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Effects of design consistency on run-off-road crashes: An application of a Random Parameters Negative Binomial Lindley model

Shinthia Azmeri Khan [a], Amir Pooyan Afghari [b], Shamsunnahar Yasmin [a,c], Md Mazharul Haque [a,*]

[a] Queensland University of Technology, School of Civil and Environmental Engineering, Brisbane, Australia
[b] Safety and Security Science Group, Faculty of Technology, Policy and Management, Delft University of Technology, Delft, the Netherlands
[c] Queensland University of Technology, Centre for Accident Research and Road Safety – Queensland (CARRS-Q), Brisbane, Australia

A R T I C L E I N F O

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A B S T R A C T

Run-off-road crashes are one of the most common crash types, especially in rural roadway environments contributing significantly to fatalities and severe injuries. These crashes are complex and multi-dimensional events, and factors like road geometry, driver behaviour, traffic characteristics and roadside features contribute to their occurrence, separately or interactively. Sudden changes in road geometry, in particular, can influence driver behaviour, and therefore, in developing a micro-level crash risk model for run-off-road crashes, one of the challenges is incorporating the effects of driver behaviour (disaggregated information) that may arise from the variations in road geometry (aggregated information). This study aims to examine the interaction between road geometry and driver behaviour through a set of measures for design consistency on two-lane rural roads. Multiple data sources, including crash data for 2014–18, traffic data, probe speed data and roadway geometric data, for twenty-three highways in Queensland, Australia, have been fused for this study. Seventeen types of design consistency measures with regard to alignment consistency, operating speed consistency and driving dynamics are tested. A run-off-road crash risk model is estimated by employing the Random Parameters Negative Binomial Lindley regression framework, which accounts for excess zeros in the crash counts and captures the effects of unobserved heterogeneity in the parameter estimates. Results indicate that the geometric design consistency capturing the interaction between driver behaviour and operational factors better predicts run-off-road crashes along rural highways. In addition, roadside attributes like clear zone width, infrastructures, terrain, and roadway remoteness also contribute to run-off-road crashes. The findings of the study provide a comprehensive understanding of the influence of variations in roadway geometry on driver behaviour and run-off-road crashes along rural highways.

1. Introduction

Run-off-road crashes are one of the most common types of crashes along rural roads (BITRE, 2017; Das and Sun, 2016), contributing to a substantial proportion (about two-thirds) of road fatalities and severe injuries at these locations (FHWA, 2019; TMR, 2018). In fact, in the United States, more than 50% of all road crashes are reported to be run-off-road crashes, whereas, in Australia, this figure is approximately 45%. These statistics raise the flag for rural roads as locations with a potentially high risk[1] of run-off-road crashes that need significant attention for safety improvement. It is, therefore, essential to understand which factors contribute to the run-off-road crash risk on rural roads.

Analysis of run-off-road crash risk is likely associated with several complexities and challenges. For instance, crashes are rare and multi-attribute events resulting from the interactions of many factors (Lord et al., 2021). These factors may arise from distinct sources of risk, such as driver behaviour, road geometry and spatial features of the road environment (Afghari et al., 2018). Previous studies have documented the effects of the above factors and their interactions on run-off-road crash risk (Das and Sun, 2016; Martensen and Dupont, 2013),

* Corresponding author.
E-mail addresses: shinthiaazmeri.khan@hdr.qut.edu.au (S.A. Khan), A.P.Afghari-1@tudelft.nl (A.P. Afghari), shams.yasmin@qut.edu.au (S. Yasmin), m1.haque@qut.edu.au (M.M. Haque).

[1] In this study, the likelihood of fatal and serious injury run-off- road crashes across a homogenous road segment is used as an indicator of risk.

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emphasizing that these interactions should be considered when studying the risk of run-off-road crashes. However, considering these interactions is not straightforward because the above critical factors may be inter-related. For example, while risk factors arising from driver behaviour and road geometry are distinct, the geometric design of the road is likely to influence driving behaviour (Afghari et al., 2019). There are mixed findings on the effects of road geometry on run-off-road crash risk. For example, some studies found that a sharper radius of horizontal curves contributes to increased run-off-road crash risk (Geedipally et al., 2019), whereas other studies have obtained the opposite findings (Schneider et al., 2010). These contrasting findings may be attributed to the varying behaviour of drivers on the curves: sharper radius of curves may surprise some drivers and cause them to lose control of the vehicle but may increase the workload for other drivers and cause them to be more cautious. Therefore, the interactions between road geometry and driver behaviour are likely to play a significant role in run-off-road crash risk. Thus, the inclusion of these driver behaviour and roadway geometry in the analysis without considering their interactions may result in erroneous estimates of their effects on run-off-road crash risk.

Afghari et al. (2018) proposed a joint econometric model of crashes to account for such inter-relationship between risk factors and empirically showed that the proposed approach provides more insight into those interactions. However, such complex models come with high computational costs. An alternative solution to incorporating the interactions of driver behaviour and road geometry could be to include a control variable in the analysis to measure such interaction directly. Geometric design consistency of roadways is one of such control variables which was employed in existing crash prediction studies to capture the interactions between driver behaviour and roadway geometry (Lamm et al., 1999; Montella and Imbriani, 2015).

Design consistency refers to the degree to which a road geometry conforms to drivers' expectations. It is an appropriate measure to capture drivers' behavioural responses to the respective changes in road geometry. A consistent road design ensures that successive geometric elements of the road are aligned so that the drivers are not surprised (Gibreel et al., 1999). In contrast, poor consistency in road geometry involves sudden changes in road alignment, confused drivers, and fluctuation in operating speed (Camacho-Torregrosa et al., 2013). Studies suggest that drivers make fewer errors along roads that better conform to their expectations (Anderson et al., 1999). In contrast, the likelihood of crashes can rise to multiple folds on the road with poor consistency in road geometry (Lamm et al., 1995). In a recent investigation of crashes along horizontal curves in the Netherlands, Afghari et al. (2023) found that the difference in the angle of horizontal curves, vertical grades, and width of consecutive road segments influence the predictability of the road and that higher road predictability is associated with a decreased likelihood of crashes along those curves.

Design consistency has been measured in different ways through (i) alignment consistency (Lamm et al., 1999), (ii) operating speed consistency (Polus and Mattar-Habib, 2004), and (iii) driving dynamics consistency (Lamm et al., 1999). Each design consistency defines different aspects of the interaction between driver behaviour and roadway geometry. Since driver behaviour (errors/expectations) is considered a primary contributing factor in run-off-road crashes (Hamilton et al., 2019; Liu and Subramanian, 2009), examining design consistency when studying the run-off-road crash risk can lead to a better understanding to these crashes.

Another challenge in studying run-off-road crash risk is that the crash causation mechanism and the underlying risk factors are unique in these crashes (Chen and Chen, 2010; Geedipally and Lord, 2010; Yu and Abdel-Aty, 2013), and thus, the risk factors should be identified separately from that of other types of crashes (Lord et al., 2005). However, separating run-off-road crashes from all crashes may result in a preponderance of zero crash observations which in turn may violate the distributional assumptions (Poisson or Negative Binomial) of crash count models. In addition, the effects of the above factors on the run-off-road crash risk may vary across road segments due to unobserved heterogeneity (Mannering et al., 2016). Therefore, examining run-off-road crash risk without accommodating excess zeros and unobserved heterogeneity may result in biased estimates.

This study aims to address the abovementioned challenges in examining run-off-road crash risk by investigating the effects of different types of design consistency on run-off-road crash risk mechanisms. Specifically, three different types of design consistency measures are considered, which include: (i) alignment consistency, (ii) operating speed consistency, and (iii) driving dynamics consistency. Alignment consistency captures the variations in curve radii and curvature change rates among successive segments. Operating speed consistency captures variations and interactions among operating speed, average operating speed, and/or design speed. Driving dynamics consistency represents interactions of side friction and the demanded side friction along with curve segments. In examining the effect of design consistency on run-off-road crash risk, a count regression model with special enhancements for excess zero observations (negative binomial Lindley specification) and unobserved heterogeneity (random parameters specification) is considered. The run-off-road crash risk models are developed at the micro-level (roadway segment level) and are estimated by using crash data collected from the State of Queensland, Australia, for the years 2014 through 2018.

This study contributes to road safety research by examining three main design consistency measures, including alignment consistency, operating speed consistency and driving dynamics, for run-off-road crashes. Specifically, 17 different functional forms of design consistency indices are examined to capture the behavioural factors (disaggregated information) from the road-geometric changes (aggregated information) for run-off-road crashes since driver behaviour is one of the critical factors contributing to these crashes. These design consistency indices were discretely studied in the literature for total crashes in general (e.g., Anderson et al., 1999; Lamm et al., 1999; Llopis-Castelló et al., 2018c; Polus and Mattar-Habib, 2004). Yet there is little research to understand the effects of these design consistency indices for estimating crash frequency models for run-off-road crashes. To the authors' best knowledge, this is the very first effort where various types of design consistency measures (17 indices under three major types) are applied and compared for run-off-road crashes to understand the relation between road-geometric changes and crash risk. Although a few studies applied alignment consistency indices for run-off-road crashes (Appiah and Zhao, 2020; Montella and Imbriani, 2015), this study developed an operating speed profile based on local speed data and examined the operating speed consistency indices along with other design consistency indices and compared all parameters for the same study area, which is new in safety analysis, particularly for run-off-road crashes.

The next section of this paper reviews the literature on run-off-road crashes and design consistency measures which is followed by a section that explains the data preparation. The fourth section describes the methodological framework, while the subsequent section presents the result of the base models (Negative Binomial model) of different design consistency indices and the full models (Random Parameters Negative Binomial Lindley model) of design consistency as well as other explanatory variables. The subsequent section presents the discussion, which is followed by the conclusions section.

2. Literature review

Extensive effort has been dedicated to existing road safety literature to explore factors contributing to run-off-road crashes. These factors include (but are not limited to) traffic characteristics, roadway geometric features, spatial features of the road environment, and driver behavioural factors (Appiah and Zhao, 2020; Das and Sun, 2016).

