and median barrier provision/type.

The basic concept of the CMF is to capture the change in crash frequency due to the change of a single element. However, this is often not the case and these factors have been developed using cross-sectional studies where multivariate models were developed and used to determine a CMF. The models typically identify all contributing factors that could influence safety, using them to estimate the change in crashes from a change in one unit of the variable of concern. This approach is typically completed with the assistance of an expert panel that evaluates the prediction models and estimates the potential effect for each variable of concern. These evaluations could be further supported by existing literature and current knowledge of the specific variable. This approach was used in the rural two-lane highway models in the Interactive Highway Safety Design Model (IHSDM), where the models developed were used as the basis for creating the CMF (FHWA n.d.). Even though CMFs may appear subjective, they synthesize the collective knowledge of expert panel knowledge and observation and literature research findings. A potentially significant issue is that there may not be adequate literature dealing with the identification of the safety impacts from the elements being examined.

The development of SPFs requires a data set of roadway segments or intersections that are homogeneous (i.e., with similar roadway characteristics). A common way to create a dataset of homogeneous roadway segments is to begin with roadway inventory data. The HSM offers guidance on what roadway characteristics can be used for creating homogeneous segments (AASHTO 2010). In the U.S., state transportation agencies benefit from a uniform set of roadway elements developed by the Federal Highway Administration (FHWA) known as the Model Inventory of Roadway Elements (MIRE) (Lefler et al. 2010). Many of these inventories were created at different times, by different groups within an agency, and, most importantly, using a variety of segmentation techniques. In the context of roadway segments, segmentation is usually defined by beginning and ending mile point. This facilitates the use of a linear reference system — encouraging the use of a Geographic Information System (GIS). The decision of where to begin and end a given segment depends on the presence of inventory attributes. For instance, traffic volumes will change at major intersections, whereas the width of a right shoulder might change due to terrain or the availability of right of way. Segments may also be defined at the beginning and end locations of vertical or horizontal curves.

Design heterogeneity contributes to overdispersion as changes in geometry are excluded from the model. This omission is typically detectable using cumulative residual (CURE) plots. A CURE plot is graph of the cumulative residuals versus an independent variable (typically traffic volume) (Srinivasan and Bauer 2013). Residuals are the difference between actual crashes and the SPF prediction at a site. In some cases, the actual number of crashes is more than the SPF predicted (positive residual); other times it is below (negative residual). Cumulative residuals are computed by adding the residuals from a roadway segment to the previous site's cumulative residual. This cumulative sum is computed, with the segments ordered by traffic volume (or in some cases segment length). Plotting the cumulative residuals versus traffic volume results in a CURE plot as shown in Figure 1.

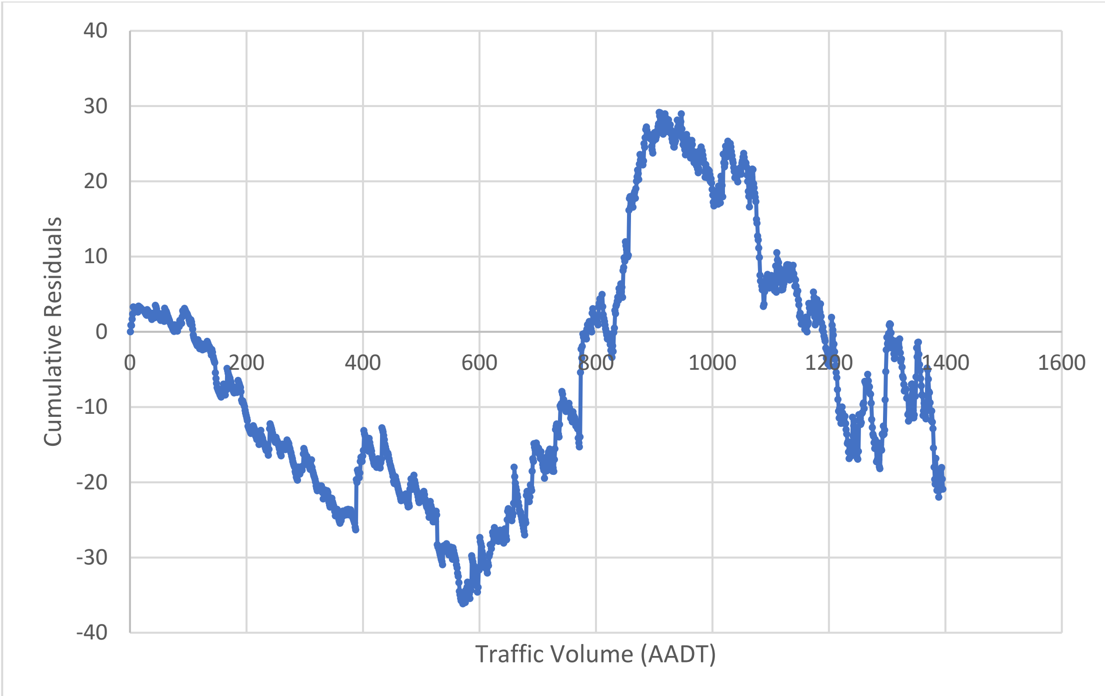


Figure 1 Cumulative Residuals Versus Traffic Volume (AADT)

Statistically, oscillation about the x-axis is expected due to random error — approximately following a normal distribution[1] (Hauer 2015). Anything that is not random error will deviate from the oscillation and can indicate a bad model fit or omitted variable bias. The overdispersion parameter is useful in CURE plots because it helps define confidence boundaries (Hauer and Bamfo 1997). Boundaries are defined by two standard deviations (positive and negative). Data points found on the CURE plot within these boundaries are more likely to be explained by a random walk.

