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Effect of horizontal curves on urban arterial crashes

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ABSTRACT

The crash prediction models of the Highway Safety Manual (HSM), 2010 estimate the expected number of crashes for different facility types. Models in Part C Chapter 12 of the first edition of the HSM include crash prediction models for divided and undivided urban arterials. Each of the HSM crash prediction models for highway segments is comprised of a "Safety Performance Function," a function of AADT and segment length, plus, a series of "Crash Modification Factors" (CMFs). The SPF estimates the expected number of crashes for the site if the site features are of base condition. The effects of the other features of the site, if their values are different from base condition, are carried out through use of CMFs. The existing models for urban arterials do not have any CMF for horizontal curvature. The goal of this research is to investigate if the horizontal alignment has any significant effect on crashes on any of these types of facilities and if so, to develop a CMF for this feature.

Washington State cross sectional data from the Highway Safety Information System (HSIS), 2014 was used in this research. Data from 2007 to 2009 was used to conduct the investigation. The 2010 data was used to validate the results. As the results showed, the horizontal curvature has significant safety effect on two-lane undivided urban arterials with speed limits of 35 mph and higher and using a CMF for horizontal curvature in the crash prediction model of this type of facility improves the prediction of crashes significantly, for both tangent and curve segments.

1. Introduction

Chapter 12 of the Highway Safety Manual (HSM), 2010 contains crash prediction models for urban arterials. These mathematical models that predict the expected number of crashes for these highway facilities (highway segments and intersections) use several highway/intersection characteristics, but not horizontal curvature. Each of these models has a Safety Performance Function (SPF) and several Crash Modification Factors/Functions (CMFs). The SPF is part of the prediction model that estimates the expected number of crashes for the site if the site features are of certain conditions (called the "base conditions"). The SPFs in the HSM models are functions of the AADT (or AADTs of all intersecting approaches, if the site is an intersection) and the length (if the site is a segment). The effects of other features of the site, if different from base conditions, are considered through the CMFs. Chapter 12 of the 1st Edition of the HSM includes five crash prediction models for urban arterials based on the number of lanes in these highways. These models do not have any CMF for horizontal curvature, meaning that the effect of horizontal curvature on these types of highways is not captured in the models. The goal of this research was to show that the effect of horizontal curvature on crashes on some types of these highways is significant, and to derive a CMF for this characteristic.

HSM crash prediction models are developed and cross validated using data from a few States/regions. For these models to be used for other regions or even the same regions but for different periods the models need to be calibrated. This calibration is conducted by calculating the ratio of the observed crashes for the most recent years for a number of sites with similar features to the number of crashes that is predicted for those sites for the same period by the model. This ratio is called calibration factor for that model and is used for adjusting the model prediction for that State/region for near future years.

The Washington State data for urban arterials segments was used in this study. The data was comprised of highway segment features and crash data over four years (2007–2010). This data – obtained from the FHWA HSIS Laboratory – was extensively manipulated and analyzed. The 2007–2009 data was used to study the need for considering horizontal curvature in the model and to develop a new CMF for horizontal curvature if the effect of this highway feature is found significant. The 2010 data was used to validate the proposed CMFs within the framework of the current HSM

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models. In this validation effort, the observed numbers of crashes of 2010 were compared to the predictions of the HSM models with and without the proposed CMFs.

2. Related research

This section reviews some major literature related to the development of Crash Modification Factors (CMF), previously known as Accident Modification Factors (AMF) and Crash Reduction Factors (CRFs) that carry similar concepts.

Harwood et al., 2000 recommended combining AMFs used to estimate the effect of certain countermeasures on crashes with a base model to estimate the predicted number of crashes. The model and AMFs presented in this research, with some minor changes, were implemented as the Crash Prediction Module of the Interactive Highway Safety Design Model (IHSDM), 2016. The IHSDM model that was developed for rural two-lane highways was later adopted as the prototype model for the development of the HSM crash prediction models. With respect to the sources for AMFs used in the rural two-lane highway crash prediction models, Harwood et al., 2000 state that, “AMFs were based on a variety of sources including results of before-and-after accident evaluations, coefficients or parameter values from regression models, and expert judgment. The expert panel considered well-designed before-and-after evaluations to be the best source for AMFs. However, relatively few well-designed before-and-after studies of geometric design elements were found in the literature···Coefficients or parameter values from regression models are considered less reliable, but were used when no before-and-after study results were available... Expert judgment alone was exercised in limited cases where no better results were available.”

