Comparison of the Highway Safety Manual Predictive Method with Safety Performance Functions Based on Geometric Design Consistency

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Abstract

Road safety is a major public health concern in our society. Effective road design and accurate safety analyses must be a component of programs focused on reducing and eliminating roadway injuries and deaths. Various methodologies exist to determine the expected number of crashes on rural two-lane rural roads. This research compares different procedures which allow for the estimation of the number of crashes on homogeneous road segments. In this effort, a total of 27 two-lane rural road sections located in North Carolina were considered, resulting in 59 homogeneous road segments composed of 350 horizontal curves and 375 tangents along 150 km of road. Four methods were applied to the selected roadways: the HSM predictive method, two jurisdiction-specific Safety Performance Functions (SPFs), and a SPF which includes a consistency parameter.

This research found that the use of SPFs which incorporate a consistency parameter allows highway engineers to consider human factor impacts on road safety assessment. The use of a consistency parameter can also simplify the crash estimation process. Analysis methods which only included local geometric variables provided unreliable results due to the calibration of only the specific road elements instead of their relationship with other road elements along homogeneous road segments.

Keywords: *geometric design consistency, road safety, operating speed, inertial operating speed, driver's behavior*

1. Introduction

Road safety is a public health concern due to the years of productive lives lost resulting from crashes. More than 35,000 people per year die in road crashes in recent years in the United States. Particularly in North Carolina (US), the number of fatal crashes increased by 7% between 2014 and 2015, which was similar to the average increase in the country. In addition, 70% of fatal crashes occurred on rural highways in this state (FHWA, 2017).

In 2010, the American Association of State Highway and Transportation Official (AASHTO) released the Highway Safety Manual (AASHTO, 2010). The HSM is the product of more than 10 years of effort and thousands of hours to develop fact-based analytical tools and techniques to quantify the potential safety impacts of planning, design, operations, and maintenance decisions (Xie et al., 2011). Part C of the HSM contains the predictive methods for rural two-lane roads, rural multilane highways, and urban and suburban arterials. The main purpose of the predictive methods is to estimate the average crash frequency for existing conditions, alternatives to existing conditions, or proposed new roadways. The HSM predictive method is based on three components to estimate the predicted number of crashes at a site:

(1) Base model, which is a Safety Performance Function (SPF),
(2) Crash modification factors (CMFs) to adjust the estimate for site-specific conditions, and
(3) A calibration factor (C) to adjust the estimate for local conditions.

These components are combined in the following general form:

$$N_{predicted} = N_{spf} \cdot \prod_{i=1}^{n} CMF_i \cdot C \quad (1)$$

$N_{predicted}$: predicted average number of crashes for a specific site

N_{spf}: predicted number of crashes for base conditions

CMF_i: crash modification factors for a specific site

C: calibration factor

The SPF for rural two-lane, two-way roadway segments is defined as follows:

$$N_{spf} = L \cdot AADT \cdot 365 \cdot 10^{-6} \cdot e^{-0.312} \quad (2)$$

N_{spf}: total number of crashes

L: length of roadway segment (miles)

$AADT$: annual average daily traffic volume (vehicles/day)

The HSM proposes a total of 12 CMFs for rural two-lane, two-way roadway segments, which are based only on geometric variables and environmental conditions. In addition, the calibration factor (C) is calibrated based on the ratio of the total number of observed crashes and the sum of the predicted number of crashes on all homogeneous segments based on a sample of locations. Therefore, the HSM predictive method does not include a surrogate measure of human factors, which along with infrastructure factors, have been thoroughly studied in recent years through geometric design consistency, which can be defined as how drivers' expectations and road behavior relate.

The main objective of geometric design consistency is to minimize the emergence of unexpected events when road users traverse a road segment. Thus, a consistent road provides a harmonious driving experience free of surprises, whereas an inconsistent road might lead to numerous unexpected events to drivers, inciting an anomalous behavior and increasing the likelihood of crash occurrence.

The most common method to assess geometric design consistency is based on the analysis of the operating speed profile (Gibreel et al., 1999; Ng and Sayed, 2004). Operating speed is commonly defined as the 85th percentile of the speed distribution of passenger cars under free-flow conditions and no external restrictions (V_{85}).

There are two types of consistency models: local and global. Local models aim to identify where road crashes are more likely to occur by analyzing localized issues, such as high differences between the design and operating speeds or sudden speed reductions. On the other hand, global consistency models study the overall speed variation along an entire road segment. They do not identify where crashes are more likely to take place, but they can be introduced into a SPF to estimate the number of crashes on an entire road segment.

Regarding the usefulness of consistency, several researchers have tried to link the number of crashes to different variables related to risk exposure (traffic volume and road length), geometry, consistency, and road environment by means of SPFs. Among those studies which incorporate consistency as an explanatory variable, all of them concluded that the level of consistency has a major influence on road crash occurrence (Anderson et al., 1999; Ng and Sayed, 2004; Awatta et al., 2006; Montella et al., 2008; Cafiso et al., 2010; de Oña et al., 2013; Quddus, 2013; Wu et al., 2013; Garach et al., 2014; Camacho-Torregrosa, 2015; Montella and Imbriani, 2015; Garach et al., 2016).

The selection of the road segment is crucial for the application of global consistency models. Selected road segments must be homogeneous, because the results depend on the appropriate selection segments (Resende and Benekohal, 1997; Cafiso et al., 2010; García et al., 2013; Camacho-Torregrosa, 2015). The HSM defines a “site” as “an intersection or a homogeneous roadway segment”. In this regard, for rural two-lane, two-way roadways, a homogeneous road segment is one which keeps constant values for all the Crash Modification Factors and for other parameters such as traffic volume or roadside condition. This means that every road element (tangent and horizontal curve) is usually considered as a homogeneous road segment. Therefore, the HSM predictive method involves the estimation of the number of crashes on an entire road segment as the sum of the number of crashes of all individual road elements along the segment, possibly losing the meaning of the phenomenon being studied and the interaction between successive elements.

Driver’s behavior is constantly changing along a road segment, so drivers might behave differently in response to the same road element located on different road sections (for instance, a sharp curve located amongst other sharp curves is likely to experience fewer crashes than a curve with the same dimensions located adjacent to long tangents). Road crashes depend not only on local geometric characteristics of a certain road element, but also on the characteristics of the preceding road section. Therefore, road safety evaluation should be carried out considering both local and global road behavior as well as drivers’ behavior.

Llopis-Castelló et al. (2019b) recently calibrated the following SPF based on consistency to estimate the predicted number of crashes on North Carolina’s two-lane rural roads (considering 665 km of highway, which resulted in 194 homogeneous road segments):

$$y = e^{-5.46301} \cdot L^{0.84067} \cdot AADT^{0.73116} \cdot e^{0.03055 \cdot C} \qquad (3)$$

y: number of fatal-and-injury crashes on an entire road segment over 5 years

L: length of homogeneous road segment (km)

C: consistency parameter (km/h) - based on the difference between the inertial operating speed profile (drivers' expectancies) and the operating speed profile (road behavior) (Llopis-Castelló et al., 2019b)

To this regard, the risk on horizontal curves is not associated with the specific radius of the curve, but the difference of this curve to the adjacent road elements. For this reason, the inertial operating speed is recommended to be used. This speed aims to represent drivers' expectancies from the speeds experienced before arriving at a certain location on the road.

