A Predictive Median Barrier Warrant to Reduce Cross-Median Crashes

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16. Abstract

The primary objective of this study was to develop a predictive median barrier warrant for Wisconsin. Towards this goal data from a diverse array of sources was assembled and transformed to be utilized by the modeling effort. Crash data was queried and manually filtered to assemble single- and multi-vehicle cross median crashes (CMC) and median barrier crash (MBC) datasets. A software method was pioneered to visually inventory roadway characteristic data from the Photolog. The spatial mismatch between the Photolog-collected data and STN was addressed to integrate the crash and roadway data for use in the modeling process. Crash prediction models were formulated to describe the cross median and barrier crash frequencies and severities. The modeling results indicate that median width, ADT, bridges, curves, and entrance and exit ramps affect CMC occurrence and ADT, curves, and ramps impact the occurrence of MBCs. CODES costs of concrete median barrier injury crashes were roughly 20 percent of multi-vehicle CMC costs and 50 percent of single-vehicle CMC costs. Using the crash frequency models developed for CMCs and MBCs and WisDOT costs for crashes and barrier installation and maintenance, predictive median barrier warrant was developed. The results indicate that median barrier has positive benefits on highway segments where the width of median is between 0 and 80 ft and directional ADT is between 40,000 and 50,000 vehicles/day and where width is between 0 and 30 ft and directional ADT is between 30,000 and 40,000 vehicles/day. None of the highway segments show benefit/cost ratio greater than one. The data used to develop frequency models for CMC is mostly from rural Wisconsin (with lower ADT) while the data for MBC model is mostly from Greater Milwaukee area (with higher ADT). This disparity in datasets skews the comparison and reduces the calculated benefits drastically, which in turn, reduces the benefit/cost ratios. It is recommended that as new MBC data becomes available, the methods outlined in this report be applied to revise the predictive warrant to better capture the effect of installing median barrier on crash occurrence and severity.

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ABSTRACT

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1 INTRODUCTION

1.1 Background

Cross-median crashes (CMCs), in which a vehicle leaves a divided highway to the left and crosses completely through the median into oncoming lanes, are one of the most severe types of crashes due to high speeds and risk of collision with an opposing vehicle. Sideswipe collisions, overcorrecting after leaving the roadway to the right, and adverse roadway conditions are typical occurrences that initiate the loss of control and contribute to CMCs. Vehicles crossing the median commonly roll over, hit guardrails or other fixed objects, or collide with oncoming vehicles.

CMCs are classified as one of two types; namely multi- and single-vehicle cross-median crashes. CMCs where the crossing vehicle collides with a vehicle in the oncoming lanes are classified as multi-vehicle cross-median crashes. The severities of these crashes are typically high due to the high rates of speed and head-on or opposing sideswipe crash types. Additionally, as more vehicles are involved in a crash, more injuries and fatalities often result. Due to the catastrophic nature of multi-vehicle crashes, many agencies have made them the primary focus of safety improvements mitigating CMCs.

In approximately 80 percent of the cross-median crashes in this study, the crossing vehicle entered or crossed the opposing travel lanes without colliding with an oncoming vehicle. These crashes, referred to as single-vehicle CMCs, are typically less severe and have fewer injuries than multi-vehicle crashes, but can still be severe as they often involve rollovers or collisions with roadside objects. Single-vehicle CMCs are expected to have contributing factors and crash dynamics that are similar to multiple-vehicle CMCs and would thus have similar treatments. Additionally, single-vehicle CMC incidents have the potential to become the more severe multi-vehicle crashes, but the crossing vehicle found a gap in the opposing traffic stream. Single-vehicle CMC frequency is an important factor in predicting safety performance on divided highways as they act as an indicator to highlight potential problem areas.

Table 1 summarizes the Wisconsin CMCs from 2001 to 2007. Figure 1 shows the geographical distribution of CMCs in Wisconsin over the same time period. The Milwaukee area highways typically include concrete median barrier, so few CMCs have occurred on those roadways. Additionally, many state and US highways in Wisconsin are not divided, thus contain no CMCs.

Table 1 Cross-Median Crash Summary for Wisconsin (2001-2007)[1]

	Number of Crashes (%)			
CMC Type	**Fatal**	**Injury**	**Property Damage**	**Total**
Multi-Vehicle	63 (22%)	171 (59%)	57 (19%)	**291 (100%)**
Single-Vehicle	43 (3%)	632 (52%)	545 (45%)	**1220 (100%)**
Total	**106 (7%)**	**803 (53%)**	**602 (40%)**	**1511 (100%)**

[1] These numbers vary from the number of CMCs reported in *A Seven-Year Analysis of the Safety Impacts of Crossover Median Crashes in Wisconsin* released in February 2009 (6) after a thorough review of the crash reports resulted in the removal of some crashes.

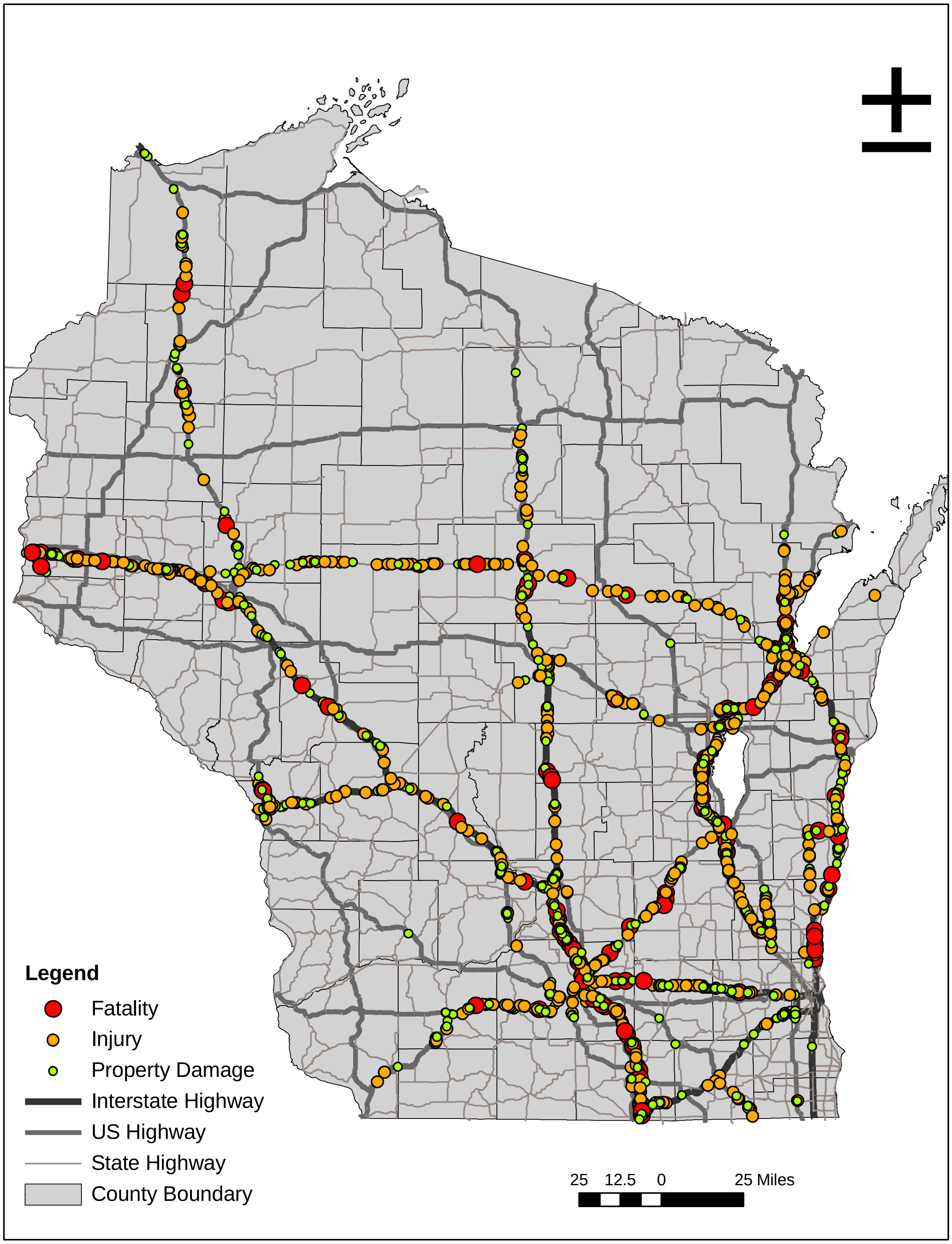


Figure 1 Single- and Multiple-Vehicle Cross-Median Crashes (2001 – 2007)

On divided highways, medians provide a measure of safety, acting as a buffer between opposing lanes and providing a recovery area for vehicles that have run off the road. The American Association of State Highway & Transportation Officials (AASHTO) defines a median as the "portion of a highway separating directions of the traveled way" and includes the vegetated area of land and the interior shoulders located between travel lanes (1). AASHTO's *A Policy on Geometric Design of Highways and Streets*, published in 2004, states that "medians are highly desirable on arterials carrying four or more lanes" of traffic. The separation of opposing volumes attempts to prevent head-on collisions. Medians also serve numerous other purposes including providing a drainage outlet for roadway runoff, providing an area for vehicles to stop in an emergency, allowing space for turning lanes, minimizing headlight glare, and providing space for the addition of future lanes (1).

AASHTO has design guidelines but no specific standards regarding median width. For medians 40 feet or wider, AASHTO states that drivers are given a "sense of separation from opposing traffic" and a "desirable ease and freedom of operation" (1). WisDOT's *Facilities Development Manual* (FDM) specifies a minimum median width of 60 feet for all Design Class A3 freeways and Design Class A3 expressways with a speed limit greater than 55 miles per hour (mph); and a minimum median width of 50 feet for all Design Class A3 expressways with speed limits of 50 or 55 mph (2). A Design Class A3 highway is an arterial with a minimum volume of 7,000 vehicles per day (vpd) and a minimum design speed of 65 mph (3). A typical median used on Wisconsin highways is depicted in Figure 2.

Figure 2 Typical Wisconsin Highway Median (I-39 Rock County – 60 feet) (4)

Historically, these median standards have been deemed adequate in providing sufficient vehicle recovery space to provide a measure of safety and in preventing vehicles from traveling across the median into opposing lanes of traffic. However, there are numerous roadways throughout the state that do not meet these standards (i.e., a narrower median width) and do not provide any additional safety features such as median barriers. Additionally, the frequency of CMCs on medians meeting these standards implies that they may no longer be adequate.

Median barrier systems are designed to reduce the chance of a vehicle crossing over the median and into the opposing direction travel lanes (1). Examples of cable, concrete, and guardrail median barrier systems are displayed in Figure 3 (4). The Wisconsin median barrier guidelines are depicted in Figure 4 and show that median barriers are only warranted based on a highway's specific combination of Average Annual Daily Traffic (AADT) and median width. A barrier is not warranted for median widths greater than 60 feet, nor for medians widths as narrow as 20 feet when AADT is less than 20,000 vehicles per day. It is not well understood whether the current median barrier warrant guidelines are sufficient in maximizing the safety of divided highways in Wisconsin.

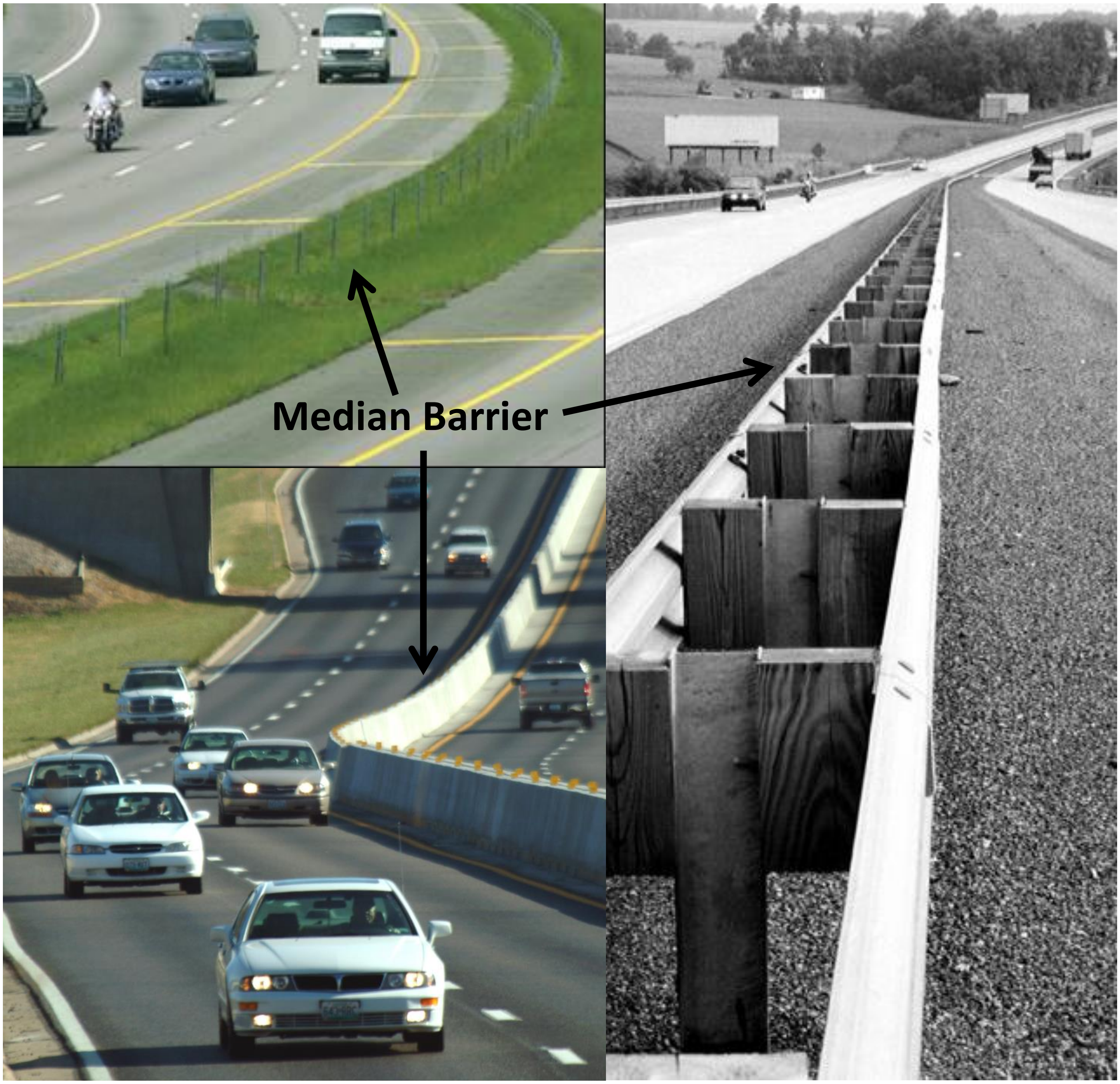


Figure 3 Typical Median Barriers (4)

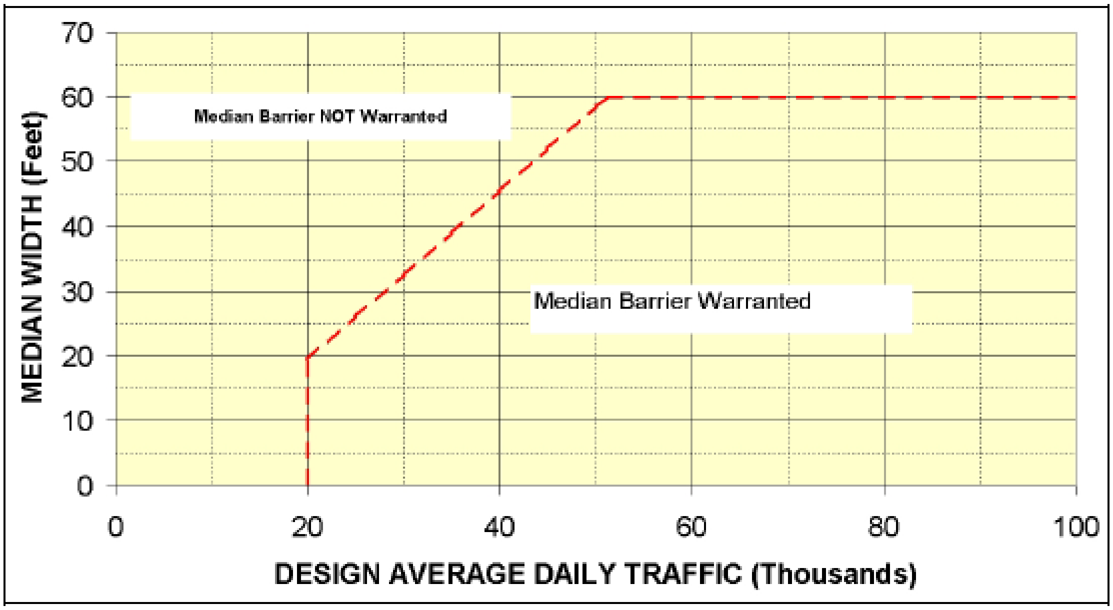


Figure 4 Wisconsin Median Barrier Warrant Guidelines (2)

Contributory factors are expected to vary by state due to variation in roadway design standards, topography, driver types, and weather conditions. A number of other states and the American Association for State Highway and Transportation Officials (AASHTO) have formulated median barrier warrants. However these warrants are typically based on median width and traffic volume only and are not consistent. While these factors are important in affecting whether a vehicle will cross a median and collide with an opposing vehicle, they are not likely the only significant factors. Additionally, several warrants are less prescriptive than may be desired, using indefinite language such as "barrier optional" or "barrier not normally considered." While offering room for interpretation and engineering judgment is important, more certain language would be helpful to practitioners.

Some states have established cross-median crash rate warrants to identify highway segments that require additional median safety analysis to supplement warrants based on traffic volume and median width. While responsive to address crash hotspots, these tools are reactive, relying on crash histories.

1.2 Problem Statement

The frequency and severity of cross-median crashes in Wisconsin dictate that efforts to reduce these crashes should be continued. Research throughout the country has sought to find mitigations and their appropriate applications. Beyond simply making medians wider, median barriers have been found to be the most effective treatment for cross-median crashes as they prevent most vehicles from crossing the median into opposing traffic. However, current median barrier warrants employed by Wisconsin and other states are basic, using only traffic volume and median width as factors, or are reactive, identifying hotspots based on crash history.

The factors that contribute to cross-median crashes are complex and are not well understood. Additionally, installing median barrier has negative aspects, chiefly increasing the frequency of lower-severity median barrier crashes. These dynamics have not been thoroughly evaluated and combined with barrier installation and maintenance costs in a comprehensive manner. As a result, CMC risk has not been adequately quantified and median barrier warrants have not been thoroughly developed. Therefore, research is needed to determine the link between roadway factors and cross-median crashes and to use that link to establish a predictive median barrier warrant for Wisconsin.

1.3 Research Objective

The objective of this research is to determine the significant factors that affect cross-median and median barrier crashes and apply these factors to create a crash prediction model for each type. These models will be utilized in conjunction with injury cost data and barrier installation and maintenance costs to formulate a comprehensive median barrier warrant based on benefit/cost analysis. This warrant would be predictive based on roadway characteristics and could be applied to all current roadways as well as to new or reconstructed roadways without crash histories. Ultimately, new warrants can be created for WisDOT use providing transportation professionals a better decision tool for median barrier decisions.

1.4 Scope

The scope of this research includes single- and multi-vehicle cross-median crashes and median barrier crashes that were available from police crash reports in the Traffic Operations and Safety (TOPS) WisTransPortal for the State of Wisconsin from 2001 through 2007. The injury cost data associated with these crashes was limited to that available through the Crash Outcome Data Evaluation System (CODES). Median barrier costs were collected from the costs associated with pilot projects throughout the state.

1.5 Report Organization

This report is composed of eight chapters. Chapter 1 provides an introduction to cross-median crashes and the objectives and scope of this study. Chapter 2 is a literature review of related relevant research on cross-median crash frequency and severity, median barrier costs and performance, and current median barrier warrants. Chapter 3 outlines the research tasks undertaken in this study. Chapter 4 provides an overview of the data collection and reduction process. Chapter 5 describes the crash modeling used to describe CMC and median barrier crash frequencies and severities. Chapter 6 describes the crash injury cost analysis. Chapter 7 details the economic analysis utilizing the crash prediction models. Chapter 8 provides conclusions and identifies areas for future work.

2 LITERATURE REVIEW

This research builds upon previous research by Chitturi et al. in 2009, Witte, et al. in 2007 and Noyce and McKendry in 2005 (6, 7, 4). These studies described the locations of CMCs in Wisconsin, detailed crash characteristics, and identified hotspots. A detailed literature review was conducted as part of this ongoing research study and has been summarized in the following sections. These sections summarize historical research into a number of median safety characteristics, highlight the safety evaluation process, describe the different types of median barrier systems commonly employed, describe state median barrier policies, and in particular focus on some of the median safety warrants applied in different states.

2.1 Median Design

2.1.1 Median Width and Cross Section Design

Hutchinson and Kennedy determined from field studies conducted in Illinois in the 1950's and 1960's that a minimum median width of 30 feet should be used on all rural highways and that the median should be obstacle-free with a mild (24:1 or greater) cross-slope (8). Similarly, computer simulations performed at the Georgia Institute of Technology in 1970 demonstrated that while median widths of 30 feet had a positive effect in reducing the severity of cross-median crashes compared to narrower or no medians, they were still inadequate at providing an acceptable level of safety (9).

2.1.2 Median Width and Overall Crash Improvement

Garner and Deen (10) and Knuiman et al. (11) demonstrated that the presence of a traversable median that can be used as a place of refuge has a beneficial effect on all crashes, not just cross-median crashes. Garner and Deen found that as median width increased, the crash rate and crash severity decreased, with benefits diminishing at median widths between 30 and 40 feet. Knuiman et al. advised that a minimum median width of 30 feet was necessary to have an effect on crash rates and that any reduction in width beyond 30 feet would be marked by a decrease in safety. This research also found that overall crash rate reduction due to increasing median width continued until a width of approximately 60 to 80 feet, at which point no improvement in safety was realized.

Garner and Deen further supported the need for a clear, traversable median by showing that raised or depressed medians led to an increase in vehicles that either lost control or rolled-over. Macedo (12) concurred with Garner and Dean on the need for a clear median, if the width was large enough to prevent a cross-median crash. However for narrower median widths, Macedo suggested that a steep raised median may be preferable, citing that a single-vehicle rollover crash was favorable to a cross-median or barrier crash.

2.2 Cross-Median Crash Analysis

2.2.1 Cross-Median Crash Survey

The Pennsylvania Department of Transportation (PennDOT) undertook a comprehensive review of cross-median crashes in 2002. An assembled expert panel listed the top four factors affecting median safety as: horizontal curvature, operating speed, median cross-slopes, and driver behavior (13). The inside shoulder width was considered the most important geometric cross-section feature affecting whether a vehicle crossed the median. The panel also made median width recommendations for the application of the three different types of median barrier systems:

- Median widths less than 20 feet: concrete safety barrier;
- Median widths between 20 and 33 feet: strong post W-beam guardrails; and
- Median widths greater than 33 feet: three-strand cable barrier.

Donnell et al. (13) identified 267 cross-median crashes, defined as crashes "in which a driver traversed the entire width of the median, entered the opposing roadway, and collided with a vehicle traveling on the opposing roadway", on Pennsylvania Interstates and expressways between 1994 and 1998. The majority of crashes were a result of drivers losing control of the vehicle (71 percent). Twenty percent occurred as a result of a same-direction vehicle collision and eight percent occurred as a result of a driver trying to avoid a same-direction vehicle. Sixty-three percent occurred during daylight (vs. 58 percent of all crashes), 32 percent while dark (vs. 37 percent of all crashes), and four percent during dawn or dusk (vs. five percent of all crashes). The weather conditions varied amongst the cross-median crashes with 43 percent of cross-median crashes occurring under dry conditions (vs. 61 percent of all crashes), 32 percent under wet conditions (vs. 19 percent of all crashes), and 25 percent under snow and ice (vs. 21 percent of all crashes). Twelve percent of cross-median crashes involved alcohol and/or drugs (vs. six percent of total crashes). A comparison of crash rates (crashes per hundred million vehicle miles traveled) showed that, although not significant, as median width increased the crash rate decreased, as shown in Figure 5.

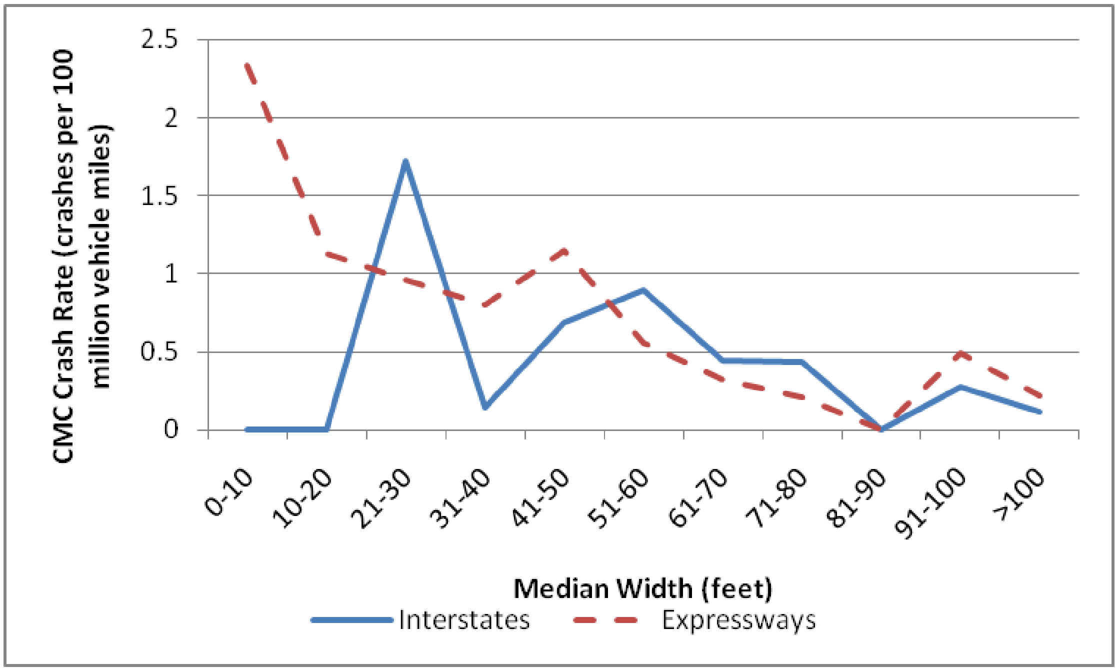


Figure 5 Pennsylvania Cross-Median Crash Rates (13)

Donnell and Hughes conducted a survey of 37 state transportation agencies (STAs) to ascertain median design and safety practices. Responses showed that mitigation measures employed in response to median-related crashes included the installation of median barrier, flattening median side slopes, installing rumble strips on the median shoulder, and general geometric improvements. The responding STAs indicated that "traveling too fast for conditions" was by far the most reported causation of median-related crashes, followed by "driver lost control", "driver inattention", "avoidance maneuver", "adverse weather conditions", and "driver under the influence of drugs or alcohol" (14).

