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# Reliability Approach to Highway Geometric Design: A Methodical Review

Afolayan, A[1*]; Oluwasola, E. A[1] and Abiola, O. S[2]
[1]Department of Civil Engineering Technology, Federal Polytechnic Ede, Osun State, Nigeria
[2]Department of Civil Engineering, Federal University of Agriculture Abeokuta, Ogun State, Nigeria

**Abstract- Highway designers are faced with the challenge of designing for different classes of driver, vehicle and roadway characteristics and conditions. There is significant variability in design inputs and design controls that influence design standards and design decisions. This variability has been considered through the deterministic design method of selecting values for geometric design parameters and criteria. The deterministic approach has two main shortcomings: First, many design parameters, such as perception and brake reaction time (PRT) and operating speed, are probabilistic in nature. Second, in some situations, the designers may need to deviate from the design standards due to some constraints (e.g. restricted right of way, nature of the road-side). Existing geometric design guides provide little knowledge on the safety implications of deviating from standard requirements. Probability design approaches that quantify both risk and reliability have been successfully used in other design disciplines for those reasons. These approaches have also been look into in highway geometric design literature and have shown promise. Given the compelling importance of reliability-based highway design, this paper presents a systematic review and appraisal of methodological alternatives for the reliability-based analysis in relation with geometric design elements for traffic safety.**

**Keywords:** ***Geometric Design, Reliability, Review, Traffic Safety and Uncertainty.***

## 1.0 Introduction

The geometric design of roads is the branch of highway engineering concerned with the positioning of the physical elements of the roadway according to standards and constraints. The basic objectives in the geometric design are to optimize efficiency and safety while minimizing cost and environmental damage. It involves the design of roads to foster broader community goals, including providing access to employment, schools, businesses, and residences, accommodate a range of travel modes such as walking, bicycling, transit, and automobiles, and minimizing fuel use, emissions and environmental damage (*FHWA, 2017*). Geometric roadway design is subdivided into three main parts: alignment, profile, and cross-section. Combined, they provide a three-dimensional layout for a roadway. The alignment is the route of the road, defined as a series of horizontal tangents and curves, the profile is the vertical aspect of the road, including crest and sag curves, and the straight grade lines connecting them while the cross section shows the position and number of vehicle and bicycle lanes and sidewalks, along with their cross slope or banking (*FHWA, 2017*).

Highway designers are faced with variability of driver, vehicle, and roadway conditions and capabilities when designing (Porter *et al.*, 2012). Quite significant variability and uncertainty exist as a result of inherent randomness and lack of perfect knowledge concerning design inputs and design controls that influence design standard and decisions. The deterministic approach has two main shortcomings: First, many design parameters, such as perception and brake reaction time (PRT) and operating speed, are probabilistic in nature. The values used for design are typically selected at conservative percentile values extracted from their respective distributions among the general population of road users. The safety margin of the design output in this approach is unknown and no clear value is known to be targeted. Second, in some situations, the designers may need to deviate from the design standards due to some constraints (e.g. restricted right of way, nature of the road-side). Existing geometric design guides provide little knowledge on the safety implications of deviating from standard requirements. As well, in the deterministic approach, a slight violation to standards is considered as unacceptable as the highest violation (Ismail and Sayed, 2010, 2012).

Reliability analysis has been recently applied as an effective approach to account for uncertainty in the geometric design process and to assess the risk associated with a specific design. In this approach, the design parameters are considered as random variables expressed in terms of their probability distributions as opposed to single value estimations in the deterministic approach (César de *et al.*, 2017). The purpose of applying the reliability theory to highway geometric design is to establish and promote a more consistent and more reliable design process (Hamid *et al*., 2017). Reliability theory can be used to develop factors of safety that incorporate the uncertainty of the supply and demand variables. The resulting factor of safety is the probability of non-compliance ($P_{nc}$) which is associated with a measure of the probability that the demand will exceed the supply or that a specific design would not meet standard requirements (Hussein *et al*., 2014). Reliability analysis is not considered as an alternative of using collision frequency to evaluate safety; rather, it represents a complementary method of measuring safety in terms of risk (Richl and Sayed, 2006).

Transportation is vital both to the economic success and to the quality of life in urban and rural areas. However, the rapid growth of city population and corresponding commuting distances of travel, commerce, and transportation infrastructure have generated negative effects such as congestion, deterioration of air quality, noise, and motor vehicle crashes. Road traffic crashes have been a threat to the safety of family members and are associated with numerous problems each of which needed to be addressed separately; human, vehicle, road and environmental factors play roles, before, during and after a traumatic event. Road accidents are becoming very common and are robbing the nation of its valuable human resources; the implications of these lead to both social and economic trauma (Tandoh, 2003).

