Developing a Methodology for Implementing Safety Improvements on Low-Volume Roads in Montana

Task Report: State of the Art Review

Prepared by

Ahmed Al-Kaisy, PhD, PE – Professor & Program Manager

Kazi Tahsin Huda – Graduate Research Assistant

of the

Western Transportation Institute
College of Engineering
Montana State University
Bozeman, MT 59717-4250

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1. INTRODUCTION

Reducing fatal and serious injury crashes by improving safety on the roadway system is a priority for highway agencies. Safety improvement programs are one way of addressing these concerns. These programs are funded by governments with the objective of continuously improving safety on the roadway system, using a data-driven strategic approach. One of the important steps of such programs is screening the network to identify candidate locations that are in most need of safety improvements. Over the years, various screening methods have been developed. Methods using historical crash data (crash frequency, severity and rates) at individual sites are the older and most widely used. However, newer screening methods are using different variables (such as roadway and traffic characteristics) to identify the level of risk on a given network. Methods in the two groups vary in complexity from the simple to the more sophisticated methods (e.g. using mathematical models). The purpose of this report is to present the results of the literature review task, summarizing the state of knowledge in network screening for safety improvement sites, with an emphasis on low-volume rural roads.

2. CHALLENGES OF SCREENING SITES FOR LOW-VOLUME RURAL ROADS

In 2018, about 50 percent of fatal crashes occurred on rural roads, even though only 19 percent of the US population reside in rural areas (NHTSA, 2018). This statistic highlights the importance of improving safety on rural roads, including those with low traffic volumes. While no uniform definition exists for low-volume roads, an average daily traffic (ADT) of a thousand vehicles per day has been used more often (Ewan et al., 2016; FHWA, 2009; Gross et al., 2011) and will be used in this project as well.

Most highway agencies use limited budgets to implement safety improvement projects on a regular basis. An important step in the process is to use an effective screening method to identify sites for further consideration. The conventional approach for screening sites for safety improvements is to use crash history, i.e. crash frequencies, rates, and/or crash severities. While this conventional approach may work for higher-volume roads, it may not prove reasonable for low-volume roads. Specifically, should frequency be used as the sole ranking criterion, sites along low-volume roads are unlikely to rank high on the list because low volumes normally result in a few sporadic crashes over the analysis period. On the contrary, when crash rate is used as the sole ranking criterion, low volumes are expected to result in higher crash rates even with only a few crashes taking place on these roads. Consequently, those sites may rank high on the list despite the fact that the few crashes occurring at these sites may not be related to roadway characteristics (e.g. distraction, DUI, etc.). Therefore, techniques based entirely on historical crash data may not be effective in screening sites for safety improvements on low-volume roads.

3. RISK FACTORS FOR LOW-VOLUME RURAL ROADS

For the purpose of this research, a risk factor is defined as any attribute or characteristic of a particular roadway that increases the likelihood of crash occurrence. These attributes or characteristics may be related to roadway, traffic, and/or environmental factors. Roadway factors primarily involve roadside features, cross-section elements, and alignment. Factors related to traffic involve percentage of trucks or motorcycles, running speeds, driver characteristics (e.g. age, experience, local versus tourist), and presence of non-motorized modes. Finally, environmental factors include weather conditions that may compromise the safety of driving conditions (heavy fog, ice or snow). Because safety improvement projects are primarily related to roadway factors, the three main characteristics of roadways (roadside features, cross-section elements, and alignment) will be the focus of this report.

3.1. Roadside Features

Roadside features include side slopes, ditches, and presence of fixed objects (trees, utility poles, culvert openings, bridge piers, etc.) within a close proximity of the roadway.

Bendigeri et al. (2011) identified potential risk factors that are likely to increase roadside tree crashes on different road classes in South Carolina. The study found that approximately 48 percent of tree crashes in the state occurred on secondary routes and that drivers under the age of 36 were involved in over 57 percent of those crashes. The study also found that 48 of the 51 study sites that had experienced a crash did not meet clear zone requirements. Specifically, critical side slopes and non-traversable ditches reduced effective clear zone distances.

A study by Ewan et al. (2016) quantified the relationship between crash occurrence and geometric and roadside features along rural low-volume roads in Oregon. Descriptive statistics, crash rate analysis, regression and correlation analyses were used. The relationship of crash occurrence with lane width, shoulder width, grade, side slope, roadside fixed objects, and horizontal and vertical curves have been quantified. The study found that an increase in side slope rating, fixed object rating and driveway density all had strong correlations to high crash rates.