Studies on run-off-road crash analysis

Average annual daily traffic (AADT) has been widely used as a measure of exposure[2] in previous studies and has been found to be positively correlated with run-off-road crash risk (Lord et al., 2011; Yu and Abdel-Aty, 2013). These studies suggest that a higher number of vehicles passing a road segment is associated with increased run-off-road crash risk. However, several studies have shown that this relationship might not be monotonic and that the risk of run-off-road crashes may decrease when the traffic flow is higher than a certain range (Lord et al., 2005; Roque and Cardoso, 2014). Speed is another traffic characteristic which has also been shown to be associated with the risk of run-off-road crashes. Many studies have investigated the effects of speed on run-off-road crashes using speed limit, operating speed, average speed, and the 85th percentile of speed across a road segment. Lee and Mannering (2002) found a positive association between a speed limit of more than 85 km/hr and run-off-road crash risk. Other studies have found similar findings for fatal run-off-road crashes (Liu and Subramanian, 2009; Spainhour and Mishra, 2008). Davis and Pei (2006) conducted a case-control study of the relationship between speed and fatal crash risk from run-off-road crashes using data from Australia and the United States and found that the relationship between speed and run-off-road crash risk is U-shaped: lower or higher speed than a certain threshold increases the risk of run-off-road crashes.

Geometric features of the road are associated with run-off-road crash risks. Studies have shown that sharper horizontal curves (smaller radius) are generally associated with an increased run-off-road crash risk (Bahar, 2008; Rusli et al., 2017). However, Hamilton et al. (2019) argued that the relationship between run-off-road crashes and the radius of the horizontal curve is not straightforward and that the risk of these crashes also depends on the subject curve (being upstream or downstream) as well as its preceding tangent. They provided additional insight into the driver's perception of roadway horizontal alignment: sharper upstream/downstream radii may be safer than flatter upstream/downstream radii because the drivers get accustomed to the roadway geometry and lower the operating speed. Other roadway geometric features that have been investigated as contributing factors to run-off-road crashes include lane width and shoulder width. Previous studies have shown that a wider lane (Geedipally and Lord, 2010; Lord et al., 2011) and a wider shoulder (Geedipally et al., 2019; Rusli et al., 2017) decrease the likelihood of run-off-road crashes along two-lane rural roads. In contrast, Harwood et al. (2000) found that a shoulder wider than 8ft increases the likelihood of run-off-road crashes because it could be used as a de facto driving lane and may have adverse psychological effects on drivers.

Due to the nature of run-off-road crashes, roadside attributes play a more crucial role in these crashes than in other types of crashes. Previous studies have examined the effects of various roadside attributes on the likelihood and severity of run-off-road crashes (Austroads, 2019; Lee and Mannering, 2002) and have shown that trees, utility poles, and other fixed obstacles increase the likelihood of fatal and serious injury run-off-road crash if the distance between the shoulder edge and the objects is insufficient (Austroads, 2019). Inadequate distance between the edge of the road and safety barriers, such as guardrails, have been reported to increase the risk of run-off-road crashes (Jalayer and Zhou, 2016b; van Petegem and Wegman, 2014). In contrast, an online static evaluation by Fitzpatrick et al. (2014) and the following field validation by Fitzpatrick et al. (2016) suggested that a narrow clear zone with vegetation (presence of dense/medium dense trees) or utility poles may decrease the risk of run-off-road crashes because it works as traffic-calming measure and so drivers are likely to adapt to lower speeds in such driving conditions.

While the above studies have provided a good understanding of the effects of operational and spatial factors on run-off-road crashes, the documented findings have been mixed in many cases. A possible reason behind such mixed findings is the interaction of driver behaviour with operational factors. Liu and Ye (2011) and MacLaughlin et al. (2009) have shown that drivers' responses, such as low-speed manoeuvring errors and decision errors, are associated with run-off-road crash risk and that these errors may be caused by the lack of consistency in horizontal curves, speed limit, and road access. Several disaggregate studies of run-off-road crash injury severities have also found a significant relationship between driver behaviour such as carelessness, lack of control of vehicles, distraction and crash severity (Islam and Pande, 2020; Zhou and Chin, 2019). These findings indicate that driver behaviour significantly contributes to run-off-road crash risk and is directly linked with the consistency in the geometric design of the roads.

Studies on design consistency

In capturing the inter-relation of driver behaviour and roadway geometry, a number of earlier studies have considered the effects of design consistency in examining crash risk. For example, Lamm et al. (1989) examined the effects of alignment consistency on crash rates by using data from the United States and Germany and found that crash rates can increase up to five times depending on the amount of change in the alignment consistency index. Also, operating speed has been used in the literature to identify the lack of consistency in successive road segments (Russo et al., 2016; Wang et al., 2018). Ng and Sayed (2004), García et al. (2013), and Llopis-Castelló et al. (2018a) developed several design consistency indices based on operating speed. In separate studies, they investigated the effects of these operating speed consistency indices on crash risk and identified them as significant for all crashes (they did not distinguish different crash types). In a similar attempt, Afghari et al. (2023) studied speed and acceleration profiles of about one million drivers along horizontal curves in the Netherlands and investigated the effects of design consistency on these profiles, and ultimately on the likelihood of crashes. They concluded that higher differences in the geometry of consecutive road segments reduces road predictability, which in turn increase the likelihood of crashes along the curves. However, they did not distinguish the crash types either.

A few studies have attempted to explore the effects of design consistency on run-off-road crashes. Montella and Imbriani (2015) developed local operating speed indices and driving dynamics index for Italian motorways and found that the geometric design consistency is significantly associated with run-off-road crash risk. Hamilton et al. (2019) investigated the relationships between alignment consistency and run-off-road crashes along horizontal curves on two-lane rural roads by using data from the United States and found that the arrangement of curves and their preceding tangents is more vital than other road geometric features (like curve radius/ length).

Research gaps:

Previous investigations of factors contributing to run-off-road crashes have focused on the effects of traffic characteristics, roadway geometric features, and spatial features of the road environment. However, the effect of changes in road geometry on run-off-road crashes is less known. Limited research has been dedicated to understanding driver behaviour, its interaction with road geometry, and its effects on run-off-road crash risk. While several studies have pursued this line of inquiry for all crashes (not separated based on types), the application of design consistency for run-off-road crashes, in particular, has not been explored much. This research gap is further highlighted when noting that separately studying run-off-road crashes is confronted with methodological challenges such as excess zero observations and unobserved heterogeneity.

[2] Exposure is one of the fundamental factors contributing to run-off- road crashes: crashes occur only when drivers are exposed to risk –there is no risk if there is no traffic on the road.

3. Methods

Count regression models have been widely used in road safety research to study the relationship between crash risk and their contributing factors (Lord and Mannering, 2010). These models assume that crashes are the outcomes of a Poisson process, and so their frequency may follow a Poisson distribution (Lord et al., 2005). However, research has repeatedly shown that crash frequency data are often over-dispersed (their mean is not equal to their variance), and so the Negative Binomial model better fits crash frequency data (Poch and Mannering, 1996). However, conventional Negative Binomial count regression models might not be efficient for modelling the frequency of run-off-road crashes in this study for the following reasons.

Firstly, run-off-road crashes are the outcomes of a complex interaction among numerous factors and excluding any of these factors or their interactions from the analysis may result in varied effects of other explanatory variables. This phenomenon is referred to as unobserved heterogeneity (Mannering et al., 2016) and, if not accounted for, may lead to biased and inefficient estimates of regression parameters. Random parameter modelling is one way of addressing unobserved heterogeneity in crash count models (Mannering et al., 2016). Secondly, the distributional assumption of Negative Binomial count regression models is violated if crash data is comprised of many zeros (more than 90% in this study), in which case the regression parameters will be biased. Employing multi-distribution variants of these models, such as *Negative Binomial Lindley,* is an effective way of addressing excess zeros (Geedipally et al., 2012). Based on the above reasoning, random parameters Negative Binomial Lindley model is adopted for modelling the frequency of run-off-road crashes with excess zeros and unobserved heterogeneity in this study.

3.1. Model specification

Let y_{it} represents the frequency of run-off-road crashes on the i^{th} roadway segment at the t^{th} time period (year). Assuming that y_{it} follows a negative binomial distribution, the probability of road segment i experiencing y_{it} crashes at period t can be obtained by (Washington et al., 2020):

$$P(y_{it}|\lambda_{it},\phi\ ) = \frac{\Gamma(\phi + y_{it})}{\Gamma(\phi)y_{it}!}\left(\frac{\phi}{\phi+\lambda_{it}}\right)^{\phi}\left(\frac{\lambda_{it}}{\phi+\lambda_{it}}\right)^{y_{it}} \quad (1)$$

where λ_{it} is the mean, Γ (·) is the gamma function, and ϕ is the over-dispersion. λ_{it} (the expected mean of run-off-road crashes) can now be structured as a function of explanatory variables using a log-linear function (Mitra and Washington, 2007):

$$\lambda_{it} = \alpha_{0it}F_{it}^{\alpha_{1it}}EXP(\boldsymbol{b}_{it}\boldsymbol{X}'_{it}) \quad (2)$$

where F_{it} is the traffic (a measure of exposure) along the i^{th} road segment of the study area for the t^{th} period, X'_{it} is the vector of explanatory variables, and $\alpha_{0it,}$ α_{1it}, and $\boldsymbol{b}_{it}$ are regression parameters. The parameters are allowed to vary across observations to account for unobserved heterogeneity:

$$b_{it} = b + \omega_{it} \quad (3)$$

where b is the (fixed) mean of the random parameters and ω_{it} is a randomly distributed term (e.g. a normally distributed term with mean zero and variance σ^2) that captures unobserved heterogeneity across observations. Please note that the parameters are allowed to vary across segments but are fixed across periods. Such grouped random parameters (Oviedo-Trespalacios et al., 2020) account for the panel nature of the data (multiple observations of the same road segment). The probability distribution function of $y_{\ it}$ can then be expressed as:

$$P(y_{it}|\lambda_{it},\phi,\ \sigma) = \int\frac{\Gamma(\phi + y_{it})}{\Gamma(\phi)y_{it}!}\left(\frac{\phi}{\phi+\lambda_{it}}\right)^{\phi}\left(\frac{\lambda_{it}}{\phi+\lambda_{it}}\right)^{y_{it}}g(\omega_{it})d\omega_{it} \quad (4)$$

where $g(\omega_{it})$ is the density of ω_{it}. This specification is referred to as the *Random Parameters Negative Binomial* (RPNB) model in the literature (Anastasopoulos and Mannering, 2009). To account for excess zeros, the RPNB model is now extended to the Rrandom Parameters Negative Binomial Lindley (RPNB-Lindley) specification. As the name implies, the model is a combination of negative binomial and Lindley distributions (Lord et al., 2021), and so a new Lindley distributed error term (δ_{it}) is multiplied by the mean function of the negative binomial distribution to create the RPNB-Lindley model (Shaon et al., 2018):

$$\lambda_{it} = \alpha_{0it}F_{it}^{\alpha_{1it}}EXP(\boldsymbol{b}_{it}\boldsymbol{X}'_{it})\delta_{it} \quad (5)$$

where δ_{it} follows a Lindley distribution with shape parameter θ. The density of this error term can be stated as follows:

$$f(\delta_{it}) = \frac{\theta^2}{\theta+1}(1+\delta_{it})exp^{-\theta\delta_{it}} \quad (6)$$