The use of the HSM predictive method has a weakness concerning the influence of risk exposure. The HSM assumes a proportional relationship between risk exposure (traffic volume and road length) and road crashes (Equation 2). Thus, a road segment with *x* predicted number of crashes will present *2x* crashes if its length or traffic volume is doubled. Under this assumption, crash rate remains constant independently of risk exposure. However, many authors have identified that this relationship is not proportional, but crash rates increase or decrease as a function of risk exposure (Montella and Imbriani, 2015; Garach et al., 2016; Llopis-Castelló et al., 2019b; Srinivasan and Carter, 2011; Mehta and Lou, 2013; Srinivasan et al., 2016; Lord et al., 2010; Li et al., 2017). Equation 4 shows the most common functional form of a SPF to estimate the number of crashes on two-lane rural roads:

$$y = \beta_0 \cdot L^{\beta_1} \cdot AADT^{\beta_2} \cdot e^{\sum_{i=3}^{k} \beta_i \cdot x_i} \qquad (4)$$

y: predicted number of crashes

β_i: regression coefficients

x_i: explanatory variables

The regression coefficient related to $AADT$ (β_2) is usually less than one when considering fatal-and-injury crashes, meaning that the crash rate decreases as traffic volume of the road segment increases. However, the influence of the road segment length on crash rate is not as clear as those observed for the traffic volume. Some authors identified that crash rates increase as the length increases ($\beta_1 > 1$), whereas other authors observed the opposite effect ($\beta_1 < 1$). Despite the uncertainty of the true value of β_1, L is likely not directly proportional to the number of crashes in many instances. Additionally, some researchers have concerns with the use of baseline models combined with CMFs and a calibration factor for predicting road crashes (Equation 1) because the increase in the variance associated with the final prediction, affecting the reliability of the model (Lord et al., 2010; Shin et al., 2015).

Alternatively, the HSM proposes the calibration of jurisdiction-specific SPFs, but does not discuss the use of other variables in developing SPFs. Most studies that have analyzed these two alternatives concluded that jurisdiction-specific SPFs allow highway engineers to more accurately estimate the number of crashes (Srinivasan and Carter, 2011; Mehta and Lou, 2013; Srinivasan et al., 2016; Lord et al., 2010; Li et al., 2017; Brimley et al., 2012; Lu et al., 2014). Therefore, this research aims to compare the application of the HSM predictive method with the use of jurisdiction-specific SPFs based on the HSM guidelines, i.e., on local geometric variables and consistency parameters on North Carolina's two-lane rural roads.

2. Objectives

The main objective of this research was to evaluate the applicability and efficacy of using jurisdiction-specific Safety Performance Functions instead of the HSM predictive method in the estimation of the number of crashes on rural two-lane, two-way roadway segments. This comparison was carried out considering two types of jurisdiction-specific SPFs calibrated in North Carolina: (i) those developed by Srinivasan and Carter (2011) and Smith et al. (2017), which were calibrated considering the HSM guidelines, i.e., only considering geometric and/or environmental variables; and (ii) that proposed by Llopis-Castelló et al. (2019b) which supplements the HSM recommendations with the concept of geometric design consistency.

The underlying hypothesis is that a SPF based on a consistency parameter provides a more reliable estimation of the number of crashes than the HSM predictive method and those SPFs based only on geometric variables, since the consistency parameter includes the interaction between the infrastructure and human factors, which plays an essential role for road safety.

3. Methodology and Data Description

3.1. Methodology

This research was focused on the analysis of the HSM predictive method and its comparison with jurisdiction-specific SPFs calibrated in North Carolina (Figure 1). A total of 27 two-lane rural road sections located along NC-96, NC-42, and NC-268 roadways were selected. The horizontal alignment for each road section was recreated by means of the procedure developed by Camacho-Torregrosa et al. (2015), while the cross-section of each road element was determined through aerial images. Crash and traffic data were also obtained. The number of predicted crashes was estimated considering the HSM predictive method as well as using the jurisdiction-specific SPFs. Finally, the relationship between the observed and predicted crashes for each procedure was studied considering the following parameters of goodness of fit: Mean Absolute Deviation (*MAD*), Root Mean Square Error (*RMSE*), and Cumulative Residuals (CURE) plots.

3.2. Road segments

A total of 27 two-lane rural road sections located in North Carolina with no geometric changes in the time period selected for crash data were selected for the study. This required the geometric recreation of approximately 150 km (90 miles) of highway covering 350 horizontal curves and 375 tangents. Therefore, 725 homogeneous road segments were obtained according to the HSM, since this selection depended on the CMFs.

Length, radius, and the presence or absence of spiral transition were identified from this geometric recreation. Lane width, shoulder width and type, number of driveways, and roadside design were obtained from aerial images for each road element (Table 1). These road sections are located in the Piedmont of North Carolina and are assumed to have a grade flatter than 3% (level grade) and do not contain centerline rumble strips, passing lanes, lighting, or automated speed enforcement (Figure 2). A superelevation rate that was adequate according to the AASHTO design guide was assumed for each horizontal curve.

The identification of homogeneous road segments was needed to apply the jurisdiction-specific SPF based on the global consistency model proposed by Llopis-Castelló et al. (2018), which was based on the following method. First, road sections were divided into segments with similar cross-section and traffic volume (Figure 2b). Major intersections also influence drivers' behavior, so they were also taken into account for segmentation. Finally, each road segment was divided considering its geometric behavior using the German methodology, which is based on the analysis of the Curvature Change Rate (*CCR*). This parameter is defined as the sum of the absolute deflection angles divided by the length of the road segment. Figure 2c represents how this last step is conducted: a profile of the cumulative absolute deflection angle versus the road station must be plotted. In this way, homogeneous road segments can be distinguished according to similar *CCR* behavior. As a result, 59 homogeneous road segments were identified (Table 1).

3.3. Traffic and crash data

Traffic volume and crash data were provided by the North Carolina Department of Transportation

(NCDOT). *AADT* and the number of reported crashes were identified for each homogeneous road segment between 2012 and 2016.

In North Carolina, a crash must only be reported if there are injuries or if the property damage is equal to or greater than $1,000. Therefore, Property Damage Only (PDO) crashes are not always reported to authorities and, consequently, to include this type of crash might lead to biased results and an inaccurate interpretation of the phenomenon under investigation (Xie et al., 2011; Shin et al., 2015). Thus, only reported fatal-and-injury crashes were considered over this study period. As a result, a total of 223 reported crashes were analyzed, 130 of which occurred on horizontal curves and 93 on tangents. For the application of the HSM predictive method, the percentage of fatal-and-injury crashes (p_i) and the proportion of related crashes (p_{ra}), which is estimated as the percentage represented by ran off road crashes, head-on collisions, and sideswipe collisions, are required. North Carolina values for this study included p_i of 33.4% and p_{ra} of 39.1% (Llopis-Castelló et al., 2019a). In this way, the number of fatal-and-injury crashes was estimated by multiplying the predicted total number of crashes by 0.334.

3.4. Crash Modification Factors and Calibration Factors

The CMFs proposed by the HSM to estimate the number of predicted crashes on rural two-lane, two-way roadway segments were calculated according to Chapter 10 of the HSM. Table 2 shows a statistical summary of these factors.

The calibration factor attempts to adjust the predicted number of crashes for local conditions. Specifically, the calibration factors used in this research are those proposed by Llopis-Castelló et al. (2019a), which were developed in North Carolina considering only fatal-and-injury crashes: 1.57 for horizontal curves and 1.15 for tangents. These are preferred instead of a global calibration factor for both tangents and horizontal curves because they result in a more accurate estimation of the number of crashes.

3.5. Jurisdiction-specific SPFs

The HSM predictive method will be compared with the state-specific SPFs developed by Srinivasan and Carter (2011), Smith et al. (2017), and Llopis-Castelló et al. (2019b). Regarding this, it should be highlighted that all these models were calibrated in the same region of North Carolina.

