Ride comfort assessment of road vehicles on a long-span truss girder suspension bridge under crosswinds

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SUMMARY:
The aerodynamic coefficients of three typical road vehicles (truck, motor bus and articulated lorry) on a truss girder were determined in the CSU-1 Wind Tunnel at Central South University by force balance measurements. The dynamic response of road vehicles on a truss girder suspension bridge with a main span of 965 m was numerically calculated using the coupled analysis of wind–vehicle–bridge system and measured aerodynamic coefficients at different wind yaw angles. The ride comfort of road vehicles in the vertical and lateral directions was then evaluated according to the ISO 2631 standard. It was found that he aerodynamic coefficients of road vehicles are sensitive not only to the shape of the bridge superstructure but also to the type of wind barrier. Wind barriers can reduce the road vehicle's aerodynamic loadings at high wind yaw angles. Wind barriers can also improve the ride comfort of road vehicles on the long-span truss girder suspension bridge.

Keywords: road vehicle, truss girder suspension bridge, aerodynamic coefficient, wind-vehicle-bridge system, ride comfort

1. GENERAL INSTRUCTIONS

The ride comfort of road vehicles running on long-span bridges under crosswinds is of increasing concern to the public (Xu and Guo, 2004). However, very few investigations have been carried out to assess the ride comfort of road vehicles running on long-span truss girder suspension bridges, compared with that on flat ground or long-span bridges with box girder (Xue et al., 2020).

This paper presents the wind tunnel results of aerodynamic coefficients of typical road vehicles on a truss girder with different types of wind barriers. The ride comfort of road vehicles on a long-span truss girder suspension bridge is then numerically evaluated using dynamic responses of the coupled wind–vehicle–bridge system.

2. THEORETICAL BACKGROUND

2.1 Coupled analysis of wind-vehicle-bridge system

The motion equation of the wind-vehicle-bridge coupled system is expressed in the following form.

$$\begin{bmatrix} \boldsymbol{M_b} & 0 \\ 0 & \boldsymbol{M_v} \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{u}}_{\boldsymbol{b}} \\ \ddot{\boldsymbol{v}}_{\boldsymbol{v}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{C_b} & 0 \\ 0 & \boldsymbol{C_v} \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{u}}_{\boldsymbol{b}} \\ \dot{\boldsymbol{v}}_{\boldsymbol{v}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{K_b} & 0 \\ 0 & \boldsymbol{K_v} \end{bmatrix} \begin{bmatrix} \boldsymbol{u_b} \\ \boldsymbol{v_v} \end{bmatrix} = \begin{bmatrix} \boldsymbol{F_{bg}} + \boldsymbol{F_{bv}} + \boldsymbol{F_{bst}} + \boldsymbol{F_{bbu}} + \boldsymbol{F_{bse}} \\ \boldsymbol{F_{vg}} + \boldsymbol{F_{vb}} + \boldsymbol{F_{vst}} \end{bmatrix} \tag{1}$$

where $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ denote the mass, damping and stiffness matrices, respectively; $\boldsymbol{u}$ represents the displacement vector; subscripts v and b denote the vehicle and bridge, respectively; $\boldsymbol{F_{bg}}$, $\boldsymbol{F_{bv}}$, $\boldsymbol{F_{bst}}$, $\boldsymbol{F_{bbu}}$ and $\boldsymbol{F_{bse}}$ are the self-weight of the bridge, the wheel-bridge contact force acting on the bridge, the static wind force, buffeting force and self-excited force, respectively; $\boldsymbol{F_{vg}}$, $\boldsymbol{F_{vb}}$ and $\boldsymbol{F_{vst}}$ are the self-weight of the vehicle, the wheel-bridge contact force acting on the vehicle and the quasi-static wind forces, respectively.

