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Vulnerability assessment for the hazards of crosswinds when vehicles cross a bridge deck

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ABSTRACT

A new procedure to assess the crosswind hazard of operating a vehicle over a bridge deck has been developed using a probabilistic approach that utilizes long-term wind data at bridge sites as well as the aerodynamic properties of bridge decks and vehicles. The proposed procedure for safety assessment considers the probabilities of two accident types: sideslip and overturning. The vulnerability of vehicles to crosswinds is represented by the number of days for traffic control that would be required to secure vehicle safety over a period of one year. The distribution of wind speed over a bridge deck was estimated from a section model wind tunnel test. A sea-crossing bridge was selected as an example, and a series of case studies were performed to identify the influential factors affecting vehicle vulnerability to crosswinds: vehicle type and loaded weight, the position of a running vehicle over a bridge deck, the bridge alignment relative to the dominant wind direction, and vehicle speed.

1. Introduction

Strong gusts of wind can reduce vehicle safety when crossing a wind-exposed structure such as a bridge. As the number of long-span bridges increases throughout the world, this issue increases in importance, and many wind-induced vehicle accidents have been reported in past decades (Baker and Reynolds, 1992; Zhu et al., 2012). In order to prevent these accidents, the installation of windscreens or traffic-control actions have been proposed for protecting vehicles from high-speed winds. These measures can effectively mitigate the vulnerability of vehicle safety while crossing a bridge under a crosswind. However, excessive designs for windscreens or overly complicated traffic control guidelines can result in a negative effect in terms of aerodynamic stability and excessive cost/benefit ratios. Hence, a vulnerability assessment that adequately considers the surrounding environmental or structural shapes of bridges is necessary.

Extensive studies for the simulation of vehicle movements and an evaluation of wind-induced accident risks for given conditions have been conducted. Baker (1986, 1987, 1991a, 1991b, 1991c) constructed an analytical framework that can be used to evaluate aerodynamic forces and vehicle motion. He performed several wind tunnel tests to examine the aerodynamic forces that act on vehicles according to wind direction, and introduced a simplified safety analysis method. Xu and Guo (2003) and Chen and Cai (2004) also presented a framework for computer simulation that considers wind-bridge-vehicle interactions. They performed time-domain analysis to evaluate vehicle motion and estimated accident-causing wind speeds for various vehicle speeds. Similarly, Batista and Perkovič (2014) proposed a simple static analysis method to estimate critical perpendicular wind speeds.

In order to propose guidelines for the decision-making process with respect to the need for windscreens, Kwon et al. (2011) and Kim et al. (2011) presented a method for assessing the frequency of exposure to hazardous crosswinds. They estimated the expected days for vehicle accidents through stochastic analysis using long-term wind data, and estimated the total expected cost induced by accidents. Using this method, decisions for the construction of windscreens can be justified from an economic perspective. However, the method focused on overall assessment strategy, rather than considering details such as the positions of running vehicles over a bridge deck. Therefore, it is necessary to use wind details and structural conditions to develop a vulnerability assessment method for the operation of vehicles over a bridge deck that is exposed to frequent lateral winds.

This study proposes a new assessment procedure for evaluating the crosswind hazards of a bridge by implementing a section-model wind-tunnel testing and a probabilistic long-term wind analysis at a particular bridge site by considering four affecting factors: 1) vehicle type, 2) loading lane, 3) bridge direction, and 4) vehicle speed. As a measure of the vulnerability of vehicles to crosswind hazards, a frequency of traffic control that will secure vehicle safety criteria is proposed. The proposed procedure was

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applied to an example bridge and a series of parameter studies were conducted to estimate the factors governing the vulnerability of vehicles to crosswind hazards.

2. Proposed assessment procedure

A probabilistic procedure is proposed for the assessment of vehicle safety in crosswind. The basic concept involves the use of the critical wind speeds for a target vehicle and long-term wind data measured at a particular bridge site. The final output from this procedure is the number of days needed for traffic control, N_C, which is the expected number of days per year that the maximum wind speed will exceed the critical wind level. Using N_C as a risk index, the vulnerability of a bridge for vehicle safety can be evaluated. This index provides intuitive information on the degree of vehicle safety.

The proposed procedure consists of three steps: (1) estimation of a cumulative distribution function for wind data, (2) estimation of critical wind speed, and, (3) estimation of the number of days for traffic control (N_C). The procedure is illustrated in Fig. 1. With this procedure, the critical wind speeds of vehicles and the cumulative distribution functions of wind data are estimated for 16 directions. This is done to consider the variations in the critical wind speed of a vehicle according to wind direction. In fact, the most vulnerable wind direction generally is not 90° because the vehicle is also subject to its own speed. Therefore, considering all wind directions is desirable for a reasonable assessment.

Also, a wind tunnel test is performed to evaluate the effect of bridge girders on the wind speed over the deck. Undisturbed oncoming wind speeds and the wind speeds over traffic lanes are different due to the flow interruption by bluff girders, and the ratio between these two wind speeds must be considered. This ratio is referred to as the wind speed modification factor, and it is measured via wind tunnel testing. Further details of each step are introduced in the following sections.