A number of previous applications of reliability analysis in geometric design centered on evaluating one particular design criterion (e.g. sight distance) with the probability of non-compliance representing one failure (non-compliance) mode (e.g. available sight distance is less than required sight distance). The main contribution of this research work will be to demonstrate the application of multi-mode (system) reliability analysis on highway elements that are subject to more than one failure mode. The goal is to assess a system probability of non-compliance of a highway element to incorporate all non-compliance modes.

## 2.0 Review Objective and Scope

The objective of this paper is to identify, review and systematically synthesize published literatures that explicitly incorporated uncertainty and reliability analyses into highway geometric design criteria and decisions. The paper will establish alternative approaches appraising geometric design criteria and decisions that critically consider uncertainties in geometric design controls and design “inputs,” and their effects on the level of uncertainty in design “outputs” in terms of safety. National and international research papers were included in the review. As a body of work, these resources attempted to indicate the various ways in which reliability have been used in highway geometric element design and to establish a research gap that require urgent attention. However, this systematic review does not include any discussion on how transportation agencies apply these reliability concepts into the current decision making process.

## 3.0 The Principle of Reliability and Limit State Function

Reliability refers to the complement of the failure probability (Eq.1). In the reliability analysis, the term probability of failure represents the probability of an undesired event exceeding a certain threshold. In road design, researchers have proposed the use of probability of non-compliance ($P_{nc}$) to label the probability of a design that does not meet standard (Essa *et al*., 2016; Richl & Sayed, 2006; Hussein *el al*., 2014, and Navin, 1990).

$$Reliability = 1 - P_{nc} \tag{1}$$

The analysis has two components: random variables that describe the uncertainty and the Limit State Function (LSF) that define the failure mode. The first step is defining a LSF, denoted by $g(X)$, which defines what is considered to be non-compliance where X is the input vector of random variables (Haukaas, 2012c). Generally, the LSF is represented as a balance between supply and demand. In this regard, a single-member system is assumed as the simplest type of systems, in which the variable S represents the supply of the system (such as the ultimate capacity, friction resistance, etc.) and the variable D is the system demand (such as the speed, traffic loading, etc.). This system is considered unsuccessful when the demand is determined to be more than the supply, which in turn leads to the system's failure (Ranagnatan, 1999), as presented in Eq. (2) (Hamid *et al*., 2017).

$$P_{nc} = P(S < D) = P(S - D <^0) = P\left(\frac{S}{D} < 1\right) \tag{2}$$

Where $P_{nc}$ = probability of non-compliance or system failure. Let $f_s(S)$ be the probability density function of the system supply and assume that D is a specific demand value of the system. In this system, the probability of non-compliance ($P_{nc}$) can be calculated by Eq. (3) (Hamid *et al*., 2017). Fig. 1 presents the probability of non-compliance of the system by the shaded area located between the horizontal axis, the $f_s(S)$ graph, and the vertical line crossing the specific demand value of D (Ranagnatan, 1999).

$$P_{nc} = \int_{-\infty}^{D} f_s(S)\,ds \qquad -\infty \leq S \leq \infty \tag{3}$$

In real life, both the supply and demand are considered as random variables. Therefore, the probability density functions of both can be determined. As shown in Fig. 2, the shaded area represents the probability of non-compliance for the system. The main reason of reliability-based design and analysis is to reduce the probability of non-compliance to meet the values considered acceptable according to the system requirements (Ranagnatan, 1999). To estimate failure probability, both the demand and supply curves are required. Supply and demand are obtained as functions of vector X, as $S = f_1(X)$ and $D = f_2(X)$ . The limit-state function is determined as the difference between the supply and demand, as follows: $g(X) = S - D = f_1(X) - f_2(X)$. Thus, failure probability can be defined as the probability that $g(X)$ will be smaller than or equal to zero, as follows: $P[g(X) \leq 0]$. If $g(X) = 0$, then the resulting surface determines the limit state between the failure and non-failure conditions. The limit state can be linear or non-linear depending on the nature of the analyzed problem. If $g(X)$is non-linear, then failure probability can be determined using different probability methods as discussed below.

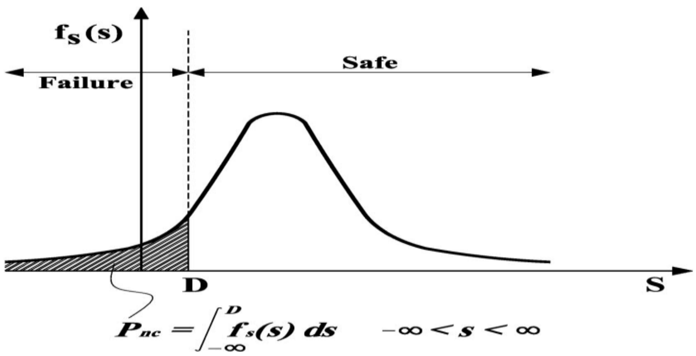

**Fig. 1**: Determination of the Probability of Non-compliance for a Specific Demand (modified by Hamid *et al*., 2017 from Ranagnatan, 1999).