Srinivasan and Carter (2011) proposed two types of state-specific SPFs (Equation 5 and 6). Type 1 only depends on risk exposure, whereas Type 2 includes different variables related to the cross-section.

$$Type\ 1: \quad y = e^{-5.2717} \cdot L \cdot AADT^{0.6071} \cdot C_{annual} \tag{5}$$

$$Type\ 2: \quad y = L \cdot e^{\left(0.1221+0.4924 \cdot \ln\left(\frac{AADT}{10,000}\right)+0.3723 \cdot \frac{AADT}{10,000}-0.0244 \cdot SW+0.0479 \cdot ST\right)} \tag{6}$$

C_{annual}: annual factor

SW: shoulder width (feet)

ST: shoulder type (1 for unpaved and 0 for paved)

Smith et al. (2017) generated different calibration functions for the three different regions in North Carolina: Coast, Mountain, and Piedmont (Equation 7, 8, and 9). These SPFs depend on the same variables proposed by the HSM predictive method.

$$Coast: \quad y = 0.965 \cdot e^{-3.1953} \cdot L \cdot AADT^{0.6496} \cdot \prod_{i=1}^{12} CMF_i \tag{7}$$

$$Mountain: \quad y = 1.02 \cdot e^{-0.1832} \cdot (HSM_p)^{0.8512} \tag{8}$$

$$Piedmont: \qquad y = 0.92 \cdot e^{-5.0530} \cdot L \cdot AADT^{0.8546} \cdot \prod_{i=1}^{12} CMF_i \tag{9}$$

CMF_i: crash modification factors

HSM_p: total number of predicted crashes for HSM procedure (base model with the CMFs)

Therefore, these state-specific SPFs estimate the predicted number of crashes based on infrastructure factors. However, Llopis-Castelló et al. (2019b) developed new SPFs based on geometric design consistency (Equation 3). In this regard, the predicted number of crashes is calculated taking into account the interaction between infrastructure and human factors.

The global consistency parameter proposed by Llopis-Castelló et al. (2019b) is calculated from the difference between the inertial operating speed profile (V_i), which represents drivers' expectancies, and the operating speed profile (V_{85}), which represents road behavior (Figure 4a). This parameter is defined as follows:

$$C = \sqrt{\frac{A(+) \cdot \sigma(+)}{L(+)}} \; [km/h] \tag{10}$$

A(+): area bounded by the difference between V_i and V_{85} and the *x* axis considering only the positive differences (m·km/h)

L(+): length of the homogeneous road segment considering only the positive differences (m)

σ(+):standard deviation of the difference between V_i and V_{85} considering only the positive differences (km/h)

Only positive differences were included to focus on locations were the inertial operating speed (V_i) exceeds the operating speed (V_{85}) because in these sections the likelihood of crash occurrence increases due to drivers expect to reach higher speeds than those that the road geometry allows them (Figure 4b).

Thus, to apply the SPF calibrated by Llopis-Castelló et al. (2019b), the operating speed profile for each road segment was estimated using the speed model for horizontal curves calibrated by Ottesen and Krammes (2000), the speed model for tangents developed by Polus et al. (2000), and the acceleration and deceleration rates proposed by the Interactive Highway Safety Design Model (Figure 4a). Each of these models were calibrated based on speed data collected on American two-lane rural roads. The primary reason for using these models is that the highways considered in this study have similar characteristics to those used in the calibration of these models regarding geometric features, road functionality, and traffic conditions.

The inertial operating speed profile was calculated for every road segment based on its operating speed profile for both forward and backward direction (Figure 4a). According to Llopis-Castelló et al. (2018), the inertial operating speed is defined for each point of the alignment as the weighted average operating speed of the preceding 15 seconds considering a linear weighting distribution:

$$V_{i,k} = \frac{\sum w_j \cdot V_{85,\,j}}{\sum w_j} \tag{11}$$

$V_{i,k}$: inertial operating speed (km/h) at point k

$V_{85,\,j}$: operating speed at point j

w_j: weighting factor at point j (ranges linearly from 0 for the furthest point to 1 for the closest one - carried out for time intervals (j) of 0.1 s)

4. Results

The analysis of this study was focused on the comparison of the defined methods to estimate the number of predicted crashes on entire road segments. Regarding the application of the HSM predicted method and those jurisdiction-specific SPFs proposed by Srinivasan and Carter (2011) and Smith et al. (2017), the predicted number of crashes on a certain homogeneous road segment was calculated as the sum of the predicted number of crashes for all road elements (tangents and horizontal curves) along that segment. The SPF calibrated by Llopis-Castelló et al. (2019b) can directly estimate the number of fatal-and-injury crashes on an entire road segment.

This comparison was carried out considering the following parameters of goodness of fit, which aim to assess how predicted and observed crashes fit:

- Mean Absolute Deviation (*MAD*):

$$MAD = \frac{1}{n}\sum_{i=1}^{n}|\hat{y}_i - y_i| \tag{12}$$

- Root Mean Square Error (*RMSE*):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}|\hat{y}_i - y_i|^2} \tag{13}$$

- Cumulative Residuals (CURE) Plots: This method consists of plotting the cumulative residuals for each independent variable to graphically observe how well the function fits the data set. The CURE method has the advantage of not being dependent on the number of observations, as are many other traditional statistical procedures. In general, a good cumulative residuals plot is one that oscillates around 0 and where the residuals do not stray beyond the $\pm 2\sigma^*$ boundaries. The residuals are calculated as the difference between the observed and predicted number of crashes and are ordered from lowest to highest value.

$$\sigma^* = \sqrt{\sigma_i^2 \cdot \left(1 - \frac{\sigma_i^2}{\sigma_T^2}\right)} \tag{14}$$

σ^*: limit of the cumulative residuals

σ_i^2: variance of the cumulative residuals until the element *i*

σ_T^2: total variance of the cumulative residuals.

Table 3 shows these parameters of goodness of fit and the relationship between the predicted and observed fatal-and-injury crashes for each procedure considering the 59 homogeneous road segments.

Overall, all methods performed relatively similarly with respect to the *MAD* and *RMSE* evaluations. However, the CURE plots provide useful information about the differences and potential shortcomings of each method. Although the use of the SPF proposed by Smith et al. (2017) resulted in the best values of *MAD* and *RMSE*, this procedure showed a poor performance regarding the CURE plots. The SPFs calibrated by Srinivasan and Carter (2011) provided the worst parameters of goodness of fit and showed a large percentage of points out of the limits of the CURE plots.

The HSM predictive method provided an appropriate estimation of the number of fatal-and-injury crashes, but the SPF calibrated by Llopis-Castelló et al. (2019b), which is based on risk exposure and a consistency parameter, resulted in the most accurate results.

The CURE plots obtained for each procedure can help explain the study's conclusions (Figure 5 and Table 3). In this regard, both SPFs developed by Srinivasan and Carter (2011) overestimate the predicted number of fatal-and-injury crashes. In addition, the SPF calibrated by Smith et al. (2017) underestimated the number of fatal-and-injury crashes. Specifically, this procedure showed an inaccurate performance relative to the length of the road segment. This can be explained by the functional form of the SPF. This considers a regression coefficient equal to 1 for the *L*. However, the relationship between the length of the road segment and crash rate is not directly proportional.

Overall, the SPF proposed by Llopis-Castelló et al. (2019b) showed the most accurate CURE plots because this resulted in the lowest percentage of points out of the limits (11.86% and 10.17% considering *AADT* and *L*, respectively). Therefore, this SPF provides a more reliable estimation of the number of fatal-and-injury crashes and, consequently, a better road safety assessment.

