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Multi-mode reliability-based design of horizontal curves

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ABSTRACT

Recently, reliability analysis has been advocated as an effective approach to account for uncertainty in the geometric design process and to evaluate the risk associated with a particular design. In this approach, a risk measure (e.g. probability of noncompliance) is calculated to represent the probability that a specific design would not meet standard requirements. The majority of previous applications of reliability analysis in geometric design focused on evaluating the probability of noncompliance for only one mode of noncompliance such as insufficient sight distance. However, in many design situations, more than one mode of noncompliance may be present (e.g. insufficient sight distance and vehicle skidding at horizontal curves). In these situations, utilizing a multi-mode reliability approach that considers more than one failure (noncompliance) mode is required. The main objective of this paper is to demonstrate the application of multi-mode (system) reliability analysis to the design of horizontal curves. The process is demonstrated by a case study of Sea-to-Sky Highway located between Vancouver and Whistler, in southern British Columbia, Canada. Two noncompliance modes were considered: insufficient sight distance and vehicle skidding. The results show the importance of accounting for several noncompliance modes in the reliability model. The system reliability concept could be used in future studies to calibrate the design of various design elements in order to achieve consistent safety levels based on all possible modes of noncompliance.

1. Introduction

Existing highway geometric design guides provide a deterministic approach for design requirements using conservative percentile values of design inputs to account for the uncertainty associated with these inputs. The deterministic approach has two main shortcomings: First, many design parameters, such as perception and brake reaction time (PRT) and operating speed, are stochastic 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 roadside). 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).

Recently, reliability analysis has been advocated as an effective approach to account for uncertainty in the geometric design process and to evaluate the risk associated with a particular 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. Design equations are represented as limit-state functions. The limit-state function (LSF) represents the difference between the supply (S) and the demand (D) (i.e. LSF = S − D). If the demand exceeds the supply (i.e. LSF < 0), the design is considered to have failed or not complied with the design requirements (Richl and Sayed, 2006). 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 noncompliance (P_{nc}) which is associated with a measure of 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 complimentary method of measuring safety in terms of risk (Richl and Sayed, 2006).

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The majority of previous applications of reliability analysis in geometric design focused on evaluating one particular design criterion (e.g. sight distance) with the probability of noncompliance representing one failure (noncompliance) mode (e.g. available sight distance is less than required sight distance). The main contribution of this paper is 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 noncompliance of a highway element to incorporate all noncompliance modes. As an example, the study considers the design of horizontal curves with limited sight distance due to the presence of median and/or side barriers. Two noncompliance modes can be identified for the horizontal curve: (1) insufficient sight distance due to the presence of median and/or side barriers; and (2) vehicle skidding due to the centrifugal force affecting moving vehicles on horizontal curves. The paper provides a procedure to estimate the lateral position of median or side barriers that lead to consistent system P_{nc} considering the two noncompliance modes. The paper also investigated the difference in results if the analysis considers only one mode of noncompliance. The process is demonstrated by a case study of Sea-to-Sky Highway located between Vancouver and Whistler, in southern British Columbia, Canada. In this case study, five cases (i.e. 5 horizontal curve segments), with constrained alignment and limited sight distance (due to median and/or roadside barriers) were selected for the system reliability analysis.

2. Previous work

Several studies used reliability analysis in transportation engineering applications. Ben-Akiva et al. (1985) proposed a probabilistic and cost-based highway design. Hirsh et al. (1986) presented an alternative approach to geometric design of highways in which sensitivity to the stochastic nature of the various factors involved in the design process and utilization of their distribution are used in calculating design values (Hirsh et al., 1986). Faghiri and Demetsky (1988) used a probabilistic approach to evaluate the limitation in sight distance at road–railway grade crossings. Easa (1993) proposed a probabilistic method for the design of the inter-green interval at signalized intersections. Easa (1994) proposed a reliability-based design of sight distance at railroad grade crossings. Easa (2000) applied the mean value first order second moment reliability method (MVFOSM) in order to evaluate sight distance at intersections. Navin (1990) proposed a model for geometric design using partial safety factors. The probability of a design that does not meet standard requirement was termed probability of noncompliance (P_{nc}) instead of the traditional term probability of failure used in the area of structural design, which is irrelevant to highway geometric design (Navin, 1990). Navin (1992) proposed a method to estimate the margin of safety and reliability index for isolated highway components. The stopping sight distance is used to demonstrate the method (Navin, 1992).