The probability distribution function of the overall RPNB-Lindley model can then be obtained by:

$$P(y_{it}|\Omega) = \int\frac{\Gamma(\phi + y_{it})}{\Gamma(\phi)y_{it}!}\left(\frac{\phi}{\phi+\delta_{it}\lambda_{it}}\right)^{\phi}\left(\frac{\delta_{it}\lambda_{it}}{\phi+\delta_{it}\lambda_{it}}\right)^{y_{it}}g(\omega_{it})f(\delta_{it})d\omega_{it}d\delta_{it} \quad (7)$$

where Ω represents all of the model parameters (α, $\boldsymbol{b}$, ϕ, σ, θ). The likelihood function of the RPNB-Lindley model can also be obtained by the product of the above probability distribution function over the entire observation. While such a likelihood function may not have a closed-form to be analytically solved in the frequentist paradigm, it has an elegant hierarchical representation of Gamma and Bernoulli distributions in the Bayesian paradigm (Geedipally et al., 2012; Shaon et al., 2018), and can be express as:

$$y_{it}\ NB(\phi,\alpha,\boldsymbol{b},\delta_{it}) \quad (8)$$

$$\delta_{it}\ Gamma(1+z_{it},\theta) \quad (9)$$

$$z_{it}\ Bernoulli(\frac{1}{1+\theta}) \quad (10)$$

3.2. Model estimation

Bayesian inference is used for estimating the models in this study. It offers a significant advantage over the maximum likelihood estimation in that complicated likelihood functions, and posteriors can be considered in model estimation (Washington et al., 2020). In Bayesian inference, Bayes' theorem is used to estimate the model in which posterior estimates are drawn based on random sampling from the likelihood and the prior (Congdon, 2007). A standard Markov Chain Monte Carlo (MCMC) simulation is employed to determine the posterior estimates of regression parameters (Gelman and Rubin, 1992).

3.3. Model selection

Deviance Information Criterion (DIC) is widely used as the measure of fit for model selection in the Bayesian paradigm. DIC is the hierarchical modelling generalization of the Akaike Information Criterion (Rosen et al., 2022) and Bayesian Information Criterion (BIC) (Spiegelhalter et al., 2003) and is can be expressed as:

$$DIC = \overline{D(\Theta)} + P_D \quad (11)$$

where $\overline{D(\Theta)}\ = E[-2logL]$

$$P_D = \overline{D(\Theta)} - D(\overline{\Theta})$$

In the formulation above, L is the likelihood of the model at convergence, Θ is the total number of parameters,P_D is the effective number of parameters reflecting model complexity, and $D(\overline{\Theta})$ is the deviance evaluated at a posterior summary of Θ. The model with a lower DIC is preferred among alternative models.

3.4. Marginal effects

Marginal effects of explanatory variables are estimated to determine their impact on the frequency of crashes. The marginal effect of an explanatory variable shows the amount of change in the expected number of crashes for a one-unit change in that explanatory variable[3]. For the NB model, the marginal effect (ME) of a categorical variable and a continuous variable for road segment i at the period t can be computed by the following equations.

$$ME_{x_{it}} = \frac{\partial\lambda_{it}}{\partial x_{it}} = \boldsymbol{b}_{it}\lambda_{it} \tag{12}$$

$$ME_{x_{it}} = [\lambda_{it}|x_{it} = 1] - [\lambda_{it}|x_{it} = 0] \tag{13}$$

The notations are as previously stated for Eqs. (12) and (13). While the analytical calculation of marginal effects is straightforward for conventional fixed parameters negative binomial models, it is much more complicated for the proposed Random Parameters Negative Binomial Lindley model. Therefore, the marginal effects are calculated using the Monte Carlo simulation method to get reliable output (Hou et al., 2021).

4. Data

The data for this study is compiled for the State-controlled two-lane rural roadway of Queensland, Australia, including 4,580 km in length. For the empirical analysis, the roadway network under consideration is segmented following the recommendations of the Highway Safety Manual (AASHTO, 2010) and based on homogeneity in traffic characteristics and road geometry. Thus, the resulting number of segments is 6,022, which forms the unit of analysis in this current study context. In this study, run-off-road crashes are defined as those crashes in which the vehicle moves out of the carriageway after losing its control, hits roadside objects or rollovers, or overturns and causes injury/fatality to its occupant(s). In addition, the likelihood of injury and fatal run-off-road crashes along a homogeneous road segment is used as an indicator of crash risk. It is noteworthy to mention that the Queensland government only records the injury crashes (minimum one person injured/ killed from crashes) data from January 2011. Thus, the Property damaged Only (PDO) crashes are not available for this study. Empirical data were collected for this roadway network from multiple sources, including crash and traffic data from the Queensland Department of Transport and Main Roads, geometric road data from the Australian Road Assessment Program and A Roads Management Information System, and spatial data from the Australian Bureau of Statistics.

4.1. Data sources and variables

The collected crash data include the yearly number of run-off-road crashes between 2014 and 2018, with a total number of 1,343 run-off-road crashes over the five years. The average and the maximum yearly number of run-off-road crashes across road segments are 0.04 and 4.00, respectively. These statistics show that the yearly run-off-road crash data for the study area are heavily skewed towards zero (more than 90% of roadway segments have zero crash counts). A possible reason for excess zero in the considered data could be attributed to the fact that the state of Queensland does not collect no-injury crash data since 2010.

The probe speed data were collected from the Department of Transport and Main Roads (TMR) in Queensland, Australia. TMR collects the speed data of its state-controlled road network from HERE (https://www.here.com/), which is a leading probe data provider and has developed a well-established method for measuring speed from GPS probe data. The collected road geometric data include segment length, lane width, shoulder width, sealed shoulder width, curve radius, and curvature change rate (CCR). Following the AusRAP (Australian Road Assessment Program) criteria for categorizing lane width, three indicator variables were developed for this variable, named as 'narrow', 'moderate', and 'wide' lanes. A similar approach was used for creating indicator variables for shoulder width. In addition, two secondary variables were developed based on these geometric data, including the change rate in horizontal curvature and the type of horizontal curves being simple, compound, reverse, or broken-back curves. Collected spatial data include the width of the clear zone, the type of roadside infrastructures and their distance from the edge of the road. In addition, the number of lateral access points to road segments was also collected and used as a proxy for the adjacent land use. The spatial data also include the terrain of the road with three different terrains: mountainous, rolling and level. These terrains were defined based on the longitudinal slope of road segments: level terrain if the grade is less than 4%, rolling terrain if it falls between 4% and 7.5%, and mountainous terrain if it is more than 7.5%.Finally, the remoteness of the roads (a categorical variable defining the accessibility of the locations) was also collected and used as a spatial roadside attribute taking into account the heterogeneity of inner and outer regional areas. Although there are five remoteness boundaries as per the division of The Australian Bureau of Statistics (ABS), as shown in Fig. 1, the explored roadway is under the two remoteness areas, the inner regional boundary and the outer

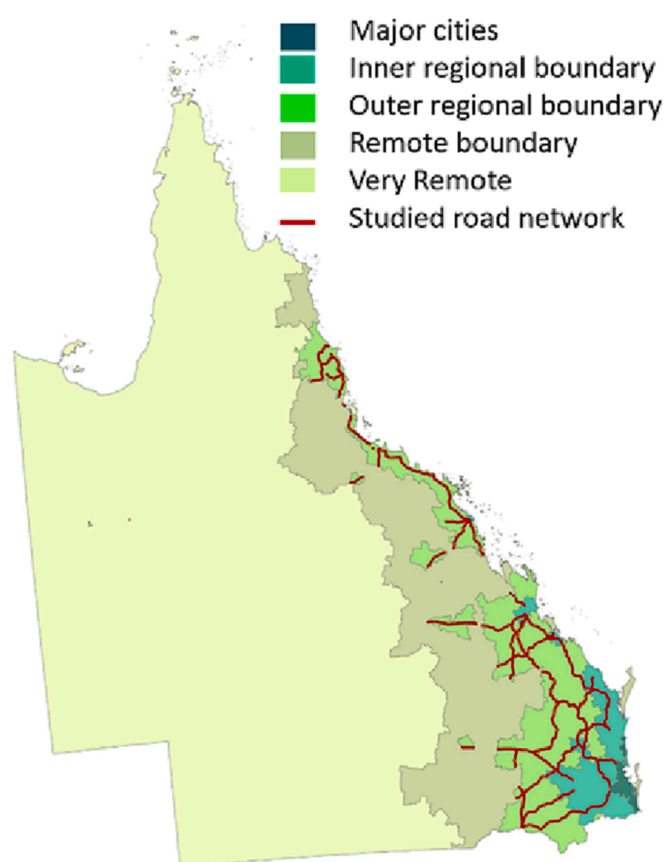


Fig. 1. Remoteness map of Queensland and studied network.