2.2.2 Cross-Median Crash Severity Modeling

The factors contributing to cross-median crashes have also been investigating using statistical methods. A number of recent studies have used ordinal logistic regression to relate crash severity, classified as fatal, injury, or property damage, to various geometric, traffic operation, and environmental conditions. Donnell and Mason (15) used roadway inventory and crash record information collected on Pennsylvania Interstate highways for the five-year period between 1994 and 1998 to develop cross-median and median barrier crash logistic regression models. The researchers found that modeling crash severity as an ordinal response produced appropriate results for cross-median crashes and that the use of drugs and the presence of a curvilinear alignment increased the odds of a fatal cross-median crash when compared to injury or property damage crashes. The predicted severity probability models developed by Donnell and Mason (15) are described in equations 1 through 3.

$$p_{fatal} = \frac{e^{Equation\ 4}}{1+e^{Equation\ 4}} \tag{1}$$

$$p_{injury} = \left(\frac{e^{Equation\ 5}}{1+e^{Equation\ 5}}\right) - p_{fatal} \tag{2}$$

$$p_{PDO} = 1 - \left(p_{fatal} + p_{injury}\right) \tag{3}$$

From the regression modeling results:

$$-2.2212 + 0.6552X_1 + 1.3694X_2 - 1.0591X_3 - 1.1884X_4 + 1.3088X_5 \tag{4}$$

$$1.4074 + 0.6552X_1 + 1.3694X_2 - 1.0591X_3 - 1.1884X_4 + 1.3088X_5 \tag{5}$$

Where:

X_1 = drug or alcohol use indicator (1 if not using, 0 otherwise);

X_2 = horizontal alignment indicator (1 if tangent, 0 otherwise);

X_3 = horizontal alignment indicator (1 if curve to right, 0 otherwise);

X_4 = interaction between drug use and horizontal alignment indicator (1 if no drug use and tangent section, 0 otherwise); and

X_5 = interaction between drug use and horizontal alignment indicator (1 if no drug use and curved section to the right, 0 otherwise).

Ordinal logistic regression was also employed by Lu et al. (16) to model the crash severity of cross-median crashes that occurred in Wisconsin during the three year period between 2001 and 2003. The researchers found that season has an effect on cross-median crash severity, likely due to deteriorated weather and roadway conditions prevalent in Wisconsin during the winter months. Additional statistical analysis showed that as well as seasonal effects (i.e., weather and roadway conditions), driver age affects the severity of cross-median crashes when the traffic volume is relatively high. However, road condition was the only significant variable identified under low traffic volumes. Under inadequate median width conditions, weather condition and emergency vehicle response time were found to be significant explanatory variables. The general severity probability prediction models developed as part of the research conducted by Lu et al. are described in equations 6 through 8.

$$p_{PDO} = \frac{e^{Equation\ 9}}{1+e^{Equation\ 9}} \tag{6}$$

$$p_{injury} = \left(\frac{e^{Equation\ 10}}{1+e^{Equation\ 10}}\right) - p_{PDO} \tag{7}$$

$$p_{fatal} = 1 - \left(p_{PDO} + p_{injury}\right) \tag{8}$$

From the regression modeling results:

$$-3.6578 + 3.0082X_1 - 1.9333X_2 - 0.0356X_3 \quad (9)$$

$$-0.4945 + 3.0082X_1 - 1.9333X_2 - 0.0356X_3 \quad (10)$$

Where:

X_1 = clear weather indicator (1 if yes, 0 otherwise);

X_2 = sleety weather indicator (1 if yes, 0 otherwise); and

X_3 = reaction time predictor.

This research was expanded upon by work done by Lu et al. in 2009 (17) who used ordinal probit models to describe the severities of both single- and multi-vehicle CMCs using Wisconsin data from 2001-2007. For multi-vehicle CMCs, poor road surface condition was found to significantly affect crash severity. For single-vehicle CMCs, road surface condition, crossover extent, lighting conditions, and posted speed limit were found to affect CMC severity.

The modeling results of Donnell and Mason (15) and Lu et al. (16, 17) were found to be statistically significant and may be useful to practitioners in determining the probability of fatal, injury, and property damage only crashes based on a given set of geometric and environmental variables.

2.2.3 Cross-Median Crash Frequency Modeling

Donnell and Mason (18) also developed crash frequency models that related the number of median barrier crashes to a number of geometric and cross-section elements using a negative binomial distribution. Median barrier crash frequency was found to be influenced by speed limit, traffic volumes, horizontal alignment, the distance the barrier was offset from the travel lanes, and the presence of interchange entrance ramps (15, 18).

Shankar et al. used random effects negative binomial (RENB) and the cross-sectional negative binomial models (NB) to develop predictive models of cross-median crash frequencies in road sections without median barriers (19*)*. Five year crash data from 1990 through 1994 was used. The negative binomial distribution was chosen as it can model the nonnegative integer nature of crashes as well as their overdispersion. Although accounting for overdispersion, the NB model does not account for location-specific effects or serial correlation over time. The authors compare the NB and RENB models developed.

The negative binomial (NB) model specifies the probability of n_{it} cross-median crashes for a section *i* in year *t* as:

$$P(n_{it}) = \frac{\Gamma(\theta + n_{it})}{\Gamma(\theta) n_{it}!} u_{it}^{\theta} (1 - u_{it})^{n_{it}}$$

(*11*)

Where $u_{it} = \frac{\theta}{\theta+\lambda_{it}}$ $u_{it} = \frac{\theta}{\theta+\lambda_{it}}$ and $= \frac{1}{\alpha} = \frac{1}{\alpha}$, $\Gamma(.)$ is a gamma function and λ_{it} is given by

$$ln\lambda_{it} = X_{it}\beta + \varepsilon_{it} \tag{12}$$

Where X_{it} is a vector of geometric, traffic and weather data for roadway section I in year t, and β is a vector of estimable coefficients and $\exp(\varepsilon_{it})$ is a gamma distributed error term with mean one and variance α.

Standard maximum likelihood procedures were used to estimate λ_{it}. This model considers the yearly frequencies of each location as independent observations and does not allow for serial correlation in the crash data. The RENB model, however assumes that the overdispersion parameter is randomly distributed across groups; thereby letting the variance-mean ratio to vary across locations.

$$ln\lambda_{ij} = X_{ij}\beta + u_i$$

Where u_i is a random effect for the i^th location group such that $\exp(u_i)$ is gamma-distributed with mean one and variance α. The joint density function is obtained by using $\frac{\theta_i}{1+\theta_i}$ to be B(a,b) where B(.) is the beta distribution.

$$P(n_{i1}, \cdots n_{iT}) = \frac{\Gamma(a+b)\Gamma\left(a + \sum_T \lambda_{it}\right)\Gamma\left(b + \sum_T n_{it}\right)}{\Gamma(a)\Gamma(b)\Gamma\left(a + b + \sum_T \lambda_{it} + \sum_T n_{it}\right)} \prod_T \frac{\Gamma(\lambda_{it} + n_{it})}{(\lambda_{it}) n_{it}!}$$

(*13*)

The parameters a, b and β vector are estimated using standard maximum likelihood procedures.

Five years of annual cross-median counts for 275 sections were used. The study was balanced with all the sections containing data for 5 years. Four specifications: basic non-location and non-time-specific regression, a location effects model, a location and time effects model and a location, time and location-time interaction model were considered and run under both NB and RENB distributions. The authors reported that the relative effectiveness of the RENB model diminished as more spatial and temporal effects were included. However the authors found location and time-specific variables to be significant and state that the RENB model offers an alternative where those effects are captured indirectly rather than by direct specification as indicator variables. Significant improvement in the likelihood was reported when the spatial effects were included indicating that significant unobserved heterogeneity occurs from roadside effects.

Ulfarsson and Shankar examined using negative multinomial (NM) model that accounts for section specific serial correlation across time, to predict the cross-median frequencies on sections without median barriers (20). This study used the same data and same model variables as Shankar et al. The temporal serial correlation in the cross-median data violates the assumption of independent error terms and if not accounted for properly, can cause the coefficient estimates to be inefficient and the estimated standard errors to be biased. The unconditional joint density function for NM distribution is given by:

$$P(Y_{i1} = y_{i1}, \ldots, Y_{it_i} = y_{it_i}) = \frac{\Gamma(y_i + \theta)}{\Gamma(\theta) y_{i1}! \ldots y_{it_i}!} \left(\frac{\theta}{\eta_i + \theta}\right)^{\theta} \left(\frac{\eta_{i1}}{\eta_i + \theta}\right)^{y_{i1}} \ldots \left(\frac{\eta_{it_i}}{\eta_i + \theta}\right)^{y_{it_i}} \quad (14)$$

Where:

$\Gamma(.)$ is a gamma function,

$y_i = y_{i1} + \cdots + y_{it_i}$

$\eta_i = \eta_{i1} + \cdots + \eta_{it_i}$, and

$\eta_{it} = e^{x_{it}.\beta}$

Variance of $exp(\varepsilon_i)$ is α and is equal to $1/\theta$. When there is no section specific correlation, in other words when each section has only one observation this formulation yields the negative binomial distribution. Maximum likelihood procedures are used to estimate coefficients β and α. The authors report that the coefficient values estimated using NM, NB and RENB models were similar but not identical. Statistical comparison of the log likelihood led the authors to conclude that the NM model outperforms the NB model even with temporal and spatial effects and the RENB model. Divided highways with low traffic volumes (i.e., less than 5,000 vehicles per lane per day) were found to experience fewer cross-median crashes than higher volume roadways. Increasing the number of horizontal curves per mile of road was found to decrease the expected number of cross-median crashes. Finally, increasing the roadway segment length was found to be associated with an increase in the expected number of cross-median crashes.

Miaou et al. used roadway inventory and crash data from Texas to develop a predictive model of cross-median crashes along divided highways (21). In the model, the expected number cross-median crashes decreased as the median width increased. Additionally, the expected number of cross-median crashes decreased as the number of through travel lanes per direction increased. Roadways with posted speed limits of 65 and 70 mph were found to experience more cross-median crashes than roadways with posted speed limits of 60 mph. No roadway geometric design features or traffic volume data were found to be statistically significant in a model of cross-median crash severity.

Harkey et al. recently used roadway inventory and crash data from California to develop predictive models of cross-median crashes (22). Separate models were specified for rural and urban roadways with and without full-access control. Additionally, separate models were specified for four- and five-or-more lane divided highways. In all models it was found that the expected cross-median crash frequency decreases as the median width increases and that the presence of an interchange entrance ramp is associated with an increase in the expected number of cross-median crashes. The magnitude of the interchange ramp influence indicator was greater on urban roadways than on rural roadways. This suggests that interchange entrance ramps may be a more important contributory factor on urban than on rural roadways.

2.3 Crash Injury Costs

2.3.1 Injury Scales

Two injury scales are in common use: Maximum Abbreviated Injury Score (MAIS) and KABCO. The MAIS scale is oriented around the threat to life and thus requires trained medical judgment. MAIS consists of six severity levels, shown in Table 2 (23).

Table 2 MAIS Scale Injury Severity Levels

MAIS Score	Threat to Life
1	Minor Injury
2	Moderate Injury
3	Serious Injury
4	Severe Injury
5	Critical Injury
6	Maximum Injury/Fatal

Note: MAIS score of 0 indicates no injury.

The KABCO scale is designed for application by police officers on the scene of a crash. The scale's name is derived from its five injury severity levels, shown in

Table 3.

Table 3 KABCO Scale Injury Severity Levels

KABCO Level	Injury Severity
K	Killed
A	Injury A, an incapacitating injury
B	Injury B, a non-incapacitating injury
C	Injury C, a possible injury
O	PDO, no injury

As the KABCO scale is based on police officers' observations instead of medical expertise, it is susceptible to inconsistencies, experience biases, overestimation of external injuries, and underestimation of internal injuries. However, the scale is useful for crash reporting and is deemed to be reliable enough to be utilized in safety analysis (24).

The two injury severity scales have been compared by FHWA and by Compton (25, 24). FHWA compared the distribution of MAIS injury scores by the KABCO scale in 1991, shown in Table 4. All fatalities were recorded at MAIS 6, regardless of original MAIS score.

Table 4 FHWA MAIS and KABCO Comparison Table (25)

	KABCO Scale				
MAIS Score	O	C	B	A	K
0	92.7%	20.5%	5.2%	1.5%	0.0%
1	7.0%	70.9%	78.8%	48.6%	0.0%
2	0.2%	7.0%	12.6%	28.0%	0.0%
3	0.0%	1.5%	3.1%	16.9%	0.0%
4	0.0%	0.1%	0.3%	2.8%	0.0%
5	0.0%	0.0%	0.1%	1.7%	0.0%
6	0.00%	0.01%	0.03%	0.50%	100.00%

Compton created a similar comparison table for crashes with MAIS 3 and under, as shown in

Table 5.

Table 5 Compton MAIS and KABCO Comparison Table (24)

	KABCO Scale			
MAIS Score	**O**	**C**	**B**	**A**
0	80.5%	20.7%	5.6%	2.6%
1	18.9%	70.5%	75.5%	41.1%
2	0.5%	7.2%	13.9%	25.3%
3	0.1%	1.6%	4.9%	31.1%

These tables indicate that KABCO scale does not effectively capture the threat to life indicated by the MAIS scale. However, KABCO is used nearly uniformly by police officers in crash reporting and thus plays a central role in safety analyses where more detailed injury information is not available.

2.3.2 CODES Injury Costs

The Crash Outcome Data Evaluation System (CODES) is a national effort overseen by the National Highway Traffic Safety Administration (NHTSA) to assemble medical and financial outcome data for motor vehicle crashes (26). The purpose of the CODES project is to provide detailed injury data, such as injury type, severity, and associated costs, for highway safety decision making. The CODES system grew from a 1996 report to Congress on seat belt and helmet use, funded by the Intermodal Surface Transportation Efficiency Act (ISTEA) (27). CODES was initially implemented in 7 states, including Wisconsin, in 1992 and has since been expanded to a total of 28 states (26).

To assemble each state's CODES database, crashes were linked to medical, driver, and other records to provide comprehensive cost data for each injured and uninjured crash participant. The linkage process sought to match the records for each incident across the various databases by comparing event data—such as location and date—and person data—such as name, date of birth, and presence and type of injury. The records were matched using a probabilistic linkage, which does not require all the record fields to match, enabling matches for records with missing or erroneous entries and for databases with no person-level entries. This method uses weights based on the likelihood of a unique match to vary the importance of the various linkage fields. Probabilistic linkage allowed for automated matching, producing more matches with greater speed and accuracy than manual linkage. In the initial study linkage, the majority of crashes were linked to medical records for five of the seven states, with the percentage linked increasing with severity. In that study, Wisconsin showed a relatively low linked percentage due to limited data access at the time (27).

Each state's CODES implementation links data from a variety of public and private databases. The databases have a variety of managing agencies, scopes, and record units. These data sources are shown in Table 6.

Table 6 State Data Sources Used in CODES Linkage (27)

Data Source	Data Collector	Statewide?	Record Unit
Crash Record	Department of Transportation/Public Safety/Motor Vehicles	✓	Crash
Vehicle Registration	Department of Motor Vehicles	✓	Vehicle
Driver Licensing	Department of Motor Vehicles	✓	Driver
Census	Department of Health	✓	Person
Roadway/Infrastructure	Department of Transportation	✓	Road Marker
Medical Data Sources			
Emergency Medical Sources (EMS)	Department of Health/Public Safety	Except Wisconsin	Event
Emergency Outpatient	Hospital/Claims		Event
Hospital Discharge	Department of Health	✓	Event
Registries: Trauma, Head and Spinal Cord, Poison	Hospital or Department of Health		Person
Death Certificates	Department of Vital Statistics	✓	Person
Insurance Claims Data			
Medicaid, Medicare	Department of Health	✓	Claim
Private Health Insurance	Health Insurance Company		Claim
Worker's Compensation	Department of Labor	✓	Claim
Private Vehicle Insurance	Vehicle Insurance Company		Claim
National Auto Insurance Files	Association of Insurance Companies		Claim

In Wisconsin, linked crash costs are enhanced by expanding upon the hospital charges collected from linked crashes in the CODES database, as outlined by Bigelow (28). The hospital charges resulting from the records linkage do not capture all medical costs and were shown to be consistently smaller than medical costs. Additionally, charges do not describe non-medical costs associated with crashes, such as property damage and quality-of-life costs.

As a result, medical costs, quality-of-life costs, and other costs were assigned to each linked crash based on the diagnostic code using injury costs from Zaloshnja, et. al. (29) to provide an estimate of the comprehensive costs associated with each crash. The Zaloshnja study compiled national injury costs based on the body part injured, the presence of a fracture, and the severity of the injury on the MAIS scale. The three types of injury costs in this report are:

- **Medical Costs:** ambulance, emergency medical, doctor, hospital, rehabilitation, medication, and special treatment cost;
- **Quality-of-Life Costs:** based on quality-adjusted life years (QALYs) which account for the loss of quality of life due to an injury and fatality with a 2000 monetary value of $91,752 which was determined by dividing the statistical value of life by a life span; and,
- **Other Costs:** emergency services, lost wages, household work, insurance administration, legal costs, and property damage (29).

The resulting year 2000 national costs were then adjusted to Wisconsin and the crash year using state cost-of-living modifiers and the Consumer Price Index, respectively (28).

2.3.3 Application of CODES

The injury and cost data accumulated in the CODES database for each participating state have been used in a wide variety of safety analyses. Many states present the data alongside crash data to supplement annual crash summaries or "fact sheets." Other studies have investigated the relationship of injury types and medical costs to crash type, location, age, vehicle type, alcohol use, roadway characteristics, and a variety of other factors. CODES data have been utilized to analyze health care costs, law enforcement, driver licensing, EMS service, and crash reporting (30). These studies have been used to identify safety problems, support safety decision makers, support safety legislation, and educate the public (31). NHTSA has compiled two reports that catalog CODES applications by state and application (30, 31). This section summarizes CODES analyses relevant to CMC and median barrier crashes and CODES data in Wisconsin.

Noyce and McKendry developed crash costs based on information held in the Wisconsin CODES database and the National Highway Traffic Safety Administration (NHTSA) Motor Vehicle System (MVS) model. The CODES analysis found that cross-median crashes, in terms of medical costs, exceed median barrier crashes by approximately $19 million per year. Although the full cost of installing median barrier could not be evaluated, the research concluded that the potential medical and societal cost savings of median barrier installation at high frequency cross-median crash locations is significant (4).

Massachusetts CODES data were used to evaluate the frequency and injury severity of run-off-the-road (ROTR) crashes by Benavente et. al. (32). ROTR crashes were divided into two categories: single-vehicle (which includes single-vehicle CMC and median barrier crashes) and lane departure head-on crashes (which includes multi-vehicle CMCs). As shown in Table 7, the study found that ROTR crashes were more severe than all combined crash types in terms of medical charges and length of hospital stay. Additionally, lane departure head-on crashes are more severe than single-vehicle ROTR crashes. Single-vehicle ROTR crashes were broken down by object the vehicle collided with, shown in

Table 8. The study indicates that single-vehicle cross-median crashes are one of the most severe of these crash types while median barrier crashes are one of the least severe types.

Table 7 Massachusetts Lane Departure Hospital Charges and Stays (32)

Type of Crash	Median Hospital Charges (2003$)	Median Length of Stay (days)
All Crashes	$16,302	3.0
Lane Departure Crashes	$18,460	3.0
Single-Vehicle Run-Off-The-Road	$17,918	3.0
Lane Departure Head On	$20,413	4.0

Table 8 Massachusetts Single-Vehicle Lane Departure Hospital Charges and Stays (32)

Object Collided With	Median Hospital Charges (2003$)	Median Length of Stay (days)
Tree	$22,197	4.0
Post, utility pole or light pole	$15,709	3.0
Guardrail, median barrier or crash cushion	$16,289	3.0
Curb, ditch, or embankment	$16,361	3.0
Parked vehicle	$18,480	4.0
Ran off road left or cross median	$21,281	3.0
Ran off road right	$14,838	3.0
Other/unknown	$17,827	3.5

Run-off-the-road crashes were also investigated using CODES data in Maine by Finison and DuBrow (33). The study found that ROTR crashes were overrepresented for fatalities and injuries, accounting for the highest proportion of inpatient hospital charges of all crash types. Young drivers were determined to be six times more likely to be injured by running off the road than older drivers (34).

The Wisconsin CODES dataset has been used in a broad variety of transportation safety applications, including:

- The impact of distance to trauma care on crash fatalities (35);
- Motorcyclist head injury risk (36, 37); and,
- Serious lower extremity injuries in motor vehicle crashes (38).

Souleyrette and Estochen utilized CODES to determine the sensitivity of injury costs on determining high crash locations in Iowa. Though the study showed significant differences between FHWA, Iowa DOT, and CODES injury costs, these differences had little effect on project ranking. The authors suggested that, despite these results, CODES injury costs could have applications with crash prediction models (39).

2.3.4 Other Sources of Injury Costs

FHWA has established nationwide comprehensive crash cost estimates by injury severity, notably in 1994 (40). That study serves as the basis for WisDOT Division of Transportation Investment Management (DTIM) crash cost estimates.

An updated FHWA study in 2005 used a variety of databases to compile injury costs by KABCO severity, including Fatality Analysis Reporting System (FARS), National Accident Sampling System (NASS), General Estimates System (GES), and Highway Safety Information System (HSIS). The major costs that make up the comprehensive cost estimates were medical costs, emergency services, property damage, lost productivity, and monetized quality-adjusted life years (QALYs) (41). The costs were presented by crash geometry and are summarized in Table 9.

Table 9 FHWA Comprehensive Crash Cost Estimates (2005$) (41)

KABCO Injury Severity	Comprehensive Crash Cost
K	$4,008,900
A	$216,000
B	$79,000
C	$44,900
O	$7,400

2.4 Economic Analysis

Economic analyses are an important component to evaluating the effectiveness of a safety project or system. FHWA released a highway safety evaluation guide in 1981 (*42*). This guide describes the safety evaluation process including data collection, statistical analysis, and economic analysis (Function E). The report recommends using benefit/cost procedures where monetary benefit values are available. The benefit/cost ratio can be determined in two ways:

$$B/C = \frac{Equivalent\ Uniform\ Annual\ Benefit}{Equivalent\ Uniform\ Annual\ Cost}$$

(*15*)

or

$$B/C = \frac{Present\ Worth\ of\ Benefits}{Present\ Worth\ of\ Costs}$$

(*16*)

Where monetary benefits are not available, the cost/effectiveness method, where the improvement cost is compared to the cost of preventing a single accident.

Donnell and Mason (5) utilized the benefit/cost method shown in Equation 15 to develop a median barrier warrant for Pennsylvania. This warrant and procedure is discussed in more detail in Section 2.7.9.

The Highway Safety Manual (HSM), released in 2010, includes procedures for economic safety evaluation in Chapter 7 as part of the Roadway Safety Management Process (*43*). Like the FHWA guide, the HSM describes both the monetized benefit/cost procedure as well as the non-monetized cost-effectiveness method. The benefit/cost analysis can be determined one of two ways:

- **Net Present Value (NPV)**: The difference between the discounted costs and benefits of the project is calculated by the following equation:

$$NPV = PV_{benefits} - PV_{costs}$$

(*17*)

Where,

$PV_{benefits}$ = Present value of project benefits

PV_{costs} = Present value of project costs

A net present value of greater than zero indicates that the project is economically justified. Projects can be ranked by net present value.

- **Benefit/Cost Ratio (BCR)**: The ratio of present-value benefits to costs is calculated by the following equation:

$$BCR = \frac{PV_{benefits}}{PV_{costs}} \tag{18}$$

Where,

BCR = Benfit/cost ratio

$PV_{benefits}$ = Present value of project benefits

PV_{costs} = Present value of project costs

A ratio of greater than 1.0 indicates that the project is economically justified. Projects can be ranked by net present value.

The cost-effectiveness method expresses the project in terms of annual cost per crash reduced by the following equation:

$$Cost - Effectiveness\ Index = \frac{PV_{costs}}{N_{predicted} - N_{observed}} \tag{19}$$

Where,

PV_{costs} = Present value of project costs

$N_{predicted}$ = Predicted crash frequency

$N_{observed}$ = Observed crash frequency

The resulting value can be compared to other projects, but does not indicate if the project is economically justified.

2.5 Median Barrier Types

2.5.1 Rigid Barriers

Concrete, or Jersey barriers, are the most rigid type of median barrier and have several shapes, each with the purpose of minimizing the severity of a crash upon collision and maximizing the ability of a driver to regain control of their vehicle. For these reasons, in addition to their minimal lateral displacement upon impact, concrete barriers are recommended for narrow median widths, often found in urban areas or corridors with minimal right of way. Concrete barriers are the most costly type of median barrier ranging from approximately $130,000 to

$1.4 million per mile for materials and labor, depending on the associated earthwork and/or paving needed (22, 45). Figure 6 displays a typical concrete barrier design (2).

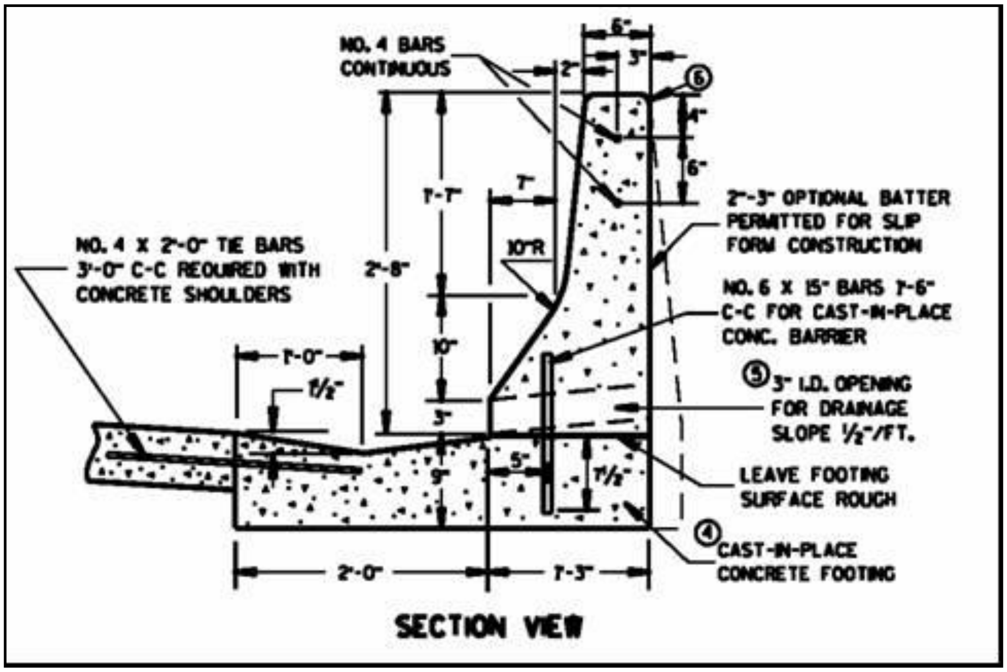


Figure 6 Typical Concrete Barrier Profile (2)

2.5.2 Semi-Rigid Barriers

Semi-rigid barriers, often referred to as guardrail, consist of connected segments of metal rail supported by heavy posts and blocks. Support posts are made of either steel or metal, and usually placed 6 feet - 3 inches apart from each other (46). There are two common types of metal rail: W-Beam and Thrie-Beam.

W-Beam guardrail is the most common type of semi-rigid barrier and contains two protrusions in the rail. The rail is typically 12 inches from top to bottom when mounted parallel with the roadway. Thrie-Beam guardrail contains three protrusions and is typically 20 inches tall (47, 48). The added width of the Thrie-Beam makes it a better choice for areas with a narrower median where a more rigid barrier is required and at connection points to rigid barriers. Guardrail is more cost effective than concrete barrier with the cost of installation of a W-Beam guardrail estimated at approximately $72,000 per mile (although costs vary widely) (47). W-Beam and Thrie-Beam guardrail can be used for a variety of surface conditions including natural earth. For narrow medians, it may be necessary to double-stripe the guardrail, i.e., run two rails back-to-back for increased strength.