5. Discussion

Multiple jurisdiction-specific SPFs have been compared to the HSM predictive method. Among these SPFs, that proposed by Llopis-Castelló et al. (2019b) showed a more accurate estimation of the number of fatal-and-injury crashes. Specifically, this SPF is based on risk exposure and adds a parameter *C* that represents geometric design consistency.

The consistency parameter *C* can be estimated by applying operating speed models. Therefore, this SPF does not require a field data collection as the application of the HSM predictive method and the use of the SPFs developed by Srinivasan and Carter (2011) and Smith et al. (2017) suggests, which can be a substantial advantage. In addition, the consistency parameter *C* proposed by Llopis-Castelló et al. (2019b) considers the interaction between infrastructure and human behavior, which is considered the primary causal factor for crash occurrence.

Furthermore, these results reveal the crucial role of the identification of the homogeneous road segments. The HSM predictive method and the SPFs proposed by Srinivasan and Carter (2011) and Smith et al. (2017) were calibrated based on road elements instead of homogeneous road segments. However, from a drivers' point of view, the likelihood of crash occurrence on a certain road element does not only depend on its local characteristics, but also on the global geometric behavior. This finding reinforces previous work by Findley et al. (2012) which quantified the importance of the influence of adjacent roadway elements. Therefore, the fact that the SPF proposed by Llopis-Castelló et al. (2019b) was calibrated for the assessment of road safety on an entire homogeneous road segment might explain why this model provided more reliable results.

To more closely examine the source of resulting analytical differences, a disaggregated analysis was developed to study the strength of the SPFs developed by Srinivasan and Carter (2011) and Smith et al. (2017). This analysis was based on the comparison between the observed and predicted number of fatal-and-injury crashes on individual road elements: horizontal curves and tangents. Figure 6 and Figure 7 show the CURE plots obtained for these SPFs considering both the traffic volume and the length of each horizontal curve and tangent, respectively.

Although the SPFs calibrated by Srinivasan and Carter (2011) resulted in a reasonable estimation of the number of fatal-and-injury crashes on horizontal curves (Figure 6a and 6b), these SPFs provided a large overestimation of the number of crashes on tangents (Figure 7a and 7b). The overestimation of crashes on tangents generally results in a broader overestimation of the number of crashes on an entire homogeneous road segment. Conversely, although the SPFs proposed by Smith et al. (2017) resulted in an accurate estimation of the predicted number of fatal-and-injury crashes on an entire homogeneous road segment, the disaggregated analysis showed that these models are not reliable at individual road elements. The number of crashes on horizontal curves was underestimated (Figure 6c), whereas the number of crashes on tangents was overestimated (Figure 7c). Therefore, this SPF may not provide results that are reliable enough to be applied to assess road safety.

Therefore, the calibration of SPFs based on consistency has two important strengths concerning the application of the HSM predictive method and jurisdiction-specific SPF based on local geometric conditions: (i) SPFs based on consistency include the interaction between the infrastructure and human factors, so they better represent the studied phenomenon and provide a more accurate assessment of road safety; and (ii) SPFs based on consistency do not necessarily require field data collection, so their application is easier and more practical for highway engineers, particularly in financially and resource-constrained environments.

6. Conclusions and further research

This research analyzes different procedures to estimate the number of fatal-and-injury crashes on entire homogeneous road segments in North Carolina. Specifically, the predicted number of crashes was calculated considering the HSM predictive method, the jurisdiction-specific SPFs proposed by Srinivasan and Carter (2011) and Smith et al. (2017), and the SPF based on consistency calibrated by Llopis-Castelló et al. (2019b).

The strength of these procedures was assessed comparing the predicted number of fatal-and-injury crashes with the reported crashes between 2012 and 2016 through the following parameters of goodness of fit: (i) Mean Absolute Deviarion (*MAD*); (ii) Root Mean Square Error (*RMSE*); (iii) Cumulative Residuals (CURE) plots.

The results of this study found that the SPFs proposed by Srinivasan and Carter (2011) overestimated the number of fatal-and-injury crashes, whereas the SPFs calibrated by Smith et al. (2017) provided a reasonable aggregate estimation of the number of crashes for an entire road segment, but underestimated the number of crashes on horizontal curves and overestimated the number of crashes on tangents. These limitations are primarily due to the functional form of these SPFs. The influence of risk exposure on crash rate is different for homogeneous road segments, horizontal curves, and tangents. The number of crashes is not directly proportional to road segment length or traffic volume as the HSM predictive method assumes. This supports the need to calibrate different models depending on the type of road element.

Although the application of the HSM predictive method based on calibration factors for each type of road segment (tangents and horizontal curves) provided an appropriate estimation of the number of fatal-and-injury crashes, the SPF calibrated by Llopis-Castelló et al. (2019b), which is based on risk exposure and a consistency parameter, resulted in the most accurate results.

In addition, the use of SPFs based on consistency has important advantages concerning the use of the HSM predictive method and jurisdiction-specific SPFs based on local geometric conditions. The first one is that a SPF based on consistency includes the interaction between drivers' expectancies and road behavior, which is the most important factor for crash occurrence. The second is that the application of this type of SPFs does not require a field data collection. This procedure can be applied using operating speed models which is a practical and simple improvement relative to other methods with respect to the assessment of road safety for highway engineers. Likewise, these SPFs are usually calibrated considering homogeneous road segment, i.e., they better represent the phenomenon studied, since the likelihood of crash occurrence at a certain road element do not only depend on the features of this road element, but also on the global conditions.

Therefore, the use of SPFs based on consistency allow practitioners and highway engineers to incorporate human factor on road safety assessment as well as an easier and more practical estimation of the number of fatal-and-injury crashes.

As this study is mainly focused on the estimation of fatal-and-injury crashes, further research is needed to extend the obtained findings to other crash types and severities. Additionally, a temporal analysis considering more years of crash data is proposed to be done so as to strengthen the results of this research. This analysis will be focused on the study of the variability of crash estimation considering different time windows.

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Table 1. Features of the homogeneous road segments.

(a) HSM

Road feature	Horizontal curves					Tangents				
	Min.	Max.	Mean	Median	St. Dev.	Min.	Max.	Mean	Median	St. Dev.
Radius (m)	37.17	9,787.37	833.46	412.68	1,371.58	na	na	na	na	na
Lane width (m)	2.44	3.66	3.03	3.05	0.32	2.44	3.66	3.04	3.05	0.32
Shoulder width (m)	2.44	3.66	3.03	3.05	0.32	0.61	1.83	0.96	0.91	0.38
Roadside Hazard Rating	2	6	3.106	3	1.210	3	5	3.795	3	0.975
DD (driveways per km)	0.00	39.33	6.96	5.59	7.39	0.00	115.4	11.31	6.03	15.22