[3] The marginal effect of a categorical variable is the amount of change in the expected number of crashes for a change from one category to another category in that variable.

regional boundary. The major cities, as well as remote area (remote boundary and very remote boundary), is not within the scope of this study.

The final dataset for the study was created by fusing data from the above sources. Linear Referencing and intersect commands in ArcMap were used for all datasets, including the crash data, to transfer it to the road segment level accordingly. Table 1 presents a summary of statistics of the variables used in this study.

4.2. Design consistency indices

A wide range of design consistency indices is considered in this study. Lamm et al. (1999) defined an index for alignment consistency based on the difference in curvature of consecutive road segments. They also proposed two ways of measuring operating speed consistency: the absolute value of the difference between design speed and operating speed and the absolute value of the difference between the operating speed of two successive road segments (Lamm et al., 1999). For both measures, they suggested three design classes (good, fair, and poor) for the level of design consistency. In addition to these local indices, several global operating speed consistency indices have been defined in the literature, which are based on continuous operating speed profiles (Fitzpatrick, 2000) and have been shown to better capture design consistency than the local operating speed indices proposed by Lamm et al. (1999). Polus and Mattar-Habib (2004) proposed two global operating speed consistency indices: Relative Area (R_a) and Operating Speed Dispersion (σ). The former index is based on the area bounded by the operating speed profile and the average operating speed for unit road length, and the latter index is based on the standard deviation of operating speed along each road segment. Llopis-Castelló et al. (2018a) proposed several other forms of the relative area (R_a) and operating speed dispersion (σ) as indices for operating speed consistency and found that they performed better than the previous operating speed consistency indices for the Italian road network. Finally, Lamm et al. (1999) developed an index for the consistency in driving dynamics which is based on the disparity between the assumed side friction and the demanded side friction. Higher differences between these two side frictions imply more consistency in road geometry.

Based on the above studies, in this study, seventeen different design consistency indices were computed under three categories: (i) alignment consistency, (ii) operating speed consistency, and (iii) driving dynamics consistency. These indices are presented in Table 2 and are discussed as follows.

Alignment consistency indices: Four alternative indices were developed for alignment consistency (AC-1, AC-2, AC-3, AC-4) using different functional forms of curve radii and curvature change rates among successive segments. These indices are particularly developed for horizontal curves (straight segments are assumed to be geometrically consistent throughout their length). Therefore, AC-1 and AC-2 become the same index for straight segments, and AC-3 becomes zero because it is based on the standard deviation of the change rate in curvature.

Operating speed consistency indices: Twelve alternative indices were developed for operating speed consistency (OSC-1 to OSC-12) using operating speed profiles across each segment of the network. Most of these indices (OSC-3 to OSC-12) are based on operating speed profile which needs to be developed based on the local speed data. Several factors like road geometry, posted speed limit, road cross-section, road class, terrain types, and road marking are identified to be significant for Operating speed profile (Bella, 2013; Martinelli et al., 2022), and these factors are vital to be considered while a single speed profile is developed for different road types (e.g., main road, secondary road, local road) (Fitzpatrick et al., 2021a). Since this study is focused on two-lane rural highways, there is no wide variation in road features. Therefore, the speed profile was developed considering the radius and the posted speed limit of the roadway, which overshadows many other road characteristics (Fitzpatrick et al., 2021b; Himes et al., 2013).

Table 1
Summary statistics of variables included in this study.

Variable	Mean	Min.	Max.	Std. Dev.	Count
Run-off-road crash count	0.04	0.0	4.00	0.22	1343
Segment length *(km)*	0.76	0.20	5.77	0.59	
Traffic Characteristics					
Annual Average Daily Traffic (AADT) *(veh/day)*	3156	183	20,927.00	2597.00	
High traffic flow: AADT > 4000 *(if yes 1, otherwise 0)*	0.28	0.00	1.00	0.45	8704
Percentage of heavy vehicles *(%)*	16.75	0.40	63.26	13.23	
Operating Speed *(km/hr)*	89.61	34.2	138.1	16.81	
Road geometric features					
Moderate curve *(1 if radius 500–900 m, otherwise 0)*	0.13	0.00	1.00	0.33	3865
Sharp curve *(1 if radius 200–500 m, otherwise 0)*	0.08	0.00	1.00	0.27	2495
Very sharp curve *(1 if radius < 200 m, otherwise 0)*	0.06	0.00	1.00	0.23	1785
Proportion of segment length with Simple curve	0.04	0.00	1.00	0.16	
Proportion of segment length with compound curve	0.12	0.00	1.0	0.28	
Proportion of segment length with reverse curve	0.03	0.00	1.00	0.13	
Proportion of segment length with broken-back curve	0.01	0.00	0.50	0.05	
Curvature Change Rate (CCR) *(gon/km)*	48.07	0.00	1828.53	118.46	
Average lane width *(m)*	3.36	0.87	6.00	0.25	
Narrow lane *(1 if lane width < 2.75 m, otherwise 0)*	0.01	0.00	1.00	0.10	270
Moderate lane *(1 if lane width 2.75–3.25 m, otherwise 0)*	0.25	0.00	1.00	0.43	6245
Wide lane *(1 if lane width > 3.25 m, otherwise 0)*	0.73	0.00	1.00	0.44	23,240
Shoulder width *(m)*	1.34	0.00	5.20	0.46	
Sealed shoulder width *(m)*	1.06	0.00	5.20	0.60	
Proportion of segment length with sealed shoulder	0.90	0.00	1.00	0.28	
Narrow shoulder *(1 if shoulder width < 1 m, otherwise 0)*	0.13	0.00	1.00	0.34	3730
Moderate shoulder *(1 if shoulder width 1–2.4 m, otherwise 0)*	0.78	0.00	1.00	0.42	23,760
Wide shoulder *(1 if shoulder width > 2.4 m, otherwise 0)*	0.02	0.00	1.00	0.14	590
Roadside attributes (as the proportion of segment length)					
Both sides clear zone > 10 m	0.14	0.00	1.00	0.24	
Both sides clear zone 5–10 m	0.33	0.00	1.00	0.30	
Both sides clear zone 1–5 m	0.26	0.00	1.00	0.28	
One sides clear zone < 5 m, other side > 5 m	0.25	0.00	1.00	0.25	
One sides clear zone < 1 m, other side > 1 m	0.02	0.00	1.00	0.08	
Both side clear zone ≤ 1 m	0.02	0.00	1.00	0.07	
Infrastructure Risk-1 *(tree/ vertical wall/ ditch in distance > 10 m or no object 5–10 m*	0.14	0.00	1.00	0.24	
Infrastructure Risk-2 *(safety Barrier/tree/pole within 5 10 m)*	0.32	0.00	1.00	0.30	

(*continued on next page*)

Table 1 (*continued*)

Variable	Mean	Min.	Max.	Std. Dev.	Count
Infrastructure Risk-3 *(vertical wall /rigid structure in 1–5 m)*	0.10	0.00	1.00	0.20	
Infrastructure Risk-4 *(ditch in 5–10 m)*	0.08	0.00	1.00	0.13	
Infrastructure Risk-5 *(tree/ pole/sign post/rigid structures in 1–5 m)*	0.17	0.00	1.00	0.22	
Level terrain *(grade 0–4%)*	0.79	0.00	1.00	0.37	
Mountainous terrain *(grade > 7.5%)*	0.02	0.00	1.00	0.14	
Rolling terrain *(grade: 4% to 7.5%)*	0.19	0.00	1.00	0.34	
Remoteness area (categorical variable)					
Inner regional *(1 if in inner boundary, otherwise 0)*	0.26	0.00	1.00	0.44	6290
Outer regional *(1 if in outer boundary, otherwise 0)*	0.73	0.00	1.00	0.45	23,820
Roadside Access					
Driving density (nos./km)	0.88	0.00	14.17	1.71	

The operating speed profile was developed by geospatial data fusion in a Geographic Information system. The probe speed data, as well as geometric/cross-sectional road data, were used in a linear regression to develop an equation for continuous operating speed profiles for two-lane rural highways in Queensland. The estimated equation is:

$$V_{85i} = 72.79 + 0.22 \times SL_i - \frac{78.99}{\sqrt{R_i}} \tag{14}$$

where V_{85i} is the 85th percentile of operating speed across the i^{th} segment, SL_i is the speed limit and R_i is the radius of the curve in that segment. The operating speed consistency indices were then calculated as composite variables comprising the different functional forms of operating speed, average operating speed, or design speed through data fusion of road inventory data, operating speed data, and design speed data. The first two indices (OSC-1 and OSC-2) proposed by Lamm et al. (1999) measure the operating speed disparity in two successive homogeneous segments. The third and the fourth indices (OSC-3 and OSC-4) are the global operating speed consistency indices proposed by Polus and Mattar-Habib (2004), for which the continuous operating speed profile (V_{85}) and the average operating speed (V_{avg}) across all segments (weighted by the length of road segments) was compared to calculate these indices. More specifically, OSC-3 was calculated using the cumulative relative area (R_a) under the curves of operating speed profile (V_{85}) and average speed (V_{avg}), as shown in Fig. 2, following the equation below.

$$Relativearea, R_a = \frac{\sum_{i=1}^{n} A_i}{L} \tag{15}$$

OSC-4 was calculated using the standard deviation (σ) of the operating speed. Moreover, eight additional indices, OSC-5 to OSC-12, were developed following the work by Llopis-Castelló et al. (2018c) based on the relative area (functions for both positive area and total area under the curve of operating speed profile and average speed) and the standard deviation of the operating speed. Similar to the alignment consistency indices, straight segments are assumed to be geometrically consistent for operating speed consistency (there is no difference between the operating speed profile and the average speed). Therefore, the operating speed consistency indices are set to zero for the straight segments.