2.5.3 Flexible Barriers

Flexible barriers, commonly known as cable-barriers, typically consist of three steel cables that are connected to a series of posts as shown in Figure 7. Cable barriers are the easiest and most inexpensive barrier system to erect, with installation cost estimates ranging from $44,000 to $55,000 per mile (22, 45). However, due to their design, cable barriers also require the most maintenance. Nearly every time a cable barrier is struck by a vehicle, the cables may need to be reattached to the posts. Flexible barriers are a popular system because they cause the least amount of damage to a vehicle. However, medians must be of sufficient width to allow for the stretching of the cable to prevent a vehicle from crossing over. The amount of deflection for an installation varies depending on site conditions (49). Several proprietary cable barriers have been developed for median applications. Three of the most common include the Brifen Wire Rope Safety Fence (WRSF), the Trinity Cable Safety System (CASS), and the Marion Steel barrier (50). Each of these systems contains cables that are pre-tensioned, unlike traditional cable-barrier systems that are not tensioned. Table 10 contains a review performed by the Ohio Department of Transportation (ODOT) on each of these systems, along with traditional cable barrier (51).

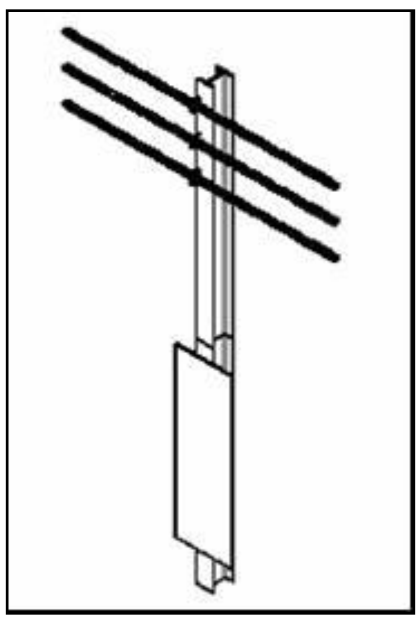


Figure 7 Typical Three-Strand Cable Barrier Profile

Table 10 ODOT Cable Barrier Comparison (51)

	Brifen	Marion	Trinity	Base (generic)
Description	4 cable woven, tensioned and pre-stretched	3 cable tensioned but not pre-stretched	3 cable tensioned and pre-stretched	3 cable un-tensioned and not pre-stretched
Product History	3000 km of use 20 foreign countries	New system, based on well used frangible sign posts	New System to the USA, but modified from an existing European system	Generic Cable has been in use in the US since 1960s but not an ODOT standard
Segment Length	14 miles	12 miles	3 miles	12 miles
Post Spacing & Crash Deflection	10 feet 6 inch spacing 7.9 foot spacing	6 feet 6 inch spacing 6.5 foot spacing	10 foot spacing 7.9 foot spacing	16 foot spacing 11.2 foot spacing
Application	On one side of a median slope	At edge of wide paved shoulder on one side	At edge of wide paved shoulder on one side	On one side of median slope
Approx. No. Hits	160 (6.5 hits/mile/year)	30 (5.0 hits/mile/year)	10 (6.7 hits/mile/year)	n/a
Issues	One penetration of unknown reason has been recorded. Cable sagging in severe hits. District decision to replace driven posts with concrete socketed foundation affects timeliness of repair.	Replacing of problem anchor foundations. Retrofitting of the remaining anchor foundation to the Project Engineer's satisfaction. Redesign of damaged line post foundations. Keeping watch on the cable tension.	Anchor system is the same as on the Marion Steel system and may be vulnerable to movement as well.	D-12 Maintenance wrote in 2000 of the problems in maintaining the cable and keeping parts. D-12 then recommended replacing the cable with Type 5 guardrail.
Performance Conclusions	Performing to NCHRP Report 350 standards	Performing to NCHRP Report 350 standards	Performing to NCHRP Report 350 standards	Conforms to previous crash test criteria, NCHRP Report 230 standards
Summary	Best accident data, longest evaluation time, proven system elsewhere, extra cable woven. System seems to be proving itself beneficial	Construction issues, first substantial installation for product, so manufacturer's installation and repair manual being written after the fact from our experiences.	Construction went smoothly and observed repair was very easy. Looks to be a good system, but the length, and thus exposure to accidents is limited.	District says cable needs immediate attention after an accident and parts are difficult to obtain.

2.6 Barrier Applications

Donnell and Hughes found seven common median barrier types used by state transportation agencies distributed amongst the three barrier categories. Table 11 presents a summary of each barrier type, design deflection, applicable site conditions, and other information (14).

Table 11 Median Barrier Types and Placement Recommendations (14)

Barrier Type	Design Deflection	Recommended Site Conditions	Other Notes
Flexible Median Barrier Systems			
Weak-post, W-Beam	7 feet	Flat, traversable slopes	• Can remain effective after struck • Sensitive to mounting height • Requires proper end anchorage
Three-Strand Cable	12 feet	Flat, traversable slopes	• Inexpensive installation • Requires proper end anchorage • Ineffective after being struck • Expensive to maintain
Semi-Rigid Median Barrier Systems			
Box-Beam	5.5 feet	Flat, traversable slopes	• Posts designed to breakaway at impact • Posts must be repaired after being struck
Blocked-out W-Beam	2 – 4 feet	Median width of 10 feet or greater	• Can remain effective after impact • May require rub-rail • Higher impact forces than flexible systems
Blocked-out Thrie Beam	1 – 3 feet	Requires effective barrier height	• Can accommodate larger range of vehicles than W-Beam • No need for rub-rail • Higher impact forces than flexible systems
Modified Thrie-Beam	2 – 3 feet	Requires effective barrier height	• Can accommodate larger range of vehicles • Does not usually require immediate repair • Higher impact forces than flexible systems
Rigid Median Barrier Systems			
Concrete Median Barrier	0 feet	Use in narrow, symmetric medians	• Low life-cycle costs • Effective performance • Maintenance-free • High impact forces • High installation cost

2.7 Current Median Barrier Warrants

2.7.1 AASHTO

The AASHTO *Roadside Design Guide* (52) established guidelines to evaluate the need for median barrier installation under specific combinations of median width and AADT as shown in Figure 8. Several selected state median barrier policies/programs are presented below.

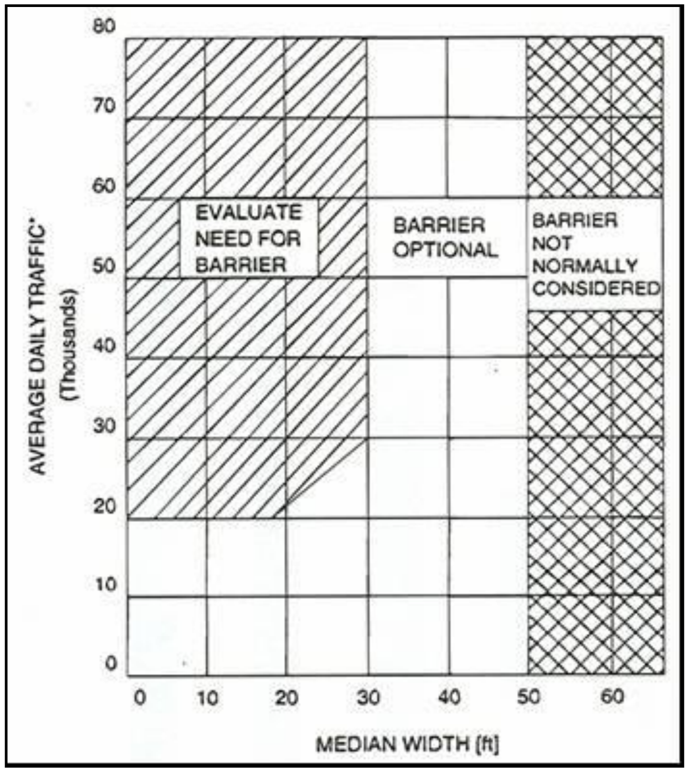


Figure 8 AASHTO Median Barrier Guidelines (1)

2.7.2 Wisconsin

The median barrier warrant criteria outlined in the WisDOT FDM (2) are based on median width and AADT and is shown in Figure 4. The WisDOT warrant is more conservative than the AASHTO recommendations. Median barrier is warranted for selected AADTs up to a median width of 60 feet.

2.7.3 South Carolina

Cable guard median barriers were installed on all freeway sections with a median width less than 60 feet. Cross-median crash fatalities dropped from over 70 during the two-year period between 1999 and 2000, to eight fatalities during the three year period subsequent to the barrier implementation. The median barrier system averages three hits per mile per year, resulting in repair costs that average approximately $1,000 per hit. Only 15 vehicles have traveled through or over the barrier during the three year analysis period (22).

2.7.4 Connecticut

The Connecticut Highway Design Manual warrants median barriers for all freeway median widths up to 66 feet and on wider medians if crash history indicates a need (52). At sections where median width varies, the median barrier should extend for 100 feet into the section where width no longer requires a barrier (53).

2.7.5 North Carolina

North Carolina installed cable guard median barriers for all freeway sections with a median width less than 70 feet. The program included installation of cable guard barriers on over 1,000 miles of freeway between 1999 and 2004 and resulted in an estimated 90 percent reduction in the amount of cross-median crashes and an average of 25 to 30 lives saved per year (54). The installation cost of approximately $55,000 per mile (approximately $55 million total), including material and labor costs, is estimated to have saved more than $290 million in crash costs, based on NHTSA's estimate of fatality and injury costs (55).

2.7.6 Washington

Approximately 25 miles of test sites were installed with cable median barriers for median widths ranging between 40 and 82 feet. The annual cross-median crash rate for these sites decreased from 16 crashes per year before installation to 3.8 crashes per year afterwards. The rate of disabling and fatal crashes decreased from 3.8 crashes per year to 0.33 crashes per year, with no fatal crashes reported since the installation of cable median barrier. Installation of the cable barrier cost $44,000 per mile with an annual maintenance cost of $2,570 per mile. Although the overall median crash rate doubled from 49 crashes per year before installation to 100 crashes per year afterwards, the decrease in fatal and disabling injury crashes resulted in a net benefit of $420,000 annually per mile (56). Cable median barrier was found to be the most cost effective system, with a benefit cost ratio ranging from 2.7 to 5.5 for median widths up to 50 feet; however, beam guardrail and concrete median barriers were also found to be cost effective for median widths up to 50 feet (57).

2.7.7 Florida

The Florida Department of Transportation (FDOT) requires median barriers be installed on all highways with a median width less than 64 feet. A five year review of cross-median crashes from 1995 to 1999 conducted by FDOT (58) showed that 19 percent of crashes involved, or were suspected to involve alcohol; two percent involved a truck as the crossing vehicle; 78 percent of crashes occurred when the crossing vehicle's speed was within five mph of the posted speed limit; 75 percent of crashes occurred in "good" weather conditions, with 83 percent of these crashes being the result of driver error and avoidance maneuvers; 62 percent and 82 percent of all cross-median crashes occurred within one-half mile and one mile of interchange ramp termini, respectively.

2.7.8 Maryland

The Maryland State Highway Administration determines the need for a median barrier based on median width and AADT. On high speed highways, defined as highways with a design speed greater than 45 mph (14), median barriers are required for: median widths up to 30 feet for all traffic volumes; median widths up to 50 feet with an AADT of at least 40,000 vpd; and median widths up to 75 feet with traffic volumes greater than 80,000 AADT.

2.7.9 Pennsylvania

A number of states, including Pennsylvania and Texas, have recently sponsored studies to review their guidelines for the application of median safety improvements. In both cases, a benefit/cost (B/C) analysis procedure was used to determine at what median width and AADT combination is the installation of median barrier economically beneficial.

Donnell and Mason (5) investigated current median barrier warrant practices in the state of Pennsylvania using a safety and economic evaluation of cross-median and median barrier crashes. The researchers found that the AASHTO guidelines currently adopted by the state did not accurately reflect "increasing traffic volume trends or the improved performance capabilities of the modern vehicle." Similar to Noyce and McKendry (4), Donnell and Mason found that there were a number of divided interstate highways that experienced a high frequency of cross-median crashes but did not warrant evaluation for median barrier under the current AASHTO guidelines.

Alternative median barrier warrant criteria were developed using crash prediction and severity models developed by the researchers from geometric and cross-section data and crash records collected on Interstate highways in Pennsylvania for the five year period between 1994 and 1998. For the study period, 138 cross-median crashes, defined as a crash in which a vehicle "leaves the roadway to the left, enters and crosses the median, and collides with a vehicle traveling in the opposite direction", were identified along with 4,416 median barrier crashes. Revised warrants for the implementation of concrete median barrier and W-Beam guardrail median barrier are shown in Figure 9 and Figure 10, respectively.

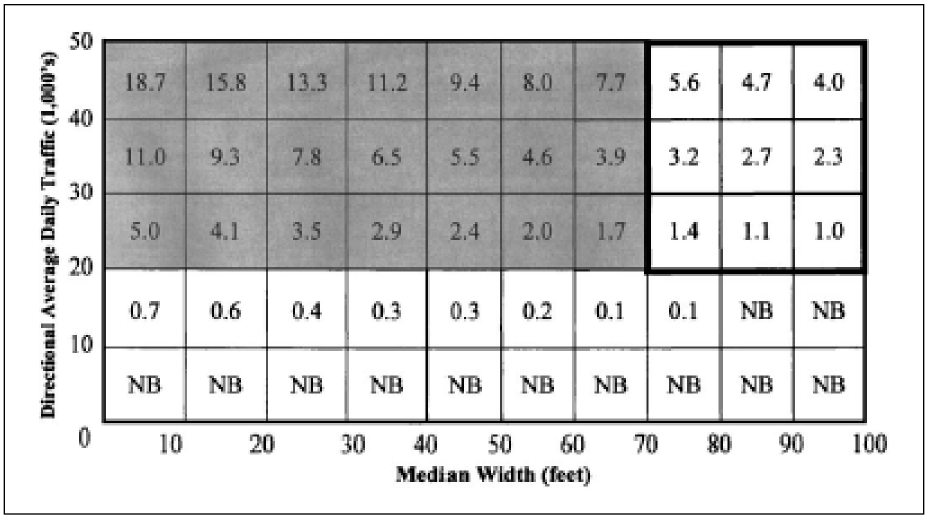


Figure 9 Pennsylvania Concrete Median Barrier Placement Guidelines (5)

Notes: Values represent the benefit/cost ratio of installing barrier along the centre of the median.
NB = No calculated benefits.

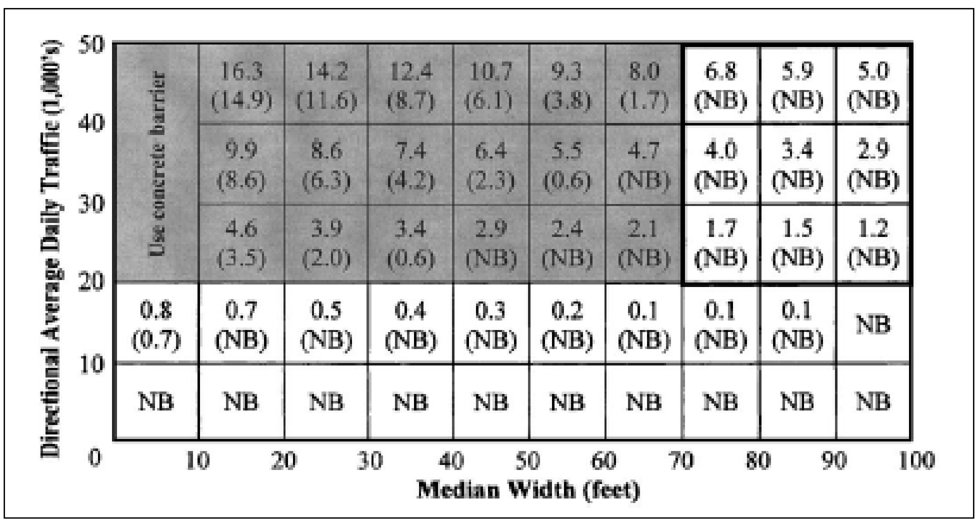


Figure 10 Pennsylvania W-Beam Guardrail Median Barrier Placement Guidelines (5)

Notes:
Values represent the benefit/cost ratio of installing barrier along the centre of the median.
Values in parentheses represent the benefit/cost ratio of installing barrier offset 4 feet from the travel lane.
NB = No calculated benefits.

The number within each cell in Figure 9 and Figure 10 is the benefit/cost (B/C) ratio for each condition based on the assumptions of a 20-year service life analysis, benefits and costs as summarized in Table 12, a negligible salvage value, and an interest rate ranging between 3.20 and 5.40 percent. The expected number of cross-median crashes of each severity was determined by multiplying the predicted probability of each severity category by the expected crash frequency for both cross-median and median barrier crashes. The shaded portion of each warrant represents scenarios where the barrier system was found to be economically beneficial in preventing cross-median crashes, that is, where the benefit of the barrier is two to 19 times the cost of implementation. The outlined portion of each warrant represents scenarios where, although found to be economically beneficial, additional evaluation based on a crash rate analysis is recommended due to the reduction in exposure and low crash rate observed at highway sections with median widths greater than 70 feet.

Table 12 Benefits and Costs Considered in the Pennsylvania B/C Analysis (5)

Benefit/Cost Source	Concrete Barrier	W-Beam Guardrail
Median Barrier Benefits		
Reduction in Crash Severity Reduction in Crash Frequency	PDO = $2,350/crash Injury = $627,000/crash Fatal = $3,060,000/crash	PDO = $2,350/crash Injury = $627,000/crash Fatal = $3,060,000/crash
Median Barrier Costs		
Site Preparation	$0 – 50,000/mi	$0 – 50,000/mile
Unit Cost	$35/linear foot	$24/linear foot
Installation	Included above	Included above
User Costs and Delays	$1,500/day/mi (low volume) - $16,000/day/mi (high volume) Included in Site Preparation	$1,500/day/mi (low volume) - $16,000/day/mi (high volume) Included in Site Preparation
Maintenance	Negligible	$5/linear foot

Two approaches for implementing the revised median barrier warrants were recommended. The first involved fitting median barrier at all highway sections that meet the warrants. This method would deliver immediate safety advantages but would likely prove cost prohibitive. An alternative procedure was also presented to prioritize the implementation of median barrier at warranted highway segments. The procedure, although not described in detail, would consider crash frequency, crash severity, median width, traffic volumes, posted speed limits, and other geometric elements in the development of a severity index for each warranted highway segment. A B/C assessment would then be conducted using the severity index to determine the worth of installing median barrier at each location and a prioritized list of implementation sites developed (5).

2.7.10 Texas

Research conducted by Bligh et al. at the Texas Transportation Institute also employed a B/C analysis to develop improved median barrier guidelines for application in the Texas Department of Transportation (TxDOT) *Roadway Design Manual* (59). Crash frequency and severity prediction models were developed using a Poisson model applied under a full Bayes approach from 3,672 median-related crashes identified in the Dallas-Fort Worth area between 1998 and 1999. These crashes included 346 cross-median crashes, defined as crashes in which a vehicle crossed the median, entered the opposing travel lanes, and collided with a vehicle in the opposing travel lanes. A B/C analysis was then conducted using the frequency and severity prediction models, information provided by TxDOT and summarized in Table 13 regarding crash costs, and the cost and analysis assumptions presented in Table 14 for each combination of AADT and median width. A sensitivity analysis was also conducted to determine the effects of changes in the assumptions adopted in the analysis. The results of the sensitivity analysis were reflected in the revised guidelines (59).

Table 13 Summary of Texas Crash Cost Assumptions (59)

Crash Severity Type	Estimated Crash Costs for All State Highways (2000 $)[1,2]	Number of Persons Involved with the Maximum Severity Incurred per Crash 1998-1999[3]			Adjusted Crash Costs (2000 $)[4]		
		No Median Barrier		With Median Barrier	No Median Barrier		With Median Barrier
		Cross Median Crashes	Other Median-Related Crashes	All Median Related Crashes	Cross Median Crashes	Other Median-Related Crashes	All Median Related Crashes
Fatal (K)	1,191, 887	1.43	1.12	1.17	1,482,086	1,160,794	1,212,615
Incapacitating (A)	69,199	1.57	1.32	1.21	82,933	69,727	63,917
Non-incapacitating (B)	25,218	1.79	1.26	1.21	32,475	22,859	21,952
Possible Injury (C)	14,198	1.88	1.36	1.36	17,001	12,299	12,299
Property Damage Only (O)	1,969	2.18	1.10	1.13	2,411	1,217	1,250

Notes:

[1] The cost was estimated by TxDOT Traffic Operations Division, based on the National Safety Council's estimate of societal cost (not the comprehensive cost) for crashes which occurred on all state-maintained highways. The estimated crash costs will roughly triple if comprehensive costs are used.

[2] 2000 $ = Value in year 2000 dollars.

[3] Obtained from Texas traffic crash records. For example, on average, 1.15 persons were killed per crash in all state system fatal crashes; while 1.43 persons were killed in a fatal cross-median crash. For PDO crashes, 1.78 vehicles were involved in each PDO crash for all state highways; while 1.1 vehicles were involved, on average, in a PDO median-related (non-cross-median) crash with no longitudinal barrier present.

[4] These adjusted costs were developed by the authors of this study. For example, the adjusted cost for a cross-median fatal crash is calculated as $1,191,887*(1.43/1.15)=$1,482,086 and as $69,199*(1.57/1.31)=$82,933 for cross-median incapacitating crashes.

Table 14 Summary of Texas B/C Analysis Assumptions (59)

	Mean B/C Estimate		Low B/C Estimate	
	Concrete Barrier	Cable Barrier (High Tension)	Concrete Barrier	Cable Barrier (High Tension)
Project Life (years)	20	20	20	20
Interest Rate (%)	5	5	5	5
AADT Annual Growth Rate (%)	3	3	1	1
Estimate of Cross-Median Crash Frequency	Mean	Mean	2.5^{th} Percentile	2.5^{th} Percentile
Installation Cost per Mile[1] ($1,000)	(190+370)/2	(65+100)/2	370	100
Site Preparation and Grading Cost[1] ($1,000)	(Median Width in feet – 20)*100/80	0	(Median Width in feet – 20)*100/80	0
Barrier Breaching Crash Rate as a Percentage of Estimated Barrier Hits[2] or Crashes	0.3% of estimated number of reported crashes	3% of estimated number of barrier-hits[2]	0.3% of estimated number of reported crashes	3% of estimated number of barrier-hits[2]
Repair Cost per Hit[2] ($1,000)	0	(0.35+0.70)/2	0	0.70
Salvage Value at End of Project Life	0	0	0	0

Notes:

[1] It is assumed that barriers are placed near the center of the median. Installation costs include material, labor, and equipment costs. The site preparation cost for concrete barriers is assumed to be a linear function of median width (excluding existing shoulder width of 20 ft), with an estimate of $100,000 at a median width of 100 ft. This assumes a relatively mild slope of 6:1 or flatter without a lot of earthwork to flatten the slope to a 10:1. These costs do not include user costs due to travel delay, and traffic control and engineering costs during constructions.

[2] To estimate the number of hits on cable barriers that require repair, the estimated number of hit-barrier crashes from the model is multiplied by a factor of two to account for unreported crashes and crashes that do not meet the reporting and coding threshold. Since July 1, 1995, Texas DPS stopped coding those PDO crashes for which vehicles did not have to be towed away.

A revised median barrier guideline that relates median width and AADT was developed by Bligh et al. and is presented on Figure 11. The guidelines are split into four distinct "priority zones" depending on the magnitude of the B/C ratio. These zones range from Zone 4, which includes scenarios with the lowest B/C ratio and in which median barrier is not generally considered, through to Zone 1, in which a median barrier is normally required and provides the highest B/C ratio. Within the same figure, Bligh et al. also developed median barrier crash rate guidelines by calculating the mean expected number of cross-median crashes for each of the B/C priority zones from the cross-median frequency model (59).

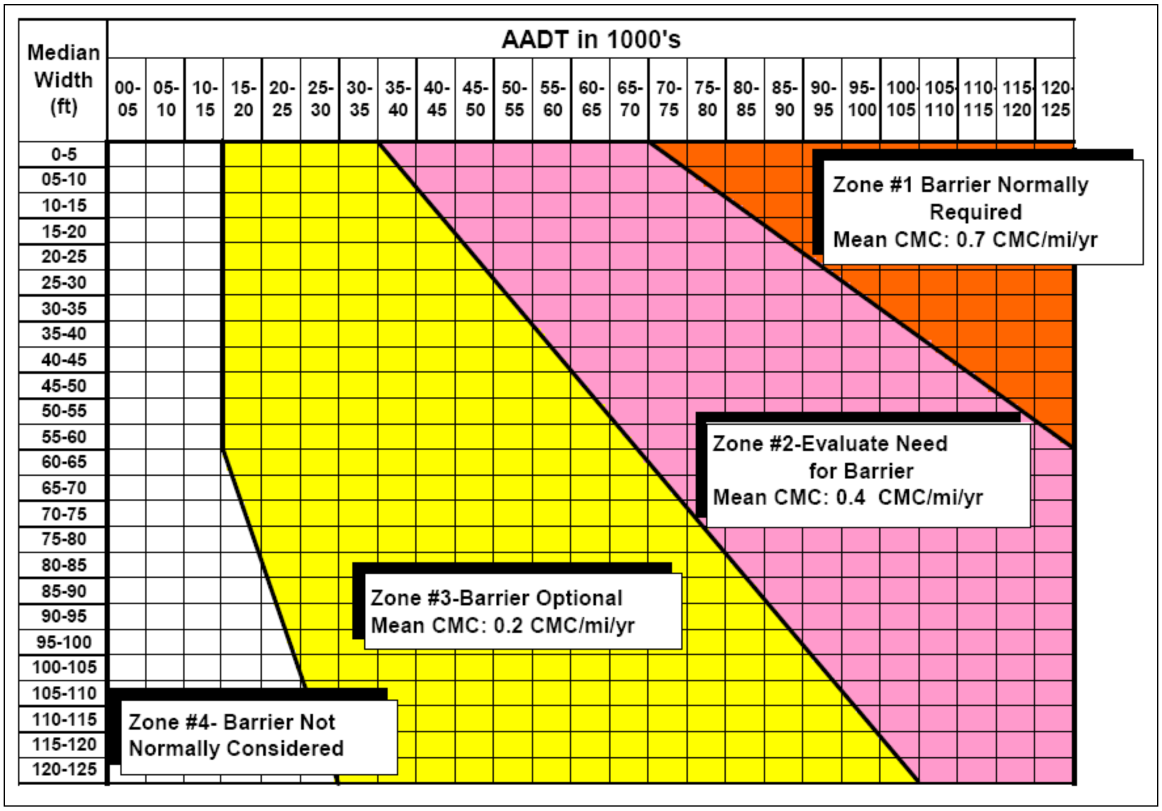


Figure 11 Recommended Guidelines for Installing Median Barrier on Texas Interstates and Freeways (59)

Practitioners can apply the guidelines by determining the priority zone in which the AADT/median width combination and/or average cross-over crash rate lies. Barriers are normally required for highway segments in which the AADT/median width combination falls within Zone 1, or if the average crash rate is greater than 0.7 cross-over crashes per mile per year. For AADT/median width combinations falling within Zone 2 or observing a crash rate greater than 0.4 cross-over crashes per mile per year, median barrier is "cost effective and should be considered." Barriers are considered optional for Zone 3 and are not normally considered at all for Zone 4.

