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Calibration of the Highway Safety Manual Given Safety Performance Functions for Rural Multilane Segments and Intersections in Kansas

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The Highway Safety Manual (HSM) provides models and methodologies for safety evaluation and prediction of safety performance of various types of roadways. However, predictive methods in the HSM are of limited use if they are not calibrated for local conditions. In this study, calibration procedures given in the HSM were followed for rural segments and intersections in Kansas. Results indicated that HSM overpredicts fatal and injury crashes and underpredicts total crashes on rural multilane roadway segments in Kansas. Therefore, existing safety performance functions (SPFs) must be adjusted for Kansas conditions, in order to increase accuracy of crash prediction. This study examined a way to adjust HSM calibration procedures by development of new regression coefficients for existing HSM-given SPF. Final calibration factors obtained through modified SPFs indicated significant improvement in crash prediction for rural multilane segments in Kansas. Additionally, obtained calibration factors indicated that the HSM is capable of predicting crashes at intersections at satisfactory level.

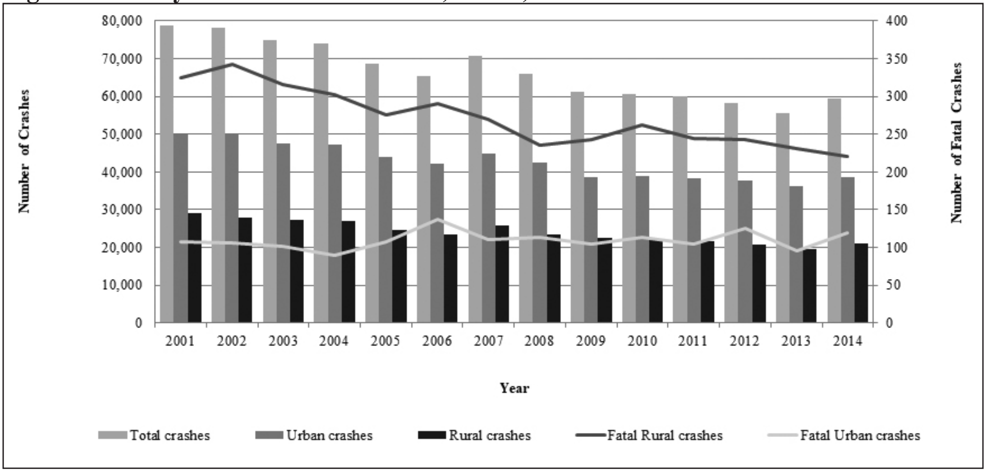
INTRODUCTION

A report in 2016 ranked motor vehicle crashes as one of the top ten causes of death in the United States (Heron 2016). Relative to 2011, fatal highway crashes increased by 1.7% to 29,989 in 2014, equivalent to an average of 90 daily fatalities (NHTSA 2015). In Kansas, rural roads account for 90.3% of the 226,504 km (140,476 miles) of total roadway (KDOT 2015). Travel on rural roads accounts for 48.5% of all vehicle miles (60% for state highways) (KDOT 2015). According to 2014 Kansas crash data, 35% of total vehicle crashes occurred on rural roads, while fatal crashes on rural roads accounted for over 66% of total fatal crashes on rural and urban roads (KDOT 2015). Figure 1 shows the distribution of rural, urban, fatal rural, fatal urban, and total crashes over a 14-year period, indicating higher fatal crashes occurring on the rural highways of Kansas. These fatality records are a matter of concern to highway safety professionals because they show that the proportion of high-level injury crashes is most problematic in rural areas. In general, Kansas has a low population density, and a majority of the roadways are located in rural areas. Because of the significant amount of travel on rural roads and the relatively alarming safety records of rural roads compared with urban roads, effective crash prevention methods must be developed.

In 2010, the American Association of State Highway and Transport Officials (AASHTO) published the Highway Safety Manual (HSM), which is the culmination of decades of safety research and practices (AASHTO 2010). The HSM presents models and methodologies for analyzing highway types based on safety. Procedures to calibrate predictive models are provided in Part C – Appendix A of the HSM (AASHTO 2010). Crash predictive methods in the HSM allow planners, designers, and reviewers to comprehensively assess expected safety performance of roadway design using methodologies endorsed by the Federal Highway Administration (FHWA). Predictive methods in the HSM were developed based on national trends and statistics or data from Texas, California, Minnesota, New York, and Washington from 1991 through 1998 (Bahar 2014). As a result, these methodologies are of limited use if they are not calibrated for individual jurisdictions or local conditions. Calibration ensures achievement of the most realistic and reliable crash estimates.

As safety conditions change with time, transportation agencies must use calibrated HSM models. At the time of this study, the Kansas Department of Transportation (KDOT) was able to apply the rural two-lane model from the HSM because a study had been completed to calibrate such facilities (Lubliner and Schrock 2012). However, when the analysis of a multilane facility was requested, it could not have been completed without calibration. Therefore, an acceptable method to predict crashes for rural multilane highway segments and intersections in Kansas must be identified or developed. Availability of an effective safety performance function (SPF) that predicts the number of crashes on a section of highway and identifies potential severe crash locations would enable designers to create safer roads and decrease roadway construction and maintenance costs if, for example, 2.4-m (8 ft.) shoulders were determined to be as beneficial as 3-m (10 ft.) shoulders.

Figure 1: Yearly Distribution of Urban, Rural, and Total Crashes in Kansas



The predictive methods given in chapter 11 of the HSM focus on rural multilane highways. According to the HSM, rural four-lane highways are categorized as rural multilane highways, and six-lane divided highways are not considered under rural multilane segments category. Therefore, this study was limited to calibrations of rural four-lane divided and undivided highways.

The objective of this study was to analyze HSM calibration procedures for rural four-lane segment and intersection models in Kansas. If the crash prediction was inadequate after performing calibration, then the methodology will be modified to allow the HSM to more accurately reflect local conditions of Kansas. This paper begins with background discussion of the HSM methodology, followed by past research conducted in similar contexts. A subsequent section discusses the HSM methodology and various data used in the analysis. Analysis results are presented in a following section, and the last section summarizes and concludes the study with future recommendations.

LITERATURE REVIEW

The HSM requires a three-step process in order to predict the expected number of crashes for any highway facility given a set of values for input variables. The first step requires calculation of the SPF, which is the regression equation that calculates the dependent variable, or predicted crash frequency, based on independent variables. The second step requires multiplying by crash modification factors (CMFs) for each independent variable. In the third step, the calibration factor (*C*) is obtained by dividing the number of observed crashes by the number of predicted crashes (AASHTO 2010). Since the first edition of the HSM provided general methodologies and statistical tools for estimating expected numbers of crashes, researchers have attempted to validate and apply the methodologies to particular areas and specific roadway facility type. In particular, safety effectiveness of multiple roadway treatments has become essential for the HSM methodology validation. This section reviews and discusses recent studies in HSM calibration.

Qin et al. (2014) applied HSM methodology for rural two-lane, two-way highway segments in South Dakota. Results showed that South Dakota-specific crash type distribution for CMFs differed significantly from default crash proportions presented in the HSM. For rural two-lane roadways, the HSM method without modification underestimated South Dakota crashes by 35%. Mehta and Lou (2013) evaluated the applicability of the HSM predictive methods for two-lane, two-way rural highways and four-lane divided highways in Alabama. In their study, the HSM-given method for calibration factor estimation was proven to be a satisfactory approach since it fits the Alabama data well, although the approach did not predict crash scenario as well as the optimal state-specific SPF. In a study conducted by Sun et al. (2013), results indicated close agreement between the number of crashes predicted by the HSM and the number of crashes observed in Missouri for site types.