Driving dynamics consistency index: Finally, one index was developed for driving dynamics consistency following Lamm et al. (1999). This index was defined as the difference between the assumed side friction and the demanded side friction along with curve segments. The assumed side friction is an empirical function of the design speed of the road as well as the topography of the area, whereas the demanded side friction relates to the operating speed, cross-fall and radius of the road. From a safety perspective, it is expected that the assumed side friction is always greater than the demanded side friction. For straight segments, it was assumed that the side friction is equal to the demanded side friction; thus, the driving dynamics consistency index was set to zero for these segments. The assumed side friction is interrelated with the design speed, while the demanded side friction is a function of operating speed and superelevation along curves. The driving dynamics index can then be expressed using Eqs. (16)–(18):

$$\Delta f_{R\_i} = f_{RA\_i} - f_{RD\_i} \tag{16}$$

$$f_{RA\_i} = 0.6*0.925*(0.59 - 4.85*10^{-3}*V_{di} + 1.51*10^{-5}*V_{di}{}^2 \tag{17}$$

$$f_{RD\_i} = \frac{V_{85i}{}^2}{127*R_i} - e_i \tag{18}$$

where f_{RA_i} is the assumed side friction for the design speed (V_{di}) in km/hr, f_{RD_i} is the demanded side friction at the operating speed (V_{85i}) in km/hr, R_i is the curve radius in meters, and e_i is the superelevation of the i^{th} road section.

5. Empirical analysis

The major focus of this study is to examine the effect of design consistency on run-off-road crash risk while also controlling for other exogenous variables. As presented in Table 2, 17 different types of design consistency indices representing Alignment consistency index, Operating speed consistency index, and Driving dynamics consistency index were computed for the roadway network under consideration. The empirical analysis involves the estimation of a series of models, including (1) traditional NB model, (2) random parameters NB model, (3) NB-Lindley model, (4) Random Parameters NB-Lindley model. As a preliminary step of our modelling, traditional NB models are developed for all 17 design consistency indices along with other explanatory variables to identify the significant design consistency variables. Among the significant variables, one from each category is selected (based on the statistical fit of the models) for developing the hierarchical models. To account for the unobserved heterogeneity as well as excess zeros in our dataset, Negative Binomial Lindley models, Random Parameters Negative Binomial models and Random Parameters Negative Binomial Lindley models are developed for each design consistency category. In the end, only the results from the best-fitted model are shown and discussed. The analytical framework that has been followed in this study is shown in Fig. 3.

5.1. Result of base models with design consistency indices

In developing the benchmark for comparison, at first, a set of base models are estimated by considering the logarithm of AADT as the exposure measure, the logarithm of segment length as the offset variable and different design consistency indices as the control variables. Specifically, 17 different base models are estimated by employing 17 different design consistency indices. These base models are estimated by employing the traditional Negative Binomial regression framework. Among 17 models, eleven indices are found to be significant at the 95% Bayesian Credible Interval (BCI) for run-off-road crashes. The parameter estimates of these 11 models and the DIC values are presented in Table 3. The results indicate that both alignment and operating speed

Table 2
A list of design consistency Indices considered in this study.

Name of Parameter (description)	Equation	Mean	Min.	Max.	Std. dev.
Alignment Consistency Indices (AC-1 to 4)					
AC-1 (Ratio of Max. and Min. Radius in curve segment)	$RR_{max\_min} = \frac{Rmax}{Rmin}$	2.70	1.00	30.80	3.70
AC-2 (Ratio of Max. and Avg. Radius in curve segment)	$RR_{max\_avg} = \frac{Rmax}{Ravg}$	1.30	1.00	6.50	0.60
AC-3 (Standard Deviation in CCR of curves in gon/ km)	$\sigma_R = \sqrt{\frac{CCR_i{}^2 - CCR_{avg}{}^2}{n}}$	86.60	0.00	1582.70	183.10
AC-4 (Difference of CCR between successive road segments in gon/km)	$\Delta CCR = \lvert CCRsi - CCRsi + 1 \rvert$	134.50	0.00	1828.50	150.50

CCRsi = Curvature Change rate of i[th] segment
Rmax = Maximum Curve radius in the segment
Rmin = Minimum Curve radius in the segment
Ravg = average Curve radius in the segment
Ri = Curve radius of i[th] curve in the segment
n = number of curves in the segment

Name of Parameter (description)	Equations	Mean	Min.	Max.	Std. dev.
Operating Speed Consistency Index (OSC-1 to 12)					
OSC-1 (Difference bet[n] Operating Speed and Design Speed of segment in km/hr)	$\lvert V_{85i} - V_{di} \rvert$	9.600	0.20	33.70	4.10
OSC-2 (Difference bet[n] Operating Speed of Successive segments in km/hr)	$\lvert V_{85i} - V_{85i+1} \rvert$	3.500	0.00	23.40	3.00
OSC-3 (Relative area under average speed and Operating speed in km/hr)	$\frac{\sum_{i=1}^{n} A_i}{L}$	9.622	0.85	33.79	4.04
OSC-4 (Standard deviation of operating speeds in a road segment in km/hr)	$\sqrt{\frac{V_i^2 - V_{avg}^2}{n}}$	2.182	0.00	7.73	1.85
OSC-5 (Function of positive relative area under operating speed profile and average speed and std. dev of operating speed in km/hr)	$\sqrt{\frac{A(+).\sigma}{L}}$	0.975	0.00	10.98	2.28
OSC-6 (Function of relative area under operating speed profile and average speed and std. dev of operating speed in km/hr)	$\sqrt{\frac{A.\sigma}{L}}$	3.825	0.00	11.17	2.41
OSC-7 (Function of positive relative area under operating speed profile and average speed km/hr)	$\frac{A(+)}{L(+)}$	2.350	0.00	33.79	5.78
OSC-8 (Function of relative area under the difference of speed more than 10 km/hr)	$\frac{A(>10km/hr)}{L}$	3.614	0.00	33.79	6.77
OSC-9 (Function of relative area under the difference of speed more than 15 km/hr)	$\frac{A(>15km/hr)}{L}$	1.997	0.00	33.79	5.99
OSC-10 (Funtion of relative area under the difference of speed more than 20 km/hr)	$\frac{A(>20km/hr)}{L}$	0.878	0.00	33.79	4.34
OSC-11 (Function of positive relative area under operating speed profile and average speed and positive std. dev. for total length in km/hr)	$\sqrt{\frac{A(+).\sigma(+)}{L}}$	0.926	0.00	10.98	2.29
OSC-12 (Function of positive relative area under operating speed profile and average speed, positive std. dev. for positive length in km/hr)	$\sqrt{\frac{A(+).\sigma(+)}{L(+)}}$	1.087	0.00	10.98	2.31

V_{85i} = operating speed of i[th] road element
A = area under V_i and V_{85} Profiles
L = length of the road element
σ = standard deviation of R_a
σ (+) = standard deviation of the difference between V_i and V_{85} considering only the positive differences.
Relative area, $R_a = \frac{\sum_{i=1}^{n} A_i}{L}$,
V_{di} = design Speed of i[th] segment
$L(+)$ = length of the road element where the operating speed profile is higher than average speed
$A(+)$ = Positive area under V_i and V_{85} where the operating speed profile is higher than average speed
A(>x km/hr) area bounded when the difference between V_i and V_{85} is higher than × km/h.

Name of Parameter (description)	Equations	Mean	Min.	Max.	Std. dev.
Driving Dynamics Consistency Index (DDC)					
DDC (Difference bet[n] assumed side friction and demanded side friction (micro/inch)	$\Delta f_R = f_{RA} - f_{RD}$	0.075	−0.87	0.71	0.116

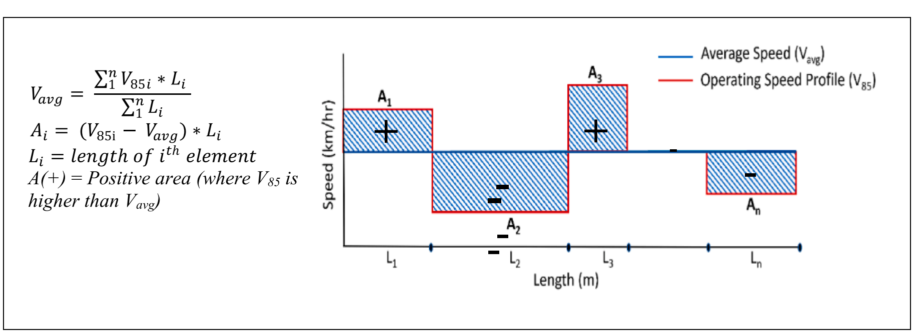
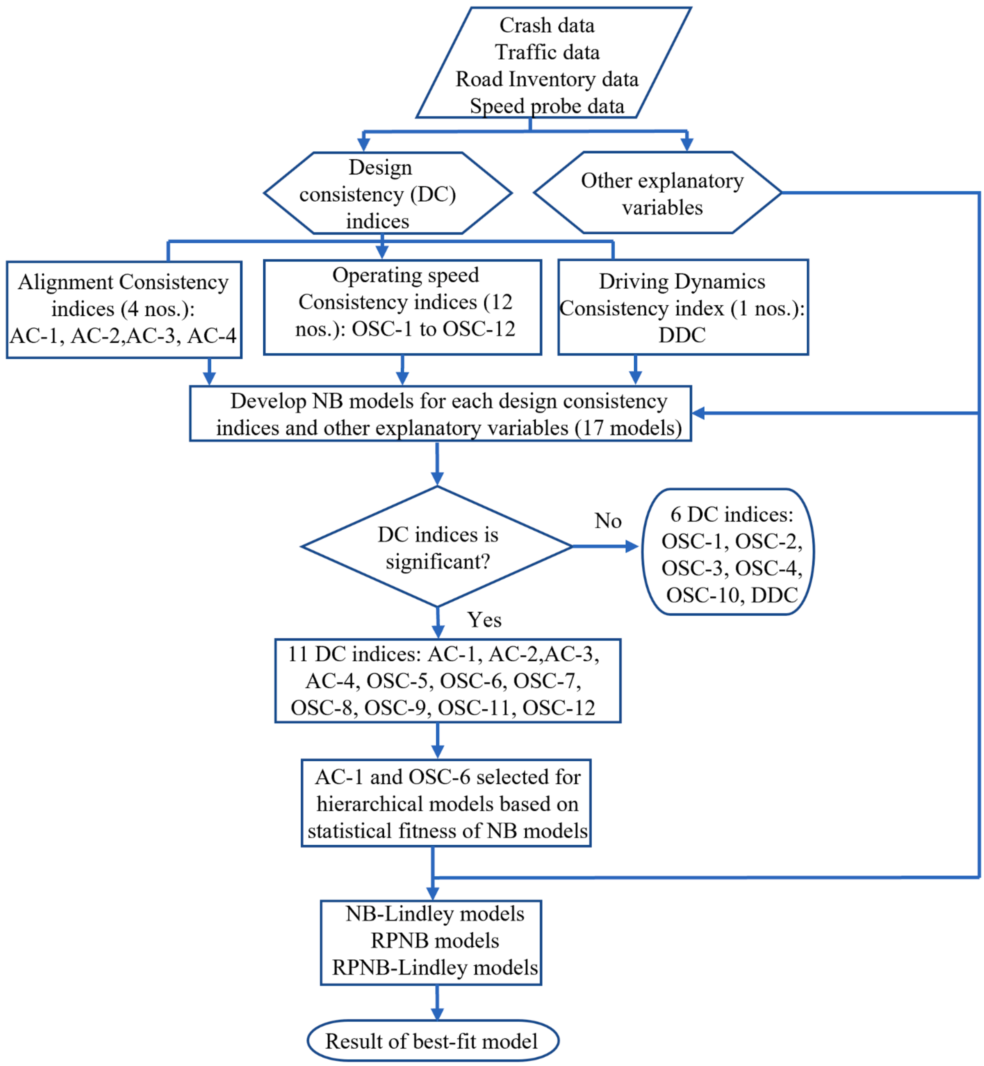


