Scientific Research Publishing

Journal of Transportation Technologies, 2023, 13, 599-614
https://www.scirp.org/journal/jtts
ISSN Online: 2160-0481
ISSN Print: 2160-0473

A Novel Network Screening Methodology for Rural Low-Volume Roads

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How to cite this paper: Al-Kaisy, A. and Raza, S. (2023) A Novel Network Screening Methodology for Rural Low-Volume Roads. *Journal of Transportation Technologies*, **13**, 599-614.
https://doi.org/10.4236/jtts.2023.134026

Received: July 25, 2023
Accepted: September 5, 2023
Published: September 8, 2023

Abstract

Low-volume roads (LVRs) are an integral part of the rural transportation network providing access to remote rural areas and facilitating the movement of goods from farms to markets. These roads pose unique challenges for highway agencies including those related to safety management on the highway network. Specifically, traditional network screening methods using crash history can be effective in screening rural highways with higher traffic volumes and more frequent crashes. However, these traditional methods are often ineffective in screening LVR networks due to low traffic volumes and the sporadic nature of crash occurrence. Further, many of the LVRs are owned and operated by local agencies that may lack access to detailed crash, traffic and roadway data and the technical expertise within their staff. Therefore, there is a need for more efficient and practical network screening approaches to facilitate safety management programs on these roads. This study proposes one such approach which utilizes a heuristic scoring scheme in assessing the level of risk/safety for the purpose of network screening. The proposed scheme is developed based on the principles of US Highway Safety Manual (HSM) analysis procedures for rural highways and the fundamentals in safety science. The primary application of the proposed scheme is for ranking sites in network screening applications or for comparing multiple improvement alternatives at a specific site. The proposed approach does not require access to detailed databases, technical expertise, or exact information, making it an invaluable tool for small agencies and local governments (e.g. counties, townships, tribal governments, etc.).

Keywords

Network Screening, Low-Volume Roads, Rural Highways, Traffic Safety

1. Introduction

Rural low-volume roads (LVRs) constitute an integral component of the United States highway system. Generally, these roads are two-lane, two-way highways with lower functional classification, and several of them are unpaved roads serving remote rural areas. Further, some of the LVRs are outside the jurisdiction of state highway departments as they are owned and operated by local agencies such as counties, townships, and tribal governments. Although a uniform or consistent definition of LVRs is lacking, average daily traffic (ADT) of one thousand vehicles per day (1000 veh/day) or less has been frequently utilized [1] [2] [3] and will also be employed in this study.

While LVRs play a significant role in connecting rural communities and facilitating the movement of crops from farms to markets, they also pose unique challenges for highway departments, particularly in terms of traffic safety. According to a recent government report, only 19% of people in the US live in rural areas, however, 31% of the vehicle miles traveled and 43% of all fatal crashes occurred on rural highways [4]. This highlights the importance of enhancing safety on rural roads, including those with low traffic volumes, and the need for incorporating LVRs into states' safety improvement programs to ensure progress toward vision zero objectives [5]. Moreover, to implement roadway safety improvement projects, it is essential to identify candidate sites through network screening. Over the years, various network screening methods for crash hotspot locations have been developed and implemented [6] [7] [8] [9]. The traditional and widely used network screening methods such as, the Empirical Bayes (EB) method [6] [10] [11] [12], predictive methods [13] [14] [15], crash severity methods [6] [16] and crash frequency/rate methods [12] [16] [17] [18] are resource intensive and require extensive historical crash and traffic data at individual sites. These methods are better suited for roadways with higher traffic volumes and more frequent crashes. However, on LVRs, crash occurrences, particularly fatal and serious injury crashes, are sporadic and infrequent due to low traffic volumes [2] [19]. Moreover, many minor/possible injury and property damage-only (PDO) crashes may go unreported on LVRs, making it challenging to identify hotspot locations and prioritize sites for safety improvements using traditional network screening methods. As such, it is important to develop network screening methods for identifying safety improvement sites on LVRs where the use of conventional network screening methods is deemed impractical.