Schrum et al. (2012) investigated low-volume roads in Kansas and Nebraska to identify common fixed objects and geometric features that have the potential for causing crashes. Features identified included culverts, bridges, driveways, trees, ditches, slopes, utility poles and public broadcast service routing stations. Infrequent obstacles, including road and advertising signs, mailboxes, tree stumps, bushes, rock walls, boulders and water bodies were also identified as presenting safety issues. The frequency of the impact and their possible treatments were identified by the Roadside Safety Analysis Program (RSAP).

Souleyrette et al. (2010) undertook a safety analysis of low-volume rural roads in Iowa. Results revealed that low-volume roads had a higher frequency of roadside crashes (e.g. those involving culverts, ditches, embankments, trees and poles) compared to their higher volume counterparts. The study also found a higher frequency of crashes at bridges, railroad crossings, driveways and T or Y configuration intersections, but a comparatively lower frequency at four-legged intersections.

Another study in Texas (Peng et al. 2012) investigated the relationship of roadside features with single vehicle crashes on rural two-lane roads. The investigation found that shoulder width, lateral clearance and side slope conditions impart a significant effect on road departure crashes. The study found that an increase in shoulder width, lateral clearance and the use of flatter side slopes decreased the probability of injury crashes.

3.2. Cross Section Elements

Cross section elements of roadways include: lane width, shoulder width, shoulder surface type, use of rumble strips, markings, and delineation.

A study by Gross et al. (2011) on low volume roads found that narrow lane widths (between 8 and 10.5 feet), narrow or unpaved shoulders, lack of turn lanes, and pavement edge drop-offs of greater than 2 inches, all raise safety concerns. These issues were identified during observations from Road Safety Audits and are not based on a statistical evaluation.

Gross and Jovanis (2007) investigated the safety effectiveness of lane and shoulder widths for rural, two lane highway segments in Pennsylvania, including low-volume segments (those with average daily traffic (ADT) of less than 500 vehicles per day). Matching case-control approach was used to investigate segment and crash data, with control segments used for safety comparisons. Conditional logistic regression was used to investigate the relationship between crashes and lane and shoulder widths. Results indicated that lane widths between 10 to 11.5 feet and greater than 13 feet were less safe than other lane widths (i.e. 12 feet). However, lane widths less than 10 feet indicated a lower crash risk, which contradicts the findings of other studies. Shoulder widths of 0 to 3 feet were found to increase crash risk, with that risk dropping as width increased.

Ivan et al. (1999) identified differences in causality factors for single and multi-vehicle crashes on two-lane roads. Even though this work did not focus on low volume roads, study results provided insights about potential risk factors. The research found that single vehicle crash rates decreased with increased traffic intensity, wider shoulder widths and longer sight distances. Multi-vehicle crash rates increased with the presence of signalized intersections.

Wang et al. (2013) compiled a review of the effects of road characteristics on safety. The review found that past evaluation of the relationship between speed and crashes produced mixed results, with some studies suggesting increased speeds reduced safety while other studies suggesting the opposite trend. Regarding road characteristics, the researchers stated that past work had found roads with narrow lanes (less than 11.5 feet) and sharp horizontal curves had decreased numbers of crashes. Similarly, increased shoulder width and pavement improvements had also been found to reduce crashes. While these findings were not focused for low-volume rural roads, they may provide information about potential risk factors on these roads.

A study in Virginia (Garber and Kassebaum, 2008) identified causal factors of crashes at high risk locations on rural and urban two-lane roads. Major causal factors were identified using fault tree analysis. Generalized linear modeling (GLM) was used to develop models for prediction of crash occurrence at study sites. Annual Average Daily Traffic (AADT) values for the routes examined ranged from 0 to over 10,000 vpd. The investigation found that variables associated with crashes did not vary between rural and urban roads. The research found that grade, operational speed, lane width and passing zone presence were factors in run-off-the-road crashes. Lane width, Average Daily Traffic (ADT), turn lane presence and operating speeds were associated with rear end crashes. Curvature, operating speed, grade, ADT and passing zone presence were factors in head-on crashes. ADT, passing zone presence, speed, curvature and lane width were associated with sideswipe crashes. Finally, grade, operational speed, ADT, curvature, lane width and passing zone presence were associated with crashes classified as “other”.

Mahgoub et al. (2011) identified a series of issues to examine when conducting field reviews of local roads (ADT less than 500 vpd). This was part of the process for developing a quantitative assessment tool for local roads. The issues identified included changes in land use, traffic, terrain, lane width, shoulder width, fixed objects, guardrail presence, pavement surface, signage adequacy and railroad crossing presence. These features were listed only for evaluation purposes with no specific quantification of the associated risks.