Assessing CURE plots, while somewhat subjective, can provide high-level screening for the SPF development process. When evaluating CURE plots, the following are considered indication of a good model:

- Oscillation around the x-axis and ending near zero;
- Free of outliers as they can adversely affect the model parameters;
- Cumulative residuals rarely transgress the confidence bands; and
- Minimal drifting either upward or downward.

Despite the subjectivity of these metrics, there are a few key advantages to this method of assessment. This evaluation is graphical and therefore can be performed quickly, especially when comparing several CURE plots at once.

2.4 Summary

The literature review identified the role of alcohol and drug use in relation to CMV drivers and noted that more research is warranted to further investigate their role in CMV crashes. Ideally, an analysis should be done to analyze the frequency of substance use for all truck collisions rather than only fatal collisions, but drug testing is neither common nor consistent on non-fatal crashes. Additionally, more research is needed

[1] The approximately normal distribution is applied to the residuals and not the actual crash data. It is well known that a normally distributed error term is typically not observed in crash count data (Zhang et al. 2009).

to understand rates at which truck drivers are at fault in crashes involving drugs or alcohol as well as the severities of those crashes.

Prior researchers have focused on identifying the influence of cable median barrier installations on crash rates and severities. They have looked at effectiveness for all crashes, by vehicle type, injury severity, and other categories. Yet little research has looked at CMV crashes involving cable median barriers. Most previous studies have examined the overall safety improvements provided by cable median barriers — for median and cross-median crashes — for all vehicle types. Previous research has indicated that cable median barriers are an effective and promising countermeasure for reducing the severity of crashes overall. But these barriers also have the potential to increase the total number of crashes due to the addition of an obstacle in the roadway. Given the influence of vehicle, roadway, and driver factors on crash severity and occurrence of CMV crashes, it is appropriate to consider the effectiveness of cable median barriers on CMV crossover crashes.

Most frequently, crash prediction models (i.e., SPFs) are developed to understand the influence of countermeasures on crash occurrence, with associated CMFs used to quantify countermeasure impacts. In addition, CMFs can be developed using the GLM approach where the countermeasure is included as a predictor variable in the SPF and is thus used to estimate the impact of the countermeasure. Using CURE plots can aid in model validation and provide some statistical support for the CMFs developed.

Chapter 3 Research Methodology

The main objective of this project is to evaluate the potential effectiveness of cable median barriers for mitigating the number and severity of CMV crashes. Analysis leveraged two approaches: 1) expert panel evaluation of crashes and 2) development of a statistical crash prediction model. The expert panel assessed CMV crashes to estimate the potential impacts on a crash if a cable median barrier were present and establish a qualitative measure of its effectiveness. Statistical modeling focused on quantifying the potential effect of cable median barriers, comparing crashes in sections with and without a barrier. Each methodology is discussed below.

3.1 Expert Panel Approach

Under this approach, expert researchers assessed crash occurrence conditions and relied on their ability to decipher the contributions of several factors. Experts used their knowledge to answer whether the presence of a cable median barrier could potentially alter crash severity. The expert panel approach has been used extensively in roadway safety and it was one of the initial methods in the development of the HSM (AASHTO 2010). An expert panel should be diverse enough and have sufficiently varied expertise to address the research questions. Panel members should typically have expertise in safety analysis, roadway design, and countermeasure development (especially if they are focal point). There are no specific guidelines on the number of experts for a panel, but a panel that is too small may not represent the collective set of views in the profession, while a panel too large might be unwieldy to manage and never reach a consensus (Washington et al. 2009)

Expert panels work either in person or through a Delphi approach. In person meetings require a process where the panel members assemble in a location at which cases are presented and reviewed collectively. Discussion typically ensues after the presentation and then panel members score the case to answer the questions posed. Additional discussion may ensue after the scoring to address possible differences among the panel scores, but this could be optional depending on the set up. Scores are then averaged to determine the quantitative answer to the research question. With the Delphi approach, panel members are given data and the research questions and each member independently scores the research question. Once all scores are collected, they are distributed to panel members for a second review, and so they can potentially modify their original scores. This ensures that there is a greater consensus among the panel members and could improve scoring accuracy. The Delphi approach relies on highly structured procedures as opposed to the in-person approach where greater fluidity may exist. In addition, the Delphi approach provides for anonymous revisions that could be otherwise influenced during in-person panel meetings. In general, the Delphi approach produces more objective forecasts than unstructured panels (Rowe and Wright 1999).

The expert panel assembled for this study consisted of two nationally recognized experts on roadway safety, each with over 30 years of experience, and two other experts with regional expertise and considerable experience with safety analysis. A hybrid approach was considered for this study in an effort to address time constraints. Initially, a Delphi approach was undertaken, where each expert was provided with the crash data and a set of basic instructions. Once all cases were scored, an in-person meeting was convened to examine the scores and identify potential reasons for large differences in scoring. This approach was selected to take advantage of the strengths of each method, while compressing the time required for the reviews.

An Access database was created using the information for each crash, where all pertinent factors were displayed, along with the crash description and a link that used the coordinates of the crash to locate it on a Google map. This let the expert consider the contributing factors in an abstract form while being able to visually inspect the location and identify additional features that may not be immediately visible through crash codes. For example, the crash record does not provide any information on the presence of access points in the vicinity of the crash, which could help an expert determine whether the location would be appropriate for installing a cable barrier due to potentially restricting access. Other items that could be easily verified through visual inspection of the site include the presence of curvature and grade, which frequently are described in the narrative without any indication of their magnitude (sharpness for curve and steepness for grade), proximity to development or urbanized areas, and overall site appearance.