In terms of barrier choice, the research concludes that high-tensioned cable barriers are "generally more cost-effective than concrete barriers for the range of median widths for which they are applicable." Depending on the deflection standards for the barrier system being considered, it is recommended that the use of high-tensioned cable barriers be limited to median widths greater than 20 feet.

2.7.11 California

A relationship between AADT and median width is one of the primary criteria used by the California Department of Transportation (Caltrans) in determining the need for additional median safety analysis. Figure 12 shows the median width and AADT combinations selected to warrant additional analysis.

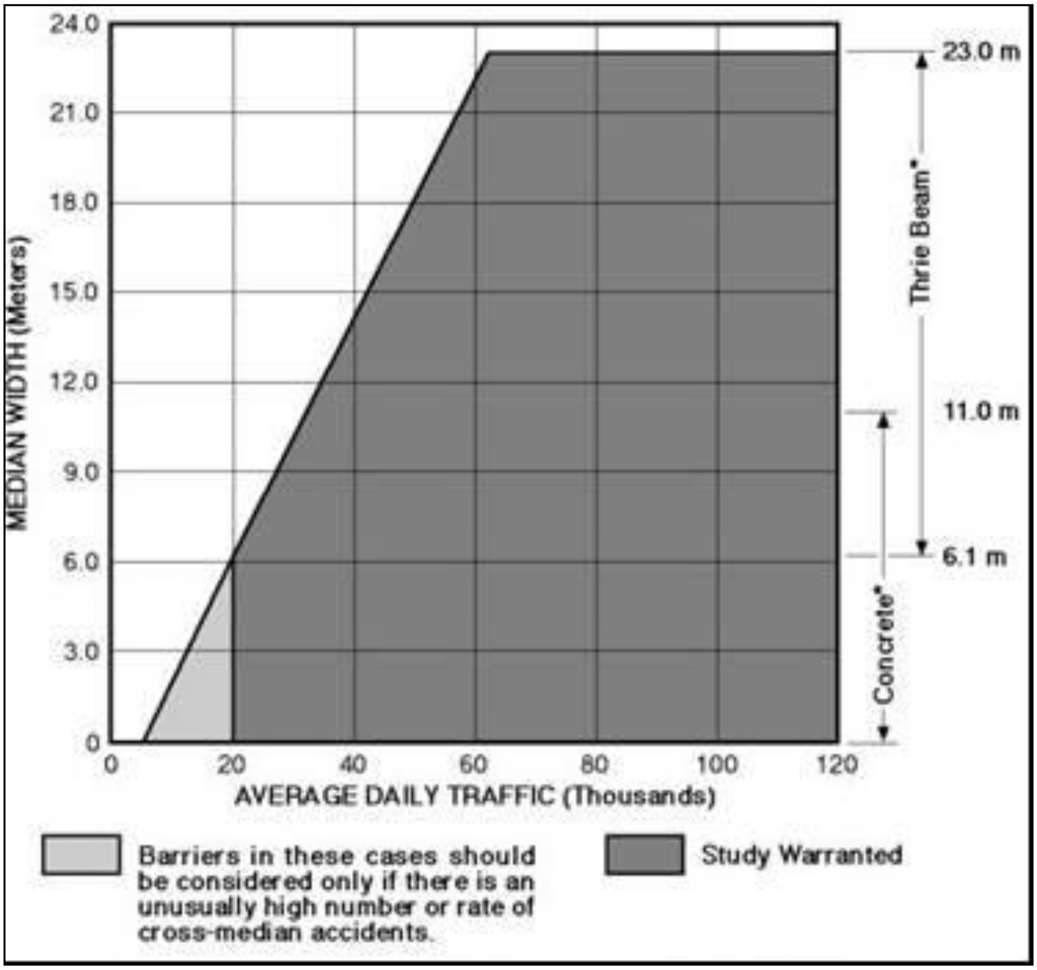


Figure 12 Caltrans Additional Analysis Warrant Guidelines (60)

California also used crash history as a factor in identifying sites requiring additional analysis. In 1978, Caltrans adopted the crash rate warrants of 0.5 cross-median crashes per mile per year and 0.12 fatal cross-median crashes per mile per year, with at least three cross-median crashes over a five year period, to determine sites that warrant additional analysis on the basis of crash history. A cross-median crash in California is defined as a crash in which a vehicle crosses the median and strikes or is struck by a vehicle from the opposite direction. This crash-rate warrant and CMC definition have been adopted as working guidelines by WisDOT.

Both the median width/traffic volume and crash rate warrants were reviewed in 1991 by Seamons and Smith and again in 1997 by Nystrom et al. (60, 61). Seamons and Smith concluded that the median width/traffic volume warrant and the crash rate warrants (identified above) be retained as guidelines for identifying sites requiring additional analysis (60). Sites meeting the warrant with three to four crashes over a five year period "frequently lost their warrants before construction" due to the random nature of crashes. Although it was suggested that the warrant be increased to require five rather than three crashes observed in a five year period, the crash frequency requirement was not changed so as not to "preclude valid projects from being identified and constructed."

Nystrom et al. used a B/C procedure to review the traffic volume/median width and crash rate warrants (61). The study employed cross-median and struck-barrier crash information along with geometric and operational data for divided, multi-lane freeways for the five year period between 1991 and 1995. The B/C analysis employed a human capital approach that incorporated all measurable direct and indirect economic costs associated with a crash and a service life of 20 years. Under this methodology, fatal crashes were valued at $850,000 per crash (in 1997 dollars), injury crashes at $17,200 per crash, and property damage crashes at $3,700 per crash. The cost of installing either concrete or metal beam median barrier was estimated at $270,000 per mile (in 1997 dollars). Nystrom et al. concluded that an economic benefit would result for an "increase in the existing traffic volume/median width guidelines up to a median width of 75 feet (61)." This is reflected in the current warrant presented in Figure 12. However, for median widths greater than 75 feet, no net reduction in fatal crashes was reported with the installation of median barrier, further offset by an increase in the frequency of property damage and injury crashes as a result of the barrier being in place. The crash rate warrant was deemed appropriate. A comparison of the Caltrans and WisDOT median width/traffic volume warrants is presented in Figure 13.

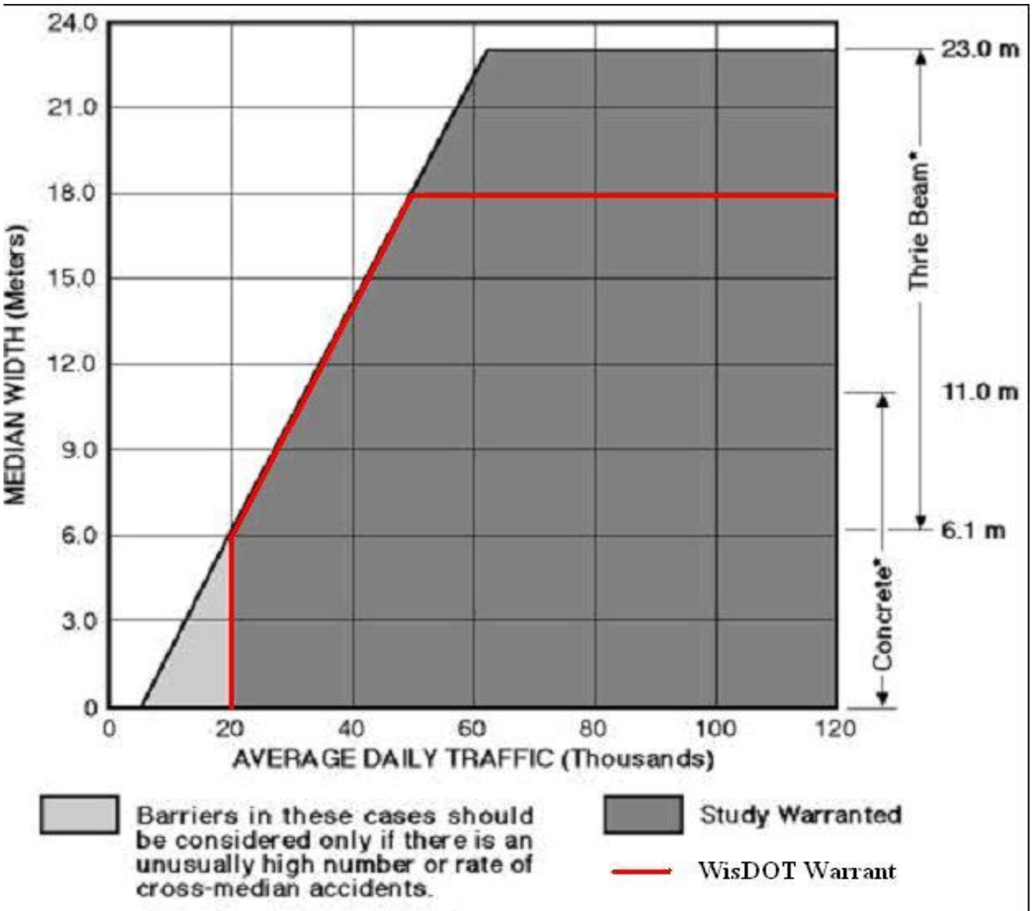


Figure 13 Comparison of Caltrans and WisDOT Warrant Guidelines

3 STUDY DESIGN

3.1 Research Methodology

The research methodology implemented in this study is shown in Figure 14. This study is classified as a regression cross-sectional study as it compares treated and untreated sites using multivariate regression models to limit the effect of confounding factors.

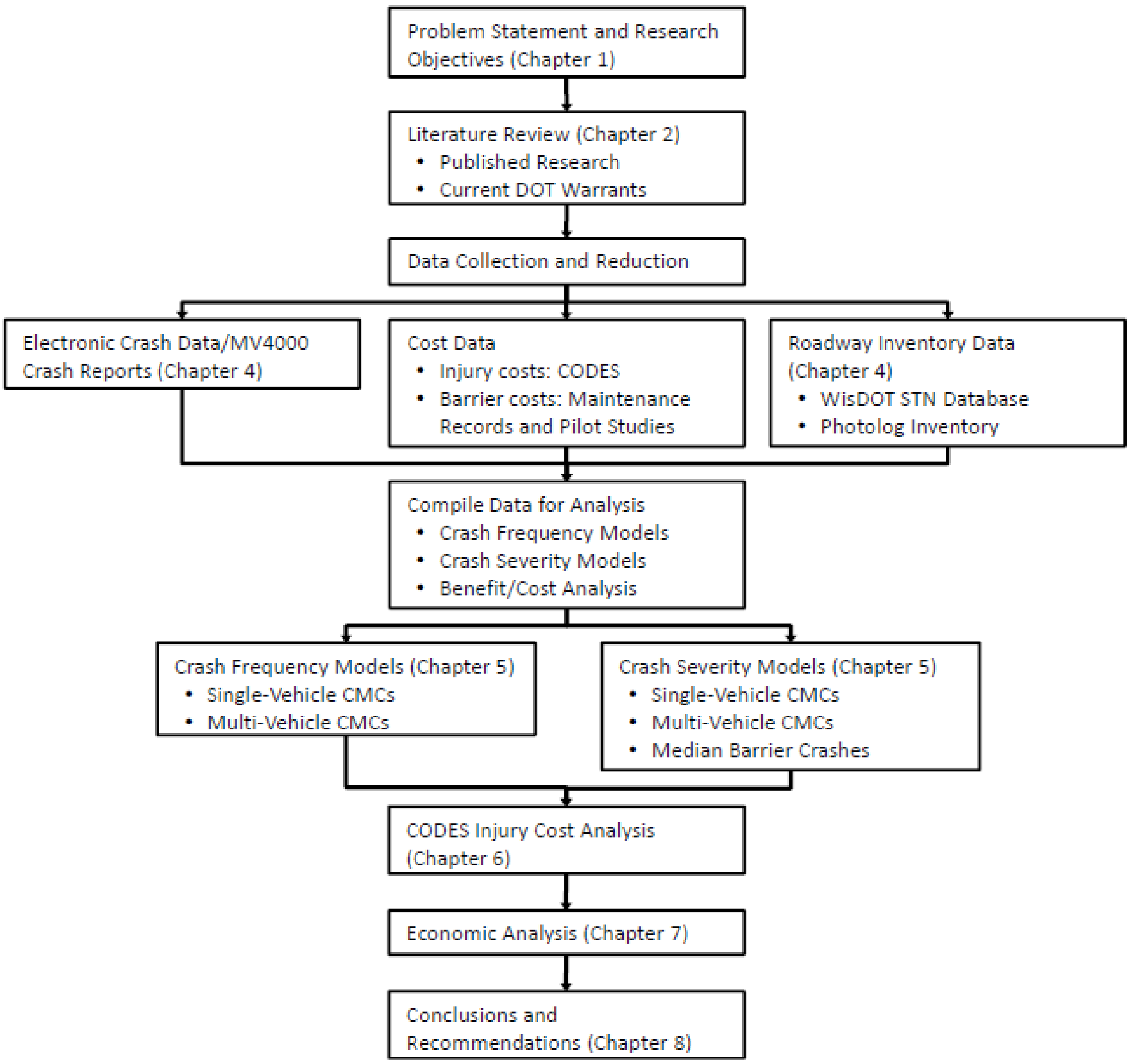


Figure 14 Research Methodology

3.2 Research Tasks

This study effort is composed of the series of tasks described in the following sections.

3.2.1 Task 1: Literature Review

A comprehensive literature review was conducted to identify previous research on median design, cross-median crash analysis, crash injury costs, median barrier types, and current median barrier warrants. This review included both published and unpublished sources. The results of this literature review are documented in Chapter 2.

3.2.2 Task 2: Data Collection

The data collection procedure consisted of assembling data from a variety of sources into a form that could be used to formulate crash prediction models. Crash record data for CMC and barrier crashes and roadway characteristic data for all Wisconsin divided highways were collected and assembled. The crash data was queried for 2001-2007 from a statewide crash database maintained by WisDOT according to the single- and multi-vehicle CMC definitions. As the MV4000 crash report form used by police in Wisconsin does not include a field that identifies cross-median crashes, the crash reports for eligible crashes were manually reviewed to indentify CMC crashes and classify them as single- or multi-vehicle. Median barrier crashes were queried based on median barrier being specified as the first or most harmful event from the crash report, then filtered by the location of median barrier. Crash direction was also reviewed as the procedures for direction on divided highways is somewhat vague and inconsistently applied.

Roadway characteristic data were collected via visual inspection and by the WisDOT roadway inventory database. As not all relevant roadway data were available in existing data sources, a software tool was developed to utilize the WisDOT Photolog dataset. The Photolog, a series of photographs taken along state highways at 1/100th mile increments, was reviewed and the locations of various roadway features were manually recorded. This data was compiled and integrated via GIS with the roadway data available in the WisDOT roadway database.

The crash and roadway data were further transformed to serve and inputs for the crash prediction models. Crash severity modeling uses crashes as a base unit, so the roadway data of each crash was attributed to that crash. Crash frequency modeling uses roadway segments as a base unit, therefore crashes and roadway characteristics were attributed to each roadway segment for that analysis. The output of this data collection effort is crash and roadway data in the forms needed to apply the crash prediction models. These processes are described in greater detail in Chapter 4.

3.2.3 Task 3: Crash Prediction Modeling

Crash prediction models were constructed to describe the interactions between cross-median crash occurrence and roadway geometry. Crash occurrence includes both the frequency of crashes and the severity of those crashes. Similar models were constructed for median barrier crashes to predict the impacts on barrier installation on crash occurrence. The resulting crash prediction models can be used to perform median barrier cost effectiveness evaluations for roadway segments based on their roadway characteristics.

Crash severity modeling seeks to describe the probability of a crash resulting in each crash severity level based on geometric factors at the crash location. Traffic crash severities are ordinal in nature with property-damage only, injury, and fatal listed in ascending severity order. As a result, ordinal logistic regression models were used to fit roadway characteristics to crash severity.

Crash frequency modeling seeks to predict the number of crashes that will occur on a roadway segment based on the geometric features of that segment. As roadway segments form the base unit of this analysis, the study roadways must first be divided into sections that are then fit to the model. These roadway segments were then fit to a regression model to formulate a crash frequency prediction model. Crash data are often overdispersed meaning that the variance exceeds the mean; as a result, the negative binominal model was selected for this modeling effort.

The crash prediction modeling process and results are discussed in greater detail in Chapter 5.

3.2.4 Task 4: Injury and Median Barrier Cost Analysis

Crash injury costs were developed for CMC and barrier crashes to monetize the estimated crashes from the crash prediction models to be used in benefit/cost analysis. These costs were extracted from the CODES database provided by the Center for Health Systems Research and Analysis (CHSRA) at the University of Wisconsin-Madison. The analysis yielded average costs by severity for single- and multi-vehicle CMCS and barrier crashes based on injury diagnostic codes, adjusted for Wisconsin. These divisions capture the varied number and types of injuries sustained in each type of crash and each severity level. This injury cost analysis is described in detail in Chapter 6.

Median barrier costs were collected to be weighed against the monetized crash benefits of installing median barrier. Two primary types of median barrier are commonly applied in Wisconsin: concrete (or “jersey”) barrier and cable barrier. In general, concrete barrier is applied on roadway segments with narrow, paved medians, while cable barrier is constructed in wider, grass medians. WisDOT provided a concrete barrier installation cost estimate based on five recent barrier projects of $60 per linear foot, or $316,800 per mile. WisDOT noted that concrete costs vary by project conditions, such as the grading, drainage, length of barrier, and transitions to other barrier. Maintenance costs for concrete barrier are negligible.

Cable barrier costs were extracted from a preliminary evaluation of pilot projects in Wisconsin by the Wisconsin Traffic Operations and Safety (TOPS) Laboratory. This study calculated installation and maintenance costs for three types of high-tension cable barrier. Annualized installation costs ranged from $5,500 to $7,400 per year per mile and maintenance costs ranged from $1,100 to $2,000 per year per mile.

3.2.5 Task 5: Economic Analysis

Economic Analysis was performed and benefit-cost ratios computed for installation of cable barriers. Benefit cost ratios were computed based on net present value of benefits and costs. Benefits included the net reduction in crash costs considering the decrease in CMC and increase in cable barrier crashes. Costs included the installation and maintenance costs of cable barrier through the life cycle. Economic analysis is described in detail in Chapter 7.

3.2.6 Task 6: Results Documentation

At the conclusion of Tasks 1-4, a detailed description of the procedure, data, and results were assembled in to a report. The results of Tasks 3 and 4 can be used as a basis for the development of a median barrier warrant based on the benefits and costs of installing median barrier based on roadway geometry. The conclusions of this study and recommendations for future work are included in Chapter 8.

4 DATA COLLECTION

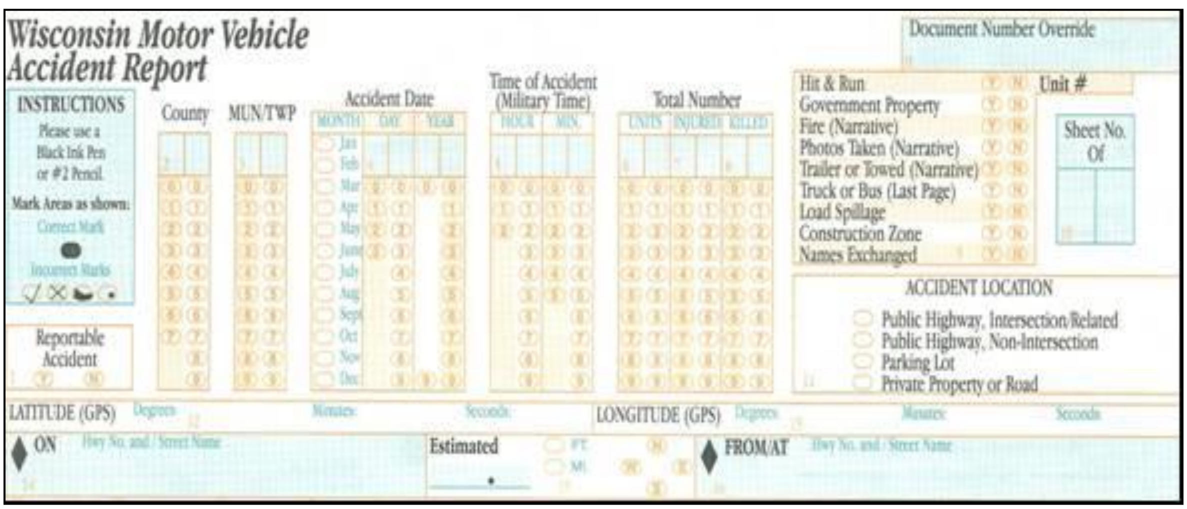
The data collection procedure described below consisted of assembling data from a variety of sources into a form that could be used to formulate crash prediction models. The two main data types are as follows:

- Crash data for CMC and median barrier crashes
- Roadway characteristics data for all Wisconsin divided highways

These data and their acquisition are described in the following sections.

4.1 Crash Database

In Wisconsin, County Sheriffs, local Police, or State Patrol troopers report crashes using the Wisconsin Motor Vehicle Accident Report (WMVAR), often referred to as MV4000, which is then scanned and archived into searchable databases that include: location and time of day, drivers and vehicles involved, weather and road conditions, presence of alcohol, and type of accident, and other relevant factors. Figure 15 through Figure 17 display the relevant sections of the WMVAR that record these data.


Wisconsin Motor Vehicle Accident Report

Document Number Override

INSTRUCTIONS
Please use a Black Ink Pen or #2 Pencil.
Mark Areas as shown:
Correct Mark
Incorrect Marks

Reportable Accident

County

MUN/TWP

Accident Date
MONTH DAY YEAR
Jan Feb Mar Apr May June July Aug Sept Oct Nov Dec

Time of Accident (Military Time)
HOUR MIN

Total Number
UNITS INJURED KILLED

Hit & Run
Government Property
Fire (Narrative)
Photos Taken (Narrative)
Trailer or Towed (Narrative)
Truck or Bus (Last Page)
Load Spillage
Construction Zone
Names Exchanged

Unit #

Sheet No. Of

ACCIDENT LOCATION
Public Highway, Intersection Related
Public Highway, Non-Intersection
Parking Lot
Private Property or Road

LATITUDE (GPS) Degrees Minutes Seconds
LONGITUDE (GPS) Degrees Minutes Seconds

ON Hwy No. and / Street Name
Estimated FT MI
FROM/AT Hwy No. and / Street Name

Figure 15 WMVAR – Date, Time, and Location Data

ACCESS CONTROL 112
1. No Control (Unlimited Access)
2. Full Control (Only Ramp Entry/Exit)
3. Partial Control

TRAFFIC WAY 115
1. Not Physically Divided (2-Way Traffic)
2. Divided Highway, Median Strip, without Traffic Barrier
3. Divided Highway, Median Strip, with Traffic Barrier
4. One-Way Traffic
5. Parking Lot or Private Property

ROAD TERRAIN 113

Part A
1. Straight
2. Curve

Part B
3. Level/Flat
4. Hill

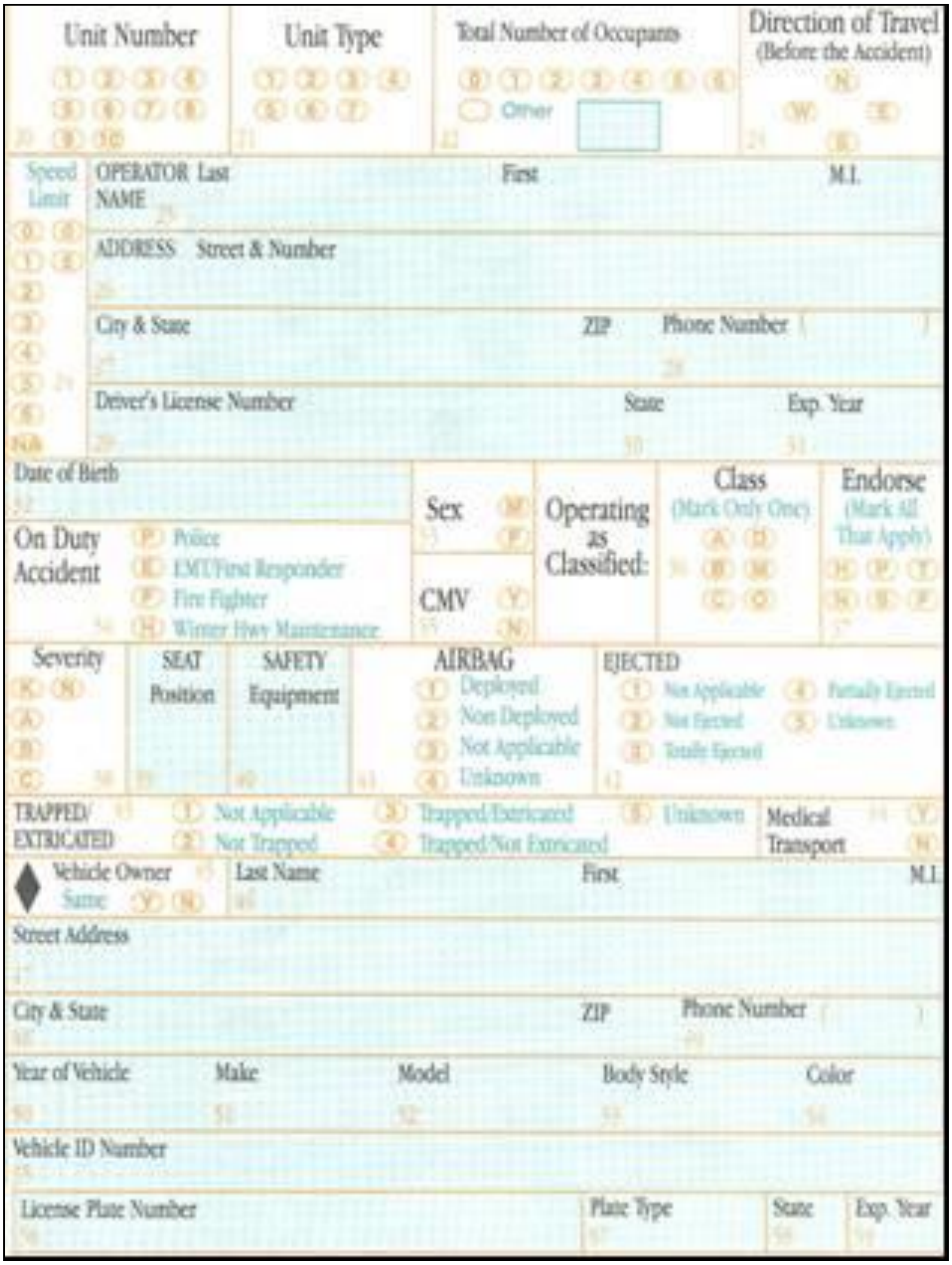
ROAD SURFACE CONDITION 116
1. Dry
2. Wet
3. Snow/Slush
4. Ice
5. Sand, Mud, Dirt, Oil
6. Other
7. Unknown

LIGHT CONDITION 114
1. Daylight
2. Dark—Not Lighted
3. Dark—Lighted
4. Dawn
5. Dusk
6. Unknown

WEATHER 118
1. Clear
2. Cloudy
3. Rain
4. Snow
5. Fog, Smog, Smoke
6. Sleet, Hail (Freezing Rain or Drizzle)
7. Blowing Sand, Soil, Dirt, Snow
8. Severe Crosswinds
9. Other
10. Unknown