Fig. 2. Illustration of Operating speed profile and average speed of road segment.



Legend		Legend	
NB	Negative Binomial	DC	Design Consistency
RPNB	Random Parameters Negative Binomial	AC	Alignment Consistency
NB-Lindley	Negative Binomial Lindley	OSC	Operating Speed Consistency
RPNB-Lindley	Random Parameters Negative Binomial Lindley	DDC	Driving Dynamics Consistency

Fig. 3. Analytical framework to examine the factors of run-off-road crashes.

consistency indices are significantly associated with run-off-road crash risk[4].

From Table 3, it can be observed that all the significant design consistency indices have a positive association with run-off-road crash risk. With regards to alignment consistency, the model with AC-1 (ratio of maximum and minimum curve radius in a homogeneous road segment) showed better data fit (DIC: 10,403) relative to other alignment consistency indices. Among operating speed consistency indices, seven alternatives (OSC-5, OSC-6, OSC-7, OSC-8, OSC-9, OSC-11, and OSC-12) were found to be significantly approach associated with run-off-road crash frequency in separate models. As shown in Table 3, OSC-6 (relative area under the operating speed and average speed) shows the lowest DIC (DIC: 10,393) compared to other operating speed consistency indices.

To delve further into the selected models and to validate the predictability of these base models, Adjusted Cumulative Residuals (CURE) were plotted against the increasing order of the exposure factor (log AADT). The adjusted CURE plots of the base NB models for different alignment consistency indices are shown in Fig. 4, and it could be observed that in low exposure, all four models resulted in cumulative residuals oscillating close to zero and maintaining a balance between the positive and negative sides. Also, the plots of all four models mostly stayed within the 95% boundaries ($\pm 2\sigma$) of cumulative residuals, indicating their good fit to exposure.

[4] The design consistency indices that are provided by the best-fitted model in this step are further considered in combinations across AC, and OSC categories. However, the different types of design consistencies are found to be correlated and hence, the model with only one design consistency is considered for further analysis.

Table 3
Base NB models with various design consistency indices.

Model Form: $\lambda_i = e^{\beta_0} * AADT^{\beta_1} * L * e^{C\beta_2}$	β_0	β_1	β_2	DIC
Alignment Consistency (AC) Indices				
Model with AC-1	−8.90	0.645	0.068	10,403
(Ratio of Max. and Min. Radius in curve segment)				
Model with AC-2	−9.22	0.644	0.373	10,410
(Ratio of Max. and Avg. Radius in curve segment)				
Model with AC-3	−8.84	0.645	0.001	10,418
(Standard Deviation in CCR of curves in gon/km)				
Model with AC-4	−8.88	0.646	0.001	10,423
(Difference of CCR between successive road segments in gon/km)				
Operating Speed Consistency Indices				
Model with OSC-5	−8.68	0.625	0.106	10,413
(Function of positive relative area under operating speed profile and average speed and std. dev of operating speed in km/hr)				
Model with OSC-6	−8.92	0.645	0.092	10,393
(Function of relative area under operating speed profile and average speed and std. dev of operating speed in km/hr)				
Model with OSC-7	−8.70	0.628	0.038	10,423
(Function of positive relative area under operating speed profile and average speed km/hr)				
Model with OSC-8	−8.81	0.642	0.028	10,437
(Function of relative area under the difference of speed more than 10 km/hr)				
Model with OSC-9	−8.79	0.64	0.032	10,434
(Function of relative area under the difference of speed more than 15 km/hr)				
Model with OSC-11	−8.69	0.626	0.105	10,414
(Function of positive relative area under operating speed profile and average speed and positive std. dev. for total length in km/hr)				
Model with OSC-12	−8.67	0.622	0.109	10,408
(Function of positive relative area under operating speed profile and average speed, positive std. dev. for positive length in km/hr)				

Further, the CURE plots for operating speed consistency indices are presented in Fig. 5. From the figure, it could be observed that the operating speed consistency indices also indicate a good fit with respect to exposure. Based on the goodness-of-fit measures, AC-1 and OSC-6 have been considered for further analysis. It is worth mentioning that, along with the base NB models, full NB models and full NB-Lindley models are developed for all 17 design consistency indices along with other explanatory variables. The models with AC-1 and OSC-6 indices provide better statistical fit compared to the models with other design consistency indices. Therefore, these two parameters are selected for developing the RPNB-Lindley models.

5.2. Model results

The NB models with AC-1 and OSC-6 are further extended to the NB-Lindley framework, Random Parameters NB framework as well as Random Parameters NB Lindley framework to examine the influence of extra zeros as well as unobserved heterogeneity on the run-off-road crash risk mechanism. The estimation results for Base NB models, Base NB-Lindley models, NB models, NB-Lindley models, and Random parameters NB-Lindley models are presented in Table 4, along with the data fit measures. The results show that the DIC values are consistently lower for the Random Parameters Negative Binomial-Lindley (RPNB-Lindley) models than for the Negative Binomial-Lindley (NB-Lindley model) or RPNB models.

Continuous variables which are found to be positively associated with run-off-road crash risk are AADT, operating speed consistency (OSC-6), percentage of heavy vehicles, both side clear zone width less than 1 m and Infrastructure Risk-4 (ditch in 5 to10 meters). Two categorical variables, rolling and mountainous terrains, are also estimated to be positively related to crash risk. On the other hand, shoulder width, both side clear zone widths of more than 5 m, and Infrastructure Risk-3 (vertical wall/rigid structures in 1 to 5 m) are negatively associated with run-off-road crash risk. Moreover, the Operating speed consistency (OSC-6) and the presence of a ditch in 5 to 10 m (Infrastructure Risk-4) are found to be random in the random parameter models.

As shown in Table 4, the RPNB-Lindley model with operating speed consistency index resulted in the lowest DIC (DIC = 8272), indicating that the operating design consistency explains the run-off-road crash risk

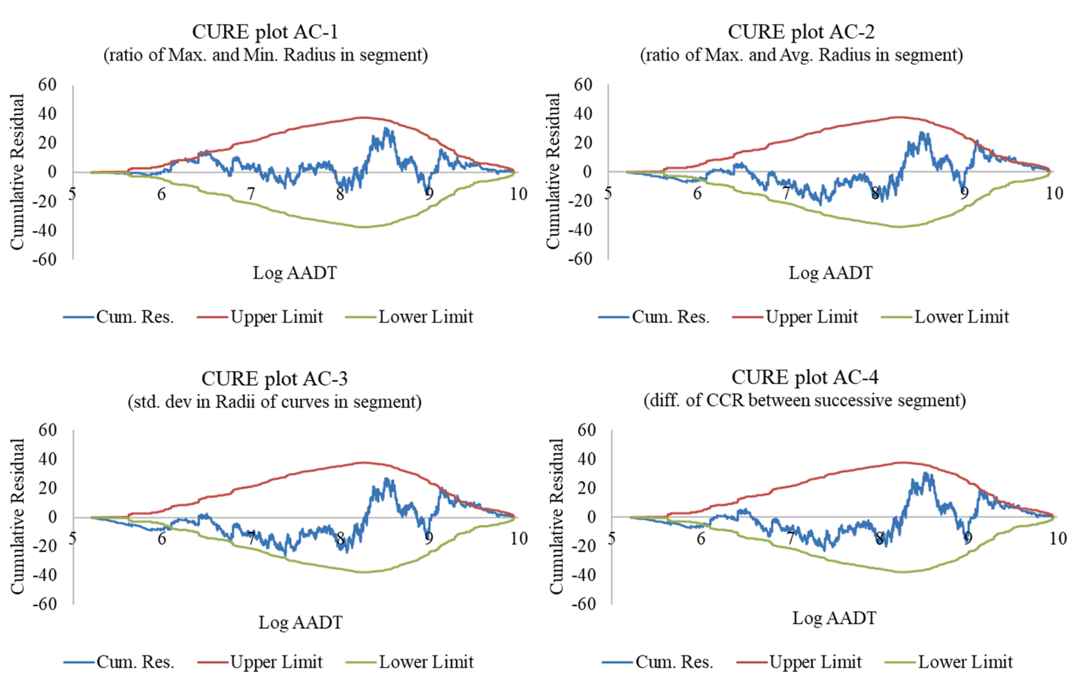


Fig. 4. CURE Plots for Alignment Consistency indices.