Sun et al. (2011) calibrated the SPF for rural multilane highway segments in Louisiana. The calibration parameters indicated that the predicted model from the HSM for rural divided multilane highways underestimated the number of expected crashes. Srinivasan and Carter (2011) compared the performance of SPF developed using negative binomial regression to the HSM methodologies for roadways in North Carolina. They found that segments within the influence of at-grade intersections and railroad grade crossings (250 ft. on either side of at-grade intersections or railroad grade crossings) significantly affected crash prediction on rural segments. Jalayer et al. (2015) provided a revised method to help state and local agencies predict the number of crashes without developing new calibration factors. Srinivasan and Bauer (2013) used the negative binomial model for the SPF, requiring the evaluation of average annual daily traffic (AADT) as the mandatory variable, while other factors (i.e., roadway geometry, traffic control features, etc.) were left to the discretion of the state DOT.

Lubliner and Schrock (2012) analyzed predictive methods for calibrating rural two-lane segments for Kansas highways. Based on study results, combined statewide calibration of total crashes was recommended for aggregate analyses that include multiple sections. The calibration factor obtained while considering animal crash frequency by county as a variable was recommended for project-level analysis performed on Kansas rural two-lane highways.

Lord et al. (2008) developed a methodology that predicts the SPF of elements considered in the planning, design, and operation of non-limited-access rural highways. The significance and influence of sample size were shown to significantly affect the calibration process. Shin et al. (2014) completed the calibration process for SPFs in the HSM for the Maryland Department of Transportation. Their study calculated the confidence interval for a range of calibration factors that would contain 90% of the population. Another study (Banihashemi 2012) that used data from the state of Washington investigated the ideal sample size for calibrating the HSM models and sensitivity related to sizes of samples used for the HSM calibration factors by evaluating factor qualities. Results showed that a single criterion for sample size may not be the ideal methodology.

Bornheimer et al. (2012) tested the original HSM-given crash prediction model (CPM) to state-specific calibrated CPMs and new, independent CPMs to determine the best model for rural two-lane highways in Kansas. Almost 483 km (300 miles) of highway geometric data were collected to create the new models using negative binomial regression. Lane width and roadside hazard rating consistently were the most significant variables in each model. These models were compared to CPMs calibrated for use by the HSM using nine validation segments (Bornheimer et al. 2012). However, comparison was difficult due to the large amount of animal-related crashes, accounting for 58.9% of crashes on Kansas highways.

A recent study conducted by Kweon et al. (2014) examined ways to customize the HSM procedures and then developed guidance to help highway agencies choose optimum customization options for their jurisdictions. Based on empirical data, the guidance recommended the best option for crash prediction for Virginia. The developed guidance flowchart can be used by agencies interested in customizing the HSM procedures. The developed flowchart can also be applied in addition to expert opinion and data analysis; however, increased reliance on data analysis would require additional time and resources (Kweon et al. 2014).

METHODOLOGY

Because the SPF significantly affects crash prediction, SPF calibration is one of the most critical and effective steps in the prediction process. Ideally, base conditions should represent typical roadway geometries, guaranteeing a sizable sample to develop statistically robust models. However, the most representative roadway type may vary by state or region. If the sample size that matches base conditions is small, then SPF calibration may not be rigorous or sufficiently representative of the larger population.

The standard approach for obtaining calibration factors given in the HSM for roadway segments can be summarized in the following five steps:

- Identify desired facility types.
- Select segments from the desired facility types.
- Collect required data for those segments.
- Apply the HSM predictive models.
- Compute calibration factors.

Facility types considered in the current study included rural four-lane divided and undivided segments. All segments under these categories were selected as analysis locations, and then the HSM methodology was followed for calibration, as described in the following sections.

Safety Performance Function

SPFs are regression equations that calculate the dependent variable, or predicted crash frequency, based on independent variables. Because this study attempted to determine suitability of HSM-specified methods, SPFs in the HSM were used to calculate the number of predicted crashes (AASHTO 2010). SPFs in the HSM differ from SPFs typically found in other crash prediction tools because they predict an average crash frequency under "base conditions" defined in the HSM. The base conditions for rural four-lane divided and undivided highways are given in Table 1. CMFs convert predictions under base conditions made by SPFs into predictions under existing conditions (AASHTO 2010). SPF for a rural four-lane highway segment is estimated as follows:

$$(1)\ N_{SPF}=e^{[a+b\times\ln(AADT)\ +\ \ln(L)]}$$

where, N_{SPF} is the base total expected average crash frequency for the rural segment, e is the exponential, ln is the natural logarithm, $AADT$ is the Average Annual Daily Traffic on the highway segment, L is the length of the highway segment (miles), and a and b are the regression coefficients.

Table 1: Base Condition for SPFs

Four-lane Divided Highways		Four-lane Undivided Highways	
Variable	Base Condition	Variable	Base Condition
Lane width	12 feet	Lane width	12 feet
Right shoulder width	8 feet	Shoulder width and type	6 feet, paved
Median Width	30 feet	Side-slope	1:7 or flatter
Lighting	None	Lighting	None
Automated Speed Enforcement	None	Automated Speed Enforcement	None

The SPF for rural intersections has two alternative functional forms in the HSM: one form considers AADT on major and minor road approaches (Equation 2), and the other form considers combined AADT on major and minor road approaches (Equation 3).

$$(2)\quad N_{spf\,int} = \exp[a + b \times \ln(AADT_{maj} + c \times \ln(AADT_{min})]$$

$$(3)\quad N_{spf\,int} = \exp[a + d \times \ln(AADT_{total})]$$

where, $N_{spf\,int}$ is the SPF estimate of intersection-related expected average crash frequency for base conditions, exp is the exponential, $AADT_{maj}$ is the AADT (vehicles per day) for major-road approaches, ln is the natural logarithm, $AADT_{min}$ is the AADT (vehicles per day) for minor-road approaches, $AADT_{total}$ is the AADT (vehicles per day) for major-road and minor-road combined approaches, and *a, b, c,* and *d* are the regression coefficients.

Crash Modification Factors

The SPF is multiplied by CMFs for each independent variable given in the HSM, as shown in Equation 4. CMFs pertain only to changes in design or operation characteristics (e.g., lane width and shoulder width) typically under the control of highway engineers and designers as compared with characteristics such as climate, driver behavior, and crash reporting threshold, which could not be controlled (Kweon et al. 2014).

$$(4)\quad N_{Predicted} = N_{SPF} \times C_r \times (CMF_1 \times CMF_2 \times \ldots\ldots\ldots\ldots \times CMF_i)$$

where, $N_{Predicted}$ is the adjusted number of predicted crash frequency, N_{SPF} is the total predicted crash frequency under base condition, CMF_i is the CMFs for i^{th} variable, and C_r is the calibration factor.

CMF for the presence of lighting was calculated using Equation 5.

$$(5)\quad CMF_{lighting} = 1 - [(1 - 0.72 \times P_{inr} - 0.83 \times P_{pnr}) \times P_{nr}]$$

where, $CMF_{lighting}$ is the crash modification factor for presence of lighting at a segment, P_{inr} is the proportion of nighttime crashes for unlighted segments that involve fatality/injury, P_{pnr} is the proportion of nighttime crashes for unlighted segments that involve property damage only (PDO) crashes, and P_{nr} is the proportion of total crashes for unlighted segments that occur at night.

CMFs for intersection skew angle (The difference between 90 degrees and the smallest acute angle between the intersection legs is referred to as the intersection skew angle.), presence of right turn lane on major road, presence of left-turn lane on major road, and presence of lighting posts were obtained using charts and equations provided in the HSM. SPFs at each intersection were multiplied by corresponding CMFs for all intersection-related attributes.