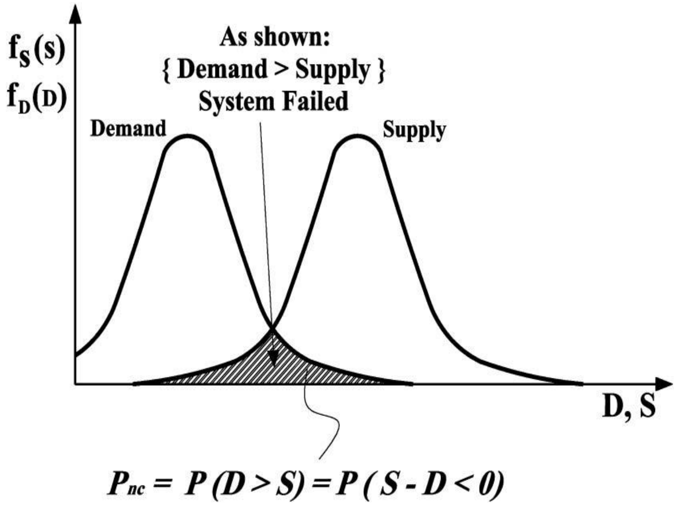


**Fig.2**: Determination of the Probability of Non-compliance for the Random Distribution of Supply and Demand (modified by Hamid *et al*., 2017 from Ranagnatan, 1999).

**4.0 Reliability Analysis in Highway Geometric Design**

Reliability theory provides the analytical tools to account for the variability of input parameters throughout the design process. The main target of the reliability analysis is to evaluate the probability that a design element is within acceptable limits. The probability of failure has been adopted as an indicator in several civil engineering disciplines. However, according to Ismail and Sayed (2009), the probability of non-compliance ($P_{nc}$) is more appropriate for road safety applications since there is no physical failure in those systems.

The aim of applying the reliability theory to highway geometric design is to establish and promote a more consistent and more reliable design process. Navin (1990) took the first initiative by introducing the limit-state concept to the field of highway geometric design; however, it has only been used in isolated conditions, such as horizontal curves. In 1991, he designated the probability of failure used in structural engineering as the probability of non-compliance to address designs that did not meet the standard requirements. Thereafter, the application of the reliability theory in transportation engineering was reported several times in related literature. Dhahir and Hassan (2019) developed a probabilistic, safety explicit approach of horizontal curve design using reliability analysis of four design criteria: vehicle stability, driver comfort, sight distance, and vehicle rollover. Rajbongshi and Kalita (2018) presented a probabilistic approach for evaluating stopping sight distance, considering the variability of all input parameters of sight distance for design of horizontal curve.

Furthermore, Hamid *et al*. (2017) assessed the safety margins obtained from the application of super-elevation in horizontal-curve design. Geometric design guides and a reliability index were used to determine variabilities in the design parameters. Assessment of the safety margins obtained from the application of super-elevation in horizontal-curve design was also demonstrated by Hamid *et al*. (2017). Dhahir and Hassan (2016) adopted a probabilistic approach while considering two criteria: vehicle dynamic stability and driver comfort to overcome the shortcomings of current horizontal curve design procedure. Reliability analysis was used to provide a quantitative evaluation for the design in terms of probability of failure (POF), probability of non-compliance (PNC), and reliability index ($\beta$). Jesna and Anjaneyulu (2016) carried out reliability analysis for single horizontal curve using the data of 118

horizontal curves in Kerala. Analysis was done using sight distance, super-elevation and extra widening as the geometric characteristics that affects the safety of a horizontal curve.
Significant number of previous studies focused specifically on sight distance, probably because it is one of the fundamental criteria for design that is relevant to any location along a roadway. Gargoum *et al*., (2018) explored the extent to which available sight distance (ASD) on highways satisfies the needs of drivers with limited abilities. César de, *et al*., (2017) investigated the safety implications of modelling available sight distance (ASD) by means of reliability analysis. The ASD of 402 horizontal curves, located in twelve two-lane rural highways, was used in their analysis. Santos-Berbel, (2017) developed a methodology for the study of sight distance in three dimensions in order to assess the alignment of in-service highways through sight distance, from the point of view of highway safety. Castro *et al*. (2016) analyzed the influence of Digital Terrain Models (DTM) and Digital Surface Models (DSM) features on the outcome of sight distance calculation in highways. Ahmed *et al.* (2016) used reliability analysis framework to evaluate the risk of limited sight distance for permitted left-turn movements due to the presence of opposing left-turn vehicles. Santos-Berbel and Castro (2015) proposed a new probabilistic approach in order to estimate stopping sight distance (SSD). They adopted the equation provided by the German guidelines, which takes the effect of grade into account along the section travelled during the stopping maneuver. LIorca *et al*., (2014) presented an application of reliability analysis for evaluating the risk associated with passing sight distance (PSD) standards in terms of the expected probability of non-compliance.