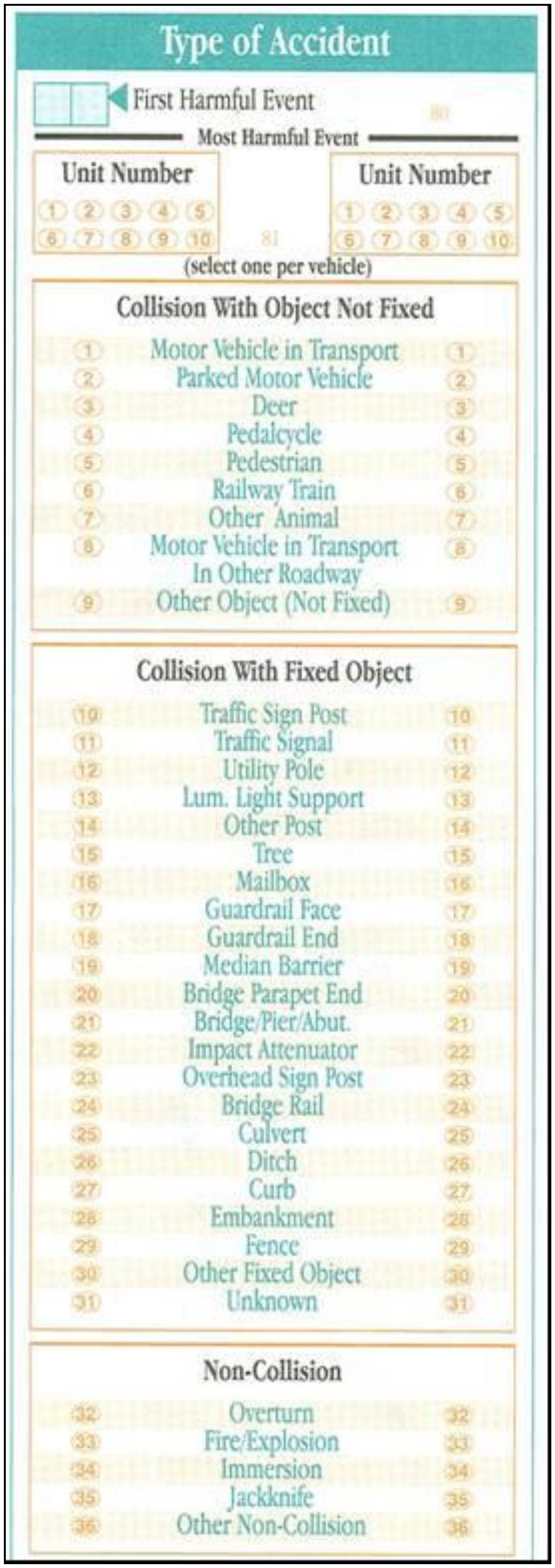
RELATION TO ROADWAY 117
1. On Roadway
2. Parking Lot or Private Property
3. Shoulder (Other Than Shoulder within Median or Gore)
4. Median (Other Than Median within Gore)
5. Outside Shoulder—Left
6. Outside Shoulder—Right
7. Off Roadway—Location Unknown
8. Gore (Area between Ramp & Highway)
9. On Ramp
10. Unknown

Figure 16 WMVAR – Weather and Road Conditions Data



Unit Number
Unit Type
Total Number of Occupants
Other
Direction of Travel (Before the Accident)
Speed Limit
OPERATOR Last NAME
First
M.I.
ADDRESS Street & Number
City & State
ZIP
Phone Number
Driver's License Number
State
Exp. Year
Date of Birth
Sex
Operating as Classified:
Class (Mark Only One)
Endorse (Mark All That Apply)
On Duty Accident
Police
EMT/First Responder
Fire Fighter
Winter Hwy Maintenance
CMV
Severity
SEAT Position
SAFETY Equipment
AIRBAG
Deployed
Non Deployed
Not Applicable
Unknown
EJECTED
Not Applicable
Not Ejected
Totally Ejected
Partially Ejected
Unknown
TRAPPED/ EXTRICATED
Not Applicable
Not Trapped
Trapped/Extricated
Trapped/Not Extricated
Unknown
Medical Transport
Vehicle Owner Same
Last Name
First
M.I.
Street Address
City & State
ZIP
Phone Number
Year of Vehicle
Make
Model
Body Style
Color
Vehicle ID Number
License Plate Number
Plate Type
State
Exp. Year

Figure 17 WMVAR – Driver and Vehicle Data



Type of Accident

First Harmful Event

Most Harmful Event

Unit Number		Unit Number
1 2 3 4 5		1 2 3 4 5
6 7 8 9 10		6 7 8 9 10

(select one per vehicle)

Collision With Object Not Fixed

1	Motor Vehicle in Transport	1
2	Parked Motor Vehicle	2
3	Deer	3
4	Pedalcycle	4
5	Pedestrian	5
6	Railway Train	6
7	Other Animal	7
8	Motor Vehicle in Transport In Other Roadway	8
9	Other Object (Not Fixed)	9

Collision With Fixed Object

10	Traffic Sign Post	10
11	Traffic Signal	11
12	Utility Pole	12
13	Lum. Light Support	13
14	Other Post	14
15	Tree	15
16	Mailbox	16
17	Guardrail Face	17
18	Guardrail End	18
19	Median Barrier	19
20	Bridge Parapet End	20
21	Bridge/Pier/Abut.	21
22	Impact Attenuator	22
23	Overhead Sign Post	23
24	Bridge Rail	24
25	Culvert	25
26	Ditch	26
27	Curb	27
28	Embankment	28
29	Fence	29
30	Other Fixed Object	30
31	Unknown	31

Non-Collision

32	Overturn	32
33	Fire/Explosion	33
34	Immersion	34
35	Jackknife	35
36	Other Non-Collision	36

Figure 18 WMVAR – Type of Crash

The accident field of the WMVAR, displayed in Figure 18, divides crashes into three categories: collision with object not fixed, collision with fixed object, and non-collision, with various sub-categories. The form does not include a field to explicitly enter crashes in which the vehicle enters or crosses the median of a divided highway. Collision with a median barrier can be indicated as the first harmful event and/or the most harmful event.

With the proliferation of computer use by police officers, an increasing number of crash reports are filled out electronically. These reports utilize the same format as the MV4000 paper reports.

WisDOT maintains a tabular database of all the fields of the MV4000 report for all reported crashes in the state. Additionally, crashes that occur on the state trunk network, composed of all Interstates, U.S. highways, and state highways, are mapped to the STN highway map. This database was queried to identify cross-median and median barrier crashes in Wisconsin over the study period. These crashes were georeferenced by WisDOT based on crash location data and mapped onto the state highway base map for further analysis.

4.1.1 Cross-Median Crashes

Interstate, expressway, and freeway segments with a divided median were selected as examination sites from the state's roadway database. The highways selected are presented in Table 15. Crash reports for the examination sites were gathered for the seven year period from 2001 to 2007. A seven year period was chosen to get comprehensive, normalized results from the most recent years of data available.

Table 15 Wisconsin Highways Reviewed for Cross-Median Crashes

Interstates	39, 43, 90, 94
U.S. Highways	10, 12, 14, 18, 41, 51, 53, 141, 151
WI State Highways	23, 29, 30, 35, 54, 57, 172, 441

The WisDOT crash database was initially queried at each of the selected roadway segments to identify potential cross-median and median entry crashes. Potential cross-median crashes were identified through query of the following topics in the WisDOT crash database:

- Accident Year = 2001 through 2007;
- Traffic Way = "Divided highway, median strip, without traffic barrier";
- Highway = All (Table 15);
- County = Selected based on roadway (Table 15);
- Posted Speed = greater than or equal to 45 mph;
- Traffic Control = All; and

- Driver Action = All.

The associated crash numbers produced a list of crash reports that were relevant to the research and required detailed review of the narrative and diagram. The current version of the MV4000 report provides no entry to highlight a crash involving a vehicle crossing the median. Each of the over 37,000 potential cross-median crash reports identified was reviewed on microfilm or digital file by a researcher to inspect whether or not the crash involved a vehicle that crossed the median on a divided highway. Determination of actual cross-median crashes was made by examining the narrative and pictorial representation written by the reporting police officer on the WMVAR.

The cross-median crashes identified were then further divided between single- and multi-vehicle CMCs. If the vehicle that crossed the median collided with an opposing-direction vehicle, the crash was labeled a multi-vehicle CMC. The remaining crashes were labeled single-vehicle CMCs. Some crashes included a sideswipe or rear end collision with a same-direction vehicle before crossing the median, but these were still labeled single-vehicle CMCs if they did not collide with an opposing-direction vehicle. The characteristics of these CMCs are summarized in

Table 1. A descriptive analysis of these crashes is presented in Chitturi et. al. (6).

4.1.2 Median Barrier Crashes

Unlike cross-median crashes, the MV4000 report does include a field to designate median barrier crashes, as show in Figure 18. As a result, the following detailed query of the crash database was sufficient to identify median barrier related crashes.

- Accident Year = 2001 through 2007;
- Accident Type or Most Harmful Event = "Median Barrier"
- Traffic Way = Not "Divided highway without traffic barrier" or "Not divided";
- Relation to Road = Not "Ramp" or "Right shoulder";
- Posted Speed = greater than or equal to 45 mph;
- Construction Zone = Not "Y".

To further verify that the resulting crashes were median barrier crashes, these crashes were filtered based on a spatial analysis using visual data from the Photolog, described below. All crashes that were located more than 30 meters from a median barrier were removed from the dataset. This filter helped to ensure that the median barrier label from the crash report was in fact a median barrier, designed to prevent vehicles from crossing the median, and not simply a left-side guardrail, designed to protect a roadside object.

Similarly, all median barrier crashes that were located within 30 meters of a bridge were also removed from the dataset. Bridges on divided highways typically include left-side guardrail or concrete barrier primarily to shield vehicles from embankments or bridge piers. As the purpose and nature of these bridge barriers differ from median barriers, crashes occurring near the former type were removed.

In both cases, 30 meters was chosen as the distance threshold to reflect the level of precision of the Photologger tool and GIS accuracy, median width, differences in GIS mapping techniques, and other sources of error. The number of crashes filtered was shown to be sensitive to threshold distances under 30 meters, where small adjustments to threshold distance resulted in substantial differences in the number of crashes. These median barrier crashes are summarized in Table 16.

Table 16 Median Barrier Crash Summary for Wisconsin (2001-2007)

Median Barrier Type	Number of Crashes (%)			
	Fatal	Injury	Property Damage	Total

Concrete	7 (0.2%)	1581 (35.0%)	2923 (64.8%)	**4511 (100%)**
Cable	2 (0.6%)	37 (10.9%)	301 (88.5%)	**340 (100%)**
Guardrail	0 (0.0%)	10 (18.9%)	43 (81.1%)	**53 (100%)**
Total	**9 (0.2%)**	**1628 (33.2%)**	**3267 (66.6%)**	**4904 (100%)**

4.1.3 Crash Direction Adjustment

Highway direction was found to have been inconsistently reported for cross-median crashes. This issue is likely a result of the crossing vehicle typically coming to rest on the opposite side of the roadway from the side the vehicle was originally traveling on. Additionally, for multi-vehicle CMCs, the most severe collision usually occurs on the opposite side of the highway from the original travel direction of the crossing vehicle. As a result, these crashes are associated with both directions of the highway, leading to inconsistent direction reporting. The Wisconsin DOT *Crash Data User Guide* describes the direction field, ONHWYDIR, as the following:

> The primary direction of travel on the "on" highway, used in conjunction with RPNMBR and RPDIS for the total reference point number for a State Trunk Numbered (STN) highway. If the highway is divided, the side of the highway where the crash occurred will be listed. This will always be the cardinal direction unless the highway is divided. (62)

This definition is not clear for CMC crashes where collisions may occur on both sides of the roadway. A manual investigation of the crash reports showed that this field was unreliable for the purposes of this study.

Another relevant field is TRVLDIR[1,2], which provides "the direction of travel of a unit prior to the crash (based on primary road direction)" (62). However, the crossing vehicle is not designated a consistent vehicle number. Additionally, a cardinal direction inconsistent with the reported highway, such as eastbound I-39, which is a north/south highway, was occasionally reported. These direction discrepancies presented a serious issue for frequency modeling as the crashes will be attributed to each highway by direction.

As this study is concerned with the characteristics of the roadway at the location where the crossing vehicle leaves the roadway, a new direction field was created to indicate the original travel direction of the crossing vehicle. Crash reports were manually reviewed to determine the direction for multi-vehicle CMCs due to their complexity with respect to direction. For the 291 multi-vehicle CMCs, the directions were revised for crossing vehicle direction or highway direction consistency for 86 crashes (30 percent).

Single-vehicle CMCs were more consistent in terms of direction, thus only a subset of these crashes were manually investigated. Only one vehicle was involved (TRVLDIR2 was blank) for 991 of the 1,220 crashes (81 percent). For 871 of these 991 crashes (88 percent), ONHWYDIR and TRVLDIR1 agreed. Where the two fields did not agree, observation showed that TRVLDIR1 was the more appropriate field. As a result, the TRVLDIR1 direction was deemed to be reliable for these 991 straightforward crashes. Crash reports were reviewed as necessary.

An additional 197 single-vehicle CMCs (16 percent) involved more than one vehicle and TRVLDIR1 and TRVLDIR2 agreed. This indicated that the two vehicles were heading in the same direction and were involved in a sideswipe or similar collision, which contributed to one vehicle crossing the median. Though these crashes involved more than one vehicle, they are consistent with the "single-vehicle CMC" definition as the crossing vehicle did not collide with an opposing direction vehicle. The agreed travel direction was adopted as the appropriate direction for these 197 crashes.

The remaining 32 single-vehicle CMCs (3 percent) involved more than one vehicle, but TRVLDIR1 and TRVLDIR2 did not agree. The crash reports were manually reviewed to determine the appropriate direction for these crashes, as with multi-vehicle CMCs.

These single-vehicle CMC direction category assumptions were confirmed via crash report spot checks. Of the 1,220 single-vehicle CMCs, the directions were revised for crossing vehicle direction or highway direction consistency for 84 crashes (7 percent).

4.2 Roadway Characteristic Data

To supplement the roadway data available through the MV4000 crash report form and to gather roadway data for all divided highways in Wisconsin, additional data sources were used. The Wisconsin DOT maintains a database of roadway characteristics for all Interstates, US Routes, and State Trunk Highways in the state called the State Trunk Network (STN) database. For data types that were missing or had an insufficient level of detail in the STN database, additional data collection was completed by visual inspection using a purpose-built Photolog tool.

Spatial techniques were implemented to combine the crash data, STN, and Photolog data sources into a complete data set that was applicable to conduct the crash prediction modeling process. The STN and Photolog data collection processes are detailed in the following sections.

4.2.1 STN Database

The Wisconsin DOT maintains the STN database of roadway features which are a cartographic representation of the Interstate, US, and state highway centerlines in Wisconsin. The STN database is associated with the major WisDOT roadway data, such as median width, AADT, and highway crashes. This database was supplied to the research team by WisDOT.

The STN database is primarily oriented for undivided highways, for which the data associated with a segment is typically stored under the "on" direction (the north or east depending on the orientation of the roadway). For divided highways, separate GIS chains are mapped for each direction with data stored under each one. However, the south and west directions are not complete and data for median width was often missing. Where the data associated with these chains were missing, the data were transferred from the corresponding chain in the opposite direction. This method is reliable for this type of data as median width is identical for both directions of a highway at the same location. AADT volume is stored as a total for both roadway directions. To create directional volumes to associate with each highway direction, these volumes were divided by two.

4.2.2 WisDOT Photolog

Not all desired data were available or in a readily useable form in the STN database. Characteristics such as entrance ramps, bridges, and curves create merge conflicts and higher demands on drivers. These elements were promising explanatory factors based on intuition and previous studies (5, 13, 15). However, these characteristics were not available in a form that could be incorporated into GIS.

Therefore, an effort was undertaken to assemble these and other data visually from the Wisconsin DOT Photolog. A software tool, called the Wisconsin Photo Logger, provided the research team with an efficient means to conduct a visual inventory of the missing variables and to precisely identify divided highway and median barrier segments.

The Photolog dataset contained a series of images for various routes along the Wisconsin State Trunk Network (STN) highways every 100th of a mile (16.1 meters). Each image contained location information such as latitude, longitude, mile marker and route identification. The Photo Logger application, which is shown as a screenshot in Figure 19, provided two functionalities.

Figure 19 Wisconsin Photo Logger Screenshot

The first was to display the Photolog images in a continuous manner while traversing a particular highway section. Although displaying the Photolog images continuously might seem like a trivial process, it defined how fast data could be collected and thus how much the labor costs would be for data collection. The Photo Logger application was designed to allow virtual navigation of the roads at variable speeds. It also allowed skipping through sections of the highway in situations where nothing of interest was located along the road.

The second function was to allow the user to create a dataset that contained the location and attributes of road features, as observed in the images, in a GIS compatible format for safety analysis as well as asset management. This was accomplished by providing a user-configurable graphical user interface designed to collect two types of road features, linear- and point-based features. Road features that had a start and end location were defined as linear features, e.g., guardrails and bridges. Point features were defined as features with only a single location, e.g., intersections and median turnarounds. For both types of features, additional attributes were collected; for example, for a guardrail location, end-type information was also entered by the user. The user defined the type, number, and attributes of features to be collected in a configuration file before starting data collection.

The workings of the Wisconsin Photo Logger application could be summarized in a series of steps. First, the user would define a series of parameters and feature types. Second, the user would load a file containing the list of images with location information. Third, the user would navigate a particular road marking the location of road features while the software would assign a roadway element to the corresponding location for the marked feature. Finally, the output from the software would be stored in a plain text file using a comma separated value structure allowing the data to be used on a GIS platform.

Note that since features were logged based on what could be seen on the images, the user had to consider that the position associated with each image corresponded to the position of the camera. In cases where a road feature was observed on a particular image but not on the next one (located in between two images), the user had to select the closest of the two images as the location of that feature. Furthermore, the GPS coordinates were representative of the traveled way; thus, a feature documented as being on the right side would have the same coordinates as of a feature on the left side of the road assuming both appeared on the same image. In such cases, the user was required to input attribute information differentiating such features.

4.2.3 Roadway Characteristic Data Integration

Data collected using the Wisconsin Photo Logger application was imported into a GIS platform based on the GPS coordinate information stored in the Photolog data. However, when the Photolog data were plotted in GIS, it revealed an unexpected issue of spatial mismatch between the Photolog GPS data and GIS base maps. Figure 20(a) and (b) shows the Photolog GPS data points plotted over the United States Geological Survey (USGS) Natural Color Aerial Photography (NAIP) and GIS base maps, respectively, for an interchange at Interstate 39 and US highway 14 in Rock County, Wisconsin (63). It is evident from Figure 20(a) that although the GPS data points match almost exactly the NAIP background, Figure 20(b) shows a clear spatial mismatch with GIS base maps. The problem was further compounded by the fact that the spatial mismatch not only occurred laterally in terms of deviation from the roadway centerline but also linearly where the Photolog GPS points were located either upstream or downstream from their corresponding locations on the GIS base map.

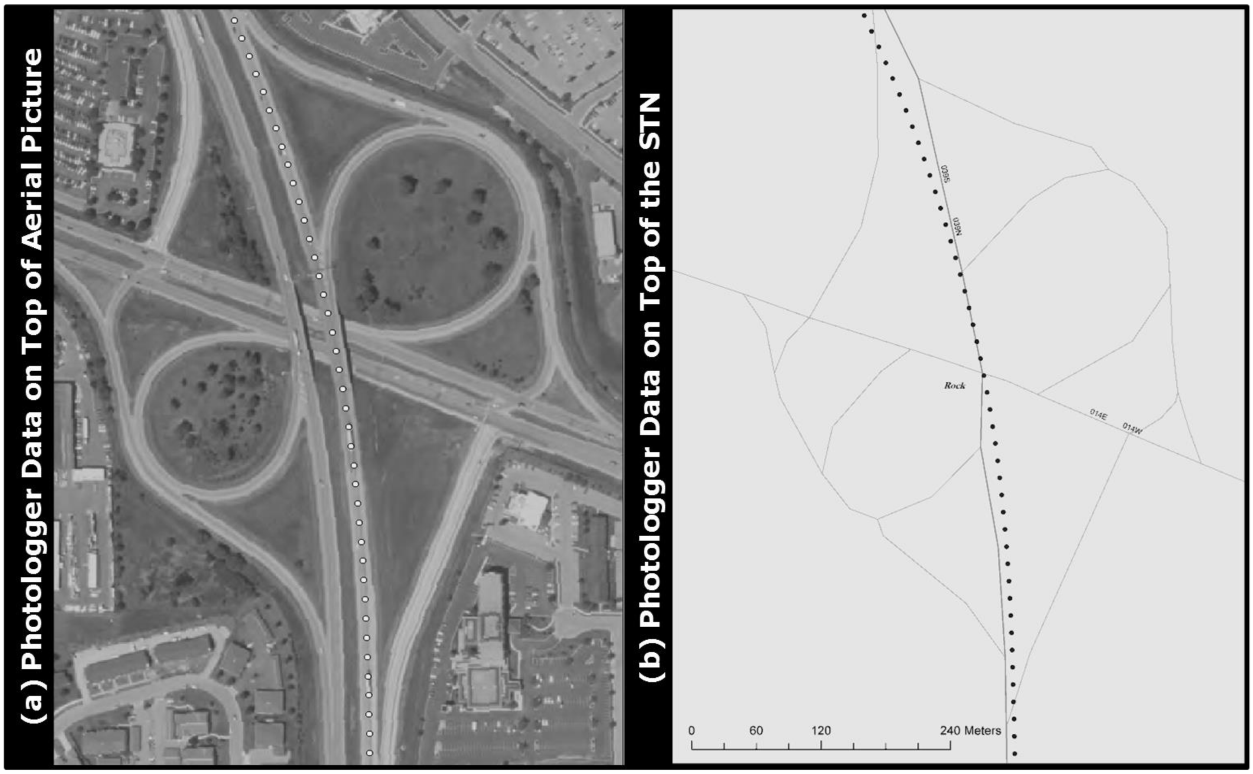


Figure 20 Problem of Spatial Mismatch between Photolog Data Points and WisDOT GIS Dataset

The problem of spatial mismatch can be a consequence of the limitations of the GPS unit used to collect the data, the accuracy of the GIS base maps, or a combination of these factors (64). In the case of this research, it could be deduced from Figure 20 that the problem was most likely due to the GIS base map. However, since most of the existing WisDOT crash and road feature data were associated with the GIS base maps, it was decided to match the Photolog GPS data to the GIS base maps rather than the other way around.

A comprehensive framework was developed to resolve the spatial mismatch problem and integrate the data with current WisDOT GIS using dynamic segmentation and route calibration. GIS base maps were obtained from WisDOT containing the STN base map comprising of the Interstate, US, and State highways in the form of chains, to which data would be matched. The chains correspond to the cartographic representation of the roadway centerline initially derived from 1:100,000 scale Digital Line Graphs (DLG) roadway centerline data built from USGS source maps and updated subsequently over the years. Additional attribute information is stored separately in database tables describing various elements of the WisDOT data.

A simple map-matching procedure was devised which would match the location of the road features to the STN base map using route calibration and dynamic segmentation. The procedure was developed in view of the characteristics of the Photolog and the STN base map datasets which contained distance measurements and route identification making dynamic segmentation possible. Dynamic segmentation is the process of locating linearly referenced data on a map provided that the data or "events" contain a unique identifier representing the name of the "route" on which the events are located and a distance measure representing the location of the events on that route. A "route" is defined as a set of linear features (for example Interstate 39) with a unique identifier and a measurement system stored within it.

The lengths of the routes were obtained from both the Photolog dataset and the database tables associated with the STN base map. Due to differences in the lengths of the routes, a route calibration had to be performed based on a set of calibration points. "Reference Points" along with the start and end points of the routes from the Photolog dataset containing distance measurements were defined as the set of calibration points. "Reference Points" (collected from the Photolog dataset) were defined as point features representing the location of major intersections along the highway, the corresponding location of which could be located on the STN base maps. The process of adjusting the lengths of the STN base map routes based on the distance measurements at calibration points is known as route calibration. The lengths of STN routes were calibrated by interpolating the distances between the calibration points. After calibrating the lengths of the STN base map, the location of an event would be calibrated based on the following equation.

$$De_{STN} = \frac{Dm_{STN}}{Dm_{Photo\log}} \times De_{photo\log} \tag{20}$$

Where:

De_{STN} = Calibrated distance on the STN base map of an event;

Dm_{STN} = Distance measurement in the STN database between calibration points adjoining an event;

$De_{photo\log}$ = Distance measurement in the Photolog dataset for an event;

$Dm_{Photo\log}$ = Distance measurement in the Photolog dataset between calibration points adjoining an event.

Although the differences in route lengths were relatively small, events could be located imprecisely without route calibration. Calibration could be performed using only two points at the start and end points of the route. However, results are more precise if more than two calibration points are used because the difference in lengths of subsections, based on the location of the calibration points, is smaller. The process of calibration would shift the Photolog data points closer to their designated location on the STN base map.

Once the calibration process was complete, the road features collected from the Photolog dataset were matched to the STN base map using dynamic segmentation and converted to a suitable GIS format. An example of the data collected and successfully matched is shown in Figure 21.

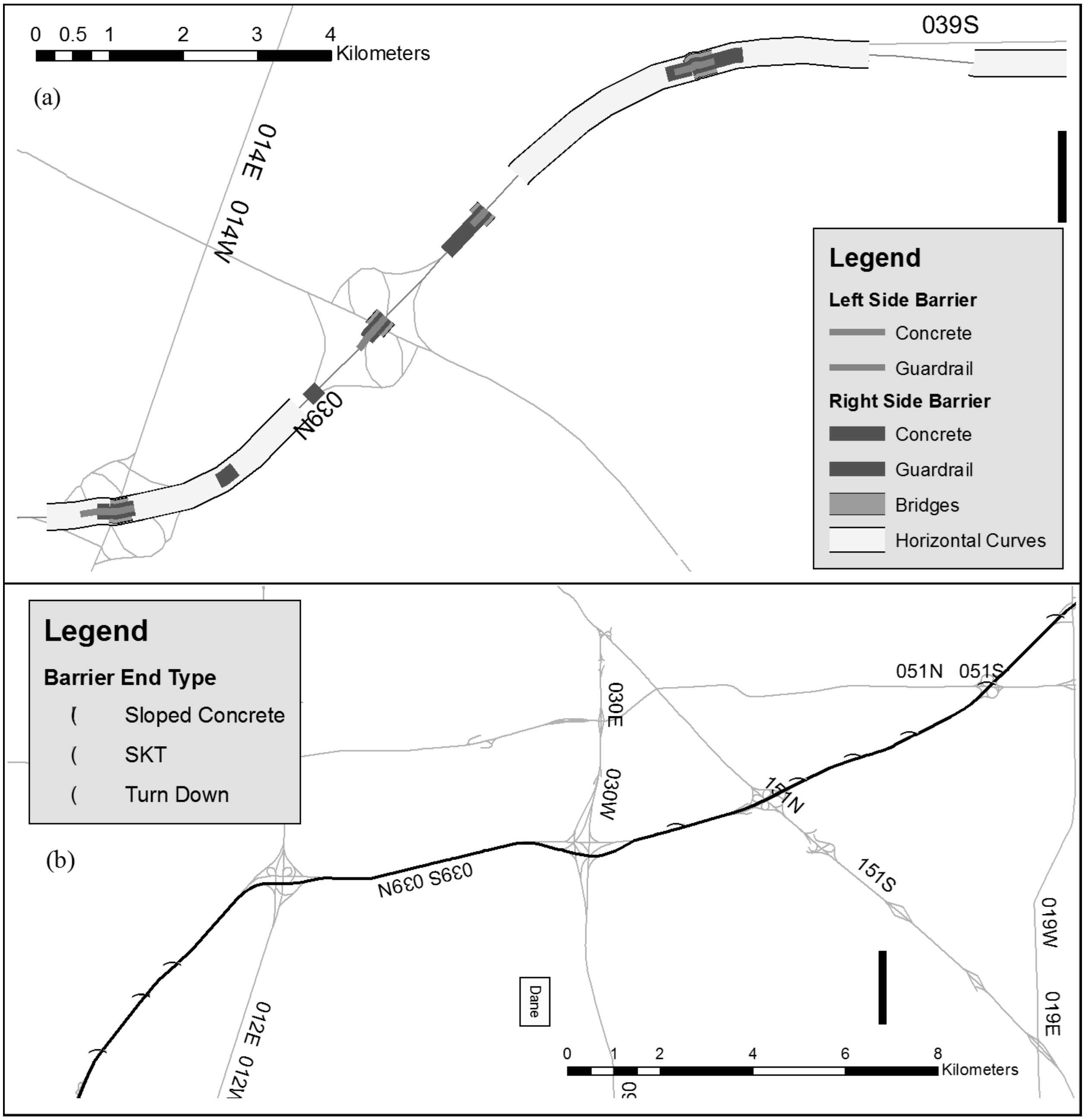


Figure 21 Example Inventory from Integration Framework

A quantitative assessment of the statewide map-matching results was conducted to quantify the level of accuracy achieved in fulfilling the goals of this research. One of the road features collected using the Wisconsin Photo Logger application was the location of bridges as linear features. The objective was to use the location of bridges not only for future research but also to assess the results of data collection and map-matching. Data on bridges were also obtained from WisDOT as part of the GIS base maps where bridges were represented by a point corresponding to the start location (the location of the abutment at the start of the bridge in the cardinal direction of the highway).