Experts scored each of the four contributing factors (i.e., human, roadway, vehicular, and environmental) on a 6-point scale, with 0 indicating no influence and 5 indicating most probable influence. The final score was reserved for assessing the potential impact of a cable median barrier on altering crash severity. The question was phrased as: "Would a cable barrier have affected the severity outcome of the crash?" Experts also scored this question using a 6-point scale, with 0 indicating no effect and 5 indicating most probable influence. A 6-point scale was used to force experts to assign a score and avoid the use of a middle point.

3.1 Cable Median Barrier Effectiveness Approach

This effort focused on developing two SPFs to quantify the benefits of cable barriers for CMV median crossover crashes. A roadway network of interstates in Kentucky was used. Previous research has demonstrated the importance of roadway homogeneity in the segmentation process (Green et al. 2017). As such, care was taken to create a roadway network with only the necessary roadway data and geometrics to minimize the number of segments. With fewer features included, there are fewer and longer segments, which produces models with better goodness-of-fit measures. An exploratory SPF development process, using a tool called SPF-R, was used to determine the most important roadway geometrics (Green et al. 2018).

Once it was determined what roadway geometrics to include in the network, two roadway networks were created. Both networks were created from all mainline interstates in Kentucky (i.e., excluding ramp segments). The network included several roadway data and geometric assets (maintained by the Kentucky Transportation Cabinet):

- TF – Traffic Flow – which includes AADT
- FS – Functional Classification – used to determine rural versus urban segments
- MD – Median – used to determine what type of median is present
- LN – Lane – used to determine number and width of the lanes
- SH – Shoulder – used to determine the shoulder width

Table 1 summarizes the segments used in the analysis and Figure 2 depicts their locations.

Table 1 Summary of Road Network by Median Type

Median Type	Length (miles)	Number of Segments
Cable	271.949	128
Concrete	293.489	316
Earthed	75.589	81
Guardrail	5.368	12
None	224.795	121
Other	2.269	9
Total	873.459	667

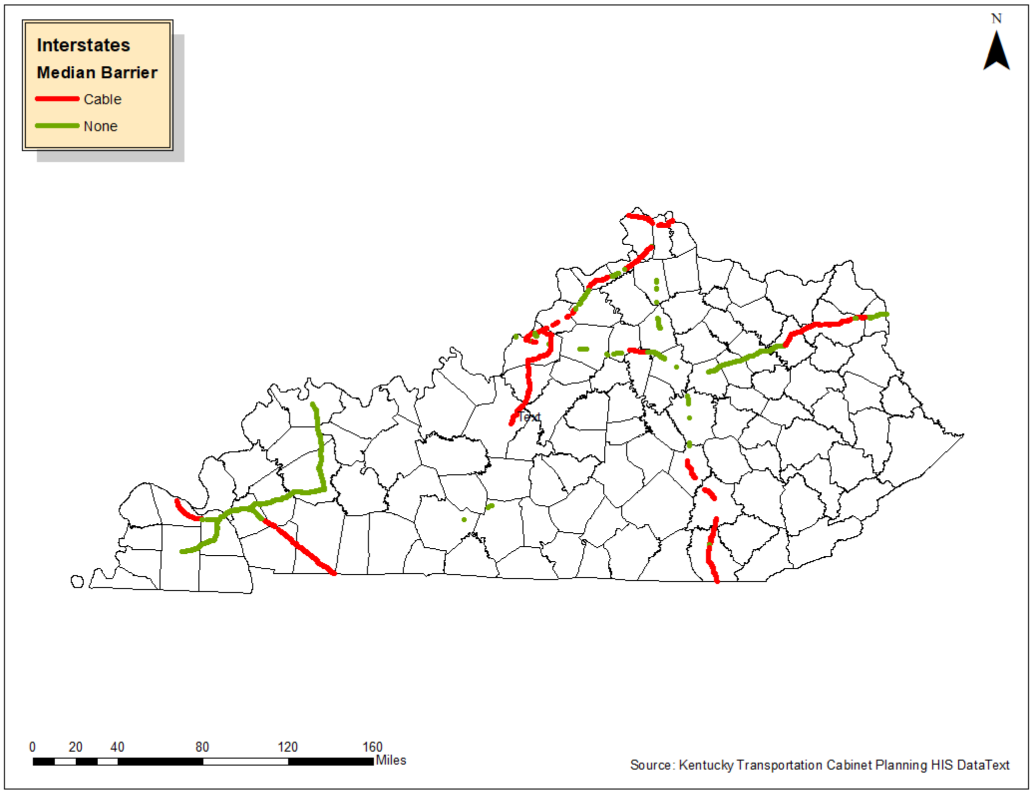


Figure 2 Analysis Segments by Median Type

Lane and shoulder widths were limited to 12 ft and 10 ft, respectively, to improve homogeneity. This slightly reduced the sample size — by 15.3 miles. The roadway network was divided into two groups. One group included roughly 260 miles of interstates with a cable median barrier installed and the other group included approximately 220 miles of interstate with no median barrier. SPFs were developed for both roadway networks using SPF-R. Equation 3 describes the relationship between crash prediction, traffic volume, and segment length.

$$y = L * e^{a} AADT^{b} \qquad (3)$$

where: y=estimated crashes, L=segment length (miles), AADT=traffic volume, and *a* and *b* are coefficients that describe the interaction among length, AADT, and the estimated number of crashes.