2. Background

Most highway departments have limited budgets to implement safety improvement projects on a regular basis. As such, it is crucial to use an effective network screening method to identify potential sites for further consideration. The conventional network screening approaches, which mainly rely on extensive crash data [6] [10] [17] [18], may be effective for higher-volume roads due to a high frequency of crash occurrence. However, these methods may not be appropriate for LVRs, given their unique characteristics. Specifically, low traffic volumes on LVRs usually result in a few sporadic crashes over the analysis period [19] [20]. Therefore, if crash frequency is used as the sole ranking criterion for network screening, sites along LVRs are unlikely to rank high on the list, even if they pose serious safety hazards. On the contrary, if a crash rate is used as the sole ranking criterion, LVRs 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 even though the few crashes occurring at these sites may not be related to roadway characteristics but rather to driver behavior (e.g., distraction, DUI, speeding, etc.). Therefore, techniques based entirely on historical crash data may not be effective in screening sites for safety improvements on LVRs. Instead, a more comprehensive approach that incorporates crash risk factors, such as roadway characteristics and traffic attributes along with crash data, may be necessary to identify safety improvement opportunities more effectively on LVRs. This study adopts a comprehensive definition of risk factors as attributes or characteristics of a roadway that are connected to the likelihood of crash occurrence. These attributes or characteristics may be related to roadway geometry [1] [21], traffic [22] [23], and/or environmental factors [24] [25]. Previous research by Ewan *et al.* (2016) analyzed rural LVRs in terms of their geometric and roadside attributes and revealed a strong correlation between crash occurrence and factors such as side-slope, roadside fixed objects, and driveway density [1]. Similarly, a study of LVRs in Kansas and Nebraska identified a range of roadside characteristics as safety hazards for traffic including culverts, bridges, trees, ditches, side-slopes, utility poles, advertising signs, mailboxes, rock walls, boulders, and water bodies [26]. Thus, the present study aims to develop a network screening method to identify candidate locations on LVRs requiring safety improvements, thus reducing crash frequencies and severities.

3. Research Approach

Given the limitations of the conventional network screening methods on LVRs, there is a compelling need for a novel and practical method that meets two important criteria: 1) the methodology should not rely solely on crash history for identifying sites for safety improvements (due to very few sporadic crashes on LVRs over the analysis period), and 2) the method should require a minimal amount of information that can conveniently be acquired by local agencies and can reasonably be applied by staff with a limited technical background. The proposed methodology utilizes heuristic scoring schemes for both roadway segments and intersections. The conceptual framework is illustrated in **Figure 1**. The schemes were developed using the safety principles and guidelines outlined in the Highway Safety Manual (HSM) [27]. The HSM is the premier guidance document in the United States for conducting quantitative safety analyses in the highway project planning and development processes.

A key component of the HSM is the use of safety performance functions (SPFs), also known as crash prediction models. SPFs are mathematical models