Reliability analysis has been employed in guide calibration in order to produce consistent safety levels for design. A general framework for the code calibration of highway geometric design models was presented by Ismail and Sayed (2009). Mohamed *et al*. (2014) presented an application of reliability analysis for the calibration of geometric design models to yield consistent and adequate safety levels. Calibration of middle ordinate charts using system reliability was carried out by Essa *et al*., (2016).

**Table 1.0:** Outline of Previous Research Work with Suggested Future Research Areas from Year 2019 to 2000

| Authors | Years | Title of Studies | Method Used | Suggested Future Research Areas |
|---|---|---|---|---|
| Bashar Dhahir, Yasser Hassan | 2019 | Probabilistic, Safety-explicit Design of Horizontal Curves on Two-lane Rural Highways Based on Reliability Analysis of Naturalistic Driving Data | -Data collection (naturalistic driving data, lateral acceleration and friction data, safety data, road geometric data, pavement friction data and trip time and weather condition data<br>-Preliminary analysis using Matlab script, one-way-ANOVA, Kolmogrov-smirno and Shapiro-Wilk tests)<br>-Drivers behaviour models<br>-Reliability analysis using FORM | i.) Use of larger data sample and other vehicle types to develop models that have higher levels of granularity. |
| Suliman A. Gargoum, Mostafa H. Tawfeek, Karim El-Basyouny, James C. Koch | 2018 | Available sight distance on existing highways: Meeting stopping sight distance requirements of an aging population | - Extraction of sight distance information from LiDAR point cloud highway models<br>- Generating observer and target points<br>- Digital surface model creation<br>- Available stopping sight distance computation | i.) Study of the extent to which design guidelines must be updated to accommodate changes in driving population when designing new roads.<br><br>ii.) Consideration of the means by which limitations on existing highways could be addressed. |
| Lu Wang, Jian-Chuan Cheng, and Yun-Long Zhang | 2018 | Reliability-Based Specification on Critical Length of Highway Sections with Near-Maximum Grade | -Variable identification and distribution<br>-Calculation of reliability and failure probability using First-Order Second-Moment (FOSM) and Monte Carlos Simulation Methods | i.) Investigation of probability distribution of geometric design variables<br>ii.) Assessment of the suitability of different reliability-based approaches to roadway geometric design needs<br><br>iii.) Introduction of other reliability methods such as a Second-Order Reliability Method<br>iv.) Improvement the approaches of simulation sampling for practical applications<br>v.) Collection of additional data on other freeways to further verify that the recommended values are applicable to design in general |

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| Pabitra Rajbongshi<br>Kuldeep Kalita | 2018 | Reliability Based Geometric Design of Horizontal Circular Curves | -Probability distribution of stopping sight distance using Monte Carlos Simulation<br>-Reliability analysis using Matlab software<br>-Development of probabilistic design chart | Nill |
| César de Santos-Berbel, Mohamed Essa, Tarek Sayed, and María Castro | 2017 | Reliability-Based Analysis of Sight Distance Modelling for Traffic Safety | - Estimation of ASD using a 2D method and two different 3D (DTM & DSM) methods. The horizontal 2D ASD was measured graphically on the horizontal projection of each horizontal curve using CAD software while GIS-based software was used for estimation of the 3D ASD<br>-Determination of operating speed (probability distribution and the 50th percentile speed ($V50$), along with statistical measures of dispersion, were considered)<br>- Application of reliability analysis using First Order Reliability Method (FORM). | i.) Enhanced calibration of the operating speed model and assessment of the sensitivity analysis of the operating speed in the LSF.<br>ii.) The influence of weather and pavement surface conditions<br>iii.) Incorporation of reliability results in safety performance functions to establish linkage to traffic safety and validation of the 3D DSM ASD model.<br>iv.) Definition of target safety values for different highway classes or according to budgetary restrictions in construction projects. |
| Hamid Farhad Mollashahi; Kasra Khajavi; and Asieh Khadem Ghaeini | 2017 | Safety Evaluation and Adjustment of Superelevation<br>Design Guides for Horizontal Curves Based on Reliability Analysis | - Used geometric design guides and a reliability index to determine uncertainties in the design parameters of horizontal curves<br><br>- Calibration of geometric design models and superelevation chart using Monte Carlo simulation techniques | i.) Consideration of rollover in horizontal curves in the dynamic stability model<br>ii.) Variability nature of the supplied radius should be considered when analyzing the failure-mode function.<br>iii.) Changes in speed as an effective parameter in the reliability analysis at different parts of the horizontal curve, particularly at the beginning, middle, and end need to be considered<br>iv.) Corresponding probabilities of |