Along with the coefficients, the regression process also produces an overdispersion parameter. The overdispersion parameter is referred to as theta which is the inverse of k (used in the HSM); thus k=1/theta. This identifies how over-dispersed the data are. Crash data typically exhibit a variance greater than the mean (known as overdispersion) and theta captures the fit of the regression model chosen. Moreover, the overdispersion parameter is used to develop the confidence bands in the CURE plots.

Chapter 4 Crash Data

Kentucky crash data were used to examine CMV crash patterns. Data covered 2013 through 2016 and were obtained from Kentucky State Police (KSP) records. Typical information collected by the KSP includes information on the crash (e.g., location, time of crash, environmental conditions), vehicles involved, driver and the occupants involved, and roadway characteristics. Information on crash severity, manner of collision, roadway characteristics, vehicle type, weather conditions, and lighting conditions were used in this analysis.

CMV crashes were initially extracted from the KSP dataset, since these were the only records of interest. To ensure that all pertinent crashes were identified, additional codes were used to determine whether a CMV was involved in each crash. The data set had 32,291 crashes where a CMV driver was involved. Among those crashes, 24,023 were two-vehicle crashes involving a CMV collision with another vehicle, 6,350 were single-vehicle CMV crashes, and the remaining crashes involved more than 2 units. Crash types of interest were lane-departure and crossover crashes. For the 2013-2016 period, there were 12,712 such crashes (4,734 single-vehicle and 7,276 two-vehicle crashes). Among the two-vehicle crashes, there were 4,269 crashes where the CMV left the travel lane, while another vehicle type (passenger car, van, pickup truck, motorcycle) was at-fault for striking a CMV in the remaining crashes. Most crashes (3,993 or 93.5 percent) occurred on roads with four or more lanes.

The expert panel reviewed only the fatal and incapacitating injury crashes — K and A in the KABCO scale. This was deemed reasonable due to the large number of cases under consideration. In total, 107 fatal (K) crashes and 193 severity A crashes were analyzed. Of these, 16 fatal and 76 incapacitating injury crashes were single-vehicle crashes, while 75 fatal and 86 incapacitating injury crashes involved two vehicles.

Chapter 5 Analysis Results

Two types of analysis were conducted — 1) Expert panel analysis of crashes fatal and incapacitating injuries and 2) Development of SPFs and CMFs to improve understanding of the potential influence of cable barriers on CMV crashes. Findings are presented in the following sections.

5.1 Expert Panel Analysis

This analysis used only the most severe crashes in the database to focus on fatalities and incapacitating injuries. Four experts reviewed each case, independently considering the crash narrative as well as all other factors that could have contributed to the crash (i.e., human, environmental, vehicular, and roadway geometry factors). The experts considered all these factors, while deliberating on whether the presence of a cable median barrier could have altered crash severity. In addition to answering the main question, the experts also determined to what extent any of the other four factors could have contributed to the crash occurrence. This was completed in anticipation of a further analysis of the scores based on the contribution of these additional factors but was not needed due to the experts agreeing about the contribution of these factors.

To determine the agreement among the experts on their final assessments, a contingency table analysis was performed that examined the level of agreement between pairs of experts. This type of analysis indicates whether panel members agree in their assessment of research questions. The analysis examines the scores for each reviewer as a pair and identifies those that are in agreement. The test statistic used here is the Kappa for agreement between individuals. Kappa values < 0.4 show poor agreement while values in the range of 0.4 to 0.75 show good agreement and values > 0.75 indicate excellent agreement. The null hypothesis (H_o) is that agreement between the reviewers is due to chance, while the alternate (H_A) is that the agreement is not by chance. P-values of < 0.05 indicate that the null hypothesis cannot be accepted, (i.e., the agreement is not by chance). Then, the Kappa value is examined to determine the level of agreement.

Comparative analysis examined the agreement based on all crashes and separated them based on severity level, number of lanes, and number of units (i.e., single- or two-vehicle crashes) involved. Additional separated analysis was conducted to determine whether any trends noted in the overall analysis could be strengthened or weakened when crashes with similar aspects were examined.

5.1.1 Analysis Examples

This section presents and discusses contingency tables for a few pairs of experts to provide an understanding of the information considered and conclusions gleaned from each comparison. Table 2 shows the comparison between the two experts with the most experience conducting safety evaluations. If in perfect agreement, all scores would lie along the diagonal of the table. However, this is not the case for any of the pairwise comparisons and this is perfectly understood, since each expert would have a difference in assessing the potential effect of the presence of a cable median barrier. The data in Table 2 indicate that these experts agreed in their assessments of the impact of a cable barrier on altering the severity of the crash, which here is fatal. The Kappa value for these data is 0.506, indicating good agreement and the p-value is 0.000 demonstrating that the agreement between the experts was not by chance. These values indicate that these two experts hold similar opinions on the impact of the cable median barrier, that their agreement is based on their assessment, and that it is not random.

Table 2 Assessment of Experts 1 and 2 (Fatal Crashes)

Expert 2	Expert 1						
	0	1	2	3	4	5	Total
0	37	0	0	0	0	4	41
1	2	0	0	1	0	0	3
2	0	0	0	0	0	0	0
3	1	0	1	2	0	3	7
4	1	0	0	3	0	4	8
5	3	1	0	8	2	34	48
Total	44	1	1	14	2	45	107

Table 3 shows a comparison between two experts where little agreement exists. In this case, there is greater variability in the scores and greater variability for crashes where the impact was assessed. For example, while both experts agreed approximately 63 percent of the time on the lack of impact (28 of the 44 cases with 0 effect) they held divergent opinions on those where the impact would have been more probable (scores 4 and 5). This reflects the individual assessment of the potential impact on the 6-point scale, where Expert 1 considered that in more crashes the barrier would have a most probable effect (scored 5) while Expert 3 considered them with a probable effect (scored 4). However, if one considers these scores together, they could conclude that in approximately 73 percent (41 of 56 crashes) of the crashes the experts agreed that the barrier would be at least probable in affecting crash severity. For these data, the Kappa value is 0.267, indicating poor agreement, and the p-value is 0.000, denoting that the agreement between the experts was not by chance.