(b) Global consistency model

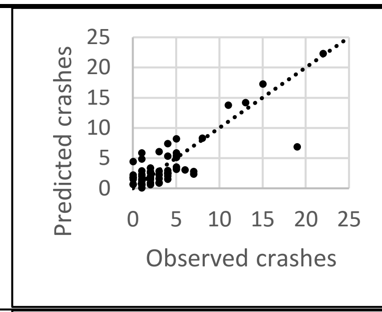
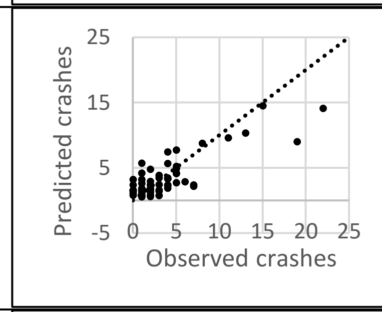
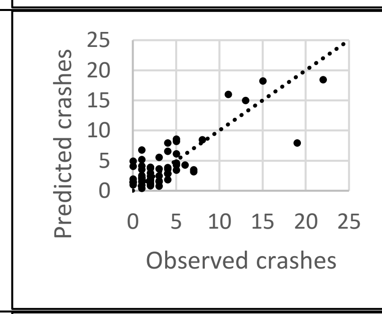
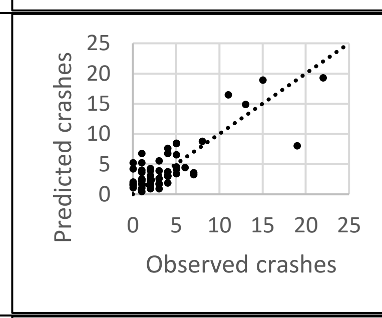
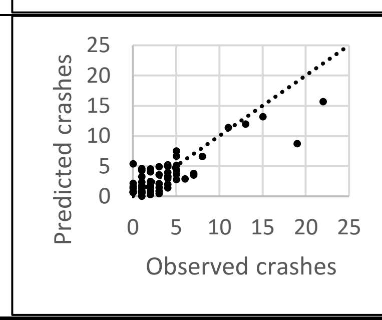
Road feature	Min.	Max.	Mean	Median	St. Dev.
Length (km)	0.57	7.30	2.49	2.29	1.30
AADT (vpd)	538	7,700	2,077	1,417	1,722
CCR (gon/km)	0	490.11	84.25	42.04	96.51
Crashes (2012-2016)	0	22	3.78	2	4.37

NOTES:
Min=Minimum; Max=Maximum; St. Dev.=Standard deviation; AADT=Annual Average Daily Traffic; DD=Driveway Density; CCR=Curvature Change Rate; na=not applicable; Crashes=Number of crashes with injuries
1 mi = 1,609.34 m, 1 ft = 0.3048 m.
1 gon/km = 1.448 °/mi

Table 2. Statistical summary of the CMFs.

CMF	Description	Type of road segment							
		Horizontal Curves				Tangents			
		Min.	Max.	Mean	St. Dev.	Min.	Max.	Mean	St. Dev.
CMF_{1r}	Lane width	1	1.1173	1.044	0.02789	1	1.1173	1.044	0.028
CMF_{2r}	Shoulder width and type	1.031	1.1321	1.066	0.02789	1.024	1.1321	1.066	0.02821
CMF_{3r}	Horizontal curves	1	10.059	1.795	1.36664	1	1	1	0
CMF_{4r}	Superelevation	1	1	1	0	1	1	1	0
CMF_{5r}	Grades	1	1	1	0	1	1	1	0
CMF_{6r}	Driveway density	1	2.8943	1.271	0.36885	1	7.526	1.693	3.76648
CMF_{7r}	Centerline rumble strips	1	1	1	0	1	1	1	0
CMF_{8r}	Passing lanes	1	1	1	0	1	1	1	0
CMF_{9r}	Two-way left-turn lanes	1	1	1	0	1	1	1	0
CMF_{10r}	Roadside design	1	1.1429	1.059	0.07002	1	1.1429	1.057	0.06964
CMF_{11r}	Lighting	1	1	1	0	1	1	1	0
CMF_{12r}	Automated speed enforcement	1	1	1	0	1	1	1	0

Table 3. Parameters of goodness of fit.

<table>
<tr><th rowspan="2">Procedure</th><th rowspan="2">MAD</th><th rowspan="2">RMSE</th><th colspan="2">CURE plots</th><th rowspan="2">Observed crashes Vs. Predicted crashes</th></tr>
<tr><th>AADT*</th><th>L**</th></tr>
<tr><td>HSM
Equation 1 and 2 and the calibration factors proposed by Llopis-Castelló et al. (2019b):
• $C_{curves} = 1.57$
• $C_{tangents} = 1.15$</td><td>1.683</td><td>2.490</td><td>16.95%</td><td>8.47%</td><td>
</td></tr>
<tr><td>SPF$_{\textbf{Llopis-Castelló et al.}}$
Equation 3</td><td>1.678</td><td>2.458</td><td>11.86%</td><td>10.17%</td><td>
</td></tr>
<tr><td>SPF$_{\textbf{Srinivasan and Carter, Type 1}}$
Equation 5</td><td>1.958</td><td>2.668</td><td>16.95%</td><td>27.12%</td><td>
</td></tr>
<tr><td>SPF$_{\textbf{Srinivasan and Carter, Type 2}}$
Equation 6</td><td>1.990</td><td>2.695</td><td>18.64%</td><td>25.42%</td><td>
</td></tr>
<tr><td>SPF$_{\textbf{Smith et al.}}$
Equation 7, 8, and 9</td><td>1.642</td><td>2.346</td><td>16.95%</td><td>28.81%</td><td>
</td></tr>
<tr><td colspan="6">*Percentage of CURE plot out of the limits for traffic volume
** Percentage of CURE plot out of the limits for road segment length</td></tr>
</table>

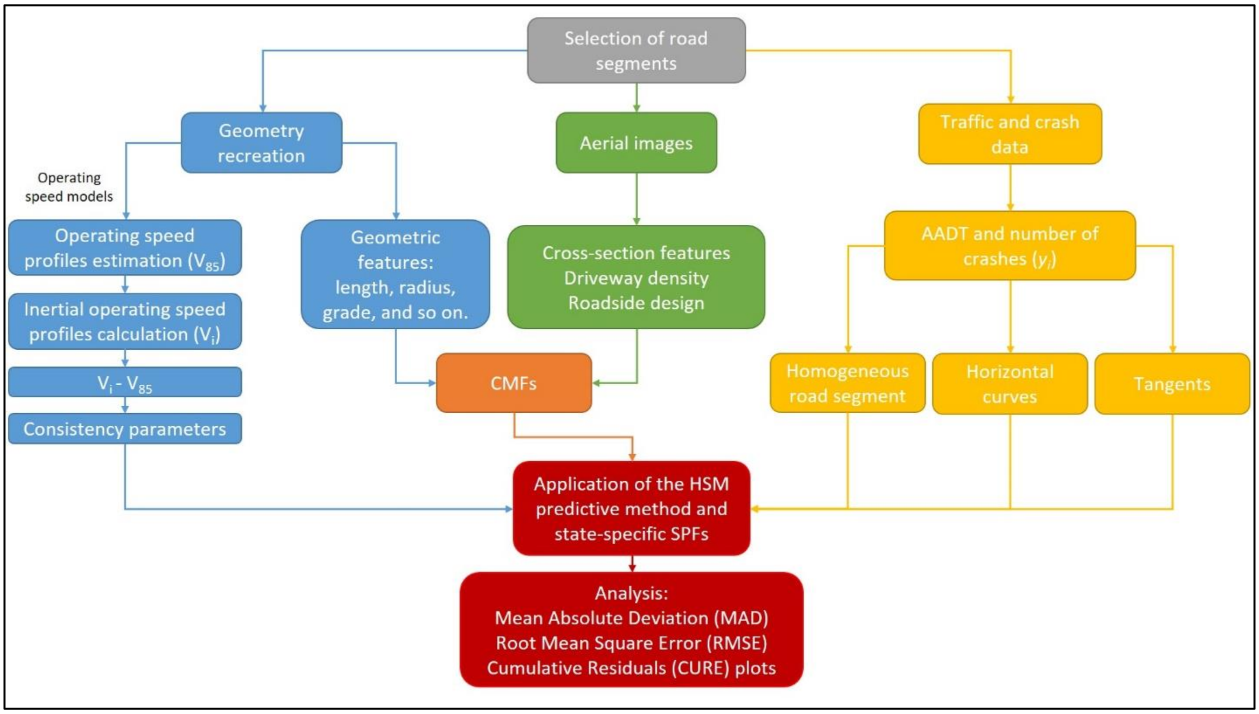


Figure 1. Methodology.