Fitzpatrick et al. (2001) identified characteristics of low-volume two lane road crashes in Texas. The study found that sites with higher crash rates had higher presence of vertical and horizontal curves, narrow lanes, narrow shoulders, higher driveway/access density or restrictive sight distances due to roadside development.

Stamatiadis et al (1999) examined the likelihood of crash involvement for young (> 35), middle age (35-64) and older (65+) drivers on low volume roads (AADT > 5000 vpd) in Kentucky and North Carolina. The roadway characteristics examined in this study were speed limits, lane widths, shoulder widths and AADT. Ratios were calculated to measure the relative crash propensity for the different driver groups. Results for single vehicle crashes indicated that for speed limits above 45 mph, all age groups were more likely to be involved in crashes. For lane widths of 8 to 9 feet, younger and middle age drivers were more likely to be involved in crashes, while only younger drivers were at risk for lane widths of 9 to 10 feet. Shoulder widths of 0 to 1 foot presented a risk to younger drivers, while widths of 1 to 5 feet were a risk for younger and middle age drivers. Finally, roads with an AADT of 0 to 1999 vpd were a risk to younger and middle age drivers. When examining two-vehicle crashes, both younger and older driver groups were at risk for all of these same features, while middle age drivers were found to be less at risk.

A study on risk factors for low-volume roads in Oregon (Ewan et al., 2016) found that lane widths of less than 12 ft had a higher crash risk than roads with the standard 12 ft lanes. Also, roads with narrow or no shoulders exhibited higher crash rates compared to shoulder widths of 4 to 5 ft. A correlation analysis also revealed that wider lane and shoulder widths were associated with lower crash rates.

A study by Sun et al. (2007) investigated the impact of pavement edge line on narrow, low volume (86 – 1,855 vpd ADT) roads in Louisiana, by examining general crash trends. The study found that fatal run-off-the-road crashes comprised up to 75 percent of total fatal crashes on rural two-lane roads where pavement widths were less than 20 feet.

Wang et al. (2008) evaluated rural two-lane roads (no traffic volumes cited) in Washington State to identify causal factors in crashes. Crashes were shown to decrease as shoulder and pavement widths increased. No specific values associated with these risks were identified by this research.

3.3. Alignment

Horizontal and vertical alignments include such elements as horizontal curves, vertical curves, grades, and their associated sight distances.

Federal Highway Administration (FHWA) found that, compared to a tangent section of road, a horizontal curve with a radius of 500 feet was 200% more likely to have a crash, while a horizontal curve with a radius of 1,000 feet was 50 percent more likely to experience a crash (FHWA, 2009; Zeeger et al., 1990). Similarly, Harwood et al. (2000) found that when curve length and radius were both 100 feet, the crash rate was more than 28 times higher than that of a tangent section.

Findley et al. (2012) investigated the impacts of spatial relationships to horizontal curve safety on rural two-lane roads in North Carolina. The factors investigated included distance to adjacent curves, radius and length of adjacent curves. The research found that the distance between adjacent curves was significant in estimating crashes, with longer distances between curves being associated with a higher number of crashes.

Van Schalkwyk and Washington (2008) identified characteristic features of two-lane rural roads for crashes in the state of Washington. The rate of run-off-the-road crashes was found to be higher in mountainous terrain than for other terrain types. Segments with shoulder widths less than 5 feet had higher overall and severe injury crash rates, including on horizontal curves. Also, horizontal curves having a degree of curvature above 2 was found to be associated with higher crash rates. In addition, Knapp and Robinson (2012) reported that a critical radius of 800 feet or less contributes to higher fatal and injury crash rates (more than 3.86 crashes per million vehicle-miles traveled).

The previously cited study by Stamatiadis et al. (1999) investigated the safety effect of degree of curvature on drivers by age group. The study found that degrees of curvature from 0.4 to 8.4 were a risk to younger drivers; degrees from 8.5 to 19.4 were a risk to younger and middle age drivers, and degrees of 19.5 and more a risk to younger and older drivers. Wang et al. (2008) also found that the increase in degree of curvature increased crash risk. In addition, the study found that grade or the presence of a curb or roadside wall also increased crash risk. However, no specific values associated with these risks were cited in this study.

Schneider et al. (2009) examined the severity of crashes at horizontal and vertical curves on rural two-lane roads. The results found that driver injuries were more likely to be severe on curves with a radius between 500 and 2,800 feet compared to sharper low-speed curves and gradual high-speed curves. When examining parametric-specific elasticities to measure the impact of different parameters on the likelihood of injury outcomes, it was found that run-off-the-road injuries increased by 7.7 percent on horizontal curves with a radius greater than 2,800 feet and 18.9 percent for curves with a radius between 500 and 2,800 feet. The combination of horizontal and vertical curves increased the likelihood of fatal crashes by 560 percent on curves with a radius of 500 to 2,800 feet.