Table 3 Assessment of Experts 1 and 3 (Fatal Crashes)

Expert 3	Expert 1						
	0	1	2	3	4	5	Total
0	28	0	0	0	0	0	28
1	3	0	0	1	0	1	5
2	0	0	0	0	0	0	0
3	6	0	0	7	0	5	18
4	7	0	1	6	2	35	51
5	0	1	0	0	0	4	5
Total	44	1	1	14	2	45	107

To further examine potential agreements considering the lack of any specificity assessments, the scores were grouped to reflect more general effects (Table 4). In this case, a 4-point scale was redesigned, where 0 indicates no effect, 1 indicates minor effect, 2 indicates some effect, and 3 indicates probable effect. In this case, the Kappa value increases to 0.546, indicating good agreement but the p-value changes to 0.064, demonstrating that the agreement is by chance.

Table 4 Revised Assessment of Experts 1 and 3 (Fatal Crashes)

Expert 3	Expert 1				
	0	1	2	3	Total
0	28	0	0	0	28
1	3	0	1	1	5
2	0	0	7	5	18
3	6	2	6	41	56
Total	44	2	14	14	107

5.1.2 Overall Values

Analysis considered the overall scores for each crash provided by the experts (Table 5).

Table 5 Summary of Overall Expert Panel Scores

	Severity		Severity and Lanes				Severity and Units			
			2 Lanes		4 Lanes		1		2	
Severity	K	A	K	A	K	A	K	A	K	A
Average	2.26	1.30	2.37	1.44	1.99	1.08	0.89	0.61	2.38	1.77
Std Dev	0.99	1.42	1.53	1.38	1.78	1.50	1.27	0.85	1.59	1.54

Values in Table 5 indicate that the effectiveness of the cable barrier is greater for fatalities, and this is true for all cases but single-vehicle crashes. The value is over 2 denoting a moderate effect in influencing crash outcomes. However, the standard deviation for most estimates is high, indicating again the variability in the responses among panel members. Values for incapacitating injury (A) are lower and most values are at approximately 1.5, indicating a minor effect. Overall, the experts believe that the presence of a cable median barrier would have some effect in reducing crash severity.

5.1.3 Summary

In general, pairwise comparisons indicate agreement in the scores for some experts but not for all (Table 6). The data suggest differences existed among the panel members that need to be reviewed to determine whether these differences can be addressed, and determine whether a collective review is necessary. The agreement remained consistent in the various types of data parsing, indicating consistency in assessing the potential of the effectiveness of the cable barrier in affecting the crash severity outcome.

Table 6 Summary of Pairwise Comparisons

Expert Pair	Severity		Severity and Lanes				Severity and Units			
			2 Lanes		4 Lanes		1		2	
	K	A	K	A	K	A	K	A	K	A
1-2	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
1-3			✔ *		✔ *		✔ *			
1-4		✔				✔		✔		
2-3							✔ *	✔ *		
2-4		✔			✔ *	✔		✔		
3-4										

Note: entries with * indicate Kappa value <0.4 but very close to it

As noted, this analysis was the first step in the Delphi approach undertaken and the next step required an in person collective review to possibly address large differences in scores. A number of crashes where large differences among at least two experts were identified for further examination during the in-person review. Review and discussion revealed the individuality of each expert in assessing the potential effectiveness of the cable median barrier. For example, one reviewer determined that it would be impractical to install any cable median barrier on two-lane roads due to either lack of space, installation and maintenance cost, or elimination of access. In this case, the expert scored the effect as 0 for most of crashes on two-lane roads, creating discrepancies with the scores of the other experts. In other cases, experts rationalized the sequence of events based on the narrative differently and thus scored the potential effectiveness differently. As noted, minor differences in the scores were also observed since there was no specific guidance on what the scores reflected (i.e., having some specific guidance as to what a score of 5 or 4 meant). Experts decided to retain their original scores since the overall averages estimated seemed reasonable and therefore, no additional changes were deemed necessary at this point.

5.2 SPF and CMF Analysis

To analyze the potential effect of cable median barriers, statistical models were developed using available crash data. The main approach was to develop a prediction model for roadways with a cable median barrier, develop another model for roadways without a cable median barrier, and then take the ratio of these models to establish the potential CMF for cable barriers. SPFs allow for a more robust consideration of the impact of ADT on CMF through the development of a Crash Modification Function (CMFunction).

Crashes were matched to interstate segments using the KABCO scale, where the severity of the crash is based on the person most severely injured in that crash. To examine the effect of median barriers on CMV crashes, the crash database was limited to CMV roadway departure crashes. That is, crashes, involving a CMV and a vehicle that leaves the roadway (either to the left or the right). Criteria for roadway departure were developed as part of Kentucky’s Highway Safety Improvement Program.

Care was taken to ensure both networks exhibited limited omitted variable bias and were mostly homogeneous. Three severity models were developed for each network. The models used were KA, KAB, and KABC severities. Models for all severities (KABCO) and fatal-only (K) were excluded. The all-severities model included a large proportion of PDO crashes (O) which, while coded as roadway departure, are typically not the type of crash mitigated by cable barriers. In many cases this is due to erroneous crash codes as reflected by reading the crash narratives. The fatal-only crashes had too small of a sample to produce meaningful SPFs. The resulting models for both the cable and non-barrier networks are described here.