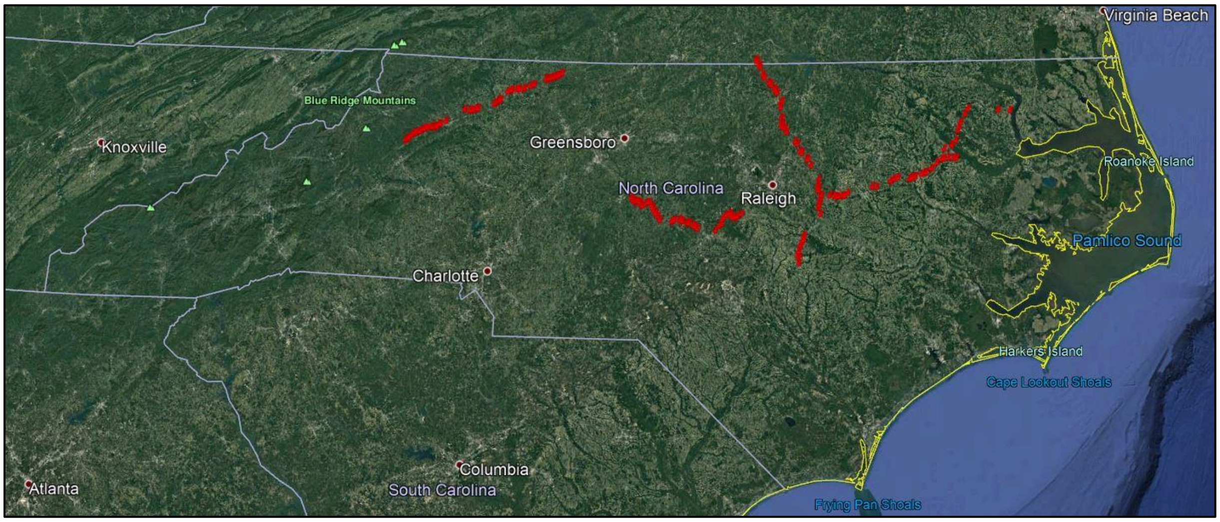
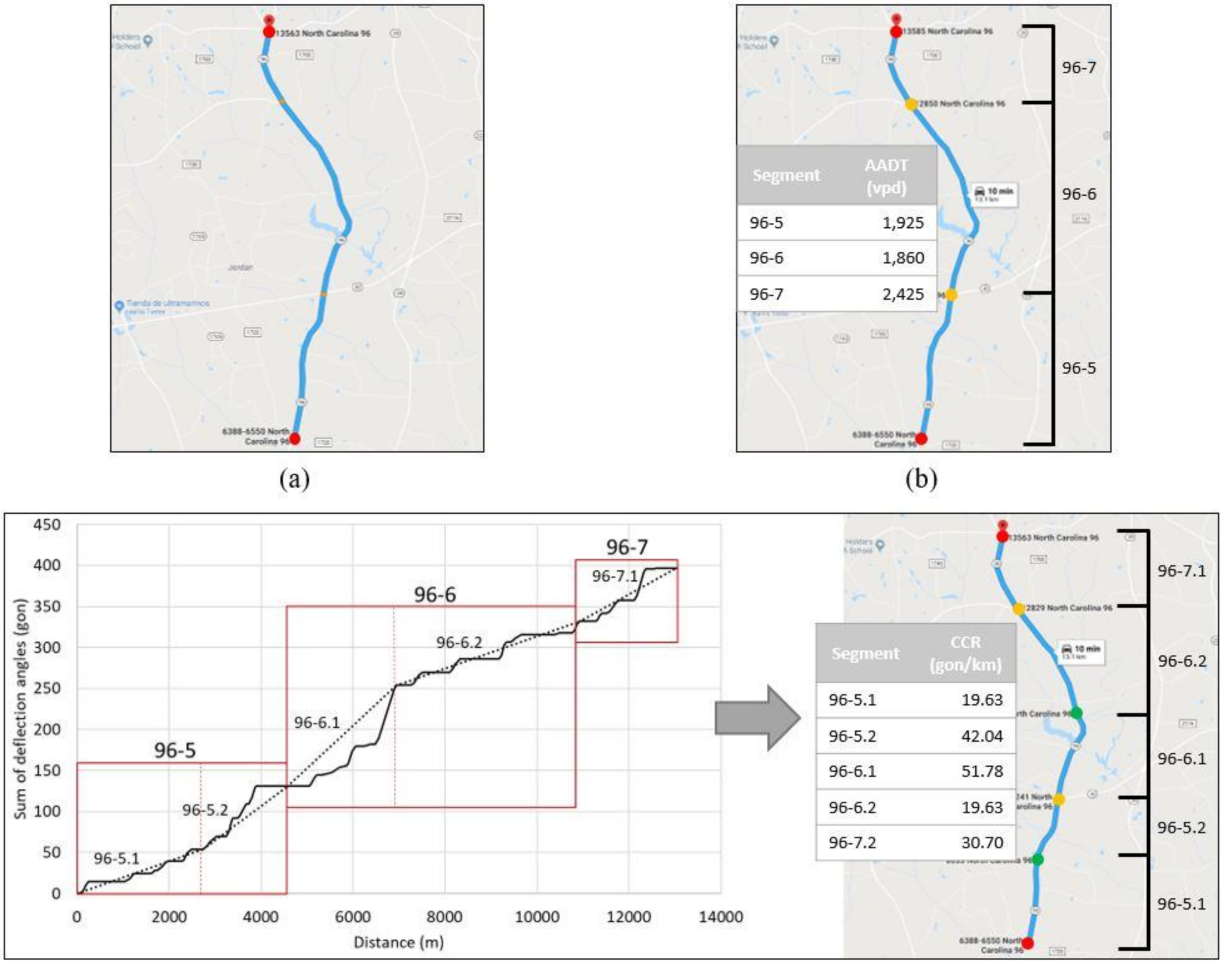
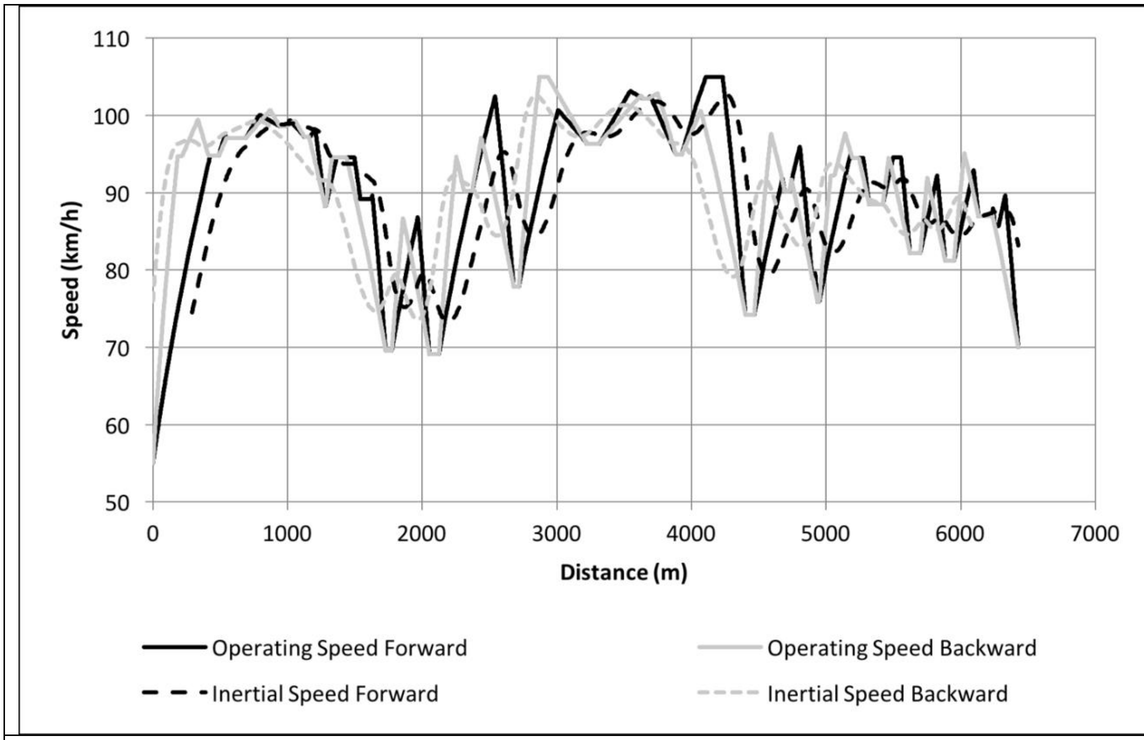