Ewan et al. (2016) found that for low-volume roads in Oregon, higher degrees of curvature were associated with higher crash risks than curves with smaller degrees of curvature. The study found that crashes are eight times more likely to occur on curves with degrees of curvature of 30 or higher compared with curves with degrees of curvature of less than 5.

In their investigation of the safety effects of horizontal curve and grade combinations on two-lane rural highways in Washington State, Bauer and Harwood (2013) found that short and sharp horizontal curves were associated with higher crash frequencies. Also, short horizontal curves at sharp crest and sag vertical curves had higher crash frequencies.

4. NETWORK SCREENING METHODS

An important step in the Highway Safety Improvement Program (HSIP) is screening the network for sites that are good candidates for safety improvement projects. The screening process follows certain criteria that are good indicators of safety performance (e.g. crash history) or the level of risk (e.g. risk factors). This section discusses network screening methods reported in literature or published online, as well as various methods for assessing or predicting the level of risk by assessing risk factors at a particular site. Screening methods are classified into three types: those that use crash history, those that use crash prediction models, and those that utilize a combination of crash history and prediction models.

4.1. Methods Based on Historical Crash Experience

This section discusses network screening methods that use historical crash experience such as crash frequencies, severities, crash types, and/or crash rates (the latter require the use of traffic exposure data). The methods that exclusively utilize historic crash data are presented first, followed by those that utilize crash data in conjunction with other information (such as traffic or roadway characteristics).

4.1.1. Methods using crash data alone

Crash Frequency/Density Method: Crash frequency methods use the number of crashes for each site in the network. These sites could be a spot location (e.g. intersection, bridge, highway-rail crossing, etc.) or a roadway segment. Crash frequency could also be established for specific crash types, such as run-of-the-road crashes, pedestrian crashes, etc. The sites are then ranked in a descending order. When crash frequency at a location is greater than a pre-determined critical value, that location is considered a “high crash location.” The critical frequency values are either calculated using average crash frequency at similar sites (and their standard deviations) or by choosing a considerably high number for that particular type of location (Pawlovich, 2007; Southeast Michigan Council of Governments [SEMCOG], 1997; National Cooperative Highway Research Program [NCHRP], 1986; NCHRP, 2000).

The crash density method is used to calculate the number of crashes per mile for roadway segments. A segment can be defined as the minimum length of roadway having consistent characteristics. Similarly, the segments are ranked in descending order and segments having a crash density greater than a pre-determined critical density are considered as “high crash locations.” The critical density is calculated in a similar fashion as described in the frequency method (Pawlovich, 2007; SEMCOG, 1997; NCHRP, 1986; NCHRP, 2000).

An illustrative approach to the crash frequency/density method is the spot map method. The spot map method develops a map showing crashes on the network, thus identifying crash clusters at spot locations and on segments of the road network. The map is then used to identify those locations or segments having the greatest numbers of total crashes or total crashes of a specific type. This is a simple and easy method more suitable for small areas and areas having lower number of crashes (Pawlovich, 2007; SEMCOG, 1997). It only provides rough estimates of high crash locations and fails to provide a list of those locations.

Crash Severity Methods: Crash injury severity is also incorporated in network screening. One method for assessing crash injury severity utilizes the ratio of fatal crashes to total number of crashes in identifying sites for further consideration. Fatal crash rates, fatal plus injury crash rates, and total crash rates may also be used. Crash severity methods incorporate injury severity in a number of ways, including: frequency/density of severe crashes, rate of severe crashes and ratio of severe crashes. In this method, severe crashes are assigned more weight than other crashes. Generally, the results for each site are compared to a system-wide average for similar roadways. This allows agencies to devote more resources to locations with a greater potential for severe crashes.

The equivalent property damage only (EPDO) method and the relative severity index (RSI) are two types of crash severity methods. The EPDO method assigns a weight to fatal and injury crashes against a baseline of property-damage-only (PDO) crashes. The EPDO for a site (or segment) is calculated using the weights, frequency of fatal, injury and PDO crashes. The EPDO rate for a site is calculated using traffic exposure data (Pawlovich, 2007; SEMCOG, 1997; NCHRP, 1986; NCHRP, 2000). The RSI method incorporates the weighted average cost of crashes at the site or segment. The RSI is calculated using frequencies and estimated crash costs for fatal, injury and property damage crashes (Pawlovich, 2007; SEMCOG, 1997; NCHRP, 1986; NCHRP, 2000).