The Calibrator User Guide defines several metrics that can be useful in comparing SPF results (Lyon et al. 2016). The following bullet points briefly describe these metrics.

- Modified R^2
  - Measures the amount of variation explained by the SPF. Higher values are optimal. Values over one indicate overfitting, which is not optimal.
  - This is a pseudo R^2 — negative binomial regression does not generate a metric strictly analogous to R^2.
- Mean Absolute Deviation (MAD)
  - Measures the average absolute variation between the predicted and observed crashes at each site. Lower values are optimal.
- Akaike Information Criterion (AIC)
  - A measure that considers both goodness-of-fit and model complexity. Lower values are optimal.

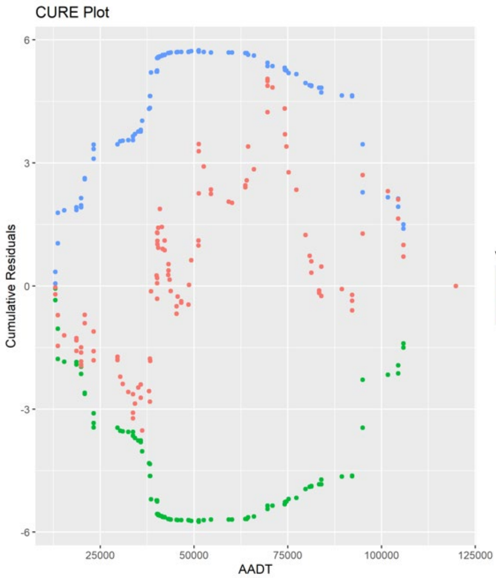
- CURE Plots
  - A unique assessment tool for SPF; unlike the other metrics, they provide a measure of the SPF's functional form.
  - CURE plots that oscillate around the x-axis indicate the absence of model bias, which is ideal.
  - Outliers can be identified as large vertical jumps.
  - Cumulative residuals should rarely transgress the confidence bands.
- Percentage CURE Deviation (PCD)
  - A more objective measure of bias in the SPF model. Values under 5% are statistically significant at the 95% confidence level.
- Maximum Absolute CURE Deviation (MACD)
  - A measure that represents the largest — positive or negative — deviation (cumulative residual) from the CURE Plot. Lower values are optimal.

5.2.1 Cable Network

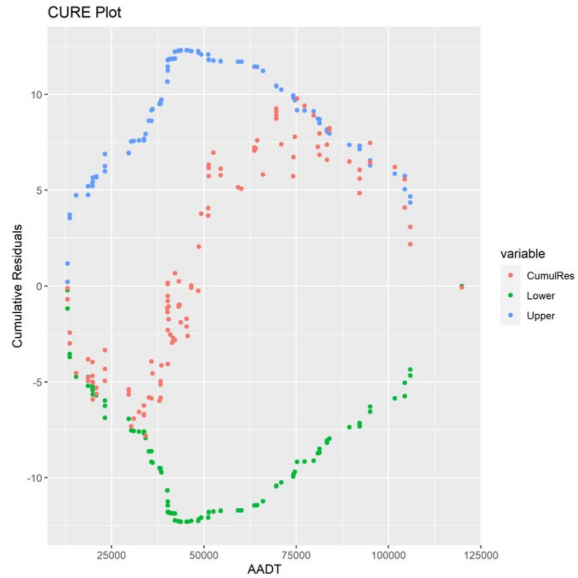
The cable network included 110 segments with a total length of 260.5 miles (after filtering out lane and shoulder widths). Goodness-of-fit measures were compared for each model (Table 7) and CURE plots produced (Figure 3) to examine their relative performances. All three models showed minimal omitted variable bias in that they exhibited the qualities described above: high R^2, low PCD, low MAD, and low MACD. The KA and KAB models had small sample sizes for SPF development, however the goodness-of-fit measures suggested they are good models.

Table 7 Goodness-of-Fit Measures and Model Parameters for Cable Network By Severity

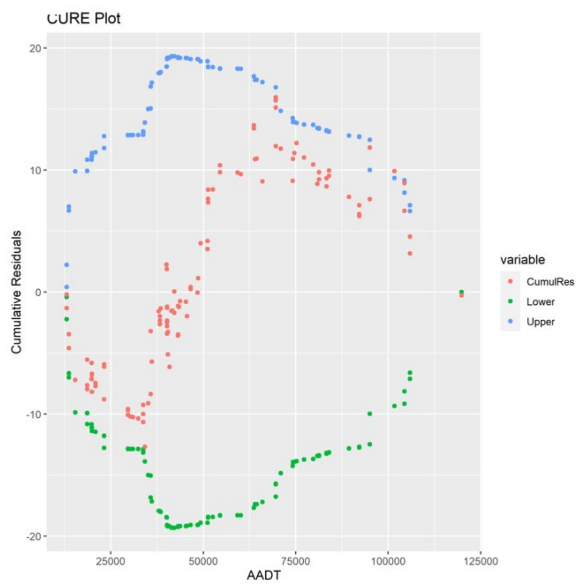
	Crash Severity		
Measure	KA	KAB	KABC
Crashes	46	150	251
R^2	2.32	0.95	0.75
PCD	2.73	9.09	3.64
MACD	5.05	9.77	15.97
MAD	0.40	0.91	1.34
Theta	5645.11	30.43	4.31
a	-11.06	-9.44	-7.85
b	0.88	0.84	0.74