A comparison was made between the locations of bridges as collected from the Photolog dataset and matched to GIS base maps (henceforth called the “Photolog bridges”), and the location of corresponding bridges as represented in the bridge dataset received from WisDOT (henceforth called the “STN bridges”). The idea was to calculate the distance, henceforth referred to as the “offset”, between the locations of corresponding STN and Photolog bridges, both of which were located on the same STN base map. If the Photolog bridges were correctly matched to their true location on the STN base map, the resulting offsets would tend to be small, representing higher accuracy while bearing in mind the inherent limitations of the data collection and map-matching procedures as noted in previous sections.

Ideally, the offsets would be zero representing an exact match. However, there were certain limitations that would inevitably affect the results. First, the Photolog dataset consisted of images that were obtained at an interval of 16.1 meters (52.8 ft.). Therefore, in the event of a road feature located in between two images, the location record would be offset by up to 8.05 meters (26.4 ft.). Second, the lengths of the routes were different in the Photolog and GIS base maps, which necessitated the calibration of routes. The accuracy of the route calibration process was dependent upon the differences in the lengths and the number of Reference Points along the routes. Thirdly, there was no knowledge of the accuracy of the WisDOT bridge dataset. The presence of any single or a combination of these limitations would contribute to the occurrence of the observed offsets. Nevertheless, the results provided crucial data necessary to assess the performance of data collection efforts. Under perfect conditions and the Photolog dataset resolution, the expected accuracy would be 8.05 meters (26.4 ft.).

The offsets between the STN and Photolog bridges’ locations were compiled for two of the four major Interstate highways in Wisconsin, Interstate 39 (I-39) and 43 (I-43) in both north and south directions separately, to provide a quantitative assessment of accuracy of the results. Figure 22 and Figure 23 present summary statistics and distribution of individual offsets for I-39 north and southbound and I-43 north and southbound, respectively. The statistics show that the mean offsets for all the highways are in the range of 6.71 (22.01 ft.) and 7.3 (23.95 ft.) meters (represented by solid lines in the figures) which reflects a high level of accuracy considering the abovementioned limitations. The maximum offset in all the routes is 26.73 meters (87.69 ft.). Crucially, the close range of the summary statistics represented consistency in the performance of the data collection and map-matching procedures, which was a critical part of this research. The differences in the lengths of the routes are also shown in Figure 22 and Figure 23.

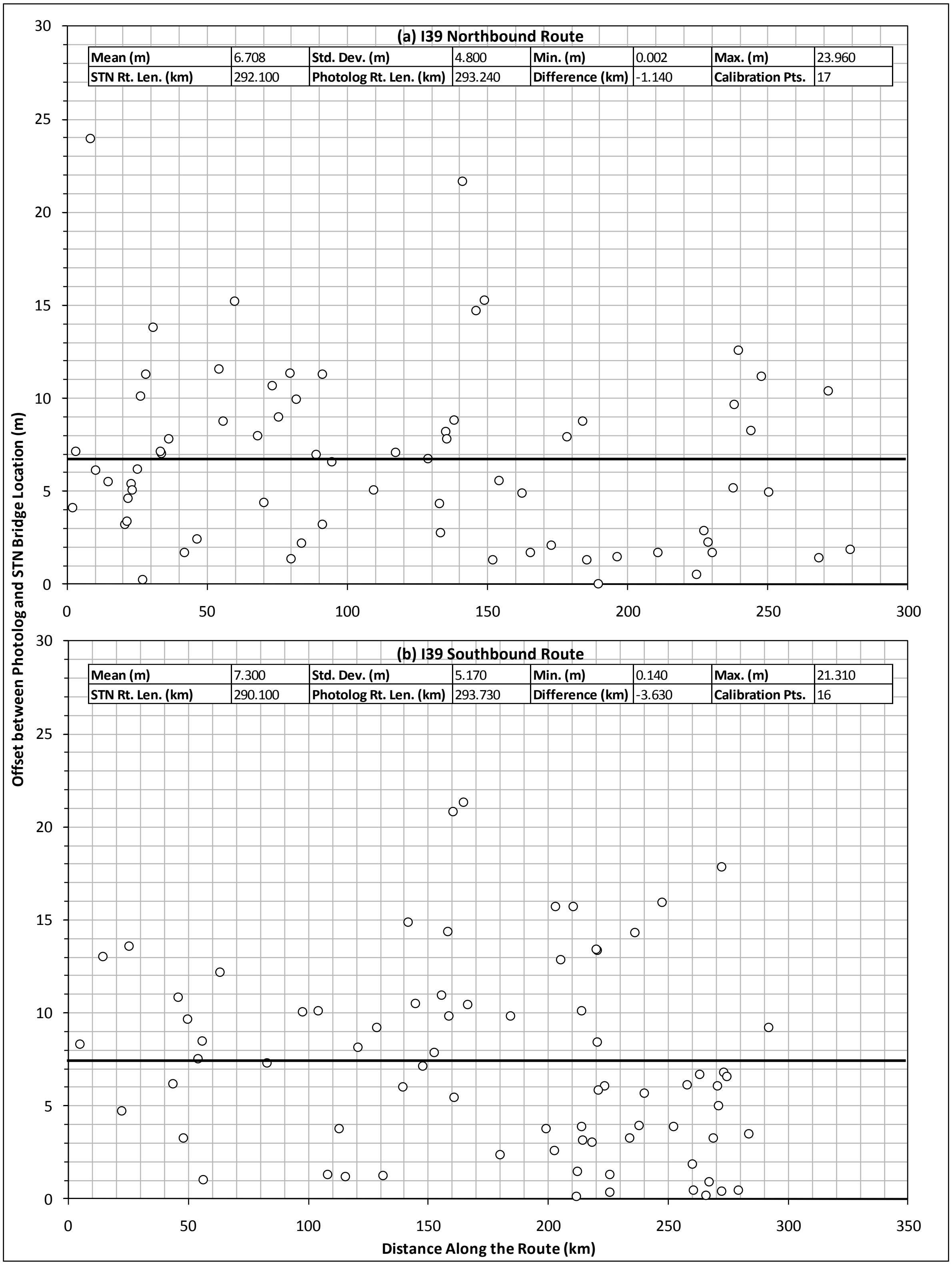


Figure 22 Summary Statistics and Offset Calculations for Interstate 39, North and Southbound.

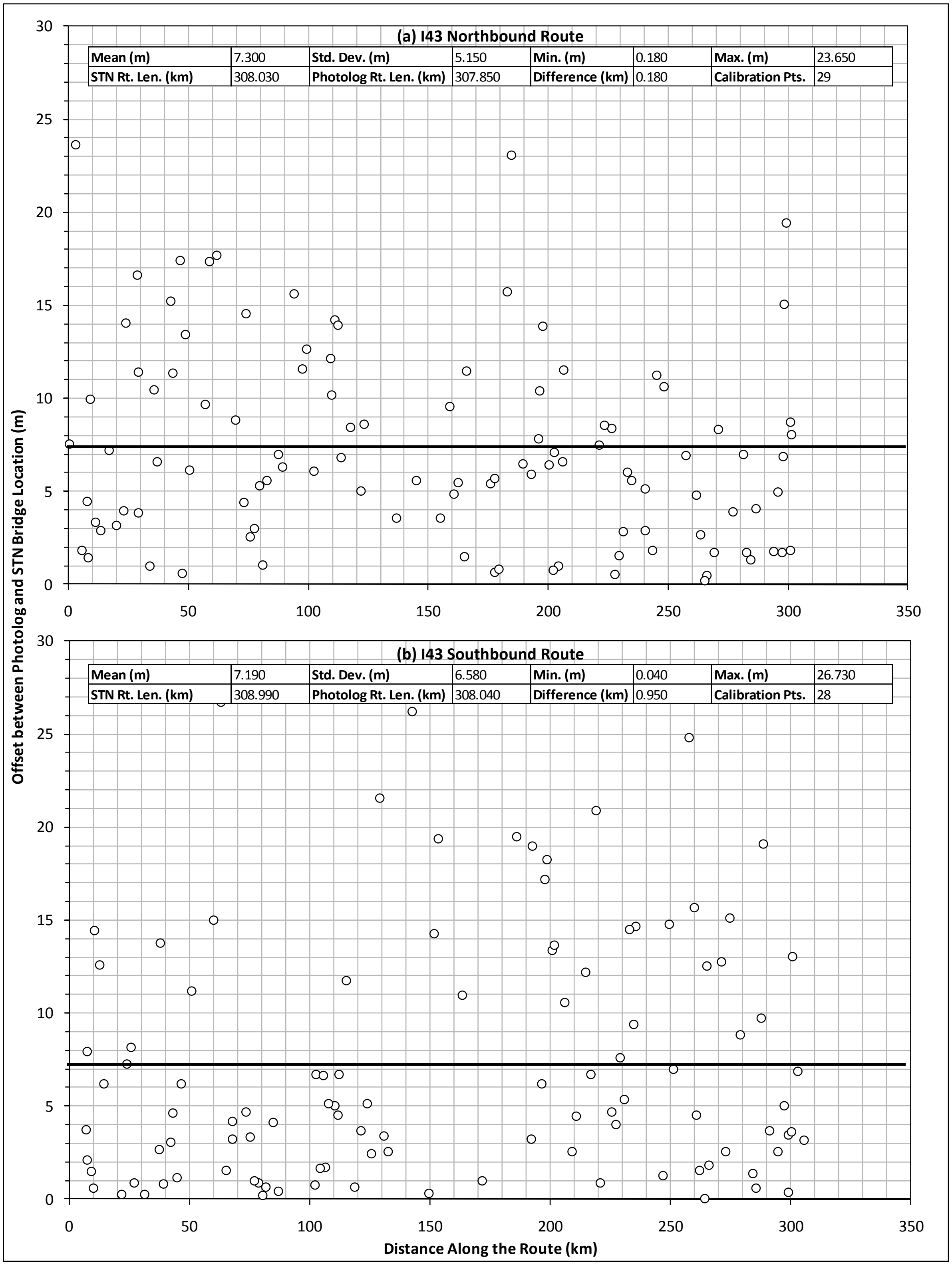


Figure 23 Summary Statistics and Offset Calculations for Interstate 43, North and Southbound.

The calculated offsets were also plotted on graphs along the length of the route in the direction of travel from start to the end point as shown in Figure 22 and Figure 23. The purpose of these plots was to analyze the distribution of the offsets and detect the presence of any trends or patterns as data were located along the length of the route. The graphs show no significant pattern or trend in the distribution of the offsets. Moreover, the graphs also present characteristics of individual offsets and additional insight into the accuracy of data collection and map-matching for individual locations or sections of the routes. For all the routes, most of the offsets are relatively small signified by the standard deviations. The offset for I-43 southbound seem to spread out more relative to the other routes which is also signified by a slightly higher standard deviation of 6.58 meters (21.58 ft.). However, it is still considerably small in the context of the data limitations.

Overall the results presented in Figure 22 and Figure 23 show that the data collection and map-matching process were highly accurate provided the scope of the research data limitations. Furthermore, the absence of any trends or patterns meant that there were no systematic errors throughout the process. The fact that the summary statistics are very close to each other for the individual routes was an important indicator of the consistency of the entire process.

4.2.4 Data Integration Summary

This data assembled from the crash database, the STN database, and the Photolog were used for two distinct crash prediction model applications: crash severity and crash frequency. Crash severity models estimate the severity of a crash when one does occur. Therefore, the base unit of the model is a CMC or barrier crash. For severity models, the accumulated roadway characteristics, such as median width, curve presence, and barrier type, were assigned to each georeferenced crash through the GIS database.

Crash frequency prediction models estimate the expected crashes on a roadway segment with particular characteristics. As a result, the base unit of the model is a road segment. To assemble the data for the frequency models, the roadways were divided into segments and crashes and roadway characteristics were then assigned to the segments. The segmentation process is described in Chapter 5.

A summary of the assembled data used in the crash prediction modeling and their sources is shown in Table 17.

Table 17 Summary of Data Elements and Sources

Data Element	Data Source
Crash Characteristics	Crash Database
Crash Location	DOT Georeferencing
AADT (2006)	STN
Median Width	STN
Number of Lanes	STN
Pavement Type	STN
Median Barrier Type, and Position	Photolog
Bridge Locations	Photolog
Curve Location and Direction	Photolog
Hill Location	Crash Database
Median Type	Photolog
Entrance Ramp	Photolog
Exit Ramp	Photolog
Divided, Median Barrier, or Undivided	Photolog

5 CRASH MODELING

Road safety analysis often includes fitting a statistical regression model to historic crash data and roadway, driver, environmental, and vehicle factors. Regression models can estimate the safety effects of various factors and can be applied as crash prediction models to estimate the expected number of crashes for a roadway element. Two models must be constructed to comprehensively estimate safety: the frequency of crash occurrence and the severity of the resultant crashes. As described in Chapter 4, the base unit for crash frequency models is a roadway segment and the attributes of that segment. The base unit for crash severity models is a crash with its attributed factors.

As the purpose of this research study is to evaluate a roadway section based on design criteria, only geometric factors—such as median width, curves, and ramps—were considered. Geometric factors can be easily assessed in the field or estimated in the design process and are applicable to a warrant. While non-geometric factors—such as weather conditions, alcohol use, and age—may be significant factors, they are not readily quantified for a particular roadway and have limited applicability to a warrant. The resulting crash prediction models can be used to perform cost effectiveness evaluations for roadway segments based on their roadway characteristics.

5.1 Crash Severity Modeling

5.1.1 Cross-Median Crash Severity Modeling

Crash severity modeling seeks to describe the probability of a crash resulting in each crash severity based on geometric factors at the crash location. Traffic crash severities are ordinal in nature with property-damage only, injury, and fatal listed in ascending order of severity. The relationship between the response and independent variables is believed to be nonlinear. Ordinal discrete-choice models, which use factors of interest to predict the probability that the severity is of an ordinal scale given a crash involvement, are appropriate. Ordinal logit (ORL) models are a common choice (5, 15, 17).

Single- and multi-vehicle cross-median crashes have different severity distributions, as shown in

Table 1. This pattern is logical based on the definitions of the two crash types; multi-vehicle crashes involve a collision with an opposing vehicle, which are often head-on or angle crashes at high speeds, while single-vehicle CMCs do not. As a result, multi-vehicle CMCs have higher proportions of fatal and injury crashes than single-vehicle CMCs. Independent models were created for each of the two crash types.

Geometric variables were gathered from the crash record, Photolog, and STN databases and attributed to each crash as discussed in Chapter 4. The variables used in this modeling effort are shown in Table 18. In addition to these main effects, the interactions between median width and ADT and between curve and hill were also modeled. Median width and ADT were initially modeled as continuous variables, but were not shown to be significant. They are modeled here as categorical variables to allow for their interaction to be analyzed.

Table 18 CMC Severity Modeling: Variables, Definition, and Statistics

Variable Name	Variable Description	Variable Type	Range of Values
Severity	Severity levels of CMC	Categorical (response)	1: PDO 2: Injury 3: Fatality
Posted Speed	Posted speed limit at the crash location	Categorical (predictor)	1: 45-50 mph 2: 55 mph 3: 65 mph
Median Width	Highway median width at the crash location	Categorical (predictor)	1: <50 feet 2: 50-59 feet 3: 60 feet 4: >60 feet
Total ADT	Total ADT for both travel direction	Categorical (predictor)	1: <15,000 2: 15,000-29,999 3: 30,000-44,999 4: 45,000-59,999 5: >=60,000
Curve	Horizontal alignment at crash location	Categorical (predictor)	1: Straight 2: Curved
Hill	Vertical alignment at crash location	Categorical (predictor)	1: Hilly 2: Level/Flat

The ORL model estimation will output a coefficient estimate and odds ratio for each significant variable. The odds ratio quantifies the effect of a significant variable on the response variable, which explains the relative effect of a unit change in the variable on the severity propensity. The regression coefficients can be applied to the following regression equations:

$$\log\left[\frac{\pi_1}{\pi_2+\pi_3}\right] = B_0 + B_1 x_1 + \ldots + B_k x_k$$

(*21*)

$$\log\left[\frac{\pi_1+\pi_2}{\pi_3}\right] = B'_0 + B_1 x_1 + \ldots + B_k x_k$$

(*17*)

Where:

π 1 = Probability of PDO severity;

π 2 = Probability of injury severity;

π 3 = Probability of fatality severity; and,

1…k = Indicator variables for geometric factors.

The predicted probabilities can be computed as follows:

$$\pi_1 = \frac{\exp\left[Equation(16)\right]}{1+\exp\left[Equation(16)\right]}$$

(*22*)

$$\pi_2 = \frac{1}{1+\exp\left[Equation(16)\right]} - \frac{1}{1+\exp\left[Equation(17)\right]}$$

(*23*)

$$\pi_3 = \frac{1}{1+\exp\left[Equation(17)\right]}$$

(*24*)

$$\pi_1 + \pi_2 + \pi_3 = 1$$

(*25*)

The results of this modeling effort are shown in Table 19. The multi-vehicle CMC severity model indicated no significant variables at the 10 percent confidence level. The median width/ADT interaction had the lowest *p* value at 0.1042, but neither of the component variables is significant, thus this variable was excluded. The score test (chi-square=19.4683, p-value=0.6737, degrees of freedom (d.f.)=23) for the proportional odds assumption indicates the modeling results adequately fit the data. However, the likelihood ratio test (p-value=0.2981, d.f.=23) indicates the global null hypothesis is not rejected. Therefore, the model with independent variables is not statistically better than that with only intercepts.

Table 19 CMC Severity Modeling Results

Parameter	Estimated Coefficient	Odds Ratio	Estimated Standard Error	Wald Chi-Square Statistic	*P* value
Multi-Vehicle CMCs					
Intercept (1)	-1.7089	--	0.5182	10.8767	0.0010
Intercept (2)	1.1839	--	0.5151	5.2827	0.0215
Posted Speed	--	--	--	0.7226	0.6968
Median Width	--	--	--	0.9282	0.8186
Total ADT	--	--	--	1.5910	0.8104
Curve	--	--	--	1.1881	0.2757
Hill	--	--	--	0.0009	0.9765
Median Width x ADT	--	--	--	17.1264	0.1042
Curve x Hill	--	--	--	0.4228	0.5156
Single-Vehicle CMCs					
Intercept (1)	-0.2096	--	0.2051	1.0449	0.3067
Intercept (2)	3.3592	--	0.2490	181.9481	<0.0001
Posted Speed	--	--	--	1.2315	0.5402
Median Width	--	--	--	2.1563	0.5406
Total ADT	--	--	--	2.4940	0.6457
Curve (1)	0.2813	1.3249	0.1039	7.3304	0.0068
Hill	--	--	--	0.9068	0.3410
Median Width x ADT	--	--	--	17.7435	0.1237
Curve x Hill	--	--	--	1.6073	0.2049

Note: -- designates not applicable or not relevant due to insignificance.

The single-vehicle CMC regression model did indicate that horizontal curve was significant with a p-value of 0.0068. The score test (chi-square=27.4760, p-value=0.2828, d.f.=24) for the proportional odds assumption and the likelihood ratio test (p-value=0.2191, d.f.=24) indicate that the parallel lines model is a good fit for the data but the significant variable does not improve the model over the intercept-only model.

As there is no significant variable in the multi-vehicle CMC model and the single-vehicle CMC model is limited, it is prescribed that crash severity proportions should be used in place of a crash severity regression model. These proportions, shown in Table 20, were derived from the CMC data used in this analysis. Using crash proportions where no crash severity prediction model is available is a method consistent with the Texas CMC study (59) and the Highway Safety Manual chapter dealing with divided multilane highways (43).

Table 20 Cross-Median Crash Severity Proportions

CMC Type	Fatal	Injury	Property Damage
Multi-Vehicle	0.216	0.588	0.196
Single-Vehicle	0.035	0.518	0.447

5.1.2 Median Barrier Crash Severity Modeling

Data were gathered for three median barrier types: concrete, cable, and guardrail barrier. As Table 16 shows, the vast majority of these 4,904 crashes involve concrete barrier. Spatial analysis shows that the vast majority of these crashes occur in the greater Milwaukee area, where nearly all of the urban freeway system consists of paved, narrow medians with concrete barriers.

The cable median barrier crashes occurred in six counties, primarily in eastern Wisconsin on USH 41 and IH 43, as shown in Table 21. Short sections of high-tension cable barrier were installed in Fond du Lac and Waukesha counties in 2006 and 2007. However, the vast majority of these crashes involved older, low-tension cable barriers. As the median barrier warrant is primarily concerned with high-tension barrier, the application of this crash data is limited. Additionally, the low number of guardrail median barrier crashes prevents regression modeling for those crashes. As a result, the concrete median barrier crashes were the focus of the barrier crash modeling effort.

Table 21 Cable Median Barrier Crash Locations

		Year							
Highway	**County**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**Total**
STH 29	Marathon	0	2	0	0	0	0	0	**2**
USH 41	Fond du Lac	6	4	1	2	1	6	15	**35**
USH 41	Washington	19	38	25	31	30	24	42	**209**
USH 41	Waukesha	0	0	0	0	1	0	0	**1**
IH 43	Milwaukee	0	0	3	5	4	5	3	**20**
IH 43	Ozaukee	0	0	8	9	5	15	32	**69**
IH 94	Waukesha	0	0	0	1	0	0	3	**4**
	Total	**25**	**44**	**37**	**48**	**41**	**50**	**95**	**340**

Geometric variables were gathered from the crash record, Photolog, and STN databases and attributed to each crash as discussed in Chapter 4. The variables used in this modeling effort are shown in Table 22. In addition to these main effects, the interactions between median width and ADT, between curve and hill, and between median width and barrier position were also modeled. The interaction between median width and barrier position was selected as median width only would play a role with barriers installed in the center of the median. Median width and ADT were initially modeled as continuous variables, but were not shown to be significant. They are modeled here as categorical variables to allow for their interaction to be analyzed.

Table 22 Concrete Median Barrier Crash Severity Modeling Variables

Variable Name	Variable Description	Variable Type	Range of Values
Severity	Severity levels of median barrier crashes	Categorical (response)	1: PDO 2: Injury 3: Fatality
Posted Speed	Posted speed limit at the crash location	Categorical (predictor)	1: 45-50 mph 2: 55 mph 3: 65 mph
Median Width	Highway median width at the crash location	Categorical (predictor)	1: <=25feet 2: 26-30 feet 3: >30 feet
Total ADT	Total ADT for both travel direction	Categorical (predictor)	1: <20,000 2: 20,000-54,999 3: 55,000-79,999 4: 80,000-104,999 5: 105,000-129,999 6: 130,000-154,999 7: >=155,000
Curve	Horizontal alignment at crash location	Categorical (predictor)	1: Curved Left 2: Curved Right 3: Straight
Hill	Vertical alignment at crash location	Categorical (predictor)	1: Hilly 2: Level/Flat
Number of Lanes	Number of lanes by direction	Categorical (predictor)	1: 3 lanes 2: 4 lanes 3: 2 lanes
Pavement Type	Pavement material at crash location	Categorical (predictor)	1: asphalt 2: concrete
Median Barrier Position	Location of median barrier at crash location	Categorical (predictor)	1: bridge 2: near-side 3: center

As with the CMC severity modeling, the response and predictor variables were fit to ordinal logistic regression models. The ORL model structure is shown in Equations 21-25. The "backward" variable section method was initially utilized at the 0.05 significance level, then at the 0.10 level shown here. The results of the concrete median barrier crash severity model, shown in Table 23 and Table 24, indicate that only median width is significant after the variable selection process.

Table 23 Concrete Median Barrier Crash Severity Analysis of Effects

Effect	DF	Wald Chi-Square Statistic	*P* value
Median Width	2	5.7719	0.0558

Table 24 Concrete Median Barrier Crash Severity Modeling Results

Parameter	Estimated Coefficient	Odds Ratio	Estimated Standard Error	Wald Chi-Square Statistic	*P* value
Multi-Vehicle CMCs					
Intercept (1)	0.7194	--	0.0697	106.4175	<0.0001
Intercept (2)	6.5783	--	0.3835	294.2673	<0.0001
Median Width (1 v. 3)	-0.0454	0.9556	0.0970	0.2189	0.6399
Median Width (2 v. 3)	-0.1727	0.8414	0.0808	4.5713	0.0325

The proportional odds score test (Chi-Square=4.4823, p-value=0.1063, d.f.=2) indicates the modeling results adequately fit the data. The likelihood ratio test (p-value=0.0551, d.f.=2) indicates the global null hypothesis is rejected. Therefore, the model with independent variables is statistically better than that with only intercepts, and the remaining variables are believed to affect the severity.

The odds ratio for median width (2 v. 3) of exp(-0.1727)=0.8414 reflects the relative effect of the median width category 2 (26-30 feet) versus the category 3 (>31 feet) used as the base level. This indicates that the odds of PDO severity versus injury or fatality severity (or PDO or injury severity versus fatality severity) decrease by 15.9 percent when the median width is narrowed from larger than 30 feet to 26-30 feet. Alternatively speaking, this implies that the median barrier crashes that occur on highways with narrower median areas will result in higher severities.

However, the odds ratio for median width (1 v. 3) of 0.9556, though not significant (p-value=0.6399), indicates that the odds of PDO severity versus injury or fatality severity (or PDO or injury severity versus fatality severity) is 4.44 percent smaller when the median width is narrowed from larger than 30 feet to less than 26 feet. By comparison, these odds ratios imply that crashes with medians narrower than 26 feet are likely to be less severe than crashes with medians 26 to 30 feet. This phenomenon, in addition to the uniformity of concrete barrier median width, where 58 percent of crashes occur at locations with median widths of 26 to 30 feet, leads to the exclusion of this parameter. As with the cross-median crash severity model, it is prescribed that crash severity proportions be used in place of a crash severity regression model. These proportions, shown in Table 25, were derived from the concrete median barrier crash data used in this analysis.