A combination of crash frequency and crash severity is sometimes used for network screenings. This method incorporates both concentration criteria and severity criteria. To meet the concentration criteria, the site crash frequency/density must exceed a pre-determined critical value. To meet the severity criteria, the EPDO rate for the site must also exceed a predetermined cut-off value. If both criteria are met, the site is considered a candidate for safety improvement measures. Critical rates for total crash frequencies, fatal crash frequencies, etc. are used to determine the cut-off values (Pawlovich, 2007).

4.1.2. Methods using crash data in conjunction with other data

The Crash Rate Method: The crash rate method incorporates traffic exposure with crash history in the network screening process. Crash rates are expressed for highway segments as the number of crashes per million vehicle miles travelled, and for spot locations as the number of crashes per million vehicles entering. Similar to the crash frequency methods, a critical crash rate has to be established, with locations higher than the critical value classified as "high-crash locations." A common practice is to use a critical value that is twice as high as the system-wide mean crash rate (Pawlovich, 2007; SEMCOG, 1997). The crash rate method often uses total crashes in calculating rates, however, rates for specific crash type (e.g. single-vehicle crashes) and severity levels (e.g. fatal crashes) are also used.

The Frequency-Rate Method: The frequency-rate method combines the results from crash frequency-density methods and the crash rate method. In this method, the crash frequencies and densities, as well as crash rates are calculated for point locations and roadway segments. Critical values are established for crash frequencies or densities as well as for crash rates both for point locations and roadway segments independently. Consequently, locations having both frequency/density value and crash rate value greater than the pre-specified critical values are considered "high crash locations" (Pawlovich, 2007; SEMCOG, 1997; NCHRP, 1986; NCHRP, 2000).

The Quality Control Method: The quality control method uses similar principles as that of the frequency and rate methods. This method involves comparing crash frequencies/densities or rates with pre-determined values for sites of similar characteristics. There are two types of quality control: number quality control and rate quality control.

The number quality control compares the actual frequency/density for each site with the critical frequency/density. A test is applied to determine the statistical significance of a site's crash frequency/density when compared to the mean crash frequency/density for similar sites. The statistical test assumes crashes have a Poisson distribution, and uses a probability constant that adjusts the critical value as per the level of confidence requirements. The rate quality control method follows the same principle but uses crash rates instead of frequency/density. The final step of this method includes the calculation of a safety index. The safety index is the ratio of observed frequency/density or crash rate to the critical frequency/density or crash rate. The sites are then ranked by the safety index (Pawlovich, 2007; SEMCOG, 1997; NCHRP, 2000).

Deacon et al. (1975) developed an effective procedure for identifying hazardous rural highway locations based on accident statistics. The procedure utilized multiple indicators of accident experience which included the number of fatal accidents, the total number of accidents, the number of effective-property-damage-only accidents, and the accident rate. Critical levels of these four indicators are expected to vary from state to state depending on the nature of the local safety improvement program as well as local traffic and roadway conditions and prevailing attitudes toward highway safety. Critical accident rates are established using quality control procedures.

Index Methods: Index methods combine crash severity indices with other methods. There are three main index methods: the weighted rank method, the crash probability index method (CPI) and the Iowa method.

The weighted rank method (Pawlovich, 2007; SEMCOG, 1997; NCHRP, 2000) combines results from other methods. For example, ranks based on the crash frequency/density, crash rate and crash severity methods are generated. Then using a weighting factor, the combined rank based on the individual ranks are calculated.

The crash probability index (CPI) combines the results from the crash rate, crash frequency and casualty ratio (CR) methods. Casualty Ratio is the ratio of fatal and all types of injury crashes to the total number of crashes at a given site or segment. This method reduces misleading results that arise from either high or low traffic volume at a site, while also incorporating the severity of the crashes. When any of the results exceed their critical values, penalty points are assigned. The CPI value for a site is the sum of all the penalty points. Sites with higher CPI values receive higher priority. The penalty points for each of the criteria (rate, frequency and CR) can be subjectively assigned based on how much importance an agency puts on each of the methods. The critical value for the rate and frequency is set using the same principle as that of crash rate and crash frequency/density methods. The critical value for CR can be determined by using the regional CR. The regional CR can also be in terms of facility and intersection type in conjunction with traffic exposure (AADT) (Pawlovich, 2007; SEMCOG, 1997). Both the weighted rank method and the CPI method allows retention of some of the benefits of the different methods while also minimizing the disadvantages of each method. For example, using the crash frequency and the crash rate together helps to address the inaccuracy of the crash frequency method that arises due to very low or high volumes.