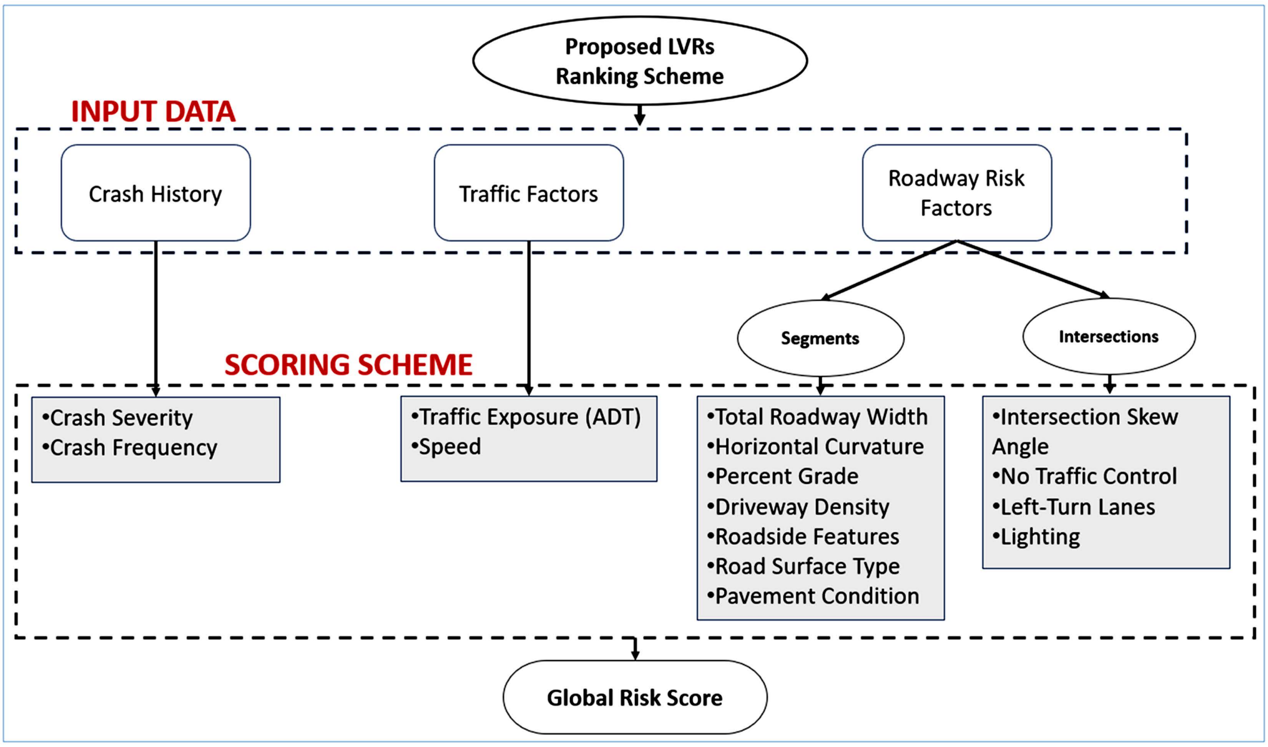

Figure 1. Conceptual framework of LVRs ranking scheme.

that estimate the expected number of crashes on a particular roadway type based on various factors such as traffic volume, speed, and roadway features. Another important aspect of the HSM is the use of crash modification factors (CMFs). A crash modification factor is a multiplicative factor that indicates the proportion of crashes that would be expected due to the presence of a roadway feature, or upon implementing a safety countermeasure (e.g., lane widening, shoulder rumble strips, etc.). Using the HSM, transportation professionals can make data-driven decisions about road safety and prioritize investments in safety programs.

The proposed heuristic scoring schemes consist of assigning a score to each individual site that is part of the roadway network based on roadway characteristics, crash history, and traffic exposure over the analysis period. Using the scoring schemes, roadway characteristics are assigned scores based on the presence of certain roadway features (e.g., horizontal curve, grade, etc.). These scores were developed based on the rural two-lane highways crash modification factors (CMFs) provided in the HSM, the Federal Highway Administration CMFs clearinghouse [28], or published in the existing literature. Roadway characteristics are expressed as simple classified variables that do not require exact values or access to detailed databases. The observed crashes involve the use of fatal and serious injury crashes as well as the remaining injury and property damage-only (PDO) crashes in assigning scores to specific sites. Unlike fatal and serious injury crashes, it is expected that many of the PDO and less serious crashes (e.g., possible injury) may go unreported on low-volume roads. Further, it is reasonable to think that local agencies have knowledge of the recent fatal and serious injury crashes occurring within their jurisdictions, as such crashes represent unusual occurrences. Fatal and serious injury crashes are assigned scores in a way to ensure that their sites will receive further consideration regardless of existing physical roadway features. Traffic exposure is another component of the proposed safety models. The models assign a multiplier (multiplicative factor) in adjusting the relative risk score based on traffic level.

Upon systemically applying the safety models assigning scores to all sites that are part of the roadway network, a list of high-priority sites (ranked from highest to lowest scores) can be established and used for further investigation and potential safety treatments. Usually, two priority lists are established: one for roadway segments and one for intersections.