Calibration Factor

SPFs in the HSM were developed using data from jurisdictions and/or time periods rather than where or when such SPFs should be utilized. For example, default HSM-SPFs for rural multilane highways were developed using data from Texas, California, Minnesota, New York, and Washington from 1991 through 1998 (Bahar 2014). However, the general level of crash frequencies may vary substantially from one jurisdiction to another and/or from one year to another due to changes in climate, driver behavior, and crash reporting thresholds among many other changes (AASHTO 2010). Therefore, in order to produce predictions that reflect levels of crash frequencies in jurisdictions and/or years of interest, the predicted number of crash frequencies must be adjusted using the calibration factor. Calibration factors should be determined for each facility-site type. Calibration factor (C_r) is obtained by dividing the total number of observed crashes by the total number of predicted crashes, as shown in Equation 6. Observed crash frequencies are obtained using a crash database, and predicted crashes are obtained using HSM methodology.

$$(6)\quad C_r = \frac{\Sigma \text{Observed crashes}}{\Sigma \text{Predicted crashes}}$$

ANALYSIS DATA

This study obtained highway crash data from the Kansas Crash Analysis and Reporting System (KCARS) database, consisting of all police-reported crashes in Kansas (KDOT (b) 2017). Geometric data were obtained from the state's highway inventory database, Control Section Analysis System (CANSYS), which provided the AADT volume for 2013, the most recent year for which data were available at the beginning of the study (KDOT (a) 2017). Accordingly, the study duration was determined to be 2011–2013.

Kansas Crash Analysis and Reporting System

The KCARS database consists of several tables that contain details of each crash occurring in Kansas roadways, such as crash location, light conditions, weather conditions, road surface type, road conditions, road character, road class, road maintenance information, date of crash, time of crash, day of crash, accident class, and manner of collision. Multiple tables were combined and queries were run to filter out crashes on rural multilane highways and five levels of crash severity.

Control Section Analysis System

The CANSYS database contains information about the geometrics, condition, and extent of the more than 16,093 km (10,000 miles) of roads in Kansas's highway system, as well as a small proportion of local roadways not on the state highway system.

CANSYS data are collected at random intervals from various sources, and the database is typically used for high-level analyses for network screening and trend evaluations. For this study, data were sorted by route name and county so that every mile was accounted for, but no data were counted twice. Based on data requested, county mile posts of beginning and ending of segments, coordinates of beginning and ending mile posts of segments, lane width, left shoulder width, right shoulder width, median width, side slope (slope of the cut or fill expressed as the ratio of horizontal distance to vertical distance), and AADT for 2013 were obtained from this database. CANSYS also contains the route ID, route direction, number of lanes, and outer shoulder and inner shoulder description. All the sources of different variables used in the study are summarized in Table 2. The HSM considers the presence of automated speed enforcement as optional (desired) data, and automated speed enforcement is not used in Kansas. Once all data were obtained, they were used in accordance with the HSM methodology.

Table 2: Data Sources for Rural Four-Lane Segments used in Calibration

Data Description	Source
AADT	CANSYS
Lane Width	CANSYS
Median Width	CANSYS
Shoulder Width	CANSYS
Sideslope	CANSYS
Presence of Lighting	Google Maps®
Number of Crashes	KCARS
Presence of Automated Speed Enforcement	Not Applicable
Segment locations	CANSYS

STUDY SEGMENTS & INTERSECTIONS

A total of 281 rural four-lane divided (4D) segments and 83 four-lane undivided (4U) segments obtained from CANSYS database were used for calibration in conjunction with HSM methodology. The rural four-lane segments were present on both Kansas and US highways. The number of observed crashes for all 4D segments in Kansas was 910 per year, and the number of crashes for 4U segments was 36 per year. All segments met the HSM segment length requirement of 0.16 km (0.1 mile). Lane width, shoulder width, median width, and side slope were obtained from the CANSYS database.

Figures 2 (a) and (b) show the distribution of 4D and 4U segments, respectively, within the state of Kansas. The markers indicate beginning and end of a roadway segment, respectively, and a small dot indicates a crash location. One segment on each figure was zoomed for clear illustration of that particular section.

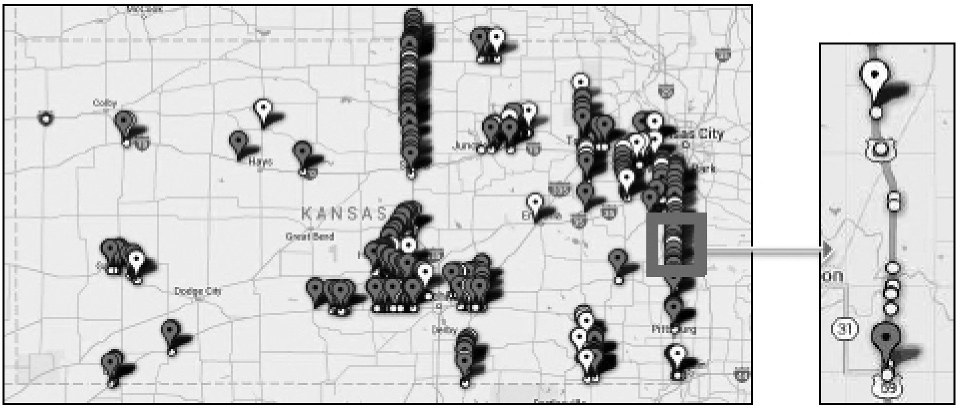
The calibration of rural multilane intersections using HSM methodology pertains to a three-leg intersection with minor-road stop control (3ST), four-leg intersection with minor-road stop control (4ST), and four-leg signalized intersection (4SG). To date, the 4SG intersection calibration methodology is not complete in HSM, so only 4ST and 3ST intersections were calibrated in this study. The intersections were preliminarily obtained from the CANSYS database. However, the CANSYS database did not have a complete list of intersections available at the time of this study, and most of the required intersection-related information was missing. Therefore, existing intersections were found via Google Maps®.

Each intersection was zoomed to Street View in these maps to obtain corresponding intersection skew angle, presence of right-turn lane on major road, presence of left-turn lane on major road, and presence of lighting posts at intersections. Several intersections were difficult to determine whether they were 3ST or 4ST, so the identified intersections were cross-checked using KDOT-monitored videologs.

After completing data collection via Google Maps and KDOT videologs, a total of 199 4ST intersections and 65 3ST intersections at minor approaches were considered in the calibration. Because the HSM provides no precise guidelines regarding the number of observed crashes at intersections, observed crashes at intersections were counted using two methods.[1] The first method considered crashes within an intersection-box of 300 ft. along each approach leading to the intersections regardless of whether or not crashes were intersection-related. Figure 3 shows an example of an intersection-box at an intersection. The second method considered the "intersection related" column in the KCARS database, which distinguishes whether or not crashes are intersection-related irrespective of crash distance from named intersections.