Figure 2. Location of the studied road segments.

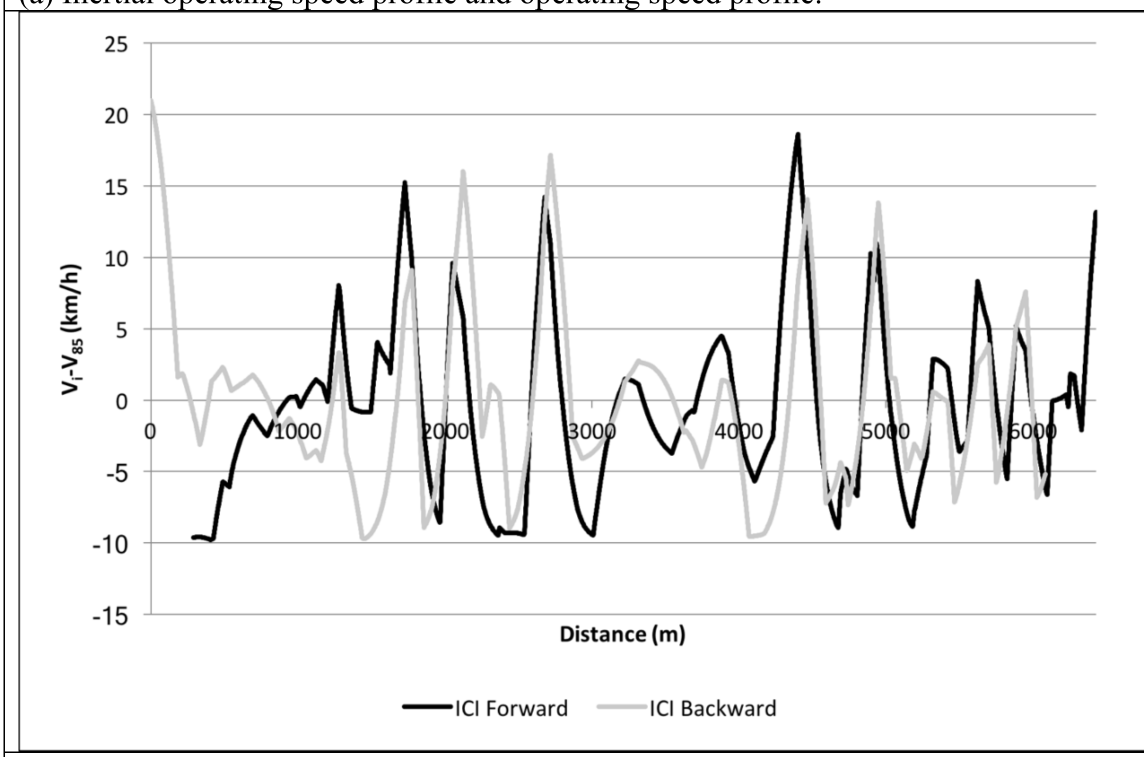


(c)

Figure 3. Road segmentation: (a) Road section; (b) Segmentation according *AADT* and cross-section; (c) Segmentation according to geometric layout.



(a) Inertial operating speed profile and operating speed profile.



(b) Difference between inertial operating speed profile (V_i) and operating speed profile (V_{85}).

Figure 4. Speed profiles.

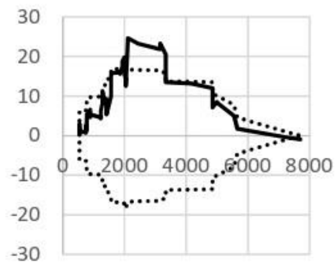
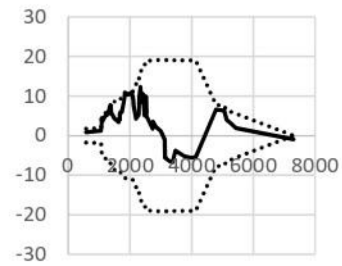
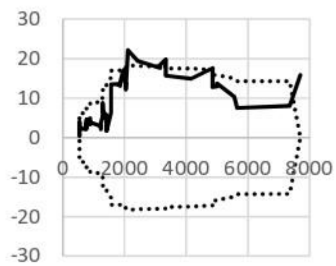
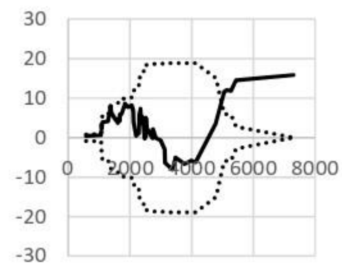
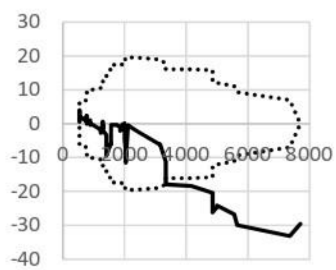
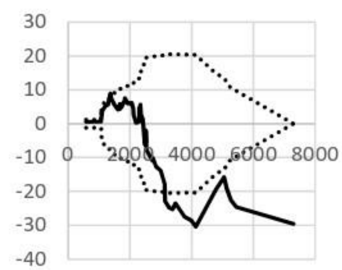
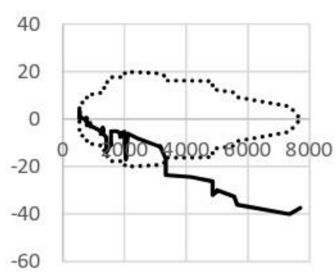
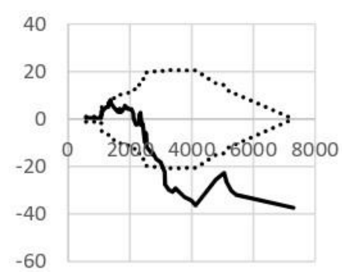
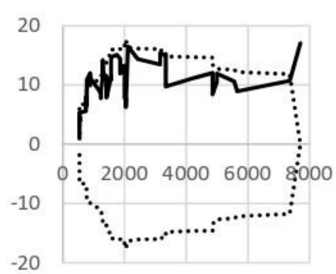
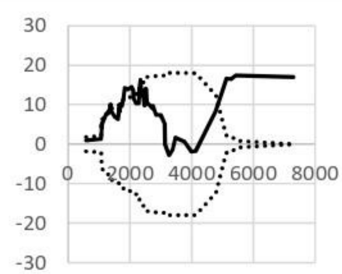
Procedure	***AADT* (vpd)**	**Length (m)**
(a) HSM		
(b) $\mathbf{SPF}_{\text{Llopis-Castelló et al.}}$		
(c) $\mathbf{SPF}_{\text{Srinivasan and Carter, Type 1}}$		
(d) $\mathbf{SPF}_{\text{Srinivasan and Carter, Type 2}}$		
(e) $\mathbf{SPF}_{\text{Smith et al.}}$		

Figure 5. CURE Plots.