3.1. Roadway Characteristics—Risk Factors

Crashes, particularly fatal and serious-injury crashes, are less frequent on LVRs. This makes it difficult to identify trends and treat hazardous sites based solely on historical crash data. Roadway and roadside features may lead to elevated crash risks at specific roadway segments or spot locations [20] [26]. The identification of such features and sites is a proactive approach to addressing safety at locations where potential hazards [20] may exist but no/few crashes may have occurred to date. This study exclusively focuses on roadway features among risk factors in developing the proposed framework as other potential risks, such as environmental factors, mostly fall beyond the scope of engineering countermeasures. The proposed methodology includes certain roadway features that: 1) are most pertinent to LVRs, 2) have tangible impact on safety per HSM guidance and existing literature, and 3) relevant information can reasonably be acquired by the prospective users, that is, local government staff.

3.1.1. Roadway Segments

For the roadway segment, the proposed methodology incorporated several roadway features that include total roadway width (lane width + shoulder width), horizontal curvature, grade, driveway density, roadside (side slope and fixed objects), roadway surface type (paved vs unpaved), and pavement condition. Roadway surface type and pavement condition were included in the proposed scoring scheme for their potential effects on safety despite the fact that these factors are not included in the HSM. This is primarily because some of the low-volume roads owned and operated by local governments are unpaved and some are paved with pavement in poor condition, and they constitute an integral part of local road networks [20].

The following subsections briefly discuss the risk factors that are associated with roadway segments and elucidate how these factors are incorporated into the proposed methodology.

Total roadway width

Total roadway width usually consists of both lane and shoulder widths. As many LVRs are unpaved or lack lane striping, the use of total roadway width instead of a separate lane and shoulder widths is deemed more appropriate [29]. Lane width, a crucial element of roadway cross-section, is associated with roadway safety [2] [22] [30] [31]. The current highway design practice recommends a standard lane width of 12 ft [32], however, narrower lanes are common on LVRs [20] [29]. According to the HSM and the current practice, a lane width less than the 12 ft standard width is associated with an increased likelihood of crashes [20] [27] [29]. Shoulder width, on the other hand, is another roadway cross-section element that is directly related to safety on rural highways [22] [29] [33]. Specifically, wider shoulders offer a space for drivers of errant vehicles to regain control and return to the travel lane thus minimizing the likelihood of roadway departure crashes [30]. As part of the proposed scoring scheme, LVRs with a total width equal to or less than 24 ft are assigned a score indicating an increased risk of crashes.

Horizontal curvature

This is the most important element of roadway alignment design that has a significant impact on crash occurrence, particularly run-off-the-road crashes on rural highways [31] [33] [34] [35] [36] [37]. The proposed methodology classifies segments into three categories: tangent segments, flatter horizontal curves, and sharper horizontal curves. Tangent segments denote straight portions of the roadway that lack horizontal curves and therefore are not assigned any score in the proposed methodology. Flatter horizontal curves are defined as curves with radii that are approximately equal to or greater than 300 ft. Whereas sharper horizontal curves are characterized by radii that are less than 300 ft. In order to quantify the risk of crashes associated with horizontal curvature, the proposed methodology assigns scores to both the flatter and sharper curve categories.

Grade

One of the important roadway alignment features that has an impact on crash risk is the presence of significant grades [31]. Specifically, the proposed methodology assigns a score to the roadway segment on significant grade (upgrade or downgrade) with a percentage grade greater than 4%.

Driveway density

The presence of driveways on local roads, stemming from adjacent land uses, has been shown to increase the number of conflict points and consequently, the risk of traffic crashes [34]. To account for this risk, the proposed methodology assigns a score to roadway segments with a number of driveways exceeding a certain threshold value. Consistent with the guidelines of the HSM [27], the driveway density is determined by considering all driveways that are used by traffic frequently or on at least a daily basis for entering or leaving the highway, serving all types of land use. Driveways that receive only occasional use, such as field entrances, are not considered in the driveway density calculation.

Roadside features

Roadsides play an important role in the number and severity of crashes along roadways in rural areas [21] [38]. In this regard, two roadside features are of particular interest: side slopes and the presence of non-breakaway fixed objects in close proximity to the roadway. The proposed methodology assigns scores for these roadside features due to their contribution to increased crash risks.