Echaveguren et al. (2005) proposed a methodology based on the reliability theory to determine the margin of safety of an existing horizontal curve. Richl and Sayed (2006) applied First Order Reliability Method (FORM) to evaluate the safety risk of narrow medians combined with tight horizontal curves. Khoury and Hobeika (2007) used Monte Carlo simulation to estimate the risk level of passing maneuvers which was defined as the probability of inadequate passing sight distance multiplied by the consequence of a collision. Sarhan and Hassan (2008) calculated the probability of three-dimension sight distance, on overlapped horizontal and vertical curves, using Monte Carlo simulation.

Ismail and Sayed (2009) introduced a general framework for calibrating standard design models and determining target value of design safety. Ismail and Sayed (2010) investigated, through case studies, the safety implications of sight distance limitation on road segments, and the risk associated with deviation from standards, and the risk variation among road segments. Ibrahim and Sayed (2011) incorporated a reliability-based quantitative risk measure in safety performance functions. Ismail and Sayed (2012) presented a decision mechanism that enables the efficient use of available right-of-way for new highway construction with restricted sight distance to minimize the overall risk of the design. Ibrahim et al. (2012) presented a methodology to select a suitable combination of cross-section elements with restricted sight distance to yield reduced collisions and consistent risk levels. Hussein et al. (2014) investigated the calibration of geometric design models to yield consistent safety (risk) levels, and provided calibrated design charts for the middle ordinate distance at different probability of non-compliance levels. Llorca et al. (2014) developed a reliability analysis for passing sight distance based on observation of maneuvers in a sample of Spanish two--lane roads (Llorca et al., 2014)

Himes and Donnell (2014) established a probabilistic approach to the design of horizontal curves and compared the results with current design criteria. The effects of wet pavements and tire characteristics for passenger cars and heavy trucks were considered. Musunuru and Porter (2014) applied reliability analysis to estimate the probability distribution of operational performance associated with decisions made to achieve a design level of service (LOS) for number of lanes on a freeway. Osama et al. (2016) used a 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 at signalized intersection in Vancouver, BC (Osama et al., 2016).

You et al. (2012) conducted a comparative study using different performance functions for calculating the probability of vehicle failure modes (skidding and rollover) at horizontal curves. The selected performance functions, representing different modes of failure, were analyzed separately and resulted in a different probability of failure for each one. You and Sun (2013) established a dynamic simulation model, considering three-dimensional alignment, for reliability analysis of vehicle stability on the combined horizontal and vertical curve. Shin and Lee (2014) presented a reliability-based analysis to assess vehicle safety on horizontal curves based on vehicle dynamics, mainly focusing on windy environments.

3. Methodology

3.1. Reliability theory

The term reliability usually refers to the complement of the failure probability (Eq. (1)). In the reliability analysis, the failure event is not necessarily a structural collapse. Rather, the term probability of failure represents the probability of undesired event exceeding a certain threshold. In road design, researchers have proposed the use of the probability of non-compliance “” to label the probability of a design that does not meet standard.

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

The reliability problem has two components: random variables that describe the uncertainty and one or more limit-state functions that define the failure mode(s). If the problem has only one limit-state function, then the problem is referred to as a component reliability problem. Otherwise, it is a system (multi-mode) reliability problem. The first step is defining a limit state function(s); denoted by $g(x)$; which defines what is considered to be noncompliance where x is a vector of random input variables (Haukaas, 2012c). Generally, the limit state function is represented as a balance between supply and demand. In road design, supply can be