In Iowa, a method similar to the weighted rank methods are used. Three rank lists are developed: frequency rank, severity rank and rate rank. The original Iowa method requires identification of sites with at least eight total crashes, four injury crashes and one fatality. The selected sites are first sorted by descending frequency of crashes (frequency rank). Then the locations are sorted by a severity rank. The severity ranks are developed using the principle of loss of value. Each crash severity (Fatal, injury, property damage only, etc.) is assigned a monetary value. The loss value at a site is calculated based on the frequency of each crash severity and the respective monetary value. Finally, using the traffic exposure data, crash rates are calculated and the sites are ranked according to the crash rates. The three ranks are then combined to create a composite rank factor which is used to prioritize the sites in a descending order (Pawlovich, 2007; Estochen, 1999; Iowa Department of Transportation Office of Traffic and Safety [IDOT TAS], n.d.)

The newer Iowa method uses a similar approach with focus on intersections. Crashes on road segments within a certain proximity of an intersection are considered as intersection related crashes. The frequency and rate rankings are developed in the same way as the original method. The injury severity ranking is developed by multiplying the frequency of each injury severity by specific weights. A normalization process of the ranks is carried out for each of the methods. This helps to reduce the impact of very large numbers, when the ranks are combined. This is done by dividing each of the frequency, rate and severity values by their respective maximum values. For example, the maximum crash frequency in the frequency based ranking is 5000. Another site has a frequency of 3000. Therefore, the normalized value for the second site would come out as 3/5. Finally, a weighted sum of the ranks of the measures is calculated. The weights are assigned based on the importance the agency puts on the individual ranks (Pawlovich, 2007).

4.2. Predictive Methods

Network screening methods based on predicted crash numbers use mathematical models to “predict” future crash numbers for a particular site in a network. These models are developed based on the relationship between crash numbers and roadway, traffic and geometric factors. This section discusses a few prediction models developed for rural roads.

4.2.1. Methods using crash prediction models

Zhong et al (2011) developed crash prediction models for rural roads in Wyoming using both the Negative Binomial Regression (NBR) and Poisson regression method. The model used historical crash rate (number of crashes per unit length), traffic volume, and speed. The study found that NBR fits the over dispersed data more accurately. The study showed statistically similar crash rates for both gravel and paved road surfaces. The study also correlated higher crash rates with high traffic volumes in conjunction with high speeds. However, only 36 effective observations were used for this investigation.

Using data from rural two lane highways in Pennsylvania, Aguero-Valverdea et al (2016) developed a methodology using crash type for identifying Sites With Promise (SWiPs). Full Bayes multivariate crash frequency model with spatial correlation to estimate crash frequency according to crash types was used. AADT at a particular time and segment length was used to predict the number of crashes. The study also compared univariate model, univariate spatial model, a multivariate Poisson lognormal model (MVPLN), and a MVPLN spatial model and found that MVPLN spatial model had a better fit of the data.

Schultz et al. (2016) developed a crash prediction model using the following variables: average daily traffic (AADT), segment length, speed limit, number of lanes, percent trucks, VMT, and the interaction between speed limit and number of lanes. About 100,000 iterations were performed on each segment to obtain posterior predictive distributions of the number of crashes that is expected to occur. The actual number of crashes were compared to the posterior predictive distribution to assign a percentile to each segment. The percentile was determined by where the actual number of crashes fell on the predicted distribution and was assigned a number between 0 and 1. The higher the percentile, the greater chance the segment is a hot spot that needs to be analyzed for safety improvements.

A Canadian study (de Leur and Sayed, 2002) developed a Road Safety Risk Index (RSRI) utilizing concepts related to the traffic conflict observation technique and drive-through safety reviews. Well-defined and quantifiable characteristics of road features are studied and scored while completing a drive-through review. These scores are then combined to produce an overall road safety risk, by combining three components of risk: the exposure of road users to road features, the probability of becoming involved in a collision, and the resulting consequences should a collision occur.

Ewan et al. (2015) developed a risk index to identify locations along Oregon's low-volume rural roads that deserve further consideration. The crash risk index was developed using three major elements: geometric features, crash history and traffic exposure. Weights, which show the contribution of geometric and roadside features, crash history, and traffic exposure elements in the overall crash risk index, are assigned to each of these elements.