Shen et al., 2004 provided a comprehensive survey of the use of Crash Reduction Factors (CRFs) in State DOTs. Of 42 states that responded to the survey, 34 confirmed that they use these factors in their safety improvement programs. As they pointed out, there are two major approaches for developing such factors: (I) before-and-after studies, and (II) regression analysis using cross-sectional data. They concluded that, “the before-and-after method is the more widely used approach for developing CRFs.” This survey confirmed that, of the three types of before-and-after studies (i.e., “simple method,” “with comparison group method,” and “with EB method”), the “simple method” was still the most widely used among state DOTs.

Lord and Bonneson, 2006 also provided a useful summary of the history of CRFs and Accident Modification Factors (AMFs). They suggested three major applications for AMFs, namely, “within the preliminary design stage”, “for assessing design consistency”, and “for evaluating design exceptions.”

Bonneson et al., 2005 noted that, “In some instances, an AMF is derived from a safety prediction model as the ratio of ‘crash frequency with a changed condition’ to “crash frequency without the change.” In other instances, the AMF is obtained directly from a before-after study. Occasionally, crash data reported in the literature were used to derive an AMF.”

Washington et al., 2005, in evaluating the IHSDM intersection crash prediction models, used a regression analysis procedure to recalibrate the models. They proposed a method using cross sectional data, with the main principles being to use a sub-set of data to develop a base model and then to use other sub-sets of data to develop AMFs. The same evaluation and approach was presented in C. Lyon et al., 2003. However, in a study by Lord and Bonneson, 2007, in which they developed a model for rural frontage road segments in Texas, they rejected the applicability of the above method to their problem mostly because of the “small number of crashes in the database.” They instead developed a negative binomial model, and from that model extracted AMFs for the explanatory variables.

Gross et al., 2010 provided a thorough overview of the CMF development process, including methods for developing reliable CMFs and issues to consider when applying the various methods. This overview shows a number of methods and provides instructions for deriving the most appropriate ones depending on a number of factors including the type of data available. With respect to cross-sectional studies it defines the CMF as “the ratio of the average crash frequency for sites with and without the feature.” In terms of method used for this type of study it identified the “multiple variable regression” as the most common modeling method for deriving CMFs in this type of study. With respect to before-after studies it focused on the studies with comparison groups and also the empirical Bayes studies.

Carter et al., 2012 provided recommendations similar to Gross et al., 2010 for cross sectional studies. Their conclusion was: “The CMF can be derived by taking the ratio of the average crash frequency of sites with the feature to the average crash frequency of sites without the feature.” They then added “For this method to work, the two groups of sites should be similar in their features except for the feature. In practice, this is difficult to accomplish and multiple variable regression models are used. These cross-sectional models are also called safety performance functions (SPFs) or crash prediction models (CPMs).” With respect to before-after studies, Carter et al., 2012 provided guidance on how to consider major biases associated with these studies including “regression-to-the-mean,” “change in traffic volume,” and “history trend” bias. However, since cross sectional data was used, most of these issues related to before-after studies did not apply.

Banihashemi, 2015 studied the effect of horizontal curvature on crashes on Rural Multilane highways and proposed CMFs for this feature that improved the prediction of crashes for both tangent and curve sections of highways. A two-step process was used by M. Banihashemi. At the first step the ratios of the observed number of crashes to the predicted number of crashes were calculated for the entire data as well as for the subsets of the data that were produced by splitting the data into bins/groups based on horizontal curvature. The deviations of these ratios for the subsets confirmed the significance of the effect of the curvature on crashes. At the second step the horizontal curvature CMFs were estimated by studying the way these ratios change. This methodology is similar to the approach Carter et al., 2012 recommended for cross sectional studied.