2.1. Step 1. estimating the cumulative distribution function of wind data

The aim of step 1 is to estimate the cumulative distribution function for 16 directions with consideration paid to the effect that girders would exert on wind speed. The probability distribution can be estimated by using a specific probability distribution model. In the present study, the wind data provided from weather stations is in the form of the daily maximum value, and, therefore, a Generalized Extreme Value (GEV) distribution model is used. This probability model combines three typical extreme value distribution models: Gumbel, Fréchet and Weibull distributions. The equation for the cumulative distribution function for a GEV distribution model is expressed as follows.

$$F(X < x;\, \mu,\, \sigma,\, \xi) = \exp\left\{-\left[1 + \xi\frac{x - \mu}{\sigma}\right]^{-1/\xi}\right\} \tag{1}$$

where σ is the scale parameter, μ is the location parameter, and ξ is the shape parameter. These three parameters can be estimated for 16 wind directions by applying the maximum likelihood estimation (Coles, 2001).

Prior to estimating the parameters, wind speed data should be modified using a correction factor and wind speed modification factors in order to consider the differences in wind speeds between a weather station and traffic lanes.

First, a correction factor is calculated, which is the ratio between wind speeds at a weather station and at a bridge site with consideration given to the differences in terrain roughness and elevation. Korean Society of Civil Engineers (2006) proposes a correction factor as follows:

$$\begin{aligned} C &= \left(\frac{z_{G1}}{z_1}\right)^{\alpha 1} \cdot \left(\frac{z_2}{z_{G2}}\right)^{\alpha 2}, \qquad z_2 \geq z_b \\ &= \left(\frac{z_{G1}}{z_1}\right)^{\alpha 1} \cdot \left(\frac{z_b}{z_{G2}}\right)^{\alpha 2}, \qquad z_2 < z_b \end{aligned} \tag{2}$$

where subscript 1 refers to the weather station and subscript 2 refers to the bridge site; α is the exponent that governs the shape of the wind profile; z is the height of the measurement point; z_G is the gradient height of the wind profile, and z_b is the minimum height.

In addition, we can estimate the wind speed modification factor, R_v, which refers to the ratio of the mean wind speed, V, at a certain location over a bridge deck to that of the undisturbed oncoming wind speed, V_∞, as shown in Eq. (3) and Fig. 2. With this

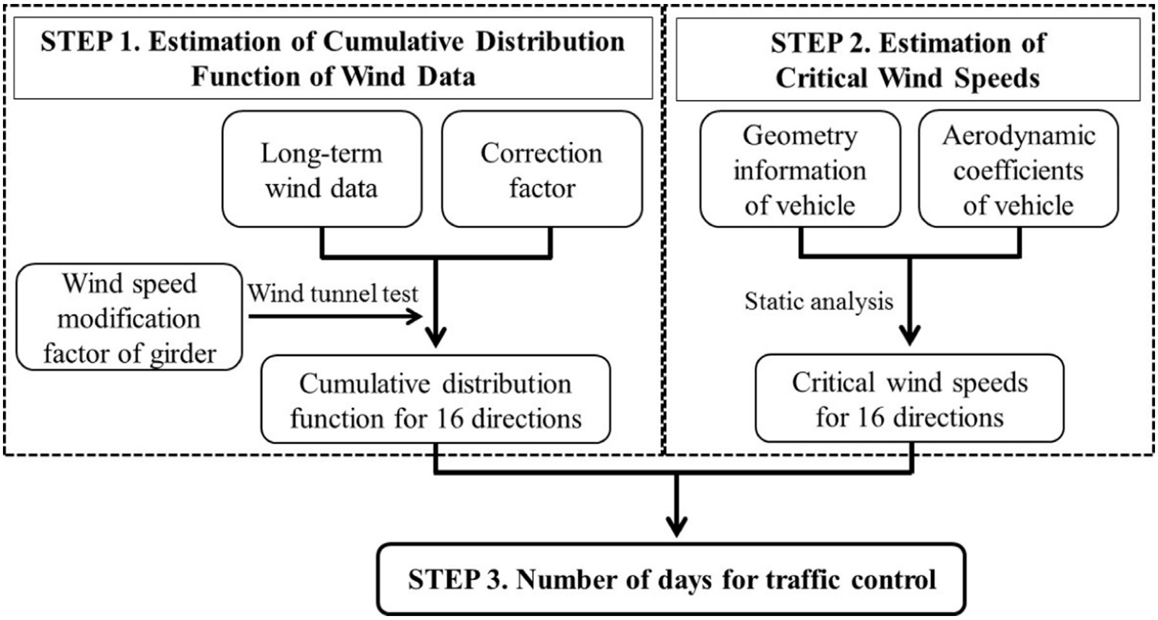

Fig. 1. Diagram of assessment procedure.