The International Road Assessment Program (iRAP) (2009) developed a methodology for network screening and for prioritizing locations for safety investments. The methodology involved inspection of the desired road either by driving and recording potential risk factors along a highway or by using video log data routinely acquired by highway agencies. The methodology introduced Road Protection Score (RPS) which is a function of likelihood, severity, crash type, and type of road users. The RPS for a site is the sum of the individual RPS of different crash types. For example, car occupant RPS is the sum of run-off RPS, head-on RPS and intersection RPS. The likelihood factor is the connection of a certain risk factor with the likelihood of death due to a certain type of crash. The severity factor is determined from the speed and the presence of roadside objects. For example, steep embankments have a potential to increase the severity of roadside crashes. The crash-type calibration factors are based on the analysis of the fatality proportions associated with each crash type along generic type of roads. Finally, a star rating is provided for different ranges of RPS. The higher the rating, the better the safety score, with one star being the least performing score and 5 star being the highest performing score.

4.2.2. Methods using surrogate safety measures

According to a FHWA study (Gettman et al., 2008), surrogate safety measures are "*measures other than actual crash frequencies*" that are helpful to assess safety needs without waiting for a statistically significant number of crashes to actually occur. Many methods for identifying candidate sites for safety improvements using surrogate safety measures have been proposed and/or used. This section discusses a few of these methods.

Speed and speed variation are identified as potential surrogate measures by many studies (Lee et al., 2002; Lee et al., 2006; Kwon et al., 2011). Studies have linked higher speeds with higher crash rates (Nilsson, 2004; Finch et al., 1994; Baruya, 1998). Studies also found that speed is a major determinant of crash severity (Aarts and van Schagen, 2006). Speed and speed variations are also used by many studies to determine crash potential (Stipanica and Miranda-

Moreno, 2015). Siddiqui and Al-Kaisy (2017) has also used speed and speed variation as part of their investigation in assessing safety effects of a variable speed limit system.

A study in New Zealand (Harris et al., 2015) developed a method to identify curves on rural highways with higher level of risk using speed. Using the Austroads (the Australian transportation agency) operating speed model, the methodology calculated speeds along road sections based on the geometric features of the road. The method then compared the calculated speed with the horizontal curve radius in order to assess the design limitations of the curve. A new Geographic Information Systems (GIS) model was developed. The model identified the curves, predicted the operating speeds along road corridors and assessed curve risk using approach speeds and radius. However, the operating speed prediction was based only on the observations of passenger car drivers and therefore, the results of the speed prediction could only refer to the predicted speed of passenger cars.

Stipancica et al. (2018) examined whether vehicle braking and accelerating maneuvers could be used as surrogate safety measure. GPS data was collected from smartphones of people who regularly drive to explore their braking and acceleration as potential surrogate measures through correlation with historical collision frequency and severity across different facility types. Data collection was done in Quebec City, Canada in 2014. The sample for this study contained over 4000 drivers and 21,000 trips. Hard braking and accelerating events were extracted and compared to historical crash data using Spearman’s correlation coefficient and pairwise Kolmogorov-Smirnov tests. Both braking and accelerating showed positive correlation with crash frequency on highway segments, and stronger correlations were found at intersections. Locations with more braking and accelerating also tended to have more collisions. Though this study did not propose an identification and screening method for these maneuvers, the proposed surrogate measures can potentially be utilized for identification of candidate sites for safety improvements at the network level.

4.3. Methods Using Crash History and Prediction Models

The previous section of the report presented methods that used predicted number of crashes for network screening purposes. However, should reliable crash data be available for highway network in question, it is possible to use crash history along with prediction models in assessing safety performance for all segments and intersections within the network. Methods that share this approach are briefly discussed in this section.

4.3.1. Empirical Bayes Method

One example of the methods using crash history and crash prediction in assessing safety performance is the well-known Empirical Bayes (EB) method. This method determines the expected number of crashes using the actual number of crashes (crash history) along with the predicted number of crashes through the use of safety performance functions (crash prediction models). The Highway Safety Manual (HSM) recommends the use of Empirical Bayes method in assessing safety performance at sites for which the observed crash frequency is available (AASHTO 2010). The HSM prediction models, like the models explained in section 4.2.1, are mathematical models developed using data from a large number of similar sites. The HSM models use traffic exposure as the main variable. The HSM refers to these models as the Safety Performance Functions (SPFs). These models were developed using data from sites with specific geometric features, traffic control, etc. For sites with different geometric features and/or traffic control, adjustment to the predicted crash numbers are required. Adjustment factors used for this purpose are called the crash modification factors (CMFs). A calibration factor may also be used to account for regional and local variations.