3. Methodology

The methodology used in this study was exactly similar to the one used by Banihashemi (*13*) except there was an additional split of the data based on the posted speed of the highways. Arterials with posted speed of 30 mph and lower were grouped together and the ones with posted speed of 35 mph and higher were grouped together. The two speed categories already exist in the HSM Chapter 12 as “Low” and “Intermediate or High.” Urban arterials were classified into five highway types as they are in HSM models. These were two-lane undivided (2U), two-lane undivided with a two-way left turn lane (3T), four-lane divided (4D), four-lane undivided (4U), and four-lane undivided with a two-way left turn lane (5T). At first for each of these arterial types it was determined whether the effect of horizontal curvature on crashes was significant, and then a CMF was developed if this effect was significant. A validation process was also developed to validate the findings of the research. Washington State data from 2007 to 2009 (experiment data) were used in the development process. 2010 data (validation data) were used to validate the quality of the developed CMF.

3.1. The effect of horizontal curvature on crashes on urban arterials

The ratios of observed crashes to the number of crashes predicted by the model for a set of sites, that is also called calibration factors, are the main components used in the first step of this methodology. In this step, these ratios were estimated from the experiment data. Then, the entire data was split into several bins/groups based on the horizontal curvature and also posted speed. The curvature split points were chosen to create relatively even sets in terms of total length of segments. Within each group the ratio of the observed number of crashes to the predicted number of crashes was calculated. These ratios were used for all predictions to normalize all calculations. If the ratios for the bins/groups that were generated based on the horizontal curvature and posted speed deviated from 1.0 significantly, the conclusion was that the effect of horizontal curvature on crashes was significant.

3.2. Developing a CMF to represent the horizontal curvature

In the second step of the research the ratios that were calculated in the first step were studied. If the changes of the ratios within the group were significant with respect to the curvature then a function was derived. This function was the CMF that represented the effect of horizontal curvature in predicting crashes for experiment data. To accomplish this task the ratios were normalized by dividing them by the ratio that was calculated for the combination of all tangent segments and curves that for any reason were not used in the curves CMF calculation (non-applicable curves). Examples of non-applicable curves could be very flat curves and curves on highways with low speed limits.

This normalization adjusted the ratios in a way that the ratio for tangent segments and non-applicable curves became one and the rest of the ratios were changed accordingly. A curve was then fitted to the adjusted ratios. This curve represented the proposed CMF for horizontal curvature for curves that were used in the curves CMF calculation. This methodology was in principal similar to the one described in Carter et al., 2012 for cross sectional studies and in details almost the same used in Banihashemi, 2015.

3.3. Validation

The original model (without the new CMF) was applied to the validation data. In this process the original calibration factors obtained in the first step of the process were used. These predictions were called "Prediction without New CMF." Then the new CMF was applied to the experiment data and a new set of calibration factors were estimated. The new model, the model with the new CMF, was applied to the validation data with the use of the new calibration factors. These predictions were called "Prediction with New CMF." The validation data was split into several bins/groups and for each group the observed number of crashes was compared to both "Prediction without New CMF" and "Prediction with New CMF." This comparison determined whether the newly developed CMF was a valid one or not.

4. Data manipulation

The 2007–2010 HSIS data, 2014 for Washington State for highway segments was obtained. Out of about 6000 miles of highway segments of different types about 560 miles of highways were urban arterial segments. Of these 560 miles the mileages for 2U, 3T, 4D, 4U, and 5T highway types were 284, 30, 34, 113, and 100 miles, respectively. Because of the low mileage of 3T and 4D segments in this database, these facility types were not investigated in this research. The data for each year was obtained from the HSIS Lab in five different databases listed below:

1 *Road Data*: general segment features including thru lane and shoulder information;
2 *Curve Data*: horizontal alignment information;
3 *Grade Data*: grades and vertical alignment information;
4 *Lane Data*: auxiliary lanes information; and
5 *Crash Data*: crash data including type and severity of crashes as well as the location and relation of the crash to intersections.

The steps taken in the data manipulations were similar to the ones explained in Banihashemi, 2015 and are listed below:

Step 1: Road Data and Curve Data were merged

Step 2: Road/Curve Data and Grade Data were merged.

Step 3: Road/Curve/Grade Data and Lane Data were merged.