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| | | | | noncompliance for different groups of drivers in accordance with their age, gender, and levels of risk acceptance need be study |
| Santos Berbel, C. D. | 2017 | A methodology for sight distance analysis on highways, alignment coordination, and their relation to traffic safety | -Sight distance computation using elevation models from airborne LiDAR<br>- Reliability analysis on horizontal curves<br>-3D alignment coordination | i.) Development of a fully automated recreation of horizontal and vertical alignment procedure, capable of recreating complex successions of alignments like the ones found in the selected highway<br>ii.) study on the safety effects of spatial alignment coordination on large network data<br>iii.) target level of safety in design through reliability analysis based on safety performance<br>iv.) Reliability-based analysis of nighttime SSD and comparison to the respective results of the daytime SSD analysis. |
| Mohamed Essa, Tarek Sayed, and Mohamed Hussein | 2016 | Multi-Mode Reliability-Based Design of Horizontal Curves | - Evaluation of the values of mid ordinate (M) to achieve pre-specified targets of system (multi-mode) $P_{nc}$.<br>- Application of system (multi-mode) reliability analysis through a case study of the Sea-to-Sky Highway in British Columbia, Canada. The case study considered includes five horizontal curve segments with sharp radii and limited sight distances. | i.) Need for code calibration considering all possible noncompliance modes of geometric elements of highways (e.g. limited sight distance, vehicle skidding, rolling over etc.)<br>ii.) Investigation of the distributions for the design inputs<br>iii.) Investigation of the distribution of parameters such as operating speed, braking deceleration, and side friction factor.<br>iv.) Development of a more accurate operating speed prediction models that incorporate different geometric elements and consider all highway classes.<br>v.) Investigation of correlation between the design inputs<br>vi.) Consideration of the use of 3-D sight distance in multi-mode reliability analysis<br>vii.) Development of a relationship between the system reliability $P_{nc}$ values and collision |

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| | | | | frequency<br>viii.) Identification of suitable target probability of noncompliance for the design code calibration process |
| M. Castro, S. Lopez-Cuervo, M. Paréns-González & C. de Santos-Berbel | 2016 | LIDAR-Based Roadway and Roadside Modelling for Sight Distance Studies | - Three different types of DEM were being used: DTM01, DSM01 and DSM MMS. DTM01 and DSM01 are high resolution models obtained through airborne LIDAR | Nill |
| Ahmed Osama, Tarek Sayed, and Said Easa | 2016 | Framework for Evaluating Risk of Limited Sight Distance for Permitted Left-Turn Movements: Case Study | - Collection of intersection geometry measurements, along with speed and time gap data of the intersection through traffic<br>- Automated video analysis<br>- Reliability analysis using first order reliability method (FORM) and importance sampling method | i.) Inclusion of the stochastic nature of the variables constituting the available sight distance (e.g., vehicle positions) in the limit state function by accounting for their probability distributions.<br>ii.) The framework can also be used to assess the risk of inadequate sight distance for traffic movements other than left turns, and for different phasing configurations<br>iii.) Establishment of a link between the sight distance $P_{nc}$ and the probability of crash occurrence at permitted left turns.<br>iv.) Development of safety performance functions that incorporate the probability of non-compliance as a risk measure using collision data. |
| Bashar Dhahir and Yasser Hassan | 2016 | Reliability-Based Design of Horizontal Curves on Two Lane Rural Highways | - Estimation of lateral friction demand and actual lateral acceleration considering vehicle characteristics by utilizing CarSIM<br>- Development of a new model to estimate the comfort threshold and vehicle speed<br>- Proposal of a new framework to design horizontal curves capable of providing a quantitative evaluation | i.) Development of safety performance functions to relate collision frequency to the aforementioned reliability measures<br>ii.) Potential of the developed reliability measures (probability of failure (POF), probability of noncompliance (PNC), probability of hazard (POH) and reliability index ($\beta$)) as design consistency measures should be explored<br>iii.) Expansion of the models to consider other |