a. KA



b. KAB



c. KABC

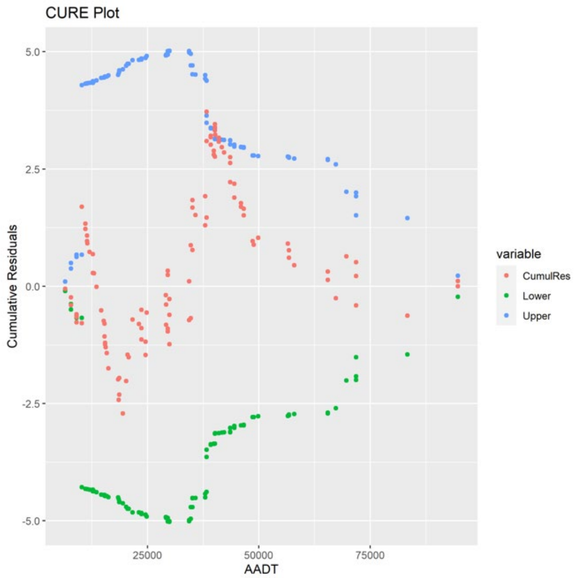
Figure 3 CURE Plots for Cable Median Barrier Models

5.2.2 Non-Barrier

The non-barrier network included 106 segments with a total length of 221.0 miles (after filtering out lane and shoulder widths). Goodness-of-fit measures (Table 8) and CURE plots (Figure 4) were compared for each model. All models showed minimal omitted variable bias although each had small sample sizes for SPF development. However, the goodness-of-fit measures indicated they are good models.

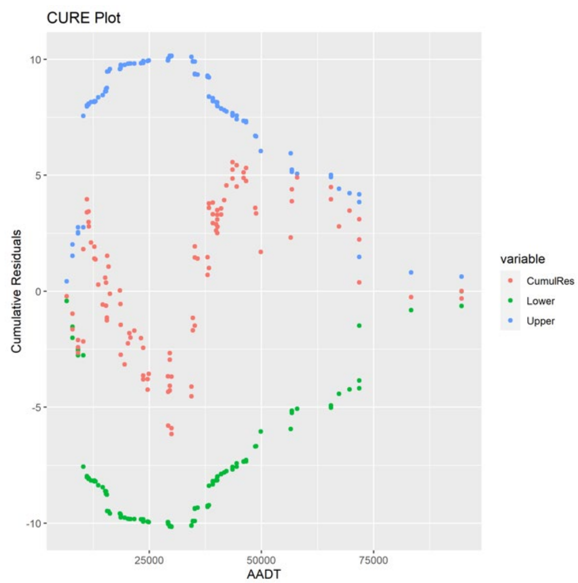
Table 8 Goodness-of-Fit Measures and Model Parameters for Non-Barrier Network By Severity

Measure	Crash Severity		
	KA	KAB	KABC
Crashes	27	63	91
R^2	1.10	0.91	0.75
PCD	9.43	3.77	1.89
MACD	3.72	3.64	6.15
MAD	0.33	0.57	0.74
Theta	8.00	28.03	3280.58
Alpha	-13.69	-15.22	-16.37
Beta	1.28	1.39	1.42



a. KA

b. KAB



c. KABC

Figure 4 CURE Plots for Non-Barrier Models

5.2.3 Model Comparisons

The resulting model parameters were used to generate predictions at specific traffic volumes to explore the prediction sensitivity caused by volume variations. This was not necessary for length, since length and prediction have a direct linear relation. A default value of 1.3 miles (the network's average segment length) was used in sample calculations. Traffic volumes of 34,000 and 100,000 vehicles per day (vpd) were used, representing the average and maximum volumes, respectively. The ratio of prediction for the cable network to the prediction for the non-barrier network was used to quantify the effect of the cable barrier on crash occurrence. A ratio under 1 indicates a reduction in crashes, which is analogous to a CMF. The predictions and the corresponding ratios are shown in Table 9.

Table 9 Crash Predictions and Effectiveness Ratio by Severity Model

Severity Model	AADT (vpd)	Median Barrier Type		Ratio
		None	Cable	
KABC	34,000	0.7	0.8	1.22
	100,000	2.7	1.9	0.68
KAB	34,000	0.5	0.5	1.00
	100,000	2.2	1.2	0.55
KA	34,000	0.2	0.1	0.70
	100,000	1.0	0.4	0.39

The data indicate an effect for the cable median barrier in the KA and KAB models at all volumes, while this is the case for large volumes in the KABC model. Some of these comparisons need to be viewed with caution due to the small number of CMV crashes from which they were developed. However, they are still indicative of the potential effects of cable median barriers to impact crashes.

Chapter 6 Conclusions

The main objective of this research was to examine the potential effects of cable median barriers on CMV crashes. A two-pronged analysis was undertaken: expert panel and SPF development. The first approach focused on studying the potential effects of cable barriers on altering the crash severity for fatal and incapacitating injuries (K and A in the KABCO severity index). The second approach resulted in crash prediction models that can be used to develop CMFs for estimating how the presence of cable median barriers can potentially affect crash occurrence and severity.

Expert panel analysis demonstrated that safety gains are possible by installing cable median barriers and that their effectiveness is greater for fatalities. The average score of over 2 from the panel (on a scale from 0-5) indicates a moderate effect on crash outcomes. However, the standard deviation for most average scores was high, pointing toward the variability in the responses of panel members. The values for incapacitating injury (A) were lower and most values were around approximately 1.5, indicating a minor effect. Overall, the experts believed that the presence of a cable median barrier would have some effect in mitigating crash severity.