Step 4: Segments relevant to each of the five HSM models for urban arterials were identified and Road/Curve/Grade/Lane Data segments were joined together.

Step 5: Number of crashes for each segment of joined Road/Curve/Grade/Lane Data was derived from the Crash Data and was added to the segment data.

The results of the data manipulation after Step 5 were "homogenous segments" or as HSM calls them "sites" to which the HSM crash prediction models were applied. Washington State data used in this study did not contain all data required for the HSM models for urban arterials. Therefore, for unavailable required data the following data were added randomly:

- Number and type of driveways
- Street parking information (with the assumption of no street parking on curve segments)

Since compared to other factors the randomly added data elements listed above have relatively minor effect on crashes, these additions could not have a significant effect on the results.

5. Experiment results and interpretations

Following the steps outlined in the "Methodology" section, the results and interpretations are summarized in this section for three types of facilities (2U, 4U, and 5T), each for two speed categories of 30 mph and lower and 35 mph and higher.

5.1. The effect of horizontal curvature on crashes on 2U, 4U, and 5Urban arterials

For each urban arterial type within each speed categories of "30 mph and less" and "35 mph and higher" the data was split into several bins/groups based on the horizontal curvature. The curvature split points were chosen to create relatively even sets in terms of total length of segments. Within each group the ratio of the observed number of crashes to the predicted number of crashes was calculated. Table 1 through 3 show the results for urban arterial types of 2U, 4U, and 5T for speed category of "35 mph and higher." For the lower speed category the lengths of sub-categories were too short for any meaningful conclusion.

The results show except for 2U highways and for the radius range around 1000 ft and lower, that is highlighted in Table 1, the horizontal curvature did not have any significant effect on crash increases. For 4U and 5T highways the results show even an opposite effect that was probably due to the correlation of horizontal curvature with some other highway features that were not accounted for in these highway types' crash prediction models. "Lane Width" might be the most important feature that is not

Table 1
Observed/Predicted Crashes for 2U Highways with Speed of 35^{mph} and Higher.

Radius Bins/Groups (ft)	Ratios of Observed to Predicted Crashes	Total Length of Sites (mile)	Number of Homogenous Segments
∞ (Tangent)	0.875	190.6	2653
> = 2000	0.756	19.0	544
2000–1000	0.830	17.5	519
<1000	**2.228**	17.0	928
All Together	0.922	244.1	4644

Table 2
Observed/Predicted Crashes for 4U Highways with Speed of 35^{mph} and Higher.

Radius Bins/Groups (ft)	Ratios of Observed to Predicted Crashes	Total Length of Sites (mile)	Number of Homogenous Segments
∞ (Tangent)	1.013	81.0	2506
> = 2000	0.640	6.4	283
2000–1000	0.769	7.4	312
<1000	0.805	6.3	328
All Together	0.965	101.1	3429

accounted for in the current HSM models for urban arterials. In cases of 4U and 5T roads since these roads have higher volume, they are usually improved better with respect to lane width, compared to the 2U cases that have much lower volume.

5.2. Developing a CMF to represent the horizontal curvature

To further investigate the effect of horizontal curvature on crashes and develop a CMF for 2U highways, the "Ratios of Observed to Predicted Crashes" were studied within a narrower "Radius Bins/Groups" for radius of 1400 ft and lower. The initial target bin/group was the group with radius of 1000 ft as identified in Table 1. However, curves with radii between 1000 ft and 1400 ft were added to provide a meaningful boundary condition for the CMF and to observe how the curve CMF changes from 1.0 to values greater than 1.0 as the radius changes. Table 4 shows the results with these narrower bins/groups.