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| | | | for safety | vehicle types and different weather conditions |
| Jesna N.M., M.V.L.R. Anjaneyulu | 2016 | Reliability Analysis of Horizontal Curves on Two Lane Highways | | |
| Altaf Hussain and Said M. Easa, | 2015 | Reliability Analysis of Left-Turn Sight Distance at Signalized Intersections | - Probabilistic approach based on such random variables as major-road speed, time gap required for left-turn vehicle, vehicle width, lateral position of left-turn vehicle, distance between driver eye of left-turn vehicle and its front, and lateral and longitudinal positions of positioned opposing left-turn vehicle.<br>- Development of the relationships for mean and standard deviation of the safety margin using the first-order second-moment (FOSM) method<br>- Validation of the proposed reliability method using Monte Carlo simulation, and establishment of design graphs. | i.) Development of collision modification factors for offsets of a specified probability of noncompliance.<br>ii.) Reliability approach to the determination of intersection sight distance with the combination of horizontal and vertical alignment on the major road.<br>iii.) Refinement of the distribution data for the related random variables<br>iv.) Verification of the coefficient of variation of the random variables. |
| César de Santos-Berbel & María Castro | 2015 | Stopping-Sight-Distance Simulation Using A New Probabilistic Approach | - Estimation of ASD using software based on geographic information system (GIS)<br>- Use of digital surface model (DSM) to shape the road and its roadsides, featuring the terrain as well as vegetation and buildings<br>- Monte Carlo simulation of the real highway segments | i.) Calibration of this probabilistic model.<br>ii.) Implementation of a more comprehensive speed prediction model for heavy vehicles<br>iii.) Derivation of the statistical distributions of many of the parameters used in this experiment<br>iv.) Performing a sensitivity analysis of the influence of the parameters with random variation<br>v.) Evaluation of the possibility of considering climate variables in geometric |

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| | | | | design, as occurs in other areas of highway design |
| Mohamed Hussein, Tarek Sayed, Karim Ismail and Adinda Van Espen | 2014 | Calibrating Road Design Guides Using Risk-Based Reliability Analysis | - Analysis of th propability of noncompliance ($P_{nc)}$ using FORM method<br>- The calibration process using prespecified (target) $P_{nc}$ | i.) Establishment of reliable distributions for the design inputs, especially operating speed.<br>ii.) Investigation of the distribution of operating speed and braking deceleration<br>iii.) Development of accurate speed prediction models that incorporate all related geometric elements and consider different highway classes.<br>iv) Investigation of the correlation of the input parameters<br>iv.) Identification of suitable target probability of noncompliance values for calibration.<br>v.) Study on the effects of different factors on the design variables (braking acceleration, perception and reaction time, and operating speed) including weather conditions, pavement surface situation among others. |
| Anusha Musunuru & Richard J. Porter | 2014 | A Reliability-Based Geometric Design Approach for Selecting Basic Number of Freeway Lanes | - Collection of traffic count data<br>- Development of statistical distributions using Minitab<br>- Reliability analysis using Monte Carlo simulation | i.) Incorporation of uncertainty involved in the projection of AADT by considering annual growth rate as a random variable;<br>ii.) Incorporation of actual free-flow speed data as well as speed-flow relationships<br>iii.) Testing the methodology for a broader range of area type, traffic volume combinations as well as in different operational settings (e.g., providing auxiliary lanes, selecting maximum vertical grade, selection of intersection control type and lane arrangement)<br>iv.) Incorporating uncertainty involved in lane-wise density by taking into account the |

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| | | | | lane changing behaviour of vehicles, which affects lane-wise density significantly |
| Carlos Llorca, Ana Tsui Moreno, Tarek Sayed, and Alfredo García | 2014 | Sight Distance Standards Based on Observational Data Risk Evaluation of Passing | - Data collection based on video recording of passing maneuvers under naturalistic conditions<br>-Reliability analysis using FORM and Monte Carlos simulation for comparism<br>-Formulation of Passing Sight Distance model | i.) Establishment of a link between the probabilities of noncompliance and other safety measures, such as crash data or traffic conflicts |
| Shin, J., and Lee, I. | 2015,2013 | Reliability-Based Design Optimization of Highway Horizontal Curves Based on First Order Reliability Method | - Reliability analysis of a vehicle's sideslip and rollover on horizontal curves using FORM<br>-Design optimization of the minimum radius of horizontal curves using the RBDO method. | i.) Vehicle model should be selected to represent all vehicles on roads<br>ii.) consideration of wind effects since the probability of accident would be higher in a high cross wind<br>iii.) Use of Second-Order Reliability Method (SORM) or a more accurate method to enhance accuracy of reliability analysis.<br>iv.) Reliability level that can guarantee comprehensive safety on curved roads |
| You, K., Sun, L., Gu, W. | 2012 | Reliability-Based Risk analysis of Roadway Horizontal Curves | -Reliability-Based Risk Analysis of Horizontal Curves | i.) Vehicle roll action and the failure model of truck rollover in reliability-based roadway horizontal curve design |
| Ismail, K., Sayed, T. | 2012 | Risk Optimal Highway Design: Methodology and Case Studies | - Definition of design requirement as a limit state function,<br>- Brief description of reliability analysis<br>-Specifics of the design optimization problem. | i.) Composition of a multi-objective cost function that more accurately reflects both practical needs and safety consequences<br>ii.) Investigation of the compound effect of simultaneous change in dimension of different cross-section elements |
| Shewkar El-Bassiouni Ibrahim, Tarek Sayed | 2011 | Developing Safety Performance Functions Incorporating Reliability-Based Risk Measures | -Performed First Order Reliability Method (FORM) analysis using the Rt software (Rt, 2010). | i.) Investigation of spatial correlation and the probability distributions of the design inputs as well as possible correlation between the variables |