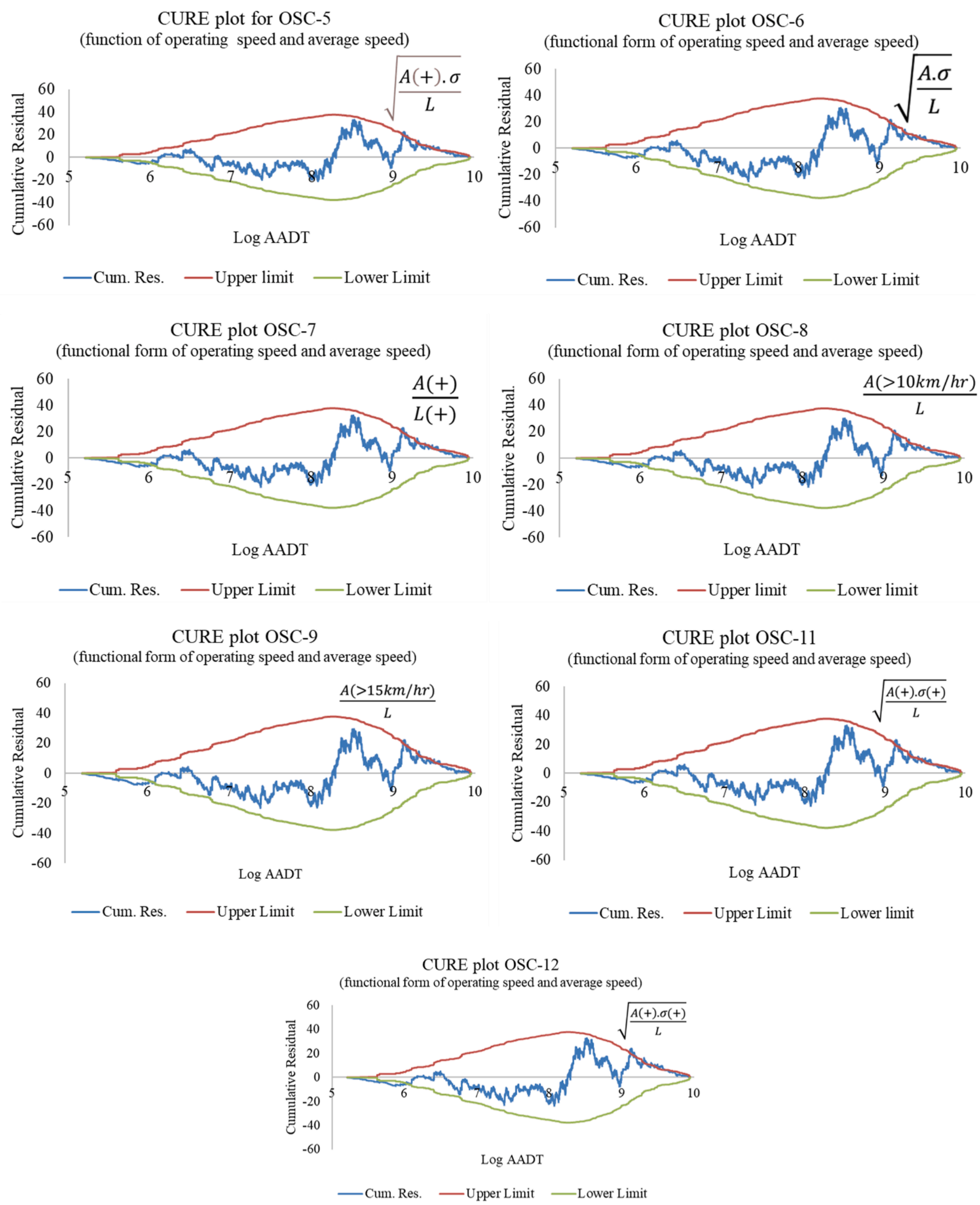


Fig. 5. CURE Plots for Operating Speed Consistency indices.

mechanism better than other design consistency indices in the current study context. Table 5 shows the means and standard deviations of posterior parameters in the RPNB-Lindley model for operating design consistency parameter (OSC-6). The 95% Bayesian Credible Intervals (BCIs) have been used to interpret the significance of variables. In particular, those coefficient estimations are significant, whose 95% BCIs do not include zero. Furthermore, to interpret the impact of variables on run-off-road crashes, the marginal effects are also shown in Table 5. However, in the following section, for brevity, we will restrict ourselves to discussing the best-specified model, the RPNB-Lindley model, for operating design consistency parameter OSC-6.

6. Discussion

In examining the effects of design consistency on run-off-road crash risk, 17 design consistency indices were considered in this study. Results suggest that several alignment consistency and operating speed consistency measures are associated with run-off-road crashes. Along with design consistency parameters, various exogenous factors related to roadway cross-section, roadside attributes, and spatial characteristics are also associated with run-off-road crashes on two-lane rural highways. The effects of design consistency variables (a total of 11 significant indices) are discussed in the subsequent section. For the other explanatory variables, the Random Parameter NB-Lindley model related to the operating speed consistency index (OSC-6) is highlighted.

6.1. *Effects of design consistency variables*

With regards to geometric design consistency, earlier studies (Anderson et al., 1999; Montella and Imbriani, 2015) considered separate models for curve sections and straight sections in examining the crash risk models. However, a single crash frequency model is developed

Table 4
Comparison of the models under alignment consistency and operating speed consistency measures.

	DIC	No. of parameters
Alignment Consistency Index, AC-1 *(Ratio of Max. and Min. Radius in curve segment)*		
Base NB Model	10,403	3
Base NB-Lindley	10,171	3
NB Model	10,224	13
NB-Lindley	10,120	13
RPNB Model	10,288	13
RPNB-Lindley	8745	13
Operating Speed Consistency Index, OSC-6 *(Function of relative area under operating speed profile and average speed and std. dev of operating speed in km/hr)*		
Base NB Model	10,393	3
Base NB-Lindley	10,146	3
NB Model	10,210	13
NB-Lindley	9967	13
RPNB Model	10,251	13
RPNB-Lindley	8272	13

Table 5
Estimate of RPNB-Lindley Models for operating speed consistency measure (OSC-6).

Variables	Mean	Std. Dev.	95% BCI	Marginal Effects
Exposure: Log AADT	0.650	0.042	[0.572, 0.756]	0.029
Log segment length (km) (offset)	1.000			
Geometric Design Consistency Parameter				
OSC-6*(Function of relative area under operating speed profile and average speed and std. dev of operating speed in km/hr)*	0.069	0.012	[0.041,0.089]	0.260
Standard deviation of distribution	0.032	0.009	[0.016, 0.049]	
Percentage of heavy vehicles (%)	0.008	0.001	[0.005, 0.011]	0.035
Cross-section: Shoulder width (m)	−0.156	0.072	[−0.300, −0.017]	−0.007
Roadside attributes (as the proportion of segment length)				
Both sides Clear zone width > 10 m	−0.553	0.154	[−0.861, −0.250]	−0.026
Both sides Clear zone width 5 to10m	−0.401	0.128	[−0.649, −0.149]	−0.024
Both sides Clear zone width ≤ 1 m	1.176	0.410	[0.352, 1.961]	0.034
Infrastructure Risk-3 *(vertical wall/ rigid structure in 1–5 m)*	−0.439	0.156	[−0.80, −0.17]	−0.019
Infrastructure Risk-4* *(ditch in 5–10 m)*	0.526	0.236	[0.062, 0.982]	0.02
Standard deviation of distribution	0.520	0.208	[0.110, 0.940]	
Terrain types (as the proportion of segment length)				
Rolling Terrain	0.278	0.100	[0.084, 0.473]	0.012
Mountainous Terrain	0.740	0.188	[0.368, 1.10]	0.032
Remoteness: Outer Regional (1 or 0)	−0.158	0.073	[−0.301, −0.012]	−0.006
Constant	−13.010	0.607	[−14.190, −12.030]	
Dispersion Parameter	3.912	1.314	[2.042, 7.123]	
Lindley Parameter	0.032	0.015	[0.010, 0.65]	
DIC	**8272**			

* Random parameter

in this study for both straight section and curved section of roadway, based on the assumption that the straight sections are geometrically consistent in design, which simplify the estimation of run-off-road crashes. Besides, there are several effects of alignment consistency as well as operating speed consistency variables, which are mentioned in the following sub-sections.

With regards to alignment consistency (AC) indices (representing changes in roadway alignment), all four indices are found to have a significant effect on run-off-road crashes. The AC index representing the ratio of the maximum and minimum radius (AC-1) is positively associated with run-off-road crashes, implying that higher variations in curve radii in a segment increase run-off-road crash risk. The AC index representing the ratio of the maximum radius and average radius in a segment (AC-2) captures the sudden flattening in a curve. The positive link of AC-2 with run-off-road crash risk indicates that any unexpected change (flattening of the curve) in road geometry may surprise drivers and increase the run-off-road crash risk. This finding implies that highway design matching the expectation of drivers is vital for a safer roadway environment. The third AC index illustrates the overall variation of curve radii in a segment (AC-3), and it captures the fluctuation of road alignment through the standard deviation of curve radii. Furthermore, the average variation of CCR among two successive road segments is captured as another alignment consistency index (AC-4). The positive link of these indices indicates that the consistency of curve radii between two consecutive segments is a vital factor. Although many studies suggested a positive association of sharp curves with run-off-road crashes (Geedipally et al., 2019; Rusli et al., 2017), this study has found that the relationship is not straightforward. The geometrical variation among upstream and downstream curves affects the crash risk, and it is suggested to consider the changes in alignment rather than just focusing on a single curve (Hamilton et al., 2019). All four alignment consistency indices separately can be considered as a measure for capturing the sudden changes in road geometry. The higher values of these indices indicate more variation in the roadway, which can impose a surprising situation for a driver and consequently increase the risk of run-off-road crashes.