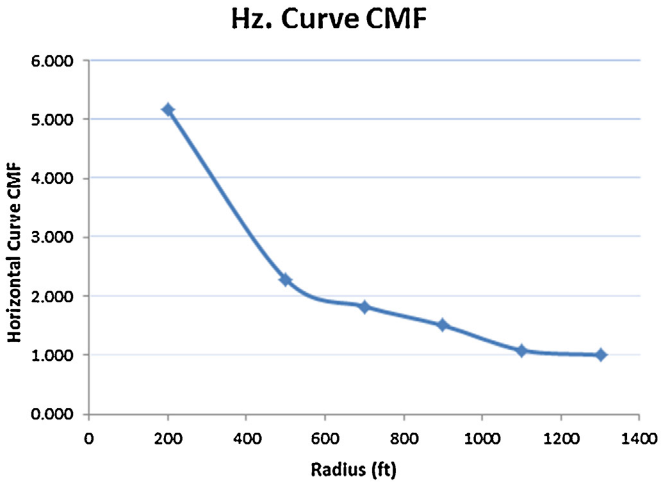
The mid-point of each curve group was chosen as the radius with the corresponding ratio. The final list of radii included radii of 1300, 1100, 900, 700, 500, and 200 ft. The results reflected in Table 4 that belong to these curves were then normalized by dividing their "Ratios of Observed to Predicted Crashes" by 0.952. This ratio was calculated by dividing the observed crashes to predicted crashes for all tangents of both speed categories and curves of the low speed category (30 mph and less) for which the effect of curvature was found insignificant, and the curvature CMF values for these items were considered 1.0. The results of this normalization were the values of the proposed CMF for each of the curve groups under investigation and are reflected in Table 5

To develop a function for the proposed CMF the data was put into the Excel Spreadsheet and a curve was fit to the data by choosing the option of "Power." This fitted a non-linear function of the independent variable "R" (Radius) to the dependent variable, CMF. Fig. 1(A) shows the variation of the normalized ratios vs. radii and Fig. 1(B) shows the fitted curve representing the horizontal curvature CMF. R^2 value for this curve fitting is 0.99, as shown in Fig. 1(B).

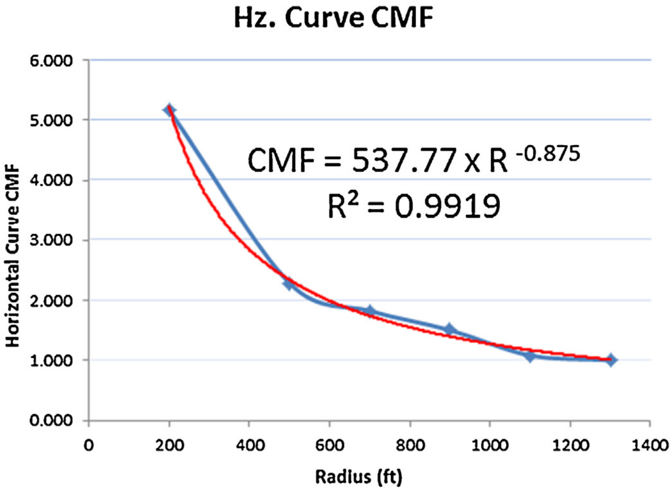
The fitted curve equation is:

$$CMF_{HC} = \frac{537.77}{R^{0.875}} \tag{1}$$

Where:
CMF_{HC}=CMF for Horizontal Curvature
R = Radius (ft)



(A) Variation of the normalized ratios vs. radii



(B) Horizontal curvature CMF

Fig. 1. Normalized Ratios and Horizontal Curvature CMF for Two-lane Urban Arterials (2U) with Speed Limit of 35^{mph} and Higher.

Table 3
Observed/Predicted Crashes for 5T Highways with Speed of 35^{mph} and Higher.

Radius Bins/Groups (ft)	Ratios of Observed to Predicted Crashes	Total Length of Sites (mile)	Number of Homogenous Segments
∞ (Tangent)	1.039	80.5	1504
> = 4000	0.612	5.0	159
4000–1500	0.456	4.0	154
<1500	0.512	7.5	317
All Together	0.977	97.1	2134

Table 4
Observed/Predicted Crashes for Two-lane Urban Arterials (2U) with Speed of 35^{mph} and Higher with Narrower Radius Groups.

Radius Bins/Groups (ft)	Ratios of Observed to Predicted Crashes	Total Length of Sites (mile)	Number of Homogenous Segments
∞ (Tangent)	0.875	190.6	2653
> = 2000	0.756	19.0	544
2000–1400	0.781	11.9	334
1400–1200	0.958	2.1	49
1200–1000	1.035	3.5	136
1000–800	1.436	5.0	232
800–600	1.742	2.9	126
600–400	2.179	5.6	298
<400	4.914	3.4	272
All Together	0.922	244.1	4644

Table 5
Proposed CMFs Values for 2U Highways with Speed of 35^{mph} and Higher.