4.3.2. Other methods

A study in Kentucky (Hummer et al., 1999) compared the collision-based method and an inventory-based method to identify candidate locations for safety improvements on rural roads. At that time, Tennessee DOT used the collision-based methods to identify those locations (the traditional hotspot identification methods). For the inventory-based methods, a seven-step process was developed. Three of the seven steps involve identifying sites for further consideration. Those three steps are: selection of suitable segments of highways on which the analysis is to be performed, breaking down those segments into distinct locations (such as bridges, curves, straight segments, etc.) and applying crash prediction models to calculate the predicted number of crashes for the segments. Then using both results, sites that are good candidates for safety improvement projects were ranked. In order to identify the effectiveness of each methods, a survey was designed and sent to safety experts. As a part of the questionnaire, photographs of the sites were included. The experts were asked to rank those sites and their results were compared with the results of the two methods. The comparison indicated that both methods have the potential to perform equally well in identifying candidate safety improvement sites, and the study recommended using the inventory method to compliment the collision-based method.

Ossenbruggen (1987) developed a probability-based method to identify hazardous sections. The expected number of crashes for a spot was identified using an equation connecting the Average Daily Traffic (ADT) and the probability of a harmful event taking place. The probability is calculated using two main variables; the probability of an individual being killed in a single motor vehicle trip and the mean number of trips made by an individual in a lifetime. The expected numbers of fatal and injury crashes are calculated by their respective equations. Sites with expected number of crashes less than the actual number of fatal and injury crashes, are identified as hazardous.

Tarko et al (2004) proposed two crash screening methods for ranking hazardous locations. One of the methods is based on the difference between expected and true crash numbers and the other is based on crash cost. The two proposed methods are index of crash frequency and index of crash cost.

The index of crash frequency (ICF) measures the difference between the estimates of the expected crashes and the typical numbers of crashes. The difference is then divided by the standard deviation of the difference estimate. Locations having an ICF value greater than 2 are considered as high crash locations. The higher the ICF value, the higher the chance of the location having higher number of crashes. This is so because it compares a location to a typical location of the same type having the same exposure.

This study did not use the Empirical Bayes method, as the aim was to identify sites that had "anomalies in crash frequencies that might indicate a need for road improvements". The study also stated that the index method has already been used in Indiana for several years.

The second method compares the total cost of reported crashes with the typical cost. For this method, crashes are divided into two main categories, namely; injury or fatality crashes and property damage- only crashes. The authors claim that this method "incorporates crash severity through average crash costs" (Tarko et al., 2004).

4.4. Non-Mathematical Models of Network Screening

Sometimes lack of accurate and reliable crash data makes it difficult to use some of the aforementioned methods to identify locations for safety improvement projects. In these cases, the presence of certain risk factors can be used. These often use simple sets of criteria in assessing the level of risk at a particular site and in ranking the sites.

One available resource from FHWA is the Systemic Safety Project Selection tool. This network screening and prioritization process uses site-specific crash information (including type and severity), considers common factors contributing to the focus crash type, traffic volumes and geometric features of the road (FHWA, 2013). A particular focus is placed on the severity of crashes. Risk factors are determined based on the analysis of crash and roadway data. Roadway and traffic attributes shown to have a correlation to a particular crash type are known as risk factors. Locations having one or more of these risk factors are scored with “1” or an asterisk. After reviewing the locations, the risk factors are reassessed for their usefulness in identification of safety improvement locations in the whole system. Any risk factor that is present in every location of the network is discarded. Finally, the locations are ranked based on the presence of risk factors. Higher number of risk factors indicate higher potential for a particular crash type and therefore has higher priority. Kentucky (KYTC, 2012), Minnesota (MnDOT, 2014), New York (Richard et al., 2013) and Thurston County in Washington (The Thurston County Public Works Department, 2013) have all reported using the systematic safety project tool.

Both the Minnesota County Roadway Safety Plan (CRSP) and North Dakota Department of Transportation employ a star approach to identify at-risk locations. The approach identifies risk factors for the network and any site having the identified risk factors receives a star. If any site has more than a pre-determined number of stars, it is identified as an at-risk site.

5. SUMMARY

This report presented the results of the literature review project task. The review focused on the different methods and approaches for identifying at-risk sites that are good candidates for safety improvements as well as the methods for assessing the level of risk at individual locations. More emphasis was placed on rural and low-volume roads and on network screening applications. The review included methods published in reports, studies and websites that have been either applied in practice or proposed by researchers.

The review is divided mainly into two parts: risk factors and network screening methods. Risk factors discussed in this report are those associated with roadway characteristics that are believed to affect safety performance in relation to roadside features, cross-section elements, and alignment design. The screening methods are further classified in this report into three major sections: methods using historical crash data, predictive methods, and methods using historical crash data and prediction models in combination.

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