Figure 2: Rural Multilane Segments and Crash Locations in Kansas

(a) Rural four-lane divided road segments



(b) Rural four-lane undivided road segments
(c)

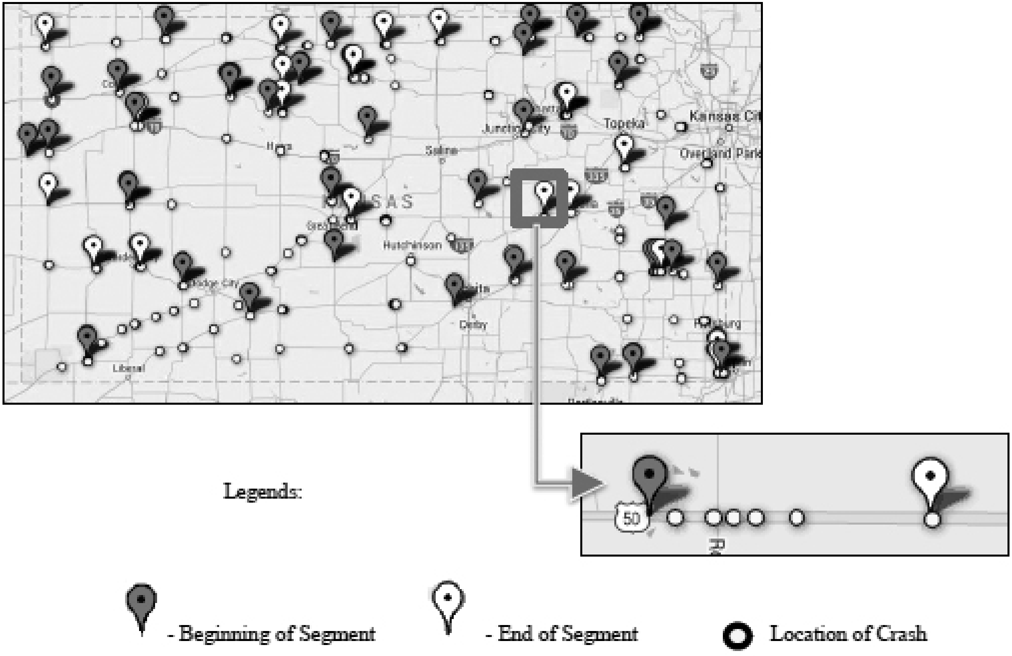
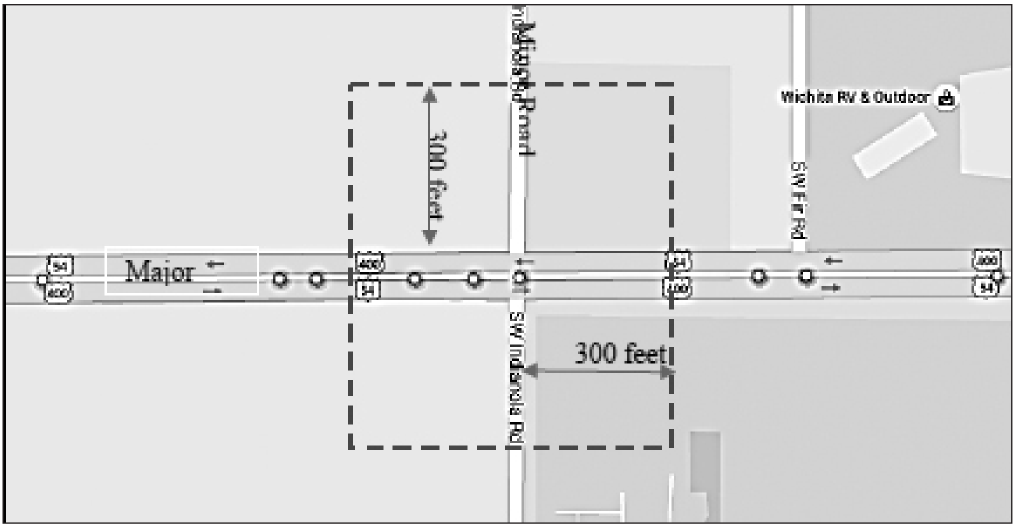


Figure 3: Intersection-Box Demonstration



ANALYSIS AND RESULTS

Crash Situation in Rural Four-lane Highways in Kansas

Table 3 demonstrates distribution by collision type for specific crash severity levels on rural four-lane roadway segments. This table also compares the Kansas crashes to the default distribution given in the HSM (AASHTO 2010). HSM recommends obtaining jurisdiction-specific crash proportions for calibrations. The Kansas Motor Vehicle Accident Report contains five categories for light conditions: daylight; dawn; dusk; dark: street lights on, dark: no street lights; and unknown. Crashes for daylight and dawn were assigned to the daylight category. Once the crashes were categorized as fatal, injury, or PDO, the crashes were assigned using collision types from the Kansas Motor Vehicle Accident Report.

HSM Calibration – Four-lane Segments

In order to perform calibration of SPFs given in the HSM, study segments were obtained from the CANSYS database. Figures 4 and 5 show the distribution of crashes throughout the 4D and 4U segments, respectively. Total crashes for 4D greatly exceeded the HSM requirement of 100 crashes per year, but all 4U segments combined did not meet this requirement. However there were more than 30-50 segments meeting the HSM requirement for segment length. Therefore, the HSM recommendation to consider all available segments with existing crashes was followed for this study (AASHTO 2010).

Table 3: Comparison of Crashes for Kansas Rural Four-Lane Highways by Collison Type

Collision Type	2011			2012			2013			3-year Kansas Average			HSM Default Value		
	Total (%)	Fatal and Injury (%)	PDO (%)	Total (%)	Fatal and Injury (%)	PDO (%)	Total (%)	Fatal and Injury (%)	PDO (%)	Total (%)	Fatal and Injury (%)	PDO (%)	Total (%)	Fatal and Injury (%)	PDO (%)
Head on	9.47	12.70	3.00	8.03	11.95	0.50	8.70	13.05	0.00	8.73	12.57	1.17	0.60	1.30	0.20
Rear End	34.67	33.00	38.10	29.43	23.35	41.60	37.67	32.85	47.30	33.92	29.73	42.33	11.60	16.30	8.80
Sideswipe	16.27	7.05	34.10	18.93	11.70	33.30	15.07	7.60	30.00	16.76	8.78	32.47	4.30	2.70	5.30
Angle	36.73	46.70	16.80	40.63	52.80	16.30	35.27	44.95	15.90	37.54	48.15	16.33	4.30	4.80	4.10
Other	2.87	0.55	8.10	2.97	0.30	8.30	3.20	1.50	6.60	3.01	0.78	7.67	79.20	74.90	81.60

Figure 4: Distribution of Crash Frequency on Four-Lane Divided Segments in Kansas