Regarding operating speed consistency measures, different functional forms of speed variations (design speed, operating speed) are considered in generating 12 different OSC indices. Among these 12 indices, seven are found to significantly affect run-off-road crash risk for the rural two-lane highways considered in this study. These parameters capture the relationships among road geometry, drivers' speeding characteristics and crash propensity from various perspectives of roadway geometry consistencies. Based on the operating and average speed profile plot (as presented in Fig. 2), the functions of significant OSC indices can be divided into two forms: 1) positive area under the operating speed profile where only higher speed variations are considered and 2) total area under the operating speed profile where both the higher and lower speed variations are counted (as shown in Table 2). Four operating speed consistency indices (OSC-5, OSC-7, OSC-11, and OSC-12) represent the higher speed variations (positive relative area) of roadway segments, and the other three indices (OSC-6, OSC-8 and OSC-9) consider both higher and lower speed variations (total area under operating speed profile and average operating speed). Both forms of operating speed consistency indices show a positive association with run-off-road crash risk. However, the lower DIC in the base model related to OSC-6 (function of total relative area and standard deviation) supported the U-shaped relationship between operating speed and run-off-road crash risk (Davis and Pei, 2006). It implies that high speed, as well as low speed of vehicles, are critical factors contributing towards run-off-road crash risk. Any sudden variation in operating speed indicates an unexpected change in road geometry/roadside attributes, which may surprise a driver requiring significant changes in driving manoeuvres, which may contribute to losing control of the vehicle resulting in a run-off-road crash (Fitzpatrick et al., 2000).

6.2. *Effects of other explanatory variables*

Several factors related to traffic characteristics, roadway cross-section, roadside attributes, and spatial characteristics are also found to be associated with run-off-road crashes. In the following subsections, the effects of these variables are briefly discussed.

Annual Average daily traffic (AADT) was considered an exposure measure in developing the run-off-road crash risk model, while the logarithm of segment length was considered an offset variable to account for roadway segment length variations. The exposure variable, the logarithm of AADT, is found to be statistically significant and positively associated with run-off-road crash risk. The marginal effects estimate in Table 5 suggests that a one unit increase in log AADT is associated with a 0.029 unit increase in run-off-road crashes. The positive association between the logarithm of AADT is intuitive for the run-off-road crash risk (Geedipally and Lord, 2010; Lord et al., 2011). In general, traffic flow/density is considered as an exposure variable starting with the logic that "no traffic flow, no crashes". In addition, a higher proportion of heavy vehicles is also found to increase the run-off-road crash risk. Heavy vehicles on two-lane two-way highways generally create speed differentials with other vehicles, which may result in aggressive overtaking manoeuvres and contribute to run-off-road crashes.

Among roadway cross-section factors, shoulder width is negatively associated with run-off-road crashes. A one unit increase in shoulder width is likely to contribute towards a 0.007 unit decrease in run-off-road crashes. The presence of a wide shoulder may offer a recovery area for the errant vehicle, or the shoulder can be used as a de facto lane, and it may reduce the likelihood of run-off-road crashes (Geedipally et al., 2019; Neuman et al., 2003).

Due to the unique mechanism of run-off-road crashes, roadside attributes are crucial. Three variables regarding the roadside's clear zone width are found to be significantly associated with run-of-road crashes. They include 1) both-side clear zone widths of more than 10 m, 2) both-side clear zone widths of 5 to 10 m, and 3) both-side clear zone widths of less than 1 m. The parameter estimates for the proportion of segment lengths with more than 10 m clear zone width on both sides has a negative association with run-off-road crashes. The average marginal effect suggests that a 1% increase in the proportion of segment lengths more than 10 m clear zones on both sides of the roadways is likely to contribute toward a 0.026 unit decrease in run-off-road crashes. Similarly, the proportion of segment lengths with clear zone widths between 5 and 10 m along both sides has a negative estimate, with an average marginal effect of − 0.024. On the other hand, the proportion of segment lengths with clear zone widths less than 1 m shows a positive correlation with run-off-road crashes, with an average marginal effect of 0.034. A comparison of marginal effects among these three variables indicates that the run-off-road crash risk reduces with the width of clear zones. A wide clear zone works as a recovery area for an errant vehicle, resulting in a reduced crash risk (Jamieson, 2012; Roque and Jalayer, 2018).

Along with the clear-zone width, infrastructure risk under roadside attributes plays a crucial role in run-off-road crashes. This study identified that the presence of vertical face/rigid structures within 1 to 5 m of roadway is negatively associated with run-off-road crash risk. The average marginal effect suggests that the proportion of segments with vertical face/ rigid structures within 1 to 5 m results in an average 0.019 decrease in run-off-road crashes. It is possible that the presence of these objects at a near distance may have some calming effect on drivers' speeding behaviour (Fitzpatrick et al., 2014; Fitzpatrick et al., 2016). Another variable, infrastructure risk-4 (ditch within 5 to 10 m), is positively associated with run-off-road crash risk for rural highways, and the corresponding parameter is found to be random with an average marginal effect of 0.02. Since the vehicle in run-off-road crashes is reported to move a wide distance at the time of the crash, the presence of a ditch may lead to rollover/overturn of the errant vehicle resulting in injury crashes (Jalayer and Zhou, 2016a; Roque and Jalayer, 2018).

The portion of rolling (grade: 8 to 15%) and the mountainous terrain (grade > 15%) are found to be positively associated with run-off-road crashes. Since run-off-road crashes are more prone to steep slopes, the crash risk is more likely to increase in mountainous or rolling roadways than in level terrain (Rusli et al., 2018; Rusli et al., 2017). The marginal effect of mountainous terrain is higher than that of rolling terrain, which suggests that the steeper the longitudinal slopes, the higher the likelihood of run-off-road crashes. In addition, the remoteness variable representing the outer regional area is found to be negatively associated with run-off-road crashes, perhaps indicating fewer variations in the roadway environment in these locations, contributing to lower run-off-road crashes.

7. Conclusions

The objective of this study was to examine the effects of design consistency on run-off-road crashes along two-lane, two-way rural highways. The data for this study were collected from run-off-road crashes recorded for two-lane rural highways in Queensland, Australia, for the years 2014 through 2018. A set of Random Parameters Negative Binomial Lindley models were developed to estimate the effects of design consistencies on run-off-road crashes by taking into account the effect of excess zeros in the crash data and unobserved heterogeneity in parameter estimates.

This study is the first of its kind to examine the effects of different geometric design consistency measures on run-off-road crash risk for rural two-lane highways. By developing an extensive dataset using the multi-source data fusion technique, this study presents a comprehensive analysis of the effect of 17 different design consistency indices on run-off-road crash risk. These 17 design consistency indices are generated building on three broad categories of geometry consistency measures – alignment consistency, operating speed consistency and driving dynamic consistency. A significant contribution of this study is the in-depth insights into the effects of design consistencies on run-off-road crash risks.

The findings of this study strongly suggest that the multiple road geometric characteristics captured through design consistency (e.g., alignment consistency) are more critical than separate geometrical characteristics. It is quite well known that curve radius/curve types are associated with run-off-road crashes, but this study reveals that alignment consistency is more critical for run-off-road crashes than the individual variables related to roadway geometric characteristics. Any sudden change in roadway geometry (sudden flatten/sharp curve) may increase the risk of run-off-road crashes, as found in the results related to alignment consistency. It implies that a sudden flattening of the curve among successive sharp curves may increase the run-off-road crash risk. In addition, variation in operating speed indicates the differences between drivers' expectations of road geometry and the existing road alignment. Multiple variables as a function of positive operating speed variation as well as total (positive and negative) operating speed variation are examined in this study. The results suggest that the crash risk of run-off-road crashes is better predicted if the model considers total variations. Operating speed within a typical range is essential for a safer roadway (Davis and Pei, 2006), and sudden changes in operating speed (much higher or lower) reflect unexpected geometrical changes for drivers, resulting in high crash risks. Roadside attributes like clear zone and infrastructure risk are crucial for run-off-road crashes on two-lane rural highways. A clear zone width of more than 5 m may be recommended to decrease the likelihood of run-off-road crashes on two-lane rural highways. Infrastructure like trees, vertical faces, and rigid structures at a distance of 1 to 5 m are found to reduce the likelihood of crashes. In contrast, the presence of a ditch at the same distance increases the possibility of run-off-road crashes.

The findings of this study shed considerable light on the factors affecting run-off-road crash risk for rural two-lane highways. It can be a reference to traffic safety experts to evaluate the run-off-road crash risks at the network/local level, which will help to identify the high-risk zones/spot for run-off-road crashes as well as suitable countermeasures at the existing roadway. For designing the new road, the critical factors may get special attention during the planning period and may work proactively to reduce run-off-road crashes. Furthermore, the developed operating speed profile can be used in rural two-lane highways of Queensland or similar conditions and may develop the operating speed indices to find the consistency of the roadway. Along with the road geometric changes, this study investigates various attributes of the roadside to strengthen the forgiving-roadside concept, like the clear zone width and infrastructure risk. Overall, the study findings will help safety experts, highway engineers, policymakers and relevant authorities to identify the critical factors related to road geometry as well as roadside attributes related to run-off-road crashes and take suitable countermeasures.

Although this study has empirical implications, there are some limitations that may require consideration for the application as well as further development. Firstly, the data quality of the secondary data (crash data, road inventory data, speed probe data etc.) is always a concern for crash analysis, which include the risk of record inaccuracy and missingness (incompletely recorded crashes and crash under-reporting). Secondly, the operating speed profile that is developed based on the speed probe data is collected from a single point for a curve, and that's why the speed profile for the deceleration/acceleration (at the beginning/ending) at the curves is not introduced in this study. Lastly, property-damage-only (PDO) crashes are not considered in this study as they are not available in the crash dataset, which may underestimate the overall crash risk of run-off-road crashes. However, in future studies, the naturalistic driving method can be used for speed data collection, which will help to make more understanding of the speed variations and road geometric changes. A prospective study on run-off-road crashes can also apply the new inertial operating speed consistency indices as proposed by Llopis-Castelló et al. (2018b), which relate to the Short Term Memory (STM) of drivers, road geometry and crash frequency. Moreover, future studies can consider methodological advancement for run-off-road crashes, which may include heterogeneity in the mean in the Random Parameters Negative Binomial Lindley model for run-off-road crashes to examine the design consistency effects.

CRediT authorship contribution statement

Shinthia Azmeri Khan: Conceptualization, Methodology, Software, Data curation, Formal analysis, Writing – original draft, Visualization. **Amir Pooyan Afghari:** Software, Validation, Writing – review & editing. **Shamsunnahar Yasmin:** Methodology, Validation, Writing – review & editing. **Md Mazharul Haque:** Conceptualization, Methodology, Investigation, Validation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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