2.2 Definition of aerodynamic coefficient of road vehicles

The wind forces on a road vehicle include side force F_S, lift force F_L, drag force F_D, pitching moment M_P, yawing moment M_Y and rolling moment M_R. The definitions and positive directions of the forces that refer to the center of gravity of the unloaded vehicle are the same as those used by Xue et al. (2020). The aerodynamic coefficients are the functions of wind yaw angle and are defined by the following equations:

$$C_S(\psi) = \frac{F_S}{0.5\rho U_R^2 A},\ C_L(\psi) = \frac{F_L}{0.5\rho U_R^2 A},\ C_D(\psi) = \frac{F_D}{0.5\rho U_R^2 A}, \tag{2}$$

$$C_P(\psi) = \frac{M_P}{0.5\rho U_R^2 A h_v}, C_Y(\psi) = \frac{M_Y}{0.5\rho U_R^2 A h_v}, C_R(\psi) = \frac{M_R}{0.5\rho U_R^2 A h_v} \tag{3}$$

where ρ is the air density. ψ represents the yaw angle. U_R is reference wind velocity relative to the vehicle. A is the frontal project area of a road vehicle, and h_v represents the height of the road vehicle's gravity center above the ground or bridge surface.

3. AERODYNAMIC COEFFICIENTS OF VEHICLES ON BRIDGE

3.1 Vehicle and bridge models

The investigated long-span bridge is a single-span steel truss girder suspension bridge with a main span of 965m and four traffic lanes, as shown in Fig.1. Three typical road vehicle models were examined in this study: truck, motor bus and articulated lorry. The geometric scale of the road vehicle and truss girder bridge in the wind tunnel was set as 1:50. The dimensions of the truck vehicle and sectional bridge models were then determined, and they are illustrated in Fig. 1. The height of the road vehicle gravity center above the bridge surface (h_v) and frontal project of the vehicle model (A) are 3 cm and 22 cm^2, respectively.

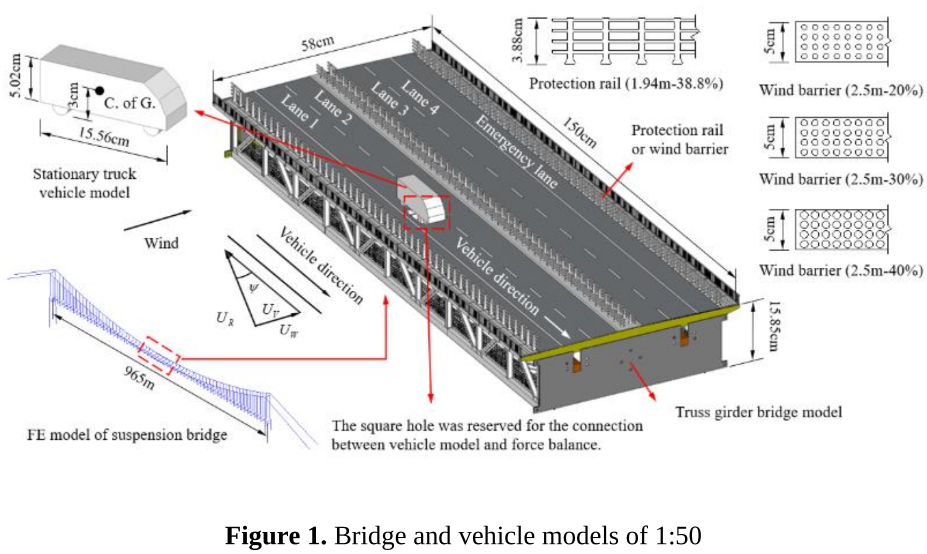

Figure 1. Bridge and vehicle models of 1:50

3.2 Measurement system

The sectional model tests in a smooth flow were carried out in the high-speed test section of the CSU-1 wind tunnel at Central South University, China. Experimental models and force balance mounted in the CSU-1 wind tunnel are shown in Fig. 2. A high-frequency force balance of six components (Mini 40, ATI Corporation) was used to measure aerodynamic forces on the stationary road vehicle model on the sectional truss girder bridge model. The force balance connecting the road vehicle model was positioned underneath the bridge deck surface via an empty square hole (as shown in Fig. 1), and it was also connected to the self-made aluminum alloy test stand through a longitudinal high-strength beam. The sampling frequency of force balance was 2000 Hz, and the number of sampling points was 480000. Two compensation model was installed on both sides to effectively reduce the end effects. The whole test stand was fixed to the turntable by weights, and the wind yaw angles from 0° to 90° with an interval of 15° were adjusted by the turntable rotation. The mean wind speed was 20 m/s, and the Reynolds number was 6.73×10^4 based on the vehicle height of 0.0502m.