Radius Bins/Groups (ft)	Radius	Proposed CMF
1400–1200	1300	1.006
1200–1000	1100	1.087
1000–800	900	1.508
800–600	700	1.829
600–400	500	2.288
<400	200	5.161

The fitted curve intersects with the CMF line of 1.00 at around R = 1320. To manage the small discrepancy that may occur if the radius is around 1300 ft, the following form is presented as the final CMF:

$$CMF_{HC} = \begin{cases} 1 \quad For\ Tangent\ Segments\ and\ Curves\ with\ Radius\ of\ 1,320\,ft\ and\ larger \\ \dfrac{537.77}{R^{0.875}} Curves\ with\ Radius\ less\ than\ 1,320\,ft \end{cases} \quad (2)$$

5.3. Sensitivity of the Model to Randomly Generated Data

To study the sensitivity of the developed CMF function to the randomly generated data for driveways and street parking the process of developing this function was repeated with the HSM base condition values for these data elements. These base conditions are no driveway and no street parking in the segments. The fitted curve equation is:

$$CMF_{HC-Base} = \frac{112.29}{R^{0.613}} \quad (3)$$

Where:

$CMF_{HC-Base}$ = CMF for Horizontal Curvature, No Driveways, No Street Parking

Fig. 2 compares the two functions for the values of Radius between 200 and 1300 ft.

This comparison shows how insignificant the sensitivity of the CMF function is with respect to the randomly generated values of driveways and street parking. However, of the two functions, the function developed from random data is recommended since it is known that there are significant number of driveways and street parking on some WA streets that better not to be ignored.

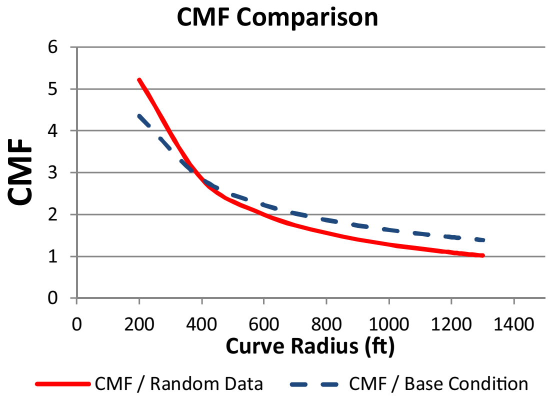


Fig. 2. Comparisons of CMFs, Random Data vs. Base Condition.

5.4. Validation

The original crash prediction model plus the original calibration factors calculated by using the experiment data (2007–2009) were applied to the validation data (2010). This produced the “Prediction without New CMF.” Then the revised crash prediction models that included the new CMF plus the new calibration factors were applied to the validation data. This produced the “Prediction with New CMF.” There is usually a short-term increasing or decreasing trend in crash occurrences if the number of crashes for a relatively large network is reviewed for a few years. This trend for Washington State for years of 2007–2010 is a slightly decreasing one. To remove the effect of the short-term trend the predictions for the validation data without and with the new CMF were normalized by dividing them by the ratio of the “Observed” to “Predicted” crashes for 2010 data. The final results summarized in Table 6 show how the prediction with and without the new CMF perform when compared to the observed number of crashes for 2010. “The normalized

Table 6
Summary of the Validation Results.