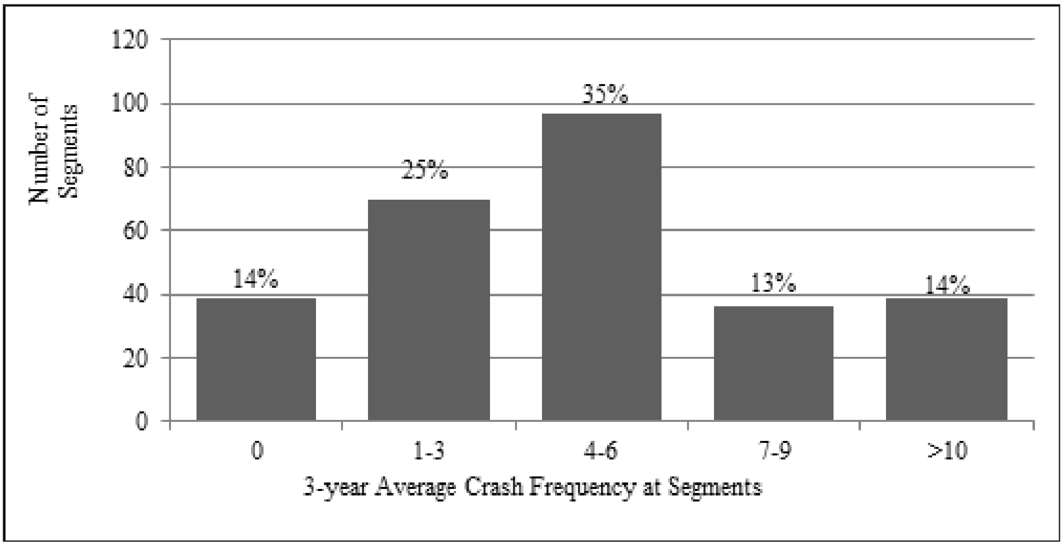
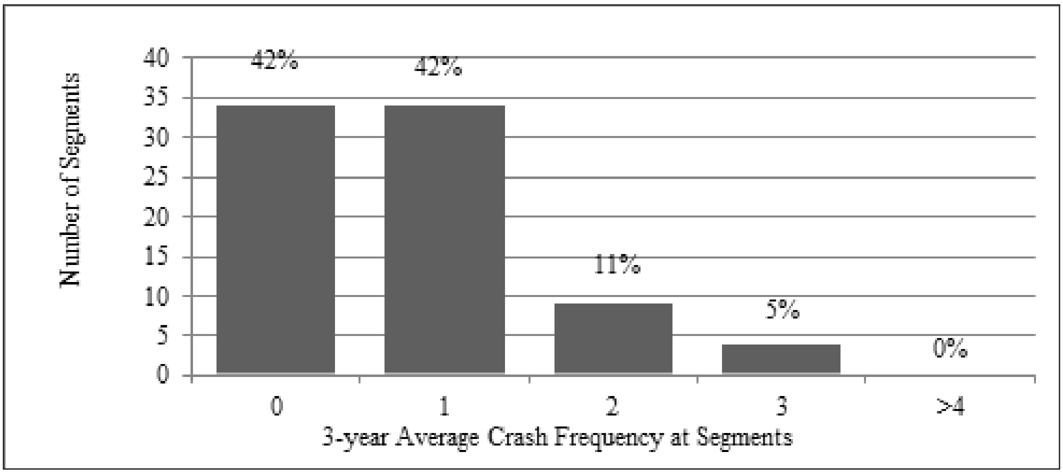


Figure 5: Distribution of Crash Frequency on Four-Lane Undivided Segments in Kansas



Descriptive statistics of 4D and 4U segment characteristics are shown in Table 4. The average length of 4D segments (2.47 km) was well above the minimum length of 0.16 km (0.1 miles), with segment lengths ranging between 0.16 km and 13.90 km (0.1 miles and 8.63 miles). Traffic volumes averaged 8,000 vpd, with a maximum of 31,000 vpd. Segments were relatively uniform with respect to lane and shoulder width, but they showed variation with respect to median width. The average number of crashes was 9.72, ranging between zero and 98 crashes. Seventy-eight segments had lighting present, but no automated speed enforcement was applicable for any highways in Kansas.

The average length of 4U segments was 0.29 km, which is very close to the HSM required minimum segment length of 0.16 km. Segments ranged in length from 0.16 km to 0.68 km Segments were relatively uniform with respect to lane width, but they showed variation with respect to shoulder width. The average number of crashes was 1.29, ranging between zero and 7 crashes. The total number of crashes was 107 for three years, or an average of 36 crashes per year, which was less than the HSM's recommendation of 100 crashes per year. Because this study considered all possible 4U segments in Kansas instead of only a sample, calibration could be performed with these segments, even with limited number of crashes (AASHTO 2010).

Table 4: Descriptive Statistics for Rural Four-Lane Segments

Roadway Type	Description	Average	Minimum	Maximum	Std. Dev.
4D	Length (km)	2.47	0.16	13.90	2.49
	AADT (2013)	8,000	490	31,000	4,657
	Left lane width (m)	3.68	3.35	6.40	0.18
	Right lane width (m)	3.68	3.35	6.40	0.18
	Left paved shoulder width (m)	1.73	0	3.00	0.44
	Right paved shoulder width (m)	2.85	0	3.00	0.56
	Median width (m)	9.34	1.50	46.33	4.81
	Number of crashes	9.72	0	98.0	11.90
	Presence of lighting	0.28	0	1	0.44
4U	Length (km)	0.29	0.16	0.68	0.11
	AADT (2013)	4,787	520	12,700	3,060
	Left lane width (m)	3.72	3.66	3.96	0.13
	Right lane width (m)	3.72	3.66	3.96	0.13
	Left paved shoulder width (m)	2.00	0	3.05	1.34
	Right paved shoulder width (m)	1.86	0	3.05	1.37
	Sideslope	-	1:2	1:6	-
	Number of crashes	1.29	0	7.0	1.55
	Presence of lighting	0.24	0	1	0.43

After obtaining the observed crash frequency at each segment using the crash database, the predicted number of crashes was estimated. For each segment, the HSM-given SPF was obtained using Equation 1. CMFs were obtained for lane width, shoulder width, median width, and sideslope for each segment using charts and equations provided in the HSM. CMF for median width is required for 4D segments only and CMF for sideslope is required for 4U segments only.

Chapter 11 of the HSM provides tables to obtain CMFs that correspond to lane width, shoulder width, median width, and sideslope. As demonstrated in Equation 3, the CMF corresponding to presence of lighting pertained to proportions of nighttime crashes. Even though the HSM provides default values of various nighttime crash proportions, it also recommends that default proportions of nighttime crashes should be replaced by jurisdiction-specific crash proportions in order to obtain more accurate crash estimations. These proportions were obtained for rural 4D and 4U highways in Kansas and compared with the HSM default values as shown in Table 5.

After applying CMFs, the final $N_{Predicted}$, or the number of predicted crash frequencies, was obtained for each rural divided and undivided segment. The sum of predicted crashes for all 281

4D segments was estimated to be 1,902, but the total number of actual observed crashes was 2,730. A calibration factor of 1.43 was obtained by dividing the total number of observed crashes by the total number of predicted crashes. A separate calibration factor was obtained for fatal and injury crashes. The total number of observed fatal and injury crashes on 4D segments was 528; predicted crashes from SPF were 1,008. Therefore, it yielded a calibration factor of 0.52. Detailed calculation of calibration factors are shown in Table 6.

Table 5: Proportions of Nighttime Crashes Obtained for Rural 4D and 4U Highways in Kansas

Roadway Type	Nighttime Crash Proportions	Kansas Four-lane Divided Highways	HM-Given Default
4D	P_{inr}	0.599	0.426
	P_{pnr}	0.124	0.323
	P_{nr}	0.876	0.677
4U	P_{inr}	0.533	0.255
	P_{pnr}	0.140	0.361
	P_{nr}	0.860	0.639

Note: P_{inr} = Proportion of nighttime crashes for unlighted segments that involved fatality or injury; P_{pnr} = Proportion of nighttime crashes for unlighted segments that involved PDO crashes; P_{nr} = Proportion of total crashes for unlighted segments that occurred at night.

Table 6: Calibration Factor Calculation of Four-Lane Divided Segments in Kansas

No. of Fatal Crashes	No. of Injury Crashes	Total (Fatal / Injury) Crashes	No. of Property Damage Crashes	Total (Fatal + Injury + Property Damage Only) Crashes	No. of Daytime Crashes	No. of Nighttime Crashes	Nighttime Fatal Crashes	Nighttime Injury Crashes	Nighttime PDO Crashes	No. of Total Nighttime Crashes	Predicted Total Crashes	Predicted Fatal / Injury Crashes
45	483	528	2202	2730	1087	1636	18	185	1433	1636	1902	1008

$$\text{Total Crash, } C_r = \frac{\text{Total Observed Crashes}}{\text{Total Predicted Crashes}} = \frac{2730}{1901.58} = 1.436$$

$$\text{Fatal and Injury Crash, } C_r = \frac{\text{Total Observed Crashes}}{\text{Total Predicted Crashes}} = \frac{528}{1007.69} = 0.524$$

The sum of predicted crashes for all 83 4U segments was 65.66, and the total number of observed actual crashes was 107. A calibration factor of 1.63 was obtained by dividing the total number of observed crashes by total predicted crashes. A separate calibration factor was obtained for fatal and injury crashes. There were 20 observed fatal and injury crashes on these segments; there were 41 predicted crashes from SPF. Therefore, it yielded a calibration factor of 0.49. Detailed calculation of calibration factors are shown in Table 7.