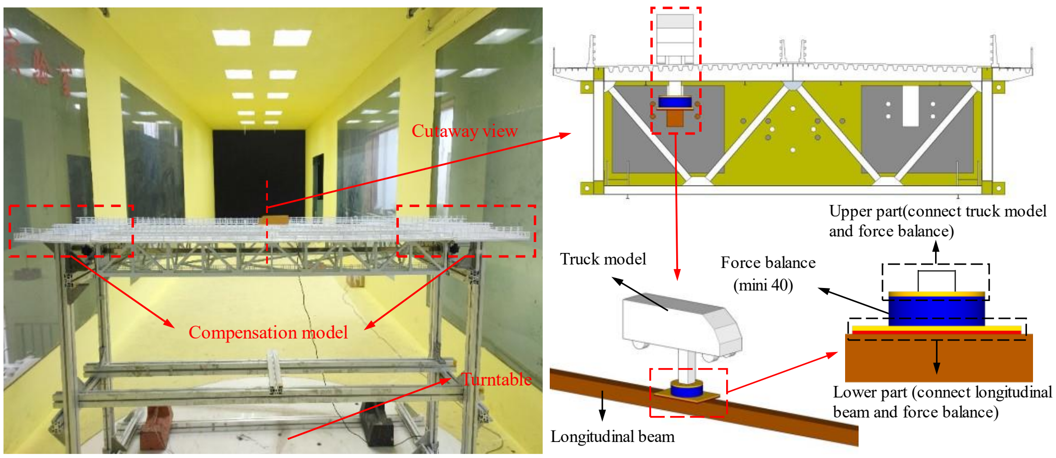

Figure 2. Experimental models and force balance mounted in CSU-1 wind tunnel.

3.3 Wind tunnel test results

Fig. 3 shows the side force, lift and rolling moment coefficients of the road vehicle on the truss girder obtained from the present tests and Xue et al.'s (2020) tests on a solid-rectangular-side girder with protection rail, in which the other three aerodynamic coefficients were omitted due to space limitations. The road vehicle's force coefficients on the truss girder are different from those on the solid-rectangular-side girder. The wind barrier can reduce the road vehicle's aerodynamic loadings at high wind yaw angles.

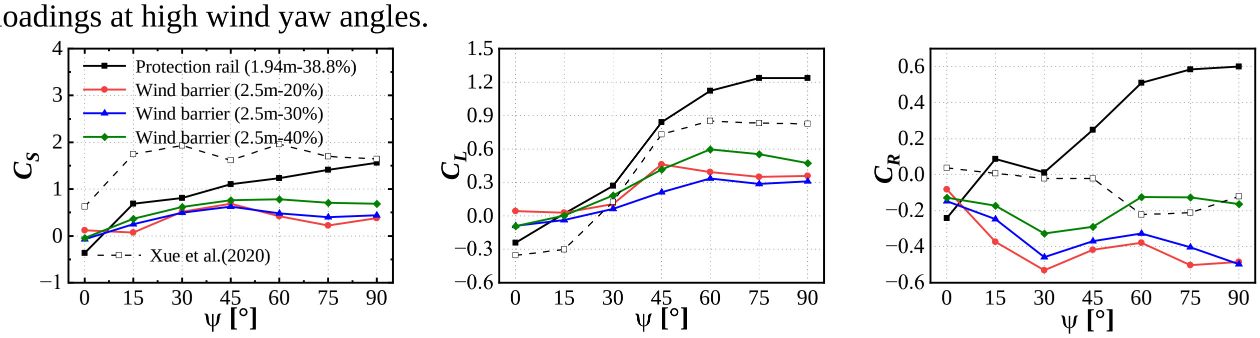

Figure 3. Side force, lift and rolling moment coefficients of road vehicle on truss girder.

