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A Bayesian procedure for evaluating the frequency of calibration factor updates in highway safety manual (HSM) applications

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ABSTRACT

The Highway Safety Manual (HSM) presents statistical models to quantitatively estimate an agency's safety performance. The models were developed using data from only a few U.S. states. To account for the effects of the local attributes and temporal factors on crash occurrence, agencies are required to calibrate the HSM-default models for crash predictions. The manual suggests updating calibration factors every two to three years, or preferably on an annual basis. Given that the calibration process involves substantial time, effort, and resources, a comprehensive analysis of the required calibration factor update frequency is valuable to the agencies. Accordingly, the objective of this study is to evaluate the HSM's recommendation and determine the required frequency of calibration factor updates. A robust Bayesian estimation procedure is used to assess the variation between calibration factors computed annually, biennially, and triennially using data collected from over 2400 miles of segments and over 700 intersections on urban and suburban facilities in Florida. Bayesian model yields a posterior distribution of the model parameters that give credible information to infer whether the difference between calibration factors computed at specified intervals is credibly different from the null value which represents unaltered calibration factors between the comparison years or in other words, zero difference. The concept of the null value is extended to include the range of values that are practically equivalent to zero. Bayesian inference shows that calibration factors based on total crash frequency are required to be updated every two years in cases where the variations between calibration factors are not greater than 0.01. When the variations are between 0.01 and 0.05, calibration factors based on total crash frequency could be updated every three years.

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1. Introduction

The Highway Safety Manual (HSM) presents advanced and quantitative tools in measuring safety performance of a roadway site, facility, or network (AASHTO, 2010). Part C of the HSM provides predictive models to estimate predicted average crash frequency for segments and intersections on rural two-lane two-way roads, rural multilane highways, and urban and suburban arterials. The key element of the predictive models is safety performance functions (SPFs).

SPFs are statistical models that describe the relation between crash frequency and site characteristics (Srinivasan and Carter, 2011). Based on the number of variables used in regression models, SPFs are referred to as either full SPFs or simple SPFs. In full SPFs, factors such as roadway geometry, traffic volume, and traffic control features are included into the model. The general functional form of a full SPF can be expressed as follows:

$$N_{predicted(f)} = \exp(\alpha + \beta \times \ln(AADT) + \gamma_1 X_1 + \gamma_2 X_2 + \ldots + \gamma_n X_n) \quad (1)$$

where $N_{predicted(f)}$ is the predicted average crash frequency estimated using a full SPF, $AADT$ is annual average daily traffic, $X_1, X_2, \ldots, X_n$ are n roadway geometric characteristics, and $\alpha, \beta, \gamma_1, \gamma_2, \ldots, \gamma_n$ are regression coefficients. One major problem associated with full SPFs is the possible correlation among the independent variables (Lu et al., 2014). This issue could be addressed using simple SPFs that relate crash frequency as a func-

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tion of traffic volume alone. A simple SPF is therefore a simplified version of Eq. (1) and expressed as follows:

$$N_{predicted(s)} = \exp(\alpha + \beta \times \ln(AADT)) \quad (2)$$

where $N_{predicted(s)}$ is the predicted average crash frequency estimated using a simple SPF. A simple SPF is developed based on some base conditions such as 12-ft lanes, no median, no on-street parking facility etc. To predict crashes for a specific site where the site characteristics deviate from base conditions, a set of crash modification factors (CMFs) are applied to account for the effects of prevailing roadway geometry and traffic control characteristics. The HSM implements this approach, as follows:

$$N_{predicted(HSM)} = N_{predicted(s)} \times (CMF_1 \times CMF_2 \times \ldots \times CMF_n) \quad (3)$$

where $N_{predicted(HSM)}$ is the predicted average crash frequency after accounting for site specific characteristics and CMF_1, CMF_2, ..., CMF_n are crash modification factors for n geometric conditions or traffic control features.

The SPFs in the HSM were developed based on specific years of data collected from only a few U.S. states including California, Michigan, Minnesota, New York State, Texas, and Washington State. The SPFs therefore are not easily transferrable to other jurisdictions without validating using local data (Farid et al., 2016; Martinelli et al., 2009). To apply the HSM-default SPFs to local jurisdictions, the manual recommends estimating local calibration factors for these SPFs. The calibration factor for a particular site type is defined as the ratio of the total number of observed crashes to the total number of predicted crashes calculated using Eq. (3) above. Calibration factors reflect the effects of differences between the jurisdiction and time period for which the predictive models were developed and the jurisdiction and time period to which the models are applied. The differences in factors include, but are not limited to, geographic area, roadway environment, seasonal characteristics, drivers' characteristics, driving patterns, animal populations, and crash reporting thresholds, which may also vary from time to time.