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| Ismail, K., and Sayed, T. | 2010 | Risk-Based Highway Design: Case Studies from British Columbia, Canada | -Reliability analysis was conducted for a range of values for design inputs (such as operating speed, horizontal curve, lateral clearance etc) | i.) Investigation of the link between road collisions and $P_{nc}$ for the admission of $P_{nc}$ into traditional benefit–cost analysis<br>ii.) Establishment of more reliable probability distributions of design inputs |
| Abia, Sonny D. | 2010 | Application of Reliability Analysis to Highway Design Problems: Superelevation (e) Design, Left Turn Bay Design-Safety Evaluation and Effect of Variation of Peak Hour Volumes on Intersection Signal Delay Performance | - First Order Probabilistic Analysis<br>- Design Application<br>- Model Formulation | i.) development of an intelligent signal system that can allocate green time to only the vehicles present at the intersection will eliminate the unused green time in any phase and minimize overall delay at signalized intersection |
| Ismail, K., and Sayed, T. | 2009 | Risk-Based Framework for Accommodating Uncertainty in Highway Geometric Design | - Defining the validity domain of the code,<br>- Selection of sample design cases from the specified range of the design inputs.<br>- Selection of a target reliability index $\beta_t$.<br>- Reliability analysis for the design cases to find the corresponding design safety levels.<br>- Select calibration factors that will minimize the scatter of the reliability indices around the target value. | i.) Determination of acceptable design safety levels and establishing statistical distributions for design inputs<br>ii.) Quantifying randomness in design inputs by means of statistical distributions should receive more focus |
| Sarhan, M., and Hassan, Y. | 2008 | Three-dimensional, Probabilistic Roadway Design: Sight Distance application | -Determination of available and required sight distance using sight distance evaluation system (SDES)<br>-Calculation of available and required sight distance using probability approach (Monte Carlos Simulation)<br>-Estimation of the probability of hazard using SDES | i.) Investigation of the significance of the different values of probability of hazard (POH) in terms of safety implications. |

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| El Koury, J., and Hobeika, A. G. | 2007 | Assessing the Risk in the Design of Passing Sight Distances | - Collecting field data on real passing maneuvers<br>- Computer simulation using ARENA The computer simulation monitors the movement of three vehicles in a passing maneuver | i.) Conducting a trade-off analysis between the level of service, length of the passing sight distance and safety risk measure using the TWOPASS software<br>ii.) Testing various PSD lengths to note the variations in the delay time of the traffic stream (PTSF). |
| Richl, L., and Sayed, T. | 2006 | Evaluating the Safety Risk of Narrow Medians Using Reliability Analysis. | - Computation of probability of noncompliance for available sight distances for given horizontal radii<br>-Calculation of probability of failure using RELAN software | i.) Establishment of link between the probability of noncompliance and the quantification of safety using collision frequency |
| Tomás Echaveguren, Marcelo Bustos, and Hernán de Solminihac | 2005 | Assessment of Horizontal Curves of an Existing Road using Reliability Concepts | - Analysis of conceptual elements to be included in the proposed methodology for the estimation of a margin of safety<br>- Formulation of the proposed methodology<br>- Application of the methodology to a case study | i.) consideration of rollover effect in dynamic stability model, which is typical of heavy vehicles to widen the application field of the methodology.<br>ii.) Analysis of the effect of speed limitation in curves over operating speed to include it as an action to reduce failure probability.<br>iii.) Study on the failure probability admitted by a specific group of drivers to objectively compare reliability of design and existing curves. |
| Easa, S. M. | 2000 | Reliability Approach to Intersection Sight Distance Design | - First order probabilistic analysis (means, variances and correlations of the component design variables)<br>- Reliability analysis of the three cases of AASHTO (no control, yield control and stop control). | i.) Establishment of a database that will include the variability of various design variables which will address different highway classes and provide necessary data for routine application of reliability method and development of reliability standard values. |