Table 25 Median Barrier Crash Severity Proportions

Median Barrier Type	Fatal	Injury	Property Damage
Concrete	0.002	0.350	0.648
Cable	0.006	0.109	0.885
Guardrail	0.000	0.189	0.811

Table 25 includes cable and guardrail median barrier crash severity proportions alongside those of concrete barrier. The proportions for cable barrier should be used with caution based on the sample size and the low-tension cable barrier issues described above.

5.2 Crash Frequency Modeling

Crash frequency modeling seeks to predict the number of crashes that will occur on a roadway segment based on the geometric features of that segment. As roadway segments form the base unit of this analysis, the study roadways must first be divided into sections that are then fit to the model. This segmentation process is described in the following section.

5.2.1 Roadway Segmentation

The first step of the segmentation process was to identify relevant roadway sections. The Wisconsin highways were filtered to remove undivided sections, which do not fit the CMC definition, and divided highway sections with median barrier. Each direction of these study sections were then divided into half-mile segments. Highway remnants with lengths less than one half mile left over from the segmentation process were combined with the upstream segment. As a result, one half mile is the minimum length of all of the created segments.

The half-mile segment length was selected based on the scale of the study features and their impact area and the distribution of crashes. A half-mile segment length is consistent with CMC frequency modeling in Pennsylvania (5, 13, 18). Additionally, a sensitivity analysis showed little sensitivity to segment length.

Roadway characteristic data assembled from the Photolog and STN databases was then attributed to each road segment. The following roadway characteristics were assigned:

- AADT;
- Median width;
- Bridges;
- Curves by direction;
- Entrance ramps; and,
- Exit ramps.

Where ADT or median width varied over the length of the segment, the average was used. However, there were relatively few of these sections based on the sparseness of the data collection points and that volume changes only occur at interchanges. The bridge, curve, and ramp factors were transformed into "influence areas," which included 500 feet downstream of bridges, curve, and entrance ramps and 500 feet upstream of exit ramps. These influence areas capture the driver workload and merge or weaving effects of these features.

The count of each of these features over the length of each segment was tallied and attributed to that segment. The count of the single- and multi-vehicle CMCs was also attributed to each segment. The segmentation process resulted in segments of consistent length complete with roadway characteristic data and CMC counts ready for the frequency prediction modeling.

5.2.2 Cross-Median Crash Frequency Modeling

The roadway segments generated in the segmentation procedure were then fit to a regression model to formulate a crash frequency prediction model. Poisson and negative binomial models are frequently used to model sparse crash count data. A limitation of the Poisson model is that is assumes the mean and variance of the data to be equal. Negative binomial modeling, a special case of the Poisson model, is used when the variance is greater than the mean, a condition referred to as overdispersion. The CMC data have a variance/mean ratio of 1.42 which indicates overdispersion. As a result, the negative binomial model was used in this analysis, which is consistent with other CMC frequency analyses (5, 13, 18).

Multi-vehicle CMC was first considered for analysis. Since the crashes involving multiple vehicles are likely to cause more damages to the properties as well as to the people either in terms of magnitude or severity, the interest in crash modeling often lies in identifying the factors that contribute solely to multi-vehicle CMC. However, although less severe, single-vehicle CMCs have same causal dynamics, respond to same countermeasures as multi-vehicle CMCs and thus could have easily been multi-vehicle crash, had the crossing vehicle not found a gap in the opposing traffic. In that regard, single- and multi-vehicle CMCs were combined to identify factors that contribute to CMCs in general. By combining the two CMC types, 1,445 CMCs were assigned to the 6,500 roadway segments, creating more meaningful results[2]. The resulting number of expected CMCs can be divided by proportions with single-vehicle crashes accounting for 79.5 percent of the total crashes and multi-vehicle CMCs accounting for the remaining 20.5 percent. Therefore the crash frequency modeling was conducted both on the multiple-vehicle CMC only and on the combined number of CMCs.

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[2] This number differs from the 1511 total CMCs identified in this study as some indentified CMCs were not able to be georeferenced and attributed to study roadway segments.

The negative binomial model estimation will output a coefficient estimate for each significant variable. The regression coefficients can be applied to the following general form regression equation:

$$\mu = \exp(\beta_0)\, L\, AADT exp(\beta_1 X_1) \cdots exp(\beta_k X_k)$$
(*26*)

Where:

μ = Predicted number of CMCs per year;

$\beta_0 \cdots \beta_k$ = Regression coefficients;

L = Length of segment;

AADT = Directional daily traffic volume; and,

$X_1 \cdots X_k$= Predictor variables;

Geometric variables were gathered from the crash record, Photolog, and STN databases and attributed to each segment. The variables used in this modeling effort are shown in Table 26.

Table 26 Cross Median Crash Frequency Modeling Variables

Variable Name	Variable Description	Variable Type	Range of Values
Number of Crashes	Total 2001-2007 CMCs	Discrete (response)	0-7
Segment Length	Length of segment in meters	Continuous (predictor)	800-1586.7
Number of Years	Number of years for data collection	Discrete (predictor)	5-7
AADT	Directional average daily traffic volume in thousands	Continuous (predictor)	0-53.297
Median Width	Distance between travel lanes in feet	Continuous (predictor)	0-1587
Bridge Influence	Presence of bridge with 500 feet upstream of crash location	Categorical (predictor)	0: No bridge 1: 1 or more bridges
Left Curve Influence	Presence of left curve with 500 feet upstream of crash location	Categorical (predictor)	0: No curve 1: 1 or more curves
Right Curve Influence	Presence of right curve with 500 feet upstream of crash location	Categorical (predictor)	0: No curve 1: 1 or more curves

Entrance Ramp Influence	Presence of entrance ramp with 500 feet upstream of crash location	Categorical (predictor)	0: No ramp 1: 1 or more ramps
Exit Ramp Influence	Presence of exit ramp with 500 feet downstream of crash location	Categorical (predictor)	0: No ramp 1: 1 or more ramps

A variety of modeling approaches were evaluated, including:

- 1-mile and ½-mile segment lengths
- Median width as continuous and categorical with between 3 and 11 categories
- Interactions between several levels of median width categorization and various factors:
    - Median width and curve
    - Median width and ramps
    - Median width and bridge
    - Median width and median type

The natural logarithm of AADT was included in the regression model ($\exp(\alpha \log(AADT)) = AADT^{\alpha}$), as the assumption that AADT has a strictly linear effect on crash frequency seems naïve. On a log scale, the ratio of crash frequency to AADT is represented by the coefficient estimate α. The segment length and number of years are scale factors in the model on the assumption that CMC frequency is proportional to the segment length as well as to the number of years for counting CMCs, and both of its regression coefficients were not estimated as a result. Median width was categorized instead of being used as a linear variable based on two reasons: 1) the distribution of median width is far from uniform: segments with median width of 50ft and 60ft comprise 14.39% and 41.41% of the total sample, respectively 2) the regression coefficient of median width as a continuous variable estimates the effect of one-foot increase of width of median on crash frequency which bears little importance to deciding warranty criteria.

The multi-vehicle CMC frequency regression results are shown in Table 27. As the table indicates, log of AADT, categorized median width between 40- and 60-ft, the influence areas of right curves and entrance ramps were all found to be significant at the 10 percent level. The influences of bridges, left curves, exit ramps and median width of smaller than 40ft and greater than 60 ft were not found to be significant at the same level.

Table 27 Multi-vehicle CMC Frequency Modeling Results

Parameter	Estimated Coefficient	Estimated Standard Error	Chi-Square Statistic	*P* value
Intercept	-15.6772	0.3503	2003.37	<0.0001
Log (AADT)	1.3905	0.1137	149.70	<0.0001
Median width <= 20ft	0.0658	0.4018	0.03	0.8700
20ft < Median width <= 30ft	0.1446	0.3606	0.16	0.6886
30ft < Median width <= 40ft	0.4035	0.3024	1.78	0.1821
40ft < Median width <= 50ft	0.4825	0.2377	4.12	0.0424
50ft < Median width <= 60ft	0.4023	0.2156	3.48	0.0620
60ft < Median width <= 70ft	0.1846	0.3001	0.38	0.5385
Bridge Influence (none)	0.0742	0.1432	0.27	0.6046
Left Curve Influence (none)	-0.1565	0.1368	1.31	0.2528
Right Curve Influence (none)	-0.2373	0.1383	2.94	0.0862
Entrance Ramp Influence (none)	0.3254	0.1360	5.72	0.0167
Exit Ramp Influence (none)	0.1587	0.1448	0.22	0.2729
Dispersion Parameter	1.043	0.444		

The effect of each explanatory variable can be determined by taking the exponential of the parameter estimates. The results indicate that the influence of entrance ramps is the only predictor expected to increase CMC frequency, by 38.46 percent, whereas CMC frequency is expected to decrease by 21.12 percent under the influence of right curves. The adverse effect of right curves on the number of multi-vehicle CMCs is not intuitive. The coefficient estimates of categorized median width, compare the effect of each category on CMC frequency to a reference category, which is median width of wider than 70-ft. Therefore, the results suggest that segments with median width ranging from 40- to 50-ft and 50- to 60-ft are likely to experience more CMCs by 62.01 and 49.53 percent than those with median width larger than 70-ft. It is hard to conclude that median width has significant effect on the frequency of multiple-vehicle CMCs, since the two categories – median width of 40 to 50ft and 50 to 60ft - being significant might as well be due to disproportionate sample size.

The deviance and Pearson chi-square values divided by their degrees of freedom are 0.2165 and 1.0154, respectively, where values near 1.0 indicate high goodness of fit. These indicators of goodness of fit suggest that the negative binomial model is not completely inadequate to the multi-vehicle CMCs, although the results based on the model is not entirely reliable either.

For the reasons specified previously, the number of single- and multi-vehicle CMCs was combined to garner more meaningful results and the model estimated from the combined CMCs is reported in Table 28.

The results indicate that bridges, entrance ramps and exit ramps are all expected to increase CMC frequency, by 13.48($\beta = 0.1265$), 41.63 ($\beta = 0.3481$) and 21.13 percent ($\beta =$

0.1918), respectively, whereas left curves are expected to decrease CMC frequency by 13.41 percent ($\beta = -0.1440$). The coefficient estimates of categorized median width, compare the effect of each category on CMC frequency to a reference category, which is median width of wider than 70-ft. Therefore, the results suggest that segments with median width ranging from 20 to 30-ft is likely to experience more CMC by 94.52 percent than those with median width larger than 70-ft. The coefficient estimates that are associated with median width in the range of 30 to 70-ft become smaller as the median gets incrementally wider. It is a valid argument that segments with narrower median width can experience larger number of CMC.

Table 28 Combined CMC Frequency Modeling Results

Parameter	Estimated Coefficient	Estimated Standard Error	Chi-Square Statistic	*P* value
Intercept	-12.4089	0.1513	6724.49	<0.0001
Log (AADT)	0.7136	0.0504	200.14	<0.0001
Median width <= 20ft	-0.3550	0.2279	2.43	0.1192
20ft < Median width <= 30ft	0.6654	0.1676	15.76	<0.0001
30ft < Median width <= 40ft	0.7285	0.1428	26.02	<0.0001
40ft < Median width <= 50ft	0.6654	0.1082	37.82	<0.0001
50ft < Median width <= 60ft	0.4086	0.0983	17.28	<0.0001
60ft < Median width <= 70ft	0.2550	0.1344	3.60	0.0578
Bridge Influence (none)	0.1265	0.0724	3.06	0.0805
Left Curve Influence (none)	-0.1440	0.0663	4.72	0.0298
Right Curve Influence (none)	0.0113	0.0643	0.03	0.8601
Entrance Ramp Influence (none)	0.3481	0.0694	25.17	<0.0001
Exit Ramp Influence (none)	0.1918	0.0740	6.72	0.0095
Dispersion Parameter	1.084	0.136		

Indicators of goodness of fit imply that the negative binomial model quite adequately fits the data: deviance and Pearson chi-square values divided by their degrees of freedom are 0.5734 and 1.0179, respectively, with values near 1.0 indicating high goodness of fit. The dispersion parameter was estimated at 1.084, confirming over-dispersion.

Other modeling approaches that deal with zero-inflation can be considered as well since no crashes were observed on 5,401 of the 6,527 segments (82.7 percent) in this model. Zero-inflated negative binomial models, which divides segments into "inherently safe" zero-inflated sites without crashes and crash sites. However, crashes do not exhibit two distinct generation procedures one of which is "safe" with an expected crash frequency is zero, which is unrealistic for crash data (65). Additionally, the data might not be accurately modeled by geometric factors alone and environmental and driver behavioral factors may play a large role in CMC occurrence.

5.2.3 Median-Barrier Crash Frequency Modeling

Similar segmentation procedure as the one used for CMC frequency model was employed to generate roadway segments for median-barrier crash (MBC) frequency prediction model. There were 475 segments available for MBC analysis. Segment length, AADT, influence areas of curve and ramp factors and the count of MBCs were tallied and attributed over the length of each segment. The count of MBCs was recorded for seven years, identically for all the segments and the number of years that was required for data collection did not need to be adjusted, as in the CMC frequency modeling. Median width was not considered as a predictor in the MBC frequency model because width of a median would not have an effect on crash frequency when a barrier is present in the middle of a median. Instead, the distance from the traffic lane to the barrier can potentially be an important variable to consider, although preliminary analysis shows there is a little variation in distance to barrier across segments and the relationship with the crash frequency does not appear to be strong.

Negative binomial regression model, with segment length as a scale factor and AADT, distance to barrier, influence areas of left curves, right curves, entrance ramps and exit ramps as predictors, was again fitted to formulate a MBC frequency prediction model since the MBC data featured over-dispersion with a variance/mean ratio of 10.41. The general form of regression equation is the same as Equation 26.

Table 29 MBC Frequency Modeling Results

Parameter	Estimated Coefficient	Estimated Standard Error	Chi-Square Statistic	*P* value
Intercept	-7.0497	0.3725	358.16	<0.0001
Log (AADT)	0.5775	0.0891	41.98	<0.0001
Distance to barrier	0.0037	0.0074	0.25	0.6143
Left Curve Influence (none)	0.2768	0.0805	11.83	0.0006
Right Curve Influence (none)	0.3516	0.0815	18.61	<0.0001
Entrance Ramp Influence (none)	0.1287	0.0780	2.72	0.0990
Exit Ramp Influence (none)	-0.1448	0.0782	3.43	0.0639
Dispersion Parameter	2.064	0.175		

The MBC frequency regression results are shown in Table 29. The results indicate that log of AADT and the influence areas of left curves, right curves, entrance ramps, and exit ramps were all found to be significant at the 10 percent level. The distance to barrier is the only variable that was not found to be significant at the same level. Based on the coefficient estimates, left curves, right curves and entrance ramps are all expected to increase MBC frequency, by 31.88, 42.14 and 13.73 percent, respectively, whereas exit ramps are expected to decrease CMC frequency by 13.48 percent. Ratio of deviance and Pearson chi-square statistic to their degrees of freedom are 1.1227 and 1.3049, respectively, suggesting that the negative binomial model quite adequately fits the data.

5.2.4 Comparison of CMC and MBC datasets

In order to compare the crash frequencies that are attributed to cross-median to the ones that are related to median-barrier, the prediction models should be based on comparable dataset. When the MBC data were gathered, concrete median barriers in Wisconsin were installed mostly in the Milwaukee metropolitan area, where the volume and flow of traffic is very different from the rest of the state in which CMC data were collected. It is thus likely that the MBC frequency prediction model based on the entire dataset currently available will yield over-estimated numbers of predicted MBC frequency.

We can verify the difference in the attributes of the roadway segments that constitute the dataset most starkly by the distribution of AADT, which is the only continuous predictor, in Figure 24. The traffic volume in Milwaukee area, where MBC data was collected, is mostly above 40,000 vehicles per day on average, whereas it is the opposite in the rest of Wisconsin.

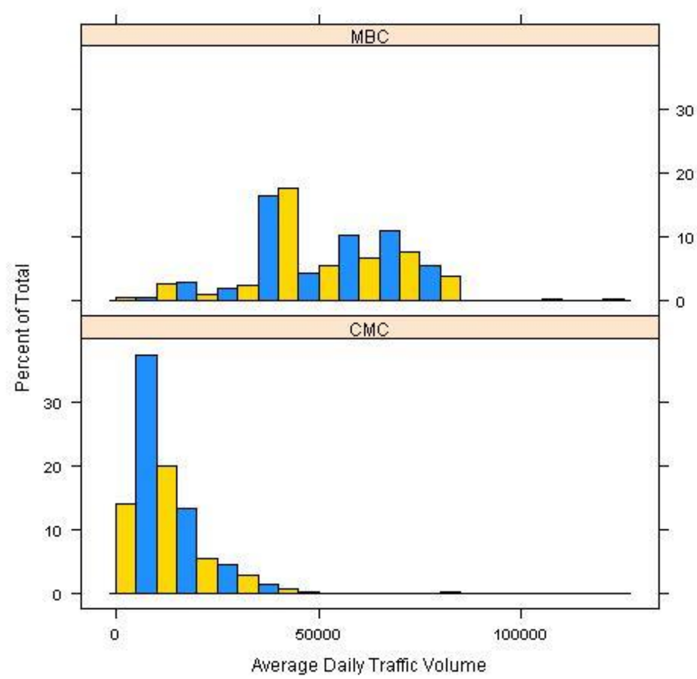

Figure 24 Distribution of AADT in segments from CMC and MBC dataset

6 CRASH INJURY ANALYSIS

Crash injury costs are a critical element in safety analysis as they are used to compare crash severities and collision types, conduct benefit/cost analyses, and to evaluate safety treatments. In this study, injury costs have several applications. These costs provide a monetary basis for comparing barrier costs to safety benefits. In addition, the detailed cost data allows for determine the distribution of number of injuries and injury types distinctly for single- and multiple-vehicle CMCs and median barrier crashes. This chapter describes the injury cost analysis methodology used in this study and provides a summary of the cost results.

6.1 CODES Data Analysis Methodology

The desired output from the crash injury analysis is reliable and representative comprehensive injury costs averaged by crash severity for single-vehicle CMCs, multi-vehicle CMCs, and median barrier crashes. Median barrier crash injury costs would be further broken down by barrier type as concrete, cable, and guardrail barriers are expected to have significantly different injury dynamics. These costs will be applied to monetize the expected crash frequencies output from the crash prediction models.

6.1.1 Data Reduction

The Wisconsin CODES database provides complete injury record, vehicle, and—for linked injuries—medical information for each crash participant. The database was provided by Center for Health Systems Research and Analysis (CHSRA) in raw text format accompanied by a SAS codes to transform the text into comma-separate value format. This format could be read by Microsoft Excel for further analysis.

Each record in the CODES database includes the corresponding accident number, a unique identifier associated with each crash. As the CODES database records data by participant, the accident number and other crash data is duplicated for each participant. The accident number was used to perform a one-to-many query to extract the CODES records for each of the single-vehicle CMC, multi-vehicle CMC, and median barrier crashes in this study.

For each injury record, the most relevant CODES fields are outlined in Table 30.

Table 30 Important CODES Data Fields

Field	Description
Accident Number	Unique crash identifier
Crash Severity	Police-reported crash severity (fatal, injury or property-damage only)
Injury Severity	Police-reported injury severity (KABCO scale)
Linked Injury Fields	

Hospital Link	Designates link to hospital databases
Emergency Department Link	Designates link to emergency department databases
Diagnostic Code	Medical staff-reported diagnostic code (body part injured, fracture, and MAIS scale)
Medical Cost	Adjusted medical costs
Other Cost	Adjusted other costs
Quality-of-Life (QOL) Cost	Adjusted QOL costs

The distinction between crash severity and injury severity is an important one. Both are supplied in the police report. Crash severity is the same for all participants in the crash, independent of injury, and represents the most severe outcome. For example, all participants in a crash with one injury would be assigned the injury crash designation. Injury severity, on the other hand, is assigned for each participant based on the injury sustained by that person on the KABCO scale. While the CODES data is recorded on the participant level, many factors and costs are aggregated by crash severity.

The detailed component injury costs were attributed to each injury in the linkage process based on the diagnostic code. As a result, the presence of a valid diagnostic code was used as the determination if an injury was "linked" in this study.

6.1.2 Error Correction

Preliminary observations into the assembled CODES data sets showed several apparent issues. First, a small number of discrepancies were made apparent between the police-entered fields and the linked crash data. Some participants were assigned a null injury severity field, though these injuries were linked and assigned a diagnostic code. It is not possible to be certain if these injuries were probabilistic matching errors. However, it was assumed that these injuries represent some of the approximately seven percent of doctor-reported injuries not recorded by police, shown in Table 4.

Some of these participants reflected the only injury in a crash that the police recorded as a property-damage only, so the crash severity of these crashes was adjusted from PDO to injury. The injury and/or crash severities were adjusted to be consistent with the MAIS scores attributed through linkage. Where injury severity was blank, MAIS 1 injuries were assigned "possible injury" and MAIS 2 injuries were assigned "non-incapacitating injury."

Further observation showed that a large number of injuries of each severity contained identical medical and other costs and QOL costs of zero. The Bigelow report indicated that these costs were imported from the NHTSA Motor Vehicle System (MVS), which does not include QOL costs (28). These costs were assigned to unlinked injuries based on the KABCO scale instead of the diagnostic code (as these injuries were not attributed a diagnostic code in the linkage process).

These MVS crash costs were disregarded Due to the lack of QOL costs and aggregation by KABCO scale. This strategy represents a departure from the previous Wisconsin study which utilized the MVS costs to supplement CODES costs for unlinked crashes (4). In doing so, the detailed injury patterns for each crash type are muddied by large numbers of default costs, which decreases the sophistication that CODES provides.

Observation of the data also showed that emergency department linked injuries for the years 2003 and 2004 were assigned MVS costs, though they contained diagnostic codes. This apparent error led to fewer injuries provided with comprehensive injury costs.

Each linked injury was assigned a cost from the Zaloshnja study that had been adjusted to Wisconsin by a cost-of-living factor, and adjusted by year using medical and overall Consumer Price Index (CPI) factors (29). This method accounts for inflation and rising costs associated with the medical field, instead of a general CPI or other adjustment method. However, for the purposes of the study, all the crash costs were adjusted to the same year using the same method to avoid yearly biases. This adjustment was accomplished by assembling all the 2005 CODES costs by diagnostic code and applying a medical CPI factor to adjust to 2009 dollars. A medical CPI factor of 1.1621 was applied to the medical costs and an overall CPI factor of 1.0986 was applied to the other and QOL costs (66). These costs were then applied to all crashes, independent of year, based on diagnostic code. This eliminated any yearly bias that would be created by using a different adjustment method and populated the unlinked crashes from the 2003-2004 emergency department linkage issue. A summary table of the 2009 comprehensive crash costs by diagnostic code is shown in Appendix B.

The proportion of injuries that were able to be linked by severity and crash type is shown in

Table 31.

Table 31 CODES Injury Linkage Percentage

Injury Severity	Multi-Vehicle CMC	Single-Vehicle CMC	Median Barrier Crash
Killed (K)	28.0%	28.6%	41.7%
Incapacitating Injury (A)	71.1%	65.5%	66.4%
Non-incapacitating Injury (B)	54.8%	50.5%	46.7%
Possible Injury (C)	39.9%	35.1%	37.6%
Total Injuries	619	989	2173
Total Injuries Linked	50.9%	47.2%	42.4%
Non-Injury Participants (O)	495	1232	6104

The table shows that the probability of injury linkage increases with severity except for fatal crashes. Many crash fatalities are not transported to the hospital and therefore create no hospital records to be linked, yielding a lower percentage. Uninjured participants were not explicitly considered in this study, though property-damage only crashes were analyzed and modeled. The table shows and overall injury linkage of 40-50 percent, which represents a sizable sample size for each of these crash types.

The linked injuries for the three crash types were combined to compare the police-reported KABCO injury severities with the doctor-reported MAIS scores. This comparison is shown in Table 32 as a percent of injuries for each KABCO scale.

Table 32 MAIS and KABCO Severity Comparison

	KABCO Scale			
MAIS Score	**C**	**B**	**A**	**K**
1	87.8%	75.3%	37.7%	0.0%
2	9.9%	16.8%	28.0%	5.0%
3	2.0%	5.0%	16.4%	15.0%
4	0.1%	2.6%	13.4%	12.5%
5	0.1%	0.3%	4.6%	30.0%
6	0.0%	0.0%	0.0%	37.5%

The table indicates a strong severity correlation between the two severity scales. Over 75% of possible and non-incapacitating injuries (Injury C and B) were classified as MAIS 1, minor injuries. Injuries reported as incapacitating in the police report represented a wider range of MAIS scores, possibly reflecting the overestimation trends for external injuries noted in

Compton (24). The range in MAIS scores for fatalities is likely due to the time of reporting. An injury may be given a MAIS score of less than 6 by a doctor, but if the injury became fatal within 30 days of the crash, the crash report would be revised to indicate a fatal crash. As a result, some fatal crashes are attributed MAIS scores of less than 6.

6.1.3 Analysis Procedure

The most straightforward crash injury summation procedure would be to average the linked injury costs for each crash severity level. However, this might introduce biases into the data based on unknown factors that could affect injury linkage. To reduce this issue and to make use of the full dataset as much as possible, an indirect procedure was used to summarize the injury costs. This methodology consists of multiplying the average number of injuries by the average injury costs for each injury severity, then summing these costs for each crash severity, as shown in the equation below. The results are average injury costs for each crash severity and crash type.

$$crash\ cost_{t,c} = \sum_{all\ i} number\ of\ injuries_{t,c,i} \times injury\ cost_{t,i} \tag{27}$$

Where:

t = crash type (multi-vehicle CMC, single-vehicle CMC, or median barrier)

c = crash severity (fatal, injury, or property-damage only)

i = injury severity (KABCO scale)

Average Number of Injuries per Crash

The first step in this indirect procedure was to calculate the average number of injuries per crash, broken out by injury and crash severity. This analysis would capture the differences between the crash types, such as number of participants involved and the distribution of injury severities for each crash severity. As this step does not consider linkage or costs, the full dataset was used for each crash type. The results of this injury analysis for single- and multi-vehicle CMCs, the average number of participants in each crash, and the number of crashes of each crash severity are shown in Table 33.

Table 33 Average Injuries per Cross-Median Crash by Crash Severity

Crash Severity	Injury Severity					Average Number of Participants	Number of Crashes
	Killed	Injury A	Injury B	Injury C	No Injury		
Multi-Vehicle CMCs							
Fatal	1.32	0.61	0.79	0.35	1.15	4.22	62
Injury	0.00	0.64	0.93	0.90	1.46	3.93	173

PDO	0.00	0.00	0.00	0.00	3.07	3.07	56
Single-Vehicle CMCs							
Fatal	1.02	0.49	0.49	0.17	0.15	2.32	41
Injury	0.00	0.28	0.59	0.52	0.51	1.90	644
PDO	0.00	0.00	0.00	0.00	1.68	1.68	535

The output of this step is the average number of injuries of each injury severity for each crash severity. For example, Table 33 shows that each fatal crash consists of, on average, 1.32 fatalities, 0.61 incapacitating injuries, 0.79 non-incapacitating injuries, 0.35 possible injuries, and 1.15 uninjured participants, based on 62 crashes. Injury crashes do not include any fatalities and PDO crashes include only uninjured participants. The minimum number of fatal injuries in a fatal crash is 1.0 and the sum of injury crashes over the three injury severity levels must be greater than 1.0. Property-damage only crashes must include at least 1.0 uninjured participant.