Road surface type

This factor considers the fact that many of the rural LVRs are unpaved, which could increase crash risks along these roadways [29] [38]. While the HSM does not consider road surface type for rural highway SPFs and CMFs, the proposed method assigns a score for sites of unpaved roads using findings published in relevant studies [20].

Pavement condition

Poor pavement conditions such as increased roughness, rutting, potholes, and surface skid resistance are all believed to affect crash risks on rural LVRs [39]. The proposed methodology assigns scores for roadways with poor pavement conditions.

3.1.2. Intersections

For local road intersections, the proposed methodology incorporated only three-leg and four-leg unsignalized intersections as they are the major intersection types on LVRs (higher traffic levels are required to warrant signal control). Several intersection features that include intersection skew angle, no traffic control (uncontrolled intersections), left-turn lanes on approaches without stop control, and lighting condition are believed to affect crash risk at intersections on rural LVRs and are therefore incorporated into the proposed intersection methodology.

The risk factors at rural LVRs intersections and how they are used in the proposed methodology are discussed in the subsequent sections.

Intersection skew angle

A skew angle at intersection has impact on sight distance required for drivers to avoid potential conflicts taking place inside the intersection conflict area. The skew angle for an intersection is defined as the absolute value of the deviation from an intersection angle of 90 degrees [27]. The ideal situation is for the roads to cross or meet at or close to a 90-degree angle. If the skew angle is more than 20 degrees, the proposed method assigns a score indicating an increase in crash risk.

No traffic control

Many intersections that are part of the low-volume road network are uncontrolled, that is right of way is not assigned through the use of traffic control devices. The lack of traffic control for right-of-way assignment is believed to contribute to higher crash occurrences. The proposed methodology assigns a score for uncontrolled intersections using information published in the current literature [40].

Left-turn lanes on approaches without stop control

For major-minor local roads, the two-way stop sign, and less often the yield sign, are typical forms of intersection traffic control. At these intersections, approaches with stop or yield signs usually do not have auxiliary lanes. Other approaches not controlled by signs may have turn lanes, though unlikely on LVRs. When left-turn lanes are provided on those approaches, crash risks tend to decrease [41]. Therefore, the proposed methodology deducts scores when left-turn lanes are available on major roadway approaches.

Lighting

Nighttime visibility is important for safe operations at intersections. Lighting improves visibility and is believed to reduce nighttime collisions between conflicting movements at intersections [42] [43]. The proposed method deducts a score when lighting is available, for its effect in reducing crash risks.

3.2. Crash History

Crashes occurring on roadway networks are frequently attributed to roadway features and traffic characteristics that increase crash risks. Safety countermeasures have been identified as an effective means of mitigating these risks. The proposed methodology considers historical crash data in network screening for sites that warrant further consideration of safety treatments. The methodology assigns scores to the sites based on the severity of the crashes that occurred during the analysis period. The scoring scheme is defined in such a way that a site with one or more fatal and/or serious injury crashes is identified for further consideration of potential safety improvements, regardless of roadway risk factors present. It is noteworthy that intersection-related crashes occurring on approaches to intersections should be taken into account when ranking intersection locations, even if they occur on segments leading to intersections.

3.3. Traffic Factors

In transportation safety research, it is well established that traffic characteristics have a significant impact on crash occurrence both on roadway segments and at intersections. The proposed methodology considered two crucial traffic variables: traffic exposure and speed. Specifically, traffic exposure has been found to be strongly associated with the frequency of crashes on roadway segments and at intersections [44]-[50]. To account for this relationship, the proposed methodology adjusts the relative risk score using a multiplier that is a function of the level of traffic exposure, which is typically represented by the average daily traffic (ADT) on a given roadway segment. In addition, intersection ADT, which is calculated as the sum of the ADT of the major and minor roadways or the sum of the ADTs on all intersection approaches divided by two (when ADTs are different on opposing approaches), is utilized as an indicator of traffic exposure at intersections.

Another key traffic variable considered in the proposed methodology is speed. It is well-established that speed is a critical determinant of crash severity and probability [51] [52] [53] [54]. Accordingly, a multiplier is developed to adjust the relative risk score for roadway segments with speed limits of 50 mph or higher, based on information drawn from published literature [55].