There was some degree of agreement between pairs of experts, and this was mainly attributed to the possible differences in levels of expertise. In general, pairwise comparisons indicated agreement in the scores for some experts but not all. Agreement remained consistent in the various types of data parsing, indicating that there was consistency in assessing the potential of the effectiveness of the cable barrier in affecting crash severity outcomes. A further collective review of crashes where large discrepancies in scores among the experts was undertaken, with the review and discussion demonstrating the individuality of each expert in assessing the potential effectiveness of cable median barriers. It was also concluded that more detailed guidance on the scoring approach would have been more beneficial and could have possibly reduced scoring variability.

SPFs developed also supported the overall expert panel assessment of the effectiveness of cable median barriers. Analysis showed that CMV crash outcomes benefit from installing cable median barriers; albeit they are only for interstate routes. In addition, the non-barrier network was mostly rural; there were only 17 segments in urban areas. In contrast, the cable network contained a mix or rural and urban segments (about half of the segments and two-thirds of the mileage were rural). This presented two issues in the modeling process. First, there may be differences in the driver behaviors and design elements between the two networks that were not modeled. Secondly, urban segments have much higher traffic volumes and, therefore, more crashes. This potentially adds a bias to the analysis when traffic volume is not considered.

Two insights can be drawn from comparing the ratios between cable and non-barrier predictions. Ratios are larger (i.e., the cable barriers are seemingly less effective) at lower traffic volumes. Additionally, the ratios are lower (i.e., the cable barriers are more effective) for the more severe models. This is intuitive when considering the types of crashes a cable barrier is most effective at preventing, particularly those involving CMVs. Furthermore, it is likely that cable barriers may increase the number of less severe crashes as the barrier introduces a fixed object for vehicles to contact, especially on roadway departure crashes.

The best comparison is between the KABC models. The ratio between these predictions can be expressed as a function of traffic volume by dividing the SPF for the cable network by the SPF of the non-barrier model. This is shown below in Equation 3 (note that length is excluded as it canceled out) in the form of a Crash Modification Function (CMFunction). This can be also depicted in a nomograph (Figure 5) that can be used to estimate the potential effects of cable median barrier installations on CMV crossover crashes.

$$CMFx = \frac{e^{-7.85}ADT^{0.74}}{e^{-13.69}ADT^{1.28}} = e^{5.84}ADT^{-0.54} \qquad (3)$$

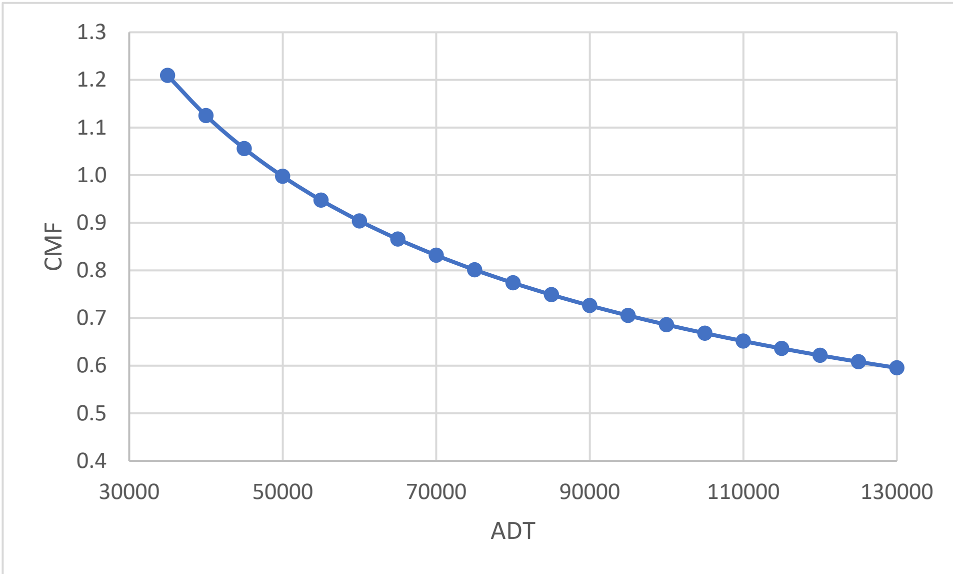


Figure 5 Crash Modification Function for Cable Median Barrier on CMV Crashes

The results here indicate that CMV crashes will indeed be mitigated by installing cable median barriers. Both analyses supported this finding, and the overall conclusion is a positive impact. Benefits may be greater on divided roadways, since installations on two-lane roads may be more problematic due to space limitations.

Analysis did not account for which vehicle is the errant vehicle, and thus did differentiate among crashes based on whether the errant vehicle was a CMV or another vehicle. As noted, most (93.5 percent) of Kentucky's two-vehicle crashes on roads with four or more lanes identified the CMV as the crossing-over vehicle. This could have significant implications for assessing the potential effectiveness of cable median barriers, since the weight of CMVs could result in their penetrating the barrier and eventually reaching the traffic traveling in the opposite direction. However, the literature is not conclusive on whether a cable median barrier will be effective in stopping a CMV from penetrating the barrier. Some researchers have found that cable median barriers are effective in preventing crossovers from much larger vehicles, such as fire trucks and CMVs (Sheikh et al. 2008, Alluri et al. 2016), while others have concluded that in crashes where a large truck strikes a barrier the most likely result is penetration mainly due to the higher impact forces associated with their large mass (Russo 2015). However, such an analysis was not possible with the current database due to lack of weight information for the CMVs. Thus, it could be a future research question.

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