Table 7: Calibration Factor Calculation of Four-Lane Undivided Segments in Kansas

No. of Fatal Crashes	No. of Injury Crashes	Total (Fatal / Injury) Crashes	No. of Property Damage Crashes	Total (Fatal + Injury + Property Damage Only) Crashes	No. of Daytime Crashes	No. of Nighttime Crashes	Nighttime Fatal Crashes	Nighttime Injury Crashes	Nighttime PDO Crashes	No. of Total Nighttime Crashes	Predicted Total Crashes	Predicted Fatal / Injury Crashes
0	20	20	87	107	50	57	0	8	49	57	65.66	41.06
Total Crash, $C_r = \frac{\text{Total Observed Crashes}}{\text{Total Predicted Crashes}} = \frac{107}{65.66} = 1.63$ Fatal and Injury Crash, $C_r = \frac{\text{Total Observed Crashes}}{\text{Total Predicted Crashes}} = \frac{20}{41.06} = 0.487$												

Calibration factors for total crashes on rural 4D and 4U segments were greater than 1.0 and it indicated that the HSM underpredicts crashes on rural multilane highways in Kansas. Therefore, multiplying the calibration factor by the prediction under base conditions lowers the predictions to match observed frequencies on average. However, the calibration factor for fatal and injury crashes on both 4D and 4U highway segments were less than 1.0, indicating overprediction by HSM; therefore, multiplying the factor increases the predictions to match observed frequencies. These calibration factors are unable to accurately predict crashes for rural highways in Kansas. Furthermore, the calibration factors contradict between total crashes and fatal and injury crashes. Rural multilane highways experienced fewer observed fatal and injury crashes compared with HSM predicted fatal and injury crashes, which resulted in such small calibration factors.

This overprediction or underprediction of crashes is caused by the observed crashes and the uncalibrated HSM predicted crashes. By applying this calibration factor, according to HSM recommendations, this overprediction or underprediction can be addressed at least partially. However, this research made an attempt to improve the crash prediction for rural multilane highways in Kansas without altering the HSM given SPF.

HSM Calibration – Four-lane Intersections

A total of 199 4ST intersections and 65 3ST intersections at minor approach were considered in the calibration for this study. Using the KDOT videologs, a total of 229 crashes were observed within an intersection-box for all 4ST intersections, and 53 crashes were observed within an intersection-box for all 3ST intersections. Using intersection-related crashes from the KCARS database, 112 and 17 intersection-related crashes were found for 4ST and 3ST intersections, respectively. Both sets of observed crashes were used to obtain two pairs of calibration factors. Figures 6 and 7 show crash distributions obtained through both methods for 4ST and 3ST intersections, respectively.

Figure 6: Distribution of Crash Frequency on 4ST Intersections

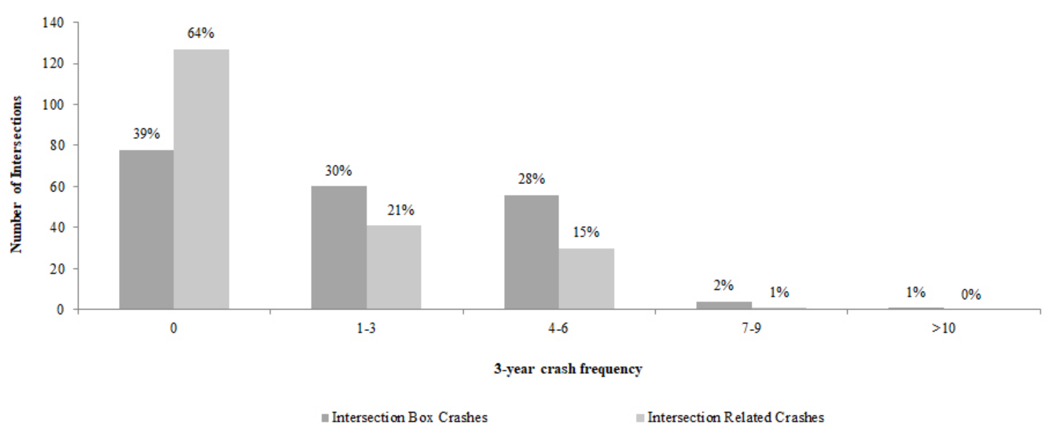
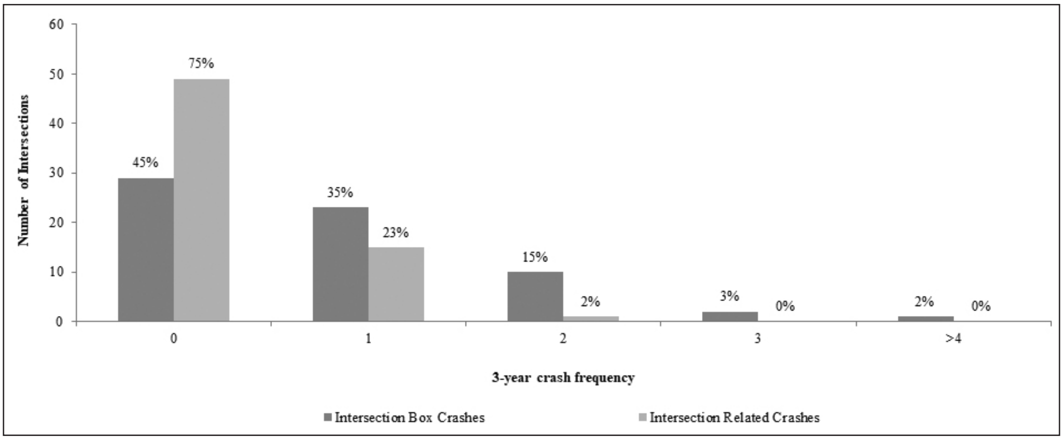


Figure 7: Distribution of Crash Frequency on 3ST Intersections



Descriptive statistics for 4ST and 3ST intersections are shown in Table 8. For 4ST intersections, the average major road traffic was 7,271 vpd and minor traffic volume was 990 vpd. Some intersections had minor traffic volumes as low as 40, but many intersections had high traffic volumes of 17,500 vpd. Intersection skew angles averaged 3.92 degrees since most of them were at exact right angles. Looking through the KDOT videologs, only 43 intersections contained right-turn lanes, and 30 intersections had lighting posts. The average number of crashes within an intersection-box was 1.15, with the number of crashes ranging from zero to 11. Intersection-related crashes from the KCARS database averaged 0.56 crashes, with the number of crashes ranging from zero to 5.

For 3ST intersections, the average major road traffic was 5,173 vpd and minor traffic volume was 544 vpd. Looking through the KDOT videologs, only seven intersections contained right turn lanes, and two intersections had lighting posts. The average number of crashes within an intersection-box was 0.81, with the number of crashes ranging between zero and 4. Intersection-related crashes from the KCARS database averaged 0.26 crashes, with the number of crashes ranging from zero to 2.