4. The Proposed Methodology

The proposed methodology for safety screening of LVRs consists of a ranking scheme where major risk factors, historical crash data, and traffic conditions are assessed and used in assigning a score to individual segments and intersections throughout the network. The sum of all scores assigned to risk factors and observed crashes is called the "relative risk compound score (RRCS)", while the final score upon adjusting the RRCS for traffic conditions using multipliers is called the "global risk score (GRS)". The GRS is an indicator of the level of risk or crash likelihood at any given roadway segment or intersection. The following sections discuss the ranking schemes for the roadway segments and intersections, respectively.

4.1. Scoring Scheme: Roadway Segments

The use of a scoring scheme and classified variables in the proposed methodology eliminated the need to access detailed information and extensive databases. The scoring scheme can be structured in a concise questionnaire format where the user can discern the presence of certain roadway characteristics, observed crashes, and traffic conditions in a user-friendly format. In the following, a few clarifications are provided about the formulation of the scoring scheme.

1) In developing scores for roadway physical characteristics, crash modification factors (CMFs) [27] were used as a guide in assigning the relative scores to different roadway characteristics or risk factors. The relative scores for the risk factors outlined in **Table 1** were derived using specific values of roadway characteristics for typical scenarios. The objective was to use scores that generally maintain the relative safety impacts of various risk factors in the proposed methodology.

2) As the Average Daily Traffic (ADT) is part of the HSM safety performance functions (and not the CMFs) [27], multiplicative factors (referred to as multipliers henceforth) were used to account for the different ranges of traffic levels. The multipliers for various traffic levels were estimated using the HSM safety performance functions for rural two-lane highways. To ensure consistency in the consideration of all traffic variables within the proposed scoring scheme, a multiplier for traffic speed was developed. The multiplier for traffic speed was derived using the crash modification factor from a study referenced in the CMF clearinghouse [55].

3) The scores assigned to observed crashes were mainly selected to ensure that sites with one or more fatal or serious injury crashes receive further consideration/review for potential safety improvements regardless of the geometric features present.

It is important to note that the proposed scoring form is primarily intended for use by local agency/government personnel with a limited technical background. Therefore, the questions in the form can be modified or revised to ensure clarity and facilitate the proper application of the proposed method. For

Table 1. Safety ranking scheme for roadway segments.

LVR Segment Ranking Scheme	
Safety-Related Questions	**If yes, add:**
Risk Factors	
Total width (TD)	
$TD \leq 20$ *ft.*?	7
20 *ft.* $< TD \leq 24$ *ft.*?	4
Horizontal curve?	
Flatter curve ($R \geq 300$ *ft.*)	30
Sharper curve ($R < 300$ *ft.*)	60
Grade steeper than ±4%?	3
Six or more driveways per mile?	5
Side slope steeper than 1V: 3H?	4
Fixed object within 15 ft of travel lane?	4
Unpaved road?	14
Poor pavement condition? (rutting, potholes, etc.)	7
Crash History	
Fatal or serious injury crashes (N_1)	$N_1 \times 80$
Other crashes (N_2)	$N_2 \times 5$
Relative Risk Compound Score (RRCS)	
Speed ≥ 50 mi/h?	RRCS × 1.25
Got ADT?	
ADT ≤ 300 veh/day	RRCS × 1.0
300 < ADT ≤ 600 veh/day	RRCS × 3.0
600 < ADT ≤ 1000 veh/day	RRCS × 5.0
ADT > 1000 veh/day	RRCS × 7.0
Global Risk Score (GRS)	

instance, the question "side slope steeper than 1V: 3H?" could be substituted with "non-traversable side slope?" if deemed more comprehensible by prospective users. Additionally, the proposed form can be seamlessly implemented in a spreadsheet application, thereby enabling users to answer the relevant questions without the need to assign scores.

4.2. Scoring Scheme: Intersections

For rural LVR intersections, a separate scoring scheme was developed using intersection characteristics, historical crash data, and traffic exposure as shown in Table 2. In this scheme, a baseline score is used to ensure that the relative risk

Table 2. Safety ranking scheme for intersections.