**Source: The Author**

**Table 2:** Summary of Highway Geometric Design Elements Included in Previous Reliability Research

| Design Parameters | Previous Research |
|---|---|
| Stopping Sight Distance | Gargoum *et al*., (2018), César de, *et al*., (2017), Santos Berbel, (2017), Castro, *et al*., (2016), Ahmed *et al.,* (2016), Altaf & Said (2015), De Santos-Berbel & Castro (2015), Sarhan & Hassan (2008) |
| Passing Sight Distance | LIorca *et al*., (2014), El Khoury and Hobeika (2007) |
| Horizontal Curve Design | Dhahir, & Hassan (2019), Rajbongshi & Kalita (2018), Hamid *et al*. (2017), Essa *et al*., (2016), Dhahir & Hassan (2016), Shin & Lee (2015, 2013), Richl and Sayed (2006) |
| Vertical Curve Design | Ismail & Sayed (2009). |
| Basic Number of Lanes | Musunuru & Porter (2014) |
| Entrance Ramp Terminals | |
| Middle Ordinate | Mohamed *et al*., (2014) |
| Grade | Wang *et al*., (2018) |

**Source: The Author**

In summary, reliability analysis has been successfully applied in geometric design research to assess design standard and quantify the probability that design decisions will perform as intended on a consistent basis (e.g., user-to-user, hour-to-hour, day-to-day, year-to-year). The random input variables have been assumed to follow selected probability density distributions, yet no empirical data were used to generate these distributions in majority of the reviewed studies. To validate the usefulness of the reliability approach, real-world data should be used (Anusha, et al., 2015). Table 1 provides a summary of design criteria that have been included in the previous reliability research reviewed in this section.

## 5.0 Discussion

Several researchers have noted that existing design guides provide a deterministic approach for design requirements; they use conservative percentile values for uncertain design inputs to account for uncertainty. These conservative percentile values are not based on safety and lead to designs with unknown safety levels (Ismail and Sayed, 2009, 2010).

Geometric design elements depend on many parameters, such as speed, acceleration, perception-reaction time, deceleration etc. knowledge about these parameters is imperfect, since they are stochastic and show a high variability among drivers, traffic conditions, or geographical locations. The problem with the traditional approach, based on the selection of conservative percentiles, is that it may result in the definition of potentially too conservative design standards. As well, the deterministic approach provides no information of the consequences of a deviation from design standards (LIorca, *et al*., 2014).

Alternative approach to account for uncertainty in the geometric design process is reliability analysis. This approach is based on the limit state design procedure and accounts for the variability of design parameters, considering them as stochastic variables defined by their probability distributions rather than single values. Different researchers have reported the application of reliability in highway geometric design elements. Their results showed that the design parameters that influence design criteria and decisions in highway geometric design have variability and uncertainty in both time and space. The applications of these reliability methodologies have demonstrated how to explicitly consider the range of expected design, operational, and/or safety performance to inform design decisions. The resulting performance-based process for establishing design criteria would allow designers to consider and balance the accommodation of driver and vehicle operating characteristics, safety, design, and construction costs in any given situation.

## 6.0 Future Research Areas

Understanding the probability distribution of random input parameters such as operating speed, braking deceleration, and side friction factor is still marginal; hence further studies on the probability distributions of the input parameters needs to be fully investigated.

Code calibration considering all possible non-compliance modes of geometric elements of highways (e.g. limited sight distance, vehicle skidding, rolling over etc.) need to be studied and the establishment of a

link between the probabilities of non-compliance and other safety measures, such as crash data or traffic conflicts.
Based on the above discussion, it is apparent that most applications of reliability analysis in geometric design in the previous research focused on evaluating one particular design feature with the probability of non-compliance representing one failure mode with suggestion for future highway design. There arises the need to apply system reliability analysis on highway elements that are subject to more than one failure mode and the development of a more accurate operating speed prediction models that will incorporate different geometric elements and consider all highway classes with their effects on traffic accident.

**7.0 Conclusion**

This paper reviewed the concept of reliability-based analysis of highway geometric elements. Probability of non-compliance was assessed for selected design standard with variabilities in their design input parameters, including stopping sight distance, passing sight distance, intersection sight distance, horizontal curve design, vertical curve design, number of lanes on freeways, highway grade length and design guide calibration. The methodologies outlined in this paper will equip highway engineers and designer with more information to reach a higher level of confidence in knowing the reliability of design performance in the presence of realistic and context-specific variabilities. The inherent risk associated with design standard has commonly been linked to a probability of non-compliance. Most of the literature advocated reliability analysis as an effective approach to account for uncertainty in the geometric design process and to evaluate the risk associated with a specific design.

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