Table 8: Descriptive Statistics for Rural Four-Lane Intersections

Roadway Type	Description	Average	Minimum	Maximum	Std. Dev.
4ST	Major Road AADT (vpd)	7,271	490	17,500	4024
	Minor Road AADT (vpd)	990	40	5,650	1122
	Skew Angle (degrees)	3.92	0	60	12.98
	Presence of Right Turn lane on Major Road	0.21	0	1	0.41
	Presence of Lighting Post	0.15	0	1	0.36
	Number of Crashes within Intersection-box	1.15	0	11	1.43
	Number of Intersection-Related Crashes	0.56	0	5	0.88
3ST	Major Road AADT (vpd)	5,173	490	12,600	3,274
	Minor Road AADT (vpd)	544	20	2,780	543
	Skew Angle (degrees)	1.23	0	30	5.45
	Presence of Right Turn lane on Major Road	0.10	0	1	0.31
	Presence of Lighting Post	0.03	0	1	0.17
	Number of Crashes within Intersection-box	0.81	0	4	0.92
	Number of Intersection-Related Crashes	0.26	0	2	0.23

After obtaining the observed crash frequency, this study obtained the predicted number of crashes. HSM-SPF has two formats for intersection calibration, as previously shown in Equations 2 and 3. Since major and minor approach AADTs were available, Equation 2 was used to obtain predicted crashes at 4ST and 3ST intersections. Charts and equations in the HSM were used to obtain CMFs for intersection skew angle, presence of right-turn lane on major road, presence of left-turn lane on major road, and presence of lighting posts (AASHTO 2010).

CMF factors were obtained from Tables 11-22 and 11-23 and Equations 11-20, 11-21, and 11-22 of Chapter 11 of the HSM for intersection skew angles, left-turn lane on major road, right turn lane on major road, and the presence of lighting (AASHTO 2010). After applying the CMFs, final N_{spf} for each rural intersection was obtained, which was the number of predicted crashes. The summation of predicted crashes for all 199 4ST intersections was 252. Using intersection-box (method one), the total number of observed crashes within an intersection-box was 229. A calibration factor of 0.91 was obtained by dividing the total observed crashes by the total predicted crashes. Using method two, a calibration factor of 0.44 was obtained from the total observed 112 intersection-related crashes.[2] A separate calibration factor was obtained for fatal and injury crashes. Total observed fatal and injury crashes on these intersections were 99 from method one and 28 from method two. Calibration factors of 0.74 and 0.21 were obtained from method one and two, respectively, using Equation 6. Table 9 shows detailed calculations for calibration factors of 4ST intersections.

Table 9: Calculation of Calibration Factors for 4ST Intersections

Method of Obtaining Observed Crashes at Intersections	No. of Fatal Crashes	No. of Injury Crashes	Total (Fatal / Injury) Crashes	No. of Property Damage Crashes	Total (Fatal + Injury + Personal Damage Only)	No. of Daytime Crashes	No. of Nighttime Crashes	Nighttime Fatal Crash	Nighttime Injury Crash	Nighttime PDO Crash	No. of Total Nighttime Crashes	Predicted Total Crashes	Predicted Fatal / Injury Crashes
1	3	96	99	130	229	62	167	2	17	148	167	252.13	134.67
2	0	28	28	84	112	37	75	0	21	54	75		

Intersection-box (Method 1),

$$\text{Total Crash, } C_r = \frac{\text{Total Observed Crashes}}{\text{Total Predicted Crashes}} = \frac{229}{252.13} = 0.91$$

$$\text{Fatal and Injury Crash, } C_r = \frac{\text{Total Observed Crashes}}{\text{Total Predicted Crashes}} = \frac{99}{134.67} = 0.74$$

Intersection-related crashes (Method 2),

$$\text{Total Crash, } C_r = \frac{\text{Total Observed Crashes}}{\text{Total Predicted Crashes}} = \frac{112}{252.13} = 0.44$$

$$\text{Fatal and Injury Crash, } C_r = \frac{\text{Total Observed Crashes}}{\text{Total Predicted Crashes}} = \frac{28}{134.67} = 0.21$$

After applying the CMFs, final Nspf for each rural intersection was obtained, which was the number of predicted crashes. The summation of predicted crashes for all 65 3ST intersections was 18.44. Using intersection-box (method one), the total number of observed crashes within an intersection-box was 53. A calibration factor of 2.87 was obtained by dividing the total observed crashes by the total predicted crashes. Using method two, a calibration factor of 0.92 was obtained for the 17 observed intersection-related crashes. A separate calibration factor was obtained for fatal and injury crashes. Total observed fatal and injury crashes on these intersections were 10 from method one and 4 from method two. Calibration factors of 1.16 and 0.47 were obtained from method one and two, respectively, using Equation 6. Table 10 details calibration factors for 3ST intersections.

Using observed crashes within an intersection-box (method one), the obtained 0.91 calibration factor for total crashes on rural 4ST intersections indicated precise crash prediction. The HSM underpredicts total crashes on 3ST intersections when considering crashes from method one but showed more precise prediction when considering intersection-related crashes (method two). Fatal and injury crash prediction followed a similar trend for both methods of observed crashes. Results indicated that, using intersection-boxes (method one), the HSM accurately predicts fatal and injury crashes when compared with actual observed crashes on rural 4ST and 3ST intersections.

Table 10: Calculation of Calibration Factors for 3ST Intersections

Method of Obtaining Observed Crashes at Intersections	No. of Fatal Crashes	No. of Injury Crashes	Total (Fatal / Injury) Crashes	No. of Property Damage Crashes	Total (Fatal + Injury + Personal Damage Only)	No. of Daytime Crashes	No. of Nighttime Crashes	Nighttime Fatal Crash	Nighttime Injury Crash	Nighttime PDO Crash	No. of Total Nighttime Crashes	Predicted Total Crashes	Predicted Fatal / Injury Crashes
1	0	10	10	43	53	15	38	0	7	31	38	18.44	8.59
2	0	4	4	13	17	8	9	0	1	8	9		

Intersection-box (Method 1),

Total Crash, $C_r = \frac{\text{Total Observed Crashes}}{\text{Total Predicted Crashes}} = \frac{53}{18.44} = 2.87$

Fatal and Injury Crash, $C_r = \frac{\text{Total Observed Crashes}}{\text{Total Predicted Crashes}} = \frac{10}{8.59} = 1.16$

Intersection-related crashes (Method 2),

Total Crash, $C_r = \frac{\text{Total Observed Crashes}}{\text{Total Predicted Crashes}} = \frac{17}{18.44} = 0.92$

Fatal and Injury Crash, $C_r = \frac{\text{Total Observed Crashes}}{\text{Total Predicted Crashes}} = \frac{4}{8.59} = 0.47$

Modification of HSM-Given SPF

Results obtained from the calibration process showed that the HSM methodology underpredicts total crashes on rural multilane highways in Kansas. Furthermore, fatal and injury crashes were overpredicted by the HSM methodology. Therefore, modification of existing SPF is necessary for application to rural Kansas.

The HSM provides guidance pertaining to SPF modification for a state with available local data. Specifically, Appendix A of Part C in the HSM describes the three outlined components. FHWA has funded efforts to develop such guidance (Srinivasan et al. 2013). In order to increase the accuracy of results of the HSM procedures, states have been encouraged to customize the procedures with local data (AASHTO 2010). One way to allow the HSM procedure to more accurately reflect local conditions is to develop calibration factors that would be applied to the default SPFs in the HSM. However, optimum HSM customization for each state requires consideration of factors such as availability of data and resources. Therefore, this paper identified a methodology to customize the HSM for Kansas as accurately as its resources allow.