Deriving calibration factor is, therefore, a crucial step for successful application of the HSM predictive models. Since the release of the HSM in 2010, several states including Alabama (Mehta and Lou, 2013), Florida (Srinivasan et al., 2011; Alluri et al., 2014), Illinois (Williamson and Zhou, 2012), Kansas (Lubliner and Schrock, 2012), Louisiana (Sun et al., 2006), Maryland (Shin et al., 2014), Missouri (Sun et al., 2013), North Carolina (Srinivasan and Carter, 2011), Oregon (Dixon et al., 2012), Utah (Brimley et al., 2012), and Virginia (Kweon et al., 2014) developed local calibration factors for the HSM predictive models. A recent study by Farid et al. (2016) explored the transferability of safety performance functions.

The studies described the task of performing the calibration process as challenging, mainly because agencies do not have the data for all the variables and it involves substantial time, effort, and resources for necessary data collection. Srinivasan et al. (2013) estimated that calibration of each HSM model may require up to 350 staff hours, even when all the necessary data are available. Therefore, determining how often an agency should update calibration factors for crash predictions is worthy of investigation.

According to the HSM, "... *new values of the calibration factors be derived at least every two to three years, and some HSM users may prefer to develop calibration factors on an annual basis*" (AASHTO, 2010). This recommendation, however, is not based on any research and does not reflect any clear guidance on the frequency of updating calibration factors (Shin et al., 2014). The agencies' efforts in updating calibration factors would go in vain if it is found that the update is not required.

The objective of this study is therefore to investigate the variation among calibration factors computed annually, biennially, and triennially, and determine how frequently they need to be updated. A robust Bayesian estimation procedure is applied to evaluate the frequency of updating calibration factors based on the variation between estimated calibration factors at specific intervals (e.g., one year, two years, and three years). Bayesian inference is based on probability distribution of model parameters and thus provides credible and comprehensive information to make decisions on the frequency of updating calibration factors. The evaluation is conducted for the following urban and suburban arterial facilities in Florida: two-lane undivided arterial segments, three-lane arterial segments with a two-way left-turn lane (TWLTL), four-lane undivided arterial segments, four-lane divided arterial segments, five-lane arterial segments with a TWLTL, three-leg stop-controlled intersections, and four-leg signalized intersections.

2. Literature review

Several studies, including Sun et al. (2006), Findley et al. (2012), and Young and Park (2013), assessed the importance of measuring calibration factors for different facilities. Alluri et al. (2014), Bahar (2014), Shirazi et al. (2016), and Trieu et al. (2014) evaluated several criteria in the HSM for developing calibration factors and recommended improved criteria for obtaining reliable calibration factors. However, no explicit research has yet been conducted to investigate the criteria for updating calibration factors. A few studies had only provided some hints with regard to updating local calibration factors (for example, Dixon et al., 2012; Srinivasan and Carter, 2011; Srinivasan et al., 2011; Williamson and Zhou, 2012).

Dixon et al. (2012) developed calibration factors for the HSM Safety Performance Functions (SPFs) for highways and intersections in Oregon for a specific year, and advised "to periodically update the calibration factors for these locations as crash conditions change over time." The authors, however, did not elaborate on this recommendation.

Srinivasan and Carter (2011) developed calibration factors for the HSM SPFs for all segment and intersection types in North Carolina. Although the study suggested evaluating a few specific issues before updating calibration factors, it did not provide insights on how frequently an agency should update the calibration factors for applying the HSM SPFs.

Srinivasan et al. (2011) developed yearly calibration factors from 2005 through 2008 for applying HSM's fatal and injury SPFs on Florida's state roads and intersections. The authors found the variation between yearly calibration factors across site types. However, they did not investigate the degree of variation among calibration factors estimated annually, biennially, and triennially.

Williamson and Zhou (2012) estimated calibration factors for both the HSM-default SPFs calibrated to Illinois data and the Illinois SPFs developed by Tegge et al. (2010) for rural two-lane two-way roads, and suggested to update the values of calibration factors when a new crash reporting threshold is adopted. This suggestion, however, suffers from one-eyed view as it accounts only for the effect of crash reporting threshold, ignoring the effects of all other possible factors that might attribute to changes in calibration factors.

The suggestion given in these studies on the frequency of updating calibration factors was mainly based on intuitive judgement rather than on the basis of evidence from research outcome. This study attempts to investigate the nature and effects of variations between calibration factors estimated annually, biennially, and triennially.

3. Data requirements, preparation, and collection

This section briefly discusses the calibration data requirements, and data collection and data preparation efforts undertaken as part of this study.

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