Radius Bins/Groups (ft)	Observed Crashes	Normalized Prediction without New CMF	Normalized Prediction with New CMF	% Improvement
Tangent and Curves with Radius > = 1320 ft	867	906	868	4
Curves with Radius < 1320 ft	83	44	82	47
All Together	950	950	950	

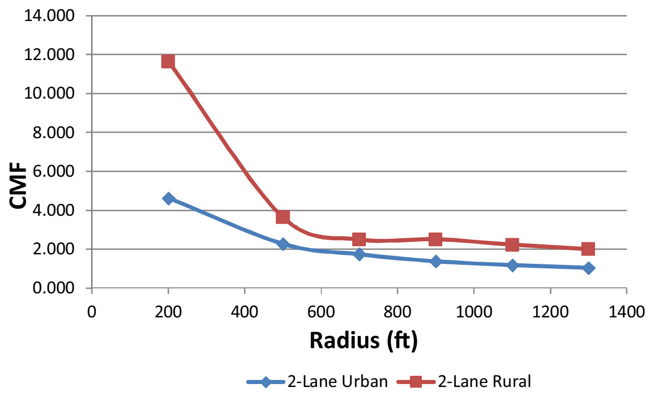


Fig. 3. Comparison of the Developed CMF to 2-Lane Rural CMF.

Prediction with New CMF” is almost exactly equal to the “Observed Crashes.”

Since the predictions were normalized, the results for the entire data for both cases of without and with the new CMF were equal to the total number of observed crashes. However, the way the total was split between two bins/groups was quite different. The accuracy of the prediction for the first group, tangents and flat curves, was improved by 4%. Considering the size of this group that was about 91% of the highway segments, the use of the new CMF made a considerable improvement. The major improvement, that was about 47%, was gained for sharper curves.

As an additional evaluation of the estimated CMFs, the average CMFs for the data used in the model development, split into bins/groups of curve radii of <400 ft, 400–600 ft, 600–800, 800–1000, 1000–1200 ft, and 1200–1400 ft was compared to the CMFs calculated for the HSM model for Rural Two-lane highways. The comparison is reflected in Fig. 3. As this comparison shows the effect of curvature on two-lane urban arterials with speed limit of 35 mph and higher is considerably less than the effect of those curves on two-lane rural highways for curves with 500 ft of radius and flatter. The gap widens even further as the curves become sharper.

6. Summary, conclusions, and future research

The HSM includes segment crash prediction models for different types of urban arterials. Each of these models is comprised of one SPF and a series of CMFs. The SPFs consider the effect of AADT and length. The effect of other highway segments features are considered through the use of CMFs, with one CMF per feature of the highway segment. The current models for urban arterials do not have any CMF for horizontal curvature. The purpose of this research was to investigate whether a horizontal curvature CMF should be added to these models, to develop this CMF. It was shown that the effect of horizontal curves on crashes was significant for two-lane undivided urban arterials (2U) and a methodology was proposed to add a horizontal curvature CMF to the HSM model for this type of facility. This research also showed that the effect of horizontal curves on crashes was not significant for four-lane undivided urban arterials (4U) and four-lane undivided urban arterials with a two-way left turn lane (5T). This is concluded from the results reflected in Tables 2 and 3. The data sample for the other two categories of urban arterials, two-lane undivided urban arterials with a two-way left turn lane (3T) and four-lane divided urban arterials (4D) were not large enough to draw any conclusion.

This research used cross sectional highway segment data from Washington State. 2007–2009 data was used to investigate the effect of horizontal curves on crashes and to develop the new CMF. 2010 data was used for validation.

The proposed methodology was to split the data into bins/groups. The mid-point radius of each group was considered as the independent variable and the normalized ratio of “Observed/Predicted” crashes was the dependent variable. The variations of these ratios that were the proposed CMF showed that the effect of horizontal curvature on crashes for 2U highways is significant. The significance of these CMFs was on prediction of crashes for both tangent and curve segments. Lack of the CMF in the original HSM models caused about%4 overestimation of crashes on tangents and segments with flat curves (Radius ≥ 1320). These segments comprised about 91% of the entire length of the database. Lack of this CMF also caused underestimation of crashes for curve segments with curves (Radius < 1320 ft), with the underestimation rate of about 47%. The main conclusion of this research was that the horizontal curvature is strongly recommended to be considered in the development of the crash prediction models of urban arterials of type 2U, and also that the use of the proposed CMF will improve the prediction significantly.

This research only showed the effect of horizontal curvature on crashes for two-lane urban arterials. Some research is currently going on to show the effect of lane and shoulder width on all types of urban arterials. If these researches conclude that lane width and shoulder width have some effect on safety on these highways, this research can be repeated by adding those effects and may get to a different conclusion.

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