Customization of the HSM is possible through a combination of the three components: SPF, CMF, and calibration factor. For example, the HSM can be customized with calibration factors calculated using local data, default SPFs, and crash proportions, which may be the typical method so states that lack available data and resources can develop individualized SPFs. However, many other methods can be used to customize the HSM by combining the three components. Although these methods are not explicitly described in the predictive methods of HSM, they can be inferred from Appendix A and relevant references. Dixon et al. (2012) explored several options related to calibration factors and crash proportions under default SPFs given in the HSM. In this study, development of new regression coefficients for existing HSM-given SPFs was utilized and executed.

Since the HSM models were calibrated using the whole rural 4D and 4U dataset, it is fair to do the same with the modified SPF. Otherwise, both methods would not be treated in the same way. Currently, while developing new Kansas-specific SPFs, two separate datasets were used for model development and model validation of these new SPFs. However, that is not part of this manuscript.

As shown in Equation 1, the SPF considers segment length and AADT as independent variables, considering *a* as the intercept of the model and *b* as the parameter estimate for AADT. The original SPF given in the HSM indicated 1.0 as the coefficient for segment length in the model.[3] However, while using Kansas-specific data, new coefficient *p*, corresponding to segment length, was considered for the model as given in Equation 7.

$$(7) \quad N_{SPF=e}{}^{[a+b\times\ln(AADT)\,+\,p\,\times\,\ln(L)]}$$

where, N_{SPF} is the base total expected average crash frequency for the rural segment, *AADT* is the average annual daily traffic on the highway segment, *L* is the length of the highway segment (miles), and *a, b*, and *p* are the regression coefficients.

In order to perform this task, data from the existing set of segments were used to run a Negative Binomial Regression model.[4] Separate models were run for 4D and 4U segments. Table 11 compares regression coefficients given in Chapter 11 of the HSM for both segments with coefficients obtained based on Kansas-specific data. R^2 for the 4D and 4U models were found to be 0.89 and 0.82 for total crashes and 0.81 and 0.72 for fatal and injury crashes, respectively.

Parameter estimates of 4D and 4U differed significantly at all three severity levels. The t-test was used to determine if slope coefficients obtained for Kansas segment data differed from default values at the 0.05 significance level. All coefficients for 4D were found to be numerically different. From t-test results, Kansas's SPFs were determined to be statistically significantly different from the corresponding default HSM-given SPFs.

Table 11: Comparison of Regression Coefficients

Severity Level	Default HSM Coefficients		Kansas-Specific Coefficients (t-statistics)		
	a	b	a	b	p
4D					
Total Crashes	-9.025	1.049	-6.317 (2.034)	0.795 (1.532)	0.898
Fatal and Injury Crashes	-8.837	0.958	-10.030 (4.923)	1.059 (2.763)	0.399
4U					
Total Crashes	-9.653	1.176	-6.347 (3.332)	0.822 (1.923)	0.912
Fatal and Injury Crashes	-9.410	1.094	-8.206 (4.287)	0.817 (2.174)	0.747

Afterward, the newly obtained regression coefficients were used to obtain predicted crashes at each 4D and 4U segment, followed by acquisition of the calibration factor for each facility type. Calculated calibration factors for 4D facilities were close to 1.0, as shown in Table 12; however, a calibration factor of 0.858 was obtained for total and injury crashes on rural 4U segments. This calibration factor was less than the usual acceptance limit.[5] A calibration factor close to 1.0 indicates that the SPF accurately predicts crash frequency for the facility type and matches the local conditions. Therefore, it is evident that by modification of the SPF with Kansas-specific regression coefficients improved the prediction of crash frequency on rural 4D roadway segments in Kansas.

However, further research must be conducted on 4U segments in order to achieve a calibration factor within an acceptable limit, especially for fatal and injury crashes. Small sample size is the biggest challenge for 4U segments. HSM suggests having at least 30-50 segments in the sample for reliable estimation. Also including additional explanatory variables in the new regression model could provide satisfactory results. Currently we are developing Kansas-specific SPFs to discover whether they can predict crashes with increased level of accuracy.

Table 12: New Calibration Factors Using the Modified SPF

Facility Type	Severity	Calibration Factor
4D	Total Crashes	0.956
	Fatal and Injury Crashes	1.002
4U	Total Crashes	1.019
	Fatal and Injury Crashes	0.858

CONCLUSIONS

Prior to this study, KDOT was able to apply the rural two-lane model from the HSM because a study had been completed to calibrate such facilities (Lubliner and Schrock 2012). However, when the analysis of a multilane facility was requested, it could not have been completed without calibration. Therefore, an acceptable method to predict crashes for rural multilane highway segments and intersections in Kansas must be identified or developed. This study calibrated rural four-lane divided and undivided highways in Kansas using SPFs described in the HSM. Crash data for years 2011 to 2013 were used to obtain observed crash frequencies, and predicted crash frequencies were obtained using SPFs in the HSM, which were further modified by multiplying by CMFs.

Results obtained from the calibration process showed calibration factors of 1.43 and 1.63 for 4D and 4U segments, respectively. Therefore, it was seen that the HSM methodology underpredicts total crashes on rural multilane highways in Kansas. These calibration factors are unable to accurately predict crashes for rural highways in Kansas. Furthermore, calibration factors for fatal and injury crashes were found to be 0.52 and 0.49 for 4D and 4U segments, respectively, thereby indicating an overprediction of fatal and injury crashes. Rural multilane highways experienced fewer number of observed fatal and injury crashes compared with HSM predicted fatal and injury crashes, which resulted in such small calibration factors.

Crash proportions based on severity, daytime to nighttime crash, and collision type indicated a significant difference compared with the default crash proportion mentioned in the HSM. An approach of modifying the HSM-given SPF regression coefficients was taken to observe variation in the crash prediction. Since the HSM models were calibrated using the whole rural 4D and 4U dataset, the same data were used for the modified SPF. Predicted crash frequency was obtained by using the SPFs with new coefficients, which was further modified by multiplying by the CMFs. The final calibration factors for both 4D and 4U facilities indicate significant improvement in terms of crash prediction for rural Kansas. Therefore, using the modified SPF for multilane highways in Kansas total crashes and fatal and injury crashes can be more accurately predicted compared with using only HSM methodology.

In addition to segments, this study calibrated multilane intersections. The HSM methodology was followed to obtain the number of predicted crashes at 4ST and 3ST intersections. Observed crashes at intersections were considered using two methods: intersection-boxes and intersection-related crashes. This study found that intersection-box crashes (method one) is predicting the fatal and injury crashes comparatively close to actual observed crashes on rural 4ST and 3ST intersections.

The results obtained from this study have enlightened new paths for proceeding with the crash predictions for rural Kansas. The next phase of this research is currently addressing development of Kansas-specific SPFs for rural multilane segments. By considering several additional variables in the new SPF, their applicability in increasing the accuracy of crash prediction will be verified. Finally, the HSM calibrated models will be compared to the new SPFs and modified HSM given SPFs to determine the best option for the most accurate crash predictions of rural multilane highway segments in Kansas.

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Endnotes

1. These methods have not been used in any previous study. Intersection data for Kansas were not available at the time of this study. Therefore, both methods were used to find out whether there is any difference in results.

2. The intersection–related crashes were extracted from the KCARS database, which was designated while entering into the crash record. On the other hand, intersection box crashes were counted based on the coordinates of the crash location, where the level of accuracy of number of crashes is higher.

3. The original SPF given in HSM was developed by AASHTO where 1.0 was the coefficient value of segment length.

4. Negative binomial model was used because it is most commonly used for developing a crash prediction model.

5. A calibration factor close to 1.0 indicates that the SPF accurately predicts crash frequency for the facility type and matches the local conditions. Usually if the factor is within 0.9-1.1, then it is considered to be within the acceptance limit.

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