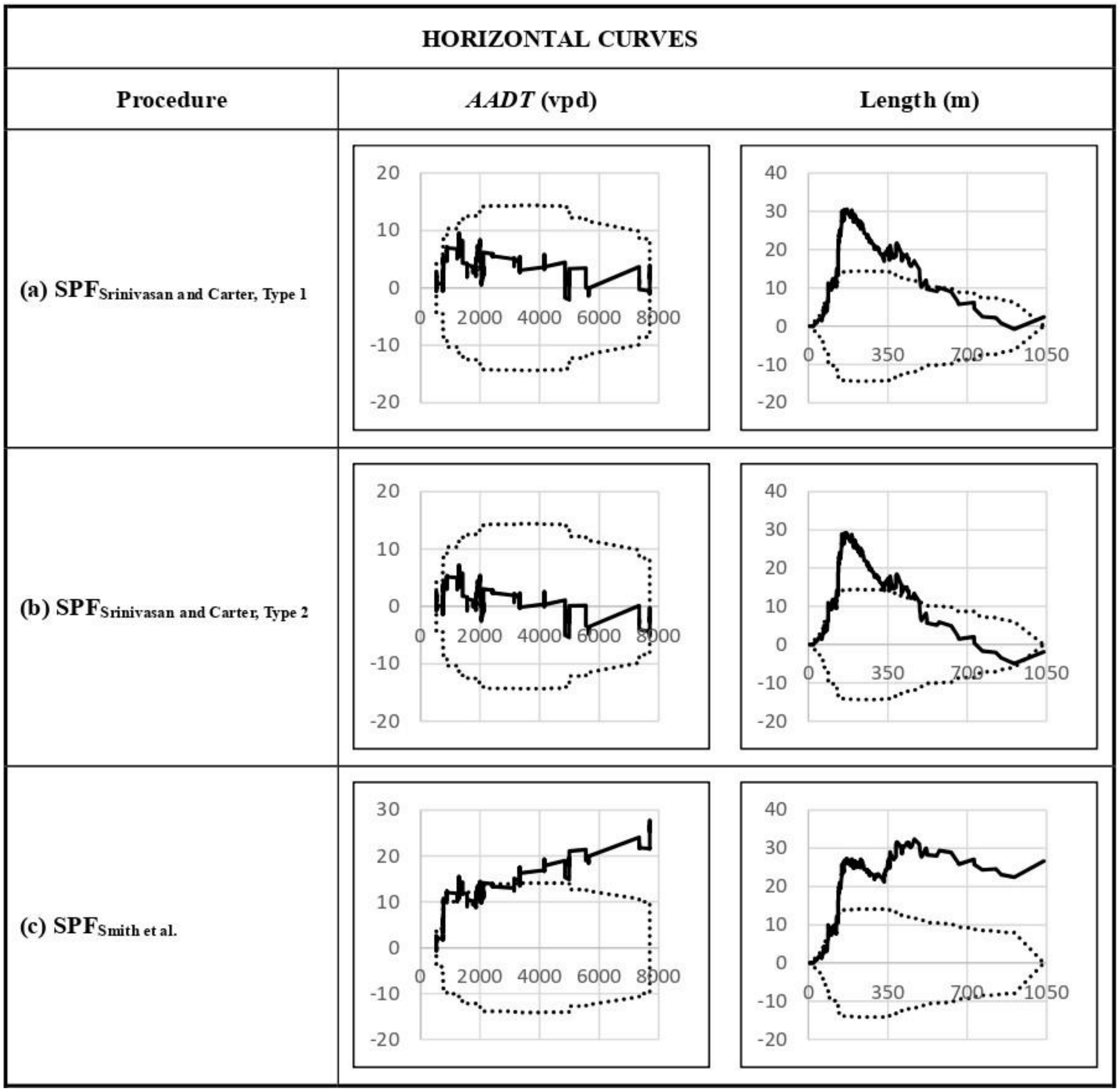


Figure 6. CURE Plots: Disaggregated analysis – Horizontal Curves.

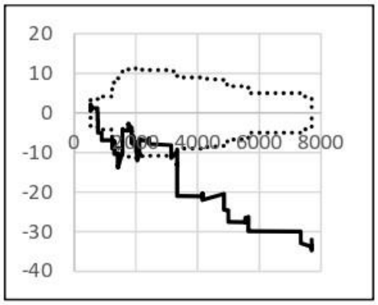
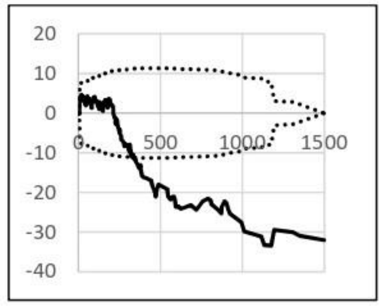
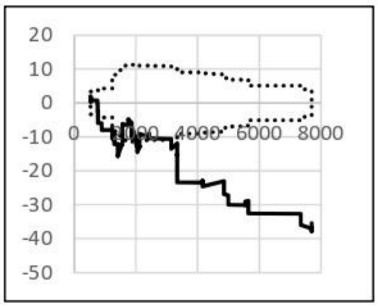
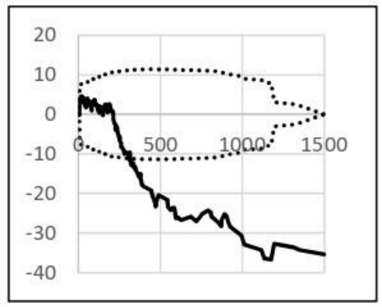
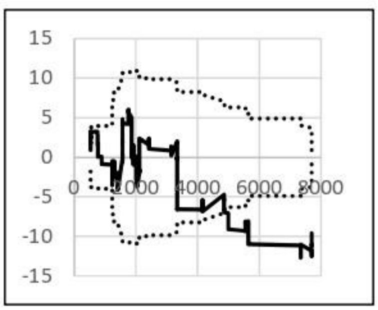
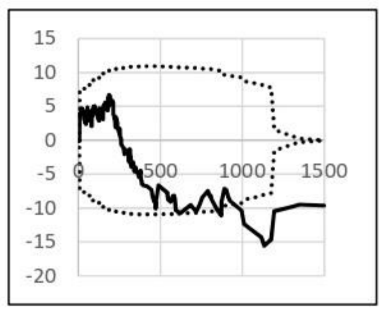
TANGENTS		
Procedure	***AADT* (vpd)**	**Length (m)**
(a) SPF$_{\text{Srinivasan and Carter, Type 1}}$		
(b) SPF$_{\text{Srinivasan and Carter, Type 2}}$		
(c) SPF$_{\text{Smith et al.}}$		

Figure 7. CURE Plots: Disaggregated analysis – Tangents.

Figure captions

Figure 1. Methodology.

Figure 2. Location of the studied road segments.

Figure 3. Road segmentation: (a) Road section; (b) Segmentation according *AADT* and cross-section; (c) Segmentation according to geometric layout.

Figure 4. Speed profiles.

Figure 5. CURE Plots.

Figure 6. CURE Plots: Disaggregated analysis – Horizontal Curves.

Figure 7. CURE Plots: Disaggregated analysis – Tangents.