Multi-vehicle cross-median crashes have more fatalities, injuries, and uninjured participants than single-vehicle CMCs, as shown in Table 33. Multi-vehicle CMCs have almost twice as many total participants as single-vehicle CMCs, which is consistent with their definitions as multi-vehicle CMCs must include at least two vehicles. The sample sizes for each crash severity indicates that the average injury results are reliable.

A similar analysis was conducted for median barrier crashes by barrier type. The results of this procedure are shown in Table 34.

Table 34 Average Injuries per Median Barrier Crash by Crash Severity

Crash Severity	Injury Severity					Average Number of Participants	Number of Crashes
	Killed	Injury A	Injury B	Injury C	No Injury		
Concrete Barrier Crashes							
Fatal*	1.14	0.00	0.43	0.14	0.71	2.42	7
Injury	0.00	0.08	0.43	0.78	0.71	2.00	1632
PDO	0.00	0.00	0.00	0.00	1.56	1.56	2872
Cable Barrier Crashes							
Fatal*	2.00	2.50	0.00	0.00	0.00	4.50	2
Injury	0.00	0.10	0.55	0.70	0.50	1.85	40
PDO	0.00	0.00	0.00	0.00	1.45	1.45	298

Guardrail Barrier Crashes							
Fatal*	--	--	--	--	--	--	0
Injury*	0.00	0.20	0.50	0.80	0.40	1.90	10
PDO	0.00	0.00	0.00	0.00	1.60	1.60	43

* Indicates small sample size; use with caution.

A substantial element of the results shown in Table 34 is the discrepancies in the number of crashes. The table indicates that fatal cable barrier crashes are much more severe than fatal concrete barrier crashes, as they have more fatalities and severe injuries. This result is counterintuitive and contrary to the injury crash comparison, which shows similar injury distributions for the two barrier types. The low number of fatal crashes for concrete and particularly cable barriers yield unreliable results. Specifically, the dataset contains only two fatal cable barrier crashes, one of which was very serious, resulting in three fatalities and four incapacitating injuries. This crash is unrepresentative of cable crashes and the resulting injury counts should be used with caution. Due to the small sample size of fatal cable barrier crashes and that these crashes likely involved low-tension cable barrier as discussed in Chapter 5, these cable barrier results have limited applicability to the placement of high-tension barrier. Similarly, the small number of guardrail crashes limits the usefulness of those analysis results.

Concrete median barrier injury crashes have a substantial sample size. The results in Table 34 indicate that injury crashes result in predominately minor injuries. Additionally, the average number of participants is consistent with that of single-vehicle CMCs, which is intuitive as both crash types do not include vehicles from the opposing direction.

This step yielded the average number of injuries for each injury severity by crash type and crash severity. These injury numbers can be applied to the crash costs formulated in the next step.

Average Injury Severity Cost

The second step in the injury cost analysis was to compute the average injury costs for each injury severity for each crash type. As this calculation uses the costs assigned to the injuries in the linking process, only linked injuries were used in this step. The average, minimum, and maximum costs per injury, the standard deviation of cost, and the number of injuries of each type are shown in Table 35.

Table 35 Average Cross-Median Crash Injury Costs by Injury Severity

Injury Severity	Average Injury Cost	Minimum Injury Cost	Maximum Injury Cost	Standard Deviation of Injury Cost	Number of Injuries
Multi-Vehicle CMCs					

Killed	$2,869,315	$330,530	$4,140,840	$853,936	23
Incapacitating	$525,201	$11,309	$4,418,972	$844,247	106
Non-incapacitating	$207,256	$10,111	$4,140,840	$509,090	115
Possible	$63,294	$10,248	$619,225	$119,628	71
Single-Vehicle CMCs					
Killed	$2,663,273	$412,559	$4,140,840	$1,381,828	12
Incapacitating	$501,418	$10,111	$5,841,408	$852,387	131
Non-incapacitating	$105,813	$10,111	$1,566,609	$259,784	203
Possible	$44,111	$10,111	$619,225	$98,843	121

This table indicates that injury costs are largely similar for single- and multi-vehicle CMCs, though single-vehicle CMCs have lower costs for the lower severities. The injury costs cover a relatively large range. This is likely partially due to the shortcomings of the police-reported injury severity. While the fatal sample sizes are smaller than would be desired, these costs were deemed to be reliable for the purposes of this study.

Similar calculations were conducted for median barrier crashes by injury severity, shown in Table 36.

Table 36 Average Median Barrier Crash Injury Costs by Injury Severity

Injury Severity	Average Injury Cost	Minimum Injury Cost	Maximum Injury Cost	Standard Deviation of Injury Cost	Number of Injuries
Concrete Barrier Crashes					
Killed*	$3,179,673	$3,179,673	$3,179,673	$0[1]	3
Incapacitating	$364,285	$10,111	$4,418,972	$758,854	82
Non-incapacitating	$115,094	$10,111	$4,418,972	$339,554	325
Possible	$48,760	$10,111	$1,248,690	$104,195	478
Cable Barrier Crashes					
Killed*	$2,270,378	$1,361,084	$3,179,673	$1,285,936	2
Incapacitating*	$745,303	$13,499	$4,418,972	$1,492,114	8
Non-incapacitating*	$35,830	$10,111	$142,036	$47,897	8
Possible*	$29,007	$13,499	$190,276	$50,804	12
Guardrail Barrier Crashes					
Killed*	--	--	--	--	0
Incapacitating*	$14,592	$13,499	$15,685	$1,546	2
Non-incapacitating*	$83,210	$11,719	$224,053	$121,978	3
Possible*	--	--	--	--	0

* Indicates small sample size; use with caution.
[1] These three fatal concrete barrier crashes all were assigned the diagnostic code “Died” and were thus assigned the same injury costs. Therefore, their standard deviation is zero.

As was the case in the first step, small sample sizes for fatalities and cable and guardrail crashes present an issue in the injury cost analysis. Guardrail crashes are particularly unreliable and should not be applied in cost analysis. Other than guardrail costs, these costs are largely consistent with concrete barrier and CMC injury costs. Barring earlier discussion about the application of the cable barrier analysis, the concrete and cable costs are viable for this study.

Property damage costs for PDO crashes were not supplied by the CODES database, which focused on property damage costs as part of the other costs element. PDO crash costs were estimated from the 2005 FHWA comprehensive costs shown in Table 9. The 2005 cost of $7,400 was adjusted to 2009 dollars based on a CPI factor of 1.0985 to be consistent with the

CODES adjustment methodology (66). The resulting estimated PDO comprehensive crash cost is $8,129[3].

The WisDOT Division of Transportation Investment Management (DTIM) uses costs adjusted from the 1994 FHWA study (40). For comparison, these costs were adjusted to 2009 dollars based on a CPI factor of 1.4476 using the same method. This calculation results in an estimated PDO cost of $2,895 per crash[4]. This increase indicates changes in automobile and emergency services costs between 1994 and 2005.

This PDO cost is used alongside the costs derived from CODES to estimate injury costs by crash severity. The costs to uninjured participants in injury and fatality crashes was assumed to be negligible. Property damage costs were assumed to be accounted for in the other costs component of the injury and fatality costs. However, this cost is derived from a national sample of crashes composed of both surface streets and freeways. It is expected that PDO crashes in this study high higher costs due to the speed and collision types, particularly for CMCs.

The CMC and concrete and cable median barrier injury costs are on same order of magnitude as the 2005 FHWA injury costs shown in Table 9. The CODES costs for each crash type in 2009 dollars and the injury costs provided by WisDOT DTIM are compared in Table 37. The DTIM costs are used for planning purposes and were derived by adjusting the 1994 FHWA costs to 2008 dollars.

Table 37 Crash Injury Costs Comparison

Injury Severity	Multi-Vehicle CMC	Single-Vehicle CMC	Concrete Median Barrier	Cable Median Barrier	FHWA/DTIM 2008 Costs
Killed	$2,869,315	$2,663,273	$3,179,673	$2,270,378	$3,494,668
Incapacitating	$525,201	$501,418	$364,285	$745,303	$241,939
Non-incapacitating	$207,256	$105,813	$115,094	$35,830	$48,388
Possible	$63,294	$44,111	$48,760	$29,007	$25,538

As shown in Table 37, CODES fatality costs are 10-35 percent lower than the FHWA costs, while incapacitating and non-incapacitating injuries are twice as large as the FHWA costs. Possible injury costs are largely equal. These discrepancies may be explained by the types of injuries sustained in CMC and median barrier crashes versus the larger FHWA data set comprised of all crash types and reflect 1994 roadway and vehicle conditions. Additionally,

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[3] The adjusted PDO cost value = 2005 cost value * adjustment factor = $7,400 * 1.0985 = $8,129.
[4] The adjusted PDO cost value = 1994 cost value * adjustment factor = $2,000 * 1.4476 = $2,895.

the FHWA costs are derived from national data while the CODES costs were adjusted for Wisconsin.

This step derived average costs by injury severity for each of the crash types. These costs can be applied to the average injuries per crash severity generated in the first step of this procedure.

Average Crash Severity Cost

The third step in the analysis procedure was to multiply the results of the first two steps to generate average crash costs by crash severity for each crash type. The results and discussion are presented in the following section.

6.2 Injury Cost Results

The results of the crash injury cost analysis described in the previous section are shown in the following tables. The single- and multi-vehicle CMC crash costs in 2009 dollars are shown in Table 38, which combines the data shown in Table 33 and Table 35 and the PDO cost estimates described above. These crash costs are calculated by multiplying the average number of injuries of each severity for each crash severity by the average crash costs for the corresponding injury severities. These costs were summed over all injury severities for each crash severity to develop average crash costs by crash severity. These costs capture the injury patterns and number of participants for each crash severity and type.

Table 38 Cross-Median Crash Average Crash Costs

Crash Severity	Injury Severity					Total Crash Cost
	Killed	Injury A	Injury B	Injury C	No Injury	
Multi-Vehicle CMCs						
Fatal	$3,794,901	$321,897	$163,799	$22,459	$0	**$4,303,057**
Injury	$0	$336,978	$192,880	$57,074	$0	**$586,933**
PDO	$0	$0	$0	$0	$8,129	**$8,129**
Single-Vehicle CMCs						
Fatal	$2,728,231	$244,594	$51,616	$7,531	$0	**$3,031,973**
Injury	$0	$140,148	$62,765	$23,151	$0	**$226,065**
PDO	$0	$0	$0	$0	$8,129	**$8,129**

The discussions of CMCs crash injury frequency and cost comparisons hold true for these final costs. Multi-vehicle CMCs have higher crash costs than single-vehicle CMCs as they have more injuries and participants with comparable injury costs.

The calculated average crash costs for median barrier crashes are shown in Table 39, which combines the data shown in Table 34 and Table 36 with PDO crash cost estimates. Guardrail barrier crashes were not included due to the sparse and absent injury costs described in previous sections.

Table 39 Median Barrier Crashes Average Crash Costs

Crash Severity	Injury Severity					Total Crash Cost
	Killed	Injury A	Injury B	Injury C	No Injury	
Concrete Barrier Crashes						
Fatal	$3,633,911	$0	$49,326	$6,966	$0	**$3,690,203**
Injury	$0	$28,348	$49,014	$38,154	$0	**$115,516**
PDO	$0	$0	$0	$0	$8,129	**$8,129**
Cable Barrier Crashes						
Fatal	$4,540,757	$1,863,258	$0	$0	$0	**$6,404,014**
Injury	$0	$74,530	$19,706	$20,305	$0	**$114,541**
PDO	$0	$0	$0	$0	$8,129	**$8,129**

The shortcomings of this CODES dataset described in the previous section are apparent in the summarized data. Fatal crashes for both concrete and cable barrier crashes are based on small sample sizes and are subjected to the particular characteristics of few crashes, such as the lack of non-incapacitating or possible injury costs for cable barrier fatal crashes. As a result, fatal crash costs of both barrier types are to be used with caution. While the injury costs used in this analysis are both comprehensive and specific by injury, the fatality costs lack specificity on particulars such as whether the patient was hospitalized. As a result, the fatal costs used in this study, while largely consistent with national studies, should be used with caution and due to the relative size of the costs, sensitivity tests should be conducted.

As described above, these cable barrier injury crash costs are largely reflective of the low-tension barrier types and have limited application to high-tension barrier evaluation. However, concrete barrier crash injury costs are based on a sizable sample of crashes and injuries. The associated injury crash costs are roughly 20 percent of multi-vehicle CMC costs and 50 percent of single-vehicle CMC costs. This is consistent with the authors' expectations as barrier crashes are largely less severe and involve collisions with barriers that designed to minimize injury.

Comprehensive injury crash costs were derived for each of the study crash types based on the injury patterns and severities suffered in those crashes. These costs are representative of the varied crash dynamics and number of participants of cross median and barrier crashes. Though the size and source of the data creates the need for caution when applying the cable and guardrail costs, this methodology resulted in reliable comprehensive costs by crash severity for single- and multi- CMCs and for concrete median barrier crashes. These costs can be utilized to monetize crashes for benefit/cost or other safety analysis.

7 ECONOMIC ANALYSIS

7.1 Predictive Warrant Development

In order to evaluate the efficacy of constructing a median barrier, economic analysis using present worth of benefits and costs was performed. For a fair evaluation, safety benefits accrued from observed accident and/or severity reduction should be compared to the physical cost of implementing and maintaining the median barrier. Such approach requires that a dollar value be placed on all cost and benefit elements related to the median barrier. Dollar value of benefits derived from saving a human life and reducing human suffering as a result of median barrier establishment is based on the difference in expected annual total crash costs between cross-median related crashes and median-barrier related ones. The annual expected crash costs calculation requires two components; number of crashes by crash type and associated crash costs, as demonstrated in Equation 28.

$$E(Total\ crash\ cost_t) = number\ of\ crashes_t \times E_c(crash\ cost_t)$$

$$= \sum_{all\ c} number\ of\ crashes_t \times crash\ cost_{t,c} \times f(c|t) \tag{28}$$

Where:

t = crash type (CMC or median barrier)

c = crash severity (fatal, injury, or property-damage only)

f(c|t) : distribution of crash severity for each crash type

Number of crashes by crash type (cross median and median barrier) was obtained by the prediction model derived in Chapter 5, using geometric and traffic characteristics of Wisconsin highway as predictors. Since number of multi and single vehicle CMCs were combined to be estimated, the proportion was later applied to the predicted total number of CMCs.

In order to come up with a measure of crash costs related to cross median and median barrier crashes, cost of crashes by crash type was averaged over levels of severity. It is important to note that crash costs vary significantly across different level of severity, especially when the human suffering is involved. To be consistent with other WisDOT projects, injury costs from the National Safety Council were used in this analysis and are shown in

Table 40.

Table 40 Average Crash Costs

	Multi-vehicle CMC	Single-vehicle CMC	Median Barrier Crash
Average Crash Cost ($)	945,193	176,696	28,669

Modeling severity proportion for each crash types by logistic regression was attempted. However, as regressing severity proportion within each crash type on independent variables have turned out to be not statistically significant than intercept-only model, simple average severity proportion of each crash type was used in place of logistic regression. Table 1 and Table 16 feature severity proportion of cross-median crashes and median barrier crashes respectively.

Combining the severity proportion and average cost of crashes by crash severity components, we can come up with an annual expected cost measure per one cross-median crash and one median-barrier crash, respectively. Expected annual total cost of one multi-vehicle CMC is $945,193, whereas the equivalent for one single-vehicle CMC is $176,696. By applying the proportion of multi-vehicle (0.80) and single-vehicle (0.20) CMCs from the dataset, expected total annual cost of one cross median crash comes around to $330,395. Expected total annual cost one median barrier crash is calculated to be $28,669.

In order to obtain present value of benefits accrued from erecting median barrier, annual difference between expected total costs of cross median crashes and median barrier crashes should be discounted over the duration of a median barrier, as shown in Equation 29. The service life expectancy of a median barrier is assumed to be 10 years and the annual dollar value per year is discounted at an interest rate of 3%.

$$PV_{benefits} = \sum_{t=0}^{9} \frac{E(crash\ cost_{cross\ median}) - E(crash\ cost_{median\ barrier})}{(1+i)^t} \tag{29}$$

Where:

$$i = interest\ rate\ (3\%)$$

Cost of establishing a median barrier on highway is the sum of the physical cost of constructing a median barrier and a present value of annual maintenance cost, as indicated by Equation 30. The construction cost of median barrier is assumed to be $100,000 per mile.

$$PV_{costs} = 100000 + \sum_{t=0}^{9} \frac{number\ of\ crashes\ \times maintenance\ cost\ per\ crash}{(1+i)^t} \tag{30}$$

In order to characterize traffic and geometric characteristics of highway where median barrier has real economic benefit, expected number of crashes, which is the key component in deriving the present value of benefit and cost equations, were calculated on varying levels of median width and ADT. An assumption is made that the segment on a highway does not have any bridges, curves or ramps for the purpose of comparison. Table 41 show the benefits and costs of setting up a median barrier based on median width and directional ADT on highway segments.

Table 42 shows the benefit/cost ratios.

Table 41 Median Barrier Benefit/Cost Analysis by Median Width and ADT

Dollar value of Benefits / Costs		Directional ADT (vehicle/day)					
		5,000	10,000	20,000	30,000	40,000	50,000
Median width (ft)	10	-45414 / 104719	-46388 / 107007	-32699 / 110405	-11267 / 113112	13652 / 115451	40542 / 117548
	20	-46397 / 104719	-48079 / 107007	-35604 / 110405	-15256 / 113112	8657 / 115451	34595 / 117548
	30	-47369 / 104719	-49750 / 107007	-38478 / 110405	-19201 / 113112	3716 / 115451	28713 / 117548
	40	-48331 / 104719	-51403 / 107007	-41320 / 110405	-23104 / 113112	-1169 / 115451	22895 / 117548
	50	-40282 / 104719	-53039 / 107007	-44131 / 110405	-26963 / 113112	-6002 / 115451	17141 / 117548
	60	-50223 / 104719	-54656 / 107007	-46912 / 110405	-30781 / 113112	-10782 / 115451	11450 / 117548
	70	-51153 / 104719	-56256 / 107007	-49662 / 110405	-34557 / 113112	-15510 / 115451	5822 / 117548
	80	-52074 / 104719	-57838 / 107007	-52838 / 110405	-38291 / 113112	-20186 / 115451	254 / 117548
	90	-52984 / 104719	-59403 / 107007	-55072 / 110405	-41984 / 113112	-24811 / 115451	-5251 / 117548
	100	-53884 / 104719	-60951 / 107007	-57733 / 110405	-45638 / 113112	-29385 / 115451	-10697 / 117548

Table 42 Median Barrier Benefit/Cost Ratios by Median Width and ADT

Dollar value of Benefits / Costs		Directional ADT (vehicle/day)					
		5,000	10,000	20,000	30,000	40,000	50,000
Median width (ft)	10	-0.434	-0.434	-0.296	-0.100	0.118	0.345
	20	-0.443	-0.449	-0.322	-0.135	0.075	0.294
	30	-0.452	-0.465	-0.349	-0.170	0.032	0.244
	40	-0.462	-0.480	-0.374	-0.204	-0.010	0.195
	50	-0.385	-0.496	-0.400	-0.238	-0.052	0.146
	60	-0.480	-0.511	-0.425	-0.272	-0.093	0.097
	70	-0.488	-0.526	-0.450	-0.306	-0.134	0.050
	80	-0.497	-0.541	-0.479	-0.339	-0.175	0.002
	90	-0.506	-0.555	-0.499	-0.371	-0.215	-0.045
	100	-0.515	-0.570	-0.523	-0.403	-0.255	-0.091

The results indicate that median barrier has positive benefits on highway segments where the width of median is between 0 and 80ft and directional ADT is between 40,000 and 50,000 vehicles/day and where width is between 0 and 30ft and directional ADT is between 30,000 and 40,000 vehicles/day. None of the highway segments show benefits-to-costs ratio of higher than 1, suggesting that the dollar value of benefits as a result of safety improvement does not exceed the cost of setting up and maintaining a median barrier.

7.2 Warrant Analysis

The benefit/cost warrant shown in

Table 42 indicates that median barrier is a more effective safety treatment at higher traffic volumes and with smaller median widths. This result is intuitive and is consistent with the pattern shown by the Pennsylvania warrant shown in Figure 9 and Figure 10 and by the Texas warrant shown in Figure 11. However, the Pennsylvania warrant indicates that the benefit/cost ratio is over 1.0 for highway locations with greater than 20,000 ADT. The Texas study included greater traffic volumes and median widths than are present in Wisconsin, though Wisconsin data that fits into the "Barrier Normally Required" zone still has a benefit/cost ratio of less than 1.0.

However, this result is subject to the difficulties in comparing the characteristics of the roadway sections with and without barrier currently present in Wisconsin, as discussed in Section 5.2.3. The differences in ADT, shown in Figure 24, make direct comparison difficult as the predicted number of CMCs is based largely on low ADTs while the predicted number of MBCs is based largely on high ADTs. This dynamic skews the comparison and reduces the calculated benefits drastically, which in turn, reduces the benefit/cost ratios shown in

Table 42.

Pennsylvania’s dataset for barrier crashes is based on concrete barrier crashes on rural interstate and turnpikes in Pennsylvania (*5*). Data from 52 counties (the counties in the Houston, Dallas, Fort Worth, San Antonio and Austin metropolitan areas and those connecting them via interstate or urban/rural freeway segments) was used for modeling median crashes in Texas (*59*). Tables 44 and 45 show the benefit/cost ratios computed using the Wisconsin CMC model with Pennsylvania’s and Texas’s MBC models. The benefit/cost ratios shown in Tables 44 and 45 are comparable to the Pennsylvania and Texas warrants illustrating that the disparity in datasets used for developing the CMC and MBC frequency models in Wisconsin is biasing the benefit/cost ratios.

Table 43 Median Barrier Benefit/Cost Ratios by Median Width and ADT with Pennsylvania Median Barrier Crash Frequency Model

Dollar value of Benefits / Costs		**Directional ADT (vehicle/day)**					
		5,000	**10,000**	**20,000**	**30,000**	**40,000**	**50,000**
Median width (ft)	10	1.269	2.209	3.827	5.262	6.586	7.830
	20	1.252	2.180	3.778	5.195	6.502	7.731
	30	1.235	2.152	3.729	5.128	6.419	7.632
	40	1.219	2.123	3.680	5.062	6.337	7.535
	50	1.202	2.095	3.633	4.997	6.256	7.439
	60	1.186	2.067	3.585	4.933	6.176	7.344
	70	1.170	2.040	3.538	4.869	6.097	7.250
	80	1.154	2.013	3.492	4.806	6.018	7.158
	90	1.138	1.986	3.446	4.743	5.940	7.066
	100	1.123	1.959	3.401	4.682	5.864	6.975

Table 44 Median Barrier Benefit/Cost Ratios by Median Width and ADT with Texas Median Barrier Crash Frequency Model

Dollar value of Benefits / Costs		Directional ADT (vehicle/day)					
		5,000	10,000	20,000	30,000	40,000	50,000
Median width (ft)	10	0.525	0.604	0.470	0.178	-0.177	-0.558
	20	0.631	0.816	0.875	0.754	0.547	0.294
	30	0.724	1.002	1.237	1.274	1.208	1.082
	40	0.804	1.164	1.558	1.741	1.809	1.805
	50	0.873	1.306	1.842	2.159	2.352	2.463
	60	0.932	1.428	2.090	2.529	2.838	3.058
	70	0.982	1.533	2.308	2.857	3.272	3.594
	80	1.024	1.624	2.497	3.144	3.656	4.072
	90	1.060	1.701	2.660	3.395	3.994	4.496
	100	1.090	1.766	2.800	3.613	4.290	4.870

As more median barrier, particularly more cable barrier, is installed around Wisconsin, MBC data that is more comparable to the current CMC database in Wisconsin will become available and can be used to revise the Warrant for Wisconsin.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The primary objective of this study was to develop a predictive median barrier warrant for Wisconsin. Towards this goal data from a diverse array of sources was assembled and transformed to be utilized by the modeling effort. Crash data was queried and manually filtered to assemble single- and multi-vehicle CMCs and median barrier crash data sets.

A software method was pioneered to visually inventory roadway characteristic data from the Photolog. The Photologger tool can accurately locate roadway features and efficiently populate a database for any visible roadway element. The spatial mismatch between the Photolog-collected data and STN was addressed to integrate the crash and roadway data for use in the modeling process.

Crash prediction models were formulated to describe the cross median and barrier crash frequencies and severities. Crash severity models were constructed for both CMC types and median barrier crashes. No geometric factors were shown to significantly affect crash severity. This result implies that while geometric factors have no effect on their own, driver and environmental factors may affect crash severity, as was shown in preliminary analyses in this study and by Lu, et. al. (17). These factors could point to mitigations beyond median barrier that could reduce crash severity.

Crash frequency models were formulated for CMCs to calculate the expected number of crashes based on roadway geometry. The negative binomial model indicated median width, ADT, bridges, curves, and entrance and exit ramps affected CMC occurrence. The model can be used to estimate the expected number of CMCs per year for a study segment. Similarly, crash frequency models were developed for MBCs to determine the expected number of crashes where median barrier is present. The modeling results indicate that ADT, curves, and ramps impact the occurrence of MBCs.

The Wisconsin CODES database provided comprehensive injury costs based on the injury types and severities suffered by participants in study crashes. The cost precision and ability to capture subtle injury patterns for each crash type make this method a marked improvement over less exacting KABCO or crash severity average costs. Multi-vehicle CMCs resulted in both more total injuries and more severe injuries than single-vehicle CMCs. Concrete median barrier crashes resulted in lower severities than CMCs. Too few cable and guardrail barrier crashes were available to obtain meaningful results for those barrier types. Concrete median barrier injury crashes are roughly 20 percent of multi-vehicle CMC costs and 50 percent of single-vehicle CMC costs. Fatal crash costs are more similar across the three types and PDO crashes were assigned default values.

Using the crash frequency models developed for CMCs and MBCs and WisDOT costs for crashes and barrier installation and maintenance, predictive median barrier warrant was developed. The results indicate that median barrier has positive benefits on highway segments where the width of median is between 0 and 80ft and directional ADT is between 40,000 and 50,000 vehicles/day and where width is between 0 and 30ft and directional ADT is between 30,000 and 40,000 vehicles/day. None of the highway segments show benefit/cost ratio greater than 1. The data used to develop frequency models for CMC is mostly from rural Wisconsin (with lower ADT) while the data for MBC model is mostly from Greater Milwaukee area (with higher ADT). This disparity in datasets skews the comparison and reduces the calculated benefits drastically, which in turn, reduces the benefit/cost ratios.

Benefit/cost ratios were computed using the MBC frequency models developed in Pennsylvania and Texas. B/C ratios calculated using the Pennsylvania were greater than 1 for all the combinations of median width and ADT and ranged from 1.123 to 7.830. B/C ratios calculated using the Texas MBC data ranged were positive for all but two conditions and the positive values ranged from 0.178 to 4.87.

8.2 Recommendations

The crash severity models in this report are mostly based on concrete barrier crashes from the Greater Milwaukee area. An important improvement to the median barrier crash frequency and severity models would be more data on crashes involving the newer, high-tension cable barriers. Crash data should be collected as more high-tension cable barrier is installed. When new MBC data is available, the methods outlined in this report can be applied to revise the predictive warrant to better capture the effect of installing median barrier on crash occurrence and severity.

Preliminary analysis indicates that driver and behavioral causes also contribute to crash occurrence and severity. Investigations into those relationships may reveal other cross-median crash mitigations or additional rationale to install median barrier.

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