4. RESULTS AND DISCUSSIONS

The mean wind speed and vehicle speed are, respectively 20 m/s and 80 km/h in the following case study. Fig.4 shows the ride comfort of a truck vehicle on a long-span truss girder suspension bridge at the driver seat for protection rail and different wind barriers, computed using acceleration and its RMS. The duration of the vehicle on the bridge is 48.25 s, but only the middle duration of 30 s (10-40 s) was analyzed here to decrease the calculation errors. The overall vibration total value (OVTV) from ISO 2631-1, 1997 was adopted for the ride comfort evaluation using 8 types of vibration (i.e. vertical and lateral vibrations at all three supporting surfaces, pitching and rolling vibrations at the seat location.). The wind barrier can improve the ride comfort of a road vehicle on the long-span truss girder suspension bridge.

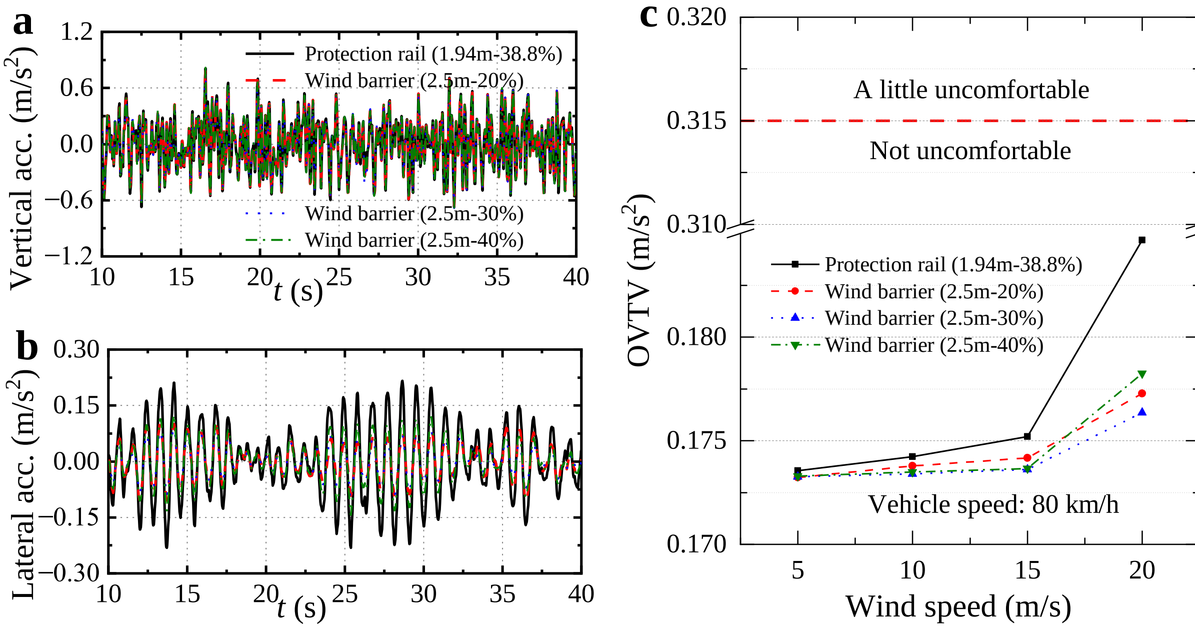

Figure 4. Ride comfort of truck vehicle on long-span truss girder suspension bridge at driver seat for different wind barriers. (a) Vertical acceleration. (b) Lateral acceleration. (c) OVTV.

5. CONCLUSIONS

The aerodynamic loadings of road vehicles are sensitive not only to the shape of the bridge superstructure but also to the type of wind barrier. The wind barrier can reduce the road vehicle's aerodynamic loadings at high wind yaw angles. It can also improve the ride comfort of a road vehicle on the long-span truss girder suspension bridge.

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