LVR Intersection Ranking Scheme	
Safety-Related Questions	**If yes, add:**
Baseline Score	50
Roadway Factors	
Skew angle > 20 degree?	10
Uncontrolled Intersection?	60
Lighting?	−5
Left-turn lanes on uncontrolled approach?	−30
Crash History	
Fatal or serious injury crashes (N_1)	$N_1 \times 80$
Other crashes (N_2)	$N_2 \times 5$
Relative Risk Compound Score (RRCS)	
Got ADT?	
$ADT_{int} \le 600$ *veh/day*	RRCS × 1.0
$600 < ADT_{int} \le 1200$ *veh/day*	RRCS × 2.0
$1200 < ADT_{int} \le 2000$ *veh/day*	RRCS × 4.0
$ADT_{int} > 2000$ *veh/day*	RRCS × 6.0
Global Risk Score (GRS)	

compound score (RRCS) does not result in a negative value regardless of intersection characteristics and crash history. The presence of left-turn lanes and lighting, while not often encountered at low-volume road intersections, are believed to improve safety at the intersection [41] [42] [43], thus assigned a negative score. Additionally, the scores for fatal and serious injury crashes were selected to ensure that intersections with one or more fatal or serious injury crashes receive further consideration/review for potential safety improvements. The method considers crashes occurring in the intersection conflict area as well as intersection-related crashes occurring on intersection approaches [56] [57].

Furthermore, intersection ADT (ADT_{int}) is used as an indicator of traffic exposure at the intersection. It is defined as the sum of the ADT for the two crossing roadways (e.g., major and minor roads) or the sum of the ADTs for intersection approaches divided by two (when ADTs of opposing approaches are different) [28]. While pedestrian and bicyclist traffic add to the crash risks at intersections, they are not included in the ranking scheme as their contribution to the crash occurrence is not reported in the literature on rural LVRs. However, users of the proposed methodology may take the pedestrians and bicyclists into consideration (if pedestrians/bicycles are using the intersection) when analyzing safety at intersections in the process of network screening.

Upon systemically applying the scoring method for all intersection sites that are part of the roadway network, a list of high-priority sites ranked on the scores (from highest to lowest) can be established and used for further investigation and potential safety treatments.

5. Concluding Remarks

This study proposed a new methodology to estimate/predict the relative level of safety on LVR roadway segments and intersections using roadway, crash, and traffic data. The main application of the proposed method is to screen the low-volume rural highway network for sites that are in most need of safety investigations and potential improvements. The main merits of the proposed methodology are summarized below.

1) The method utilizes simple classified variables for roadway characteristics and traffic attributes that do not require exact values or access to detailed databases. This is very important for small agencies which often lack access to resources and technical expertise such as counties, townships, and tribal governments. Further, the proposed methodology can be employed with and without traffic exposure data.

2) While the main utility of the proposed methodology is for rural low-volume roads mostly owned and operated by local governments, the methodology is also applicable to high-volume roads often owned and operated by state agencies. The development of the proposed scoring schemes was primarily based on the Highway Safety Manual (HSM) guidance on two-lane rural highways regardless of traffic exposure.

3) The proposed methodology has the potential to facilitate the decision-making process involved in the implementation of systemic safety improvements at the network level. Many states use systemic improvements at the network level to address roadway features associated with certain types of crashes that are separate from their ongoing network screening and hot-spot identification process. Systemic safety improvements consist of low-cost safety countermeasures, which make it a good fit for low-volume roads (usually receiving limited resources for safety improvements).

It is important to keep in mind that while the HSM is the main reference document for performing safety analyses in the U.S., it represents the general U.S. context which could be different from that in a specific state or region. Further, the proposed method is only meant for use in comparative analysis such as for network screening applications or for comparing multiple improvement alternatives at a specific site. This is because the framework cannot be used to predict crash numbers or crash rates at any specific site. The next phase of this research is currently ongoing and aims at validating the effectiveness of the proposed safety screening method using extensive field data from the state of Oregon in the United States.

Acknowledgements

The authors would like to acknowledge the financial support to this project by the Montana Department of Transportation (MDT).

Conflicts of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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