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Wind tunnel tests for mean wind loads on road vehicles

Xianzhi Liu [a], Yan Han [b,*], C.S. Cai [a,*], Marc Levitan [c], Dimitris Nikitopoulos [d]

[a] Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, LA 70803, USA
[b] School of Civil Engineering and Architecture, Changsha University of Science & Technology, Changsha 410004, China
[c] Formerly Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, LA 70803, USA
[d] Department of Mechanical Engineering, Louisiana State University, Baton Rouge, LA 70803, USA

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ABSTRACT

Evaluation of the safety and performance of road vehicles in windy conditions requires accurate descriptions of wind loads on vehicles. However, the research in this area has been far from comprehensive. In the present study, wind tunnel tests were carried out on various vehicle models under different flow conditions, including smooth flow, turbulent flow, and boundary layer flow. The lift, drag, and side forces, and the pitching, rolling, and yawing moments for these vehicle models were measured and analyzed to interpret the effects of flow conditions on these forces. The results were also compared with other wind tunnel tests results published in the literature. The experimental results reveal that the flow conditions did have effects on the variation of wind loads; the smooth flow case is a conservative estimation in general. The height of the center of gravity of the vehicle will significantly affect the results of the aerodynamic moment coefficients, which causes the significant difference between different studies. The results under the boundary layer flow also provide a good reference guide for the context of applications such as stability problem of still vehicles under extreme wind events.

1. Introduction

Economic and social developments result in a tremendous increase of the traffic volume over roads and bridges. In the scenario of land falling hurricanes or severe local storms, strong winds may pose threats to the safety of the motorists and vehicles on the road or the bridge. A large number of wind-induced accidents have been reported all around the world (Baker and Reynolds, 1992). In order to evaluate the accident risk and stability for road vehicles under wind actions, the aerodynamic load is among the essential information needed to carry out the evaluation. Various approaches can be adopted to evaluate the wind loads on vehicles. Due to the difficulties in computational fluid dynamics and the expense involved in full-scale measurements, a wind tunnel study is probably the most convenient and reliable approach to investigate this problem.

Data of aerodynamic loads on a double deck bus provided by Garry (1984) were quoted by Baker (1986), who performed wind tunnel tests with a 1/12-scaled model of a Leyland Altantaean bus. It was noted that the effects of atmospheric turbulence and model/ground relative motion were not modeled for the tests, and the accuracy of these results were in doubt. In order to assess the effect of high winds on traffic in general, several standard types of vehicles were defined in a later study by Baker (1987), including cars, coaches, large rigid vans, and articulated tractor–trailers. In both of the above studies, the six aerodynamic coefficients were given in a simplified formula format. While comparisons of the Large Van category and Leyland Altantean Bus category in these two different studies show that they have very similar geometric parameters, the aerodynamic loads have significant difference. There are insufficient further details given in these reports that may be held accountable for this difference. In order to study the behavior of high-side vehicles in cross wind, Baker (1988) carried out a wind tunnel study on a 1/25 scale articulated-lorry model, using a low turbulence flow and a static setup (neither moving ground nor atmospheric turbulence effect were simulated). The test results for the aerodynamic force coefficients were fitted with simple analytical curves. The comparison of this formulation to the earlier mentioned study (Baker 1987) show close values and similar trends in some cases, but also significant difference of magnitudes in other cases. Coleman and Baker (1990) measured the load coefficients of an articulated lorry positioned on the bridge deck model. Their studies showed that the effect of turbulence on the aerodynamic properties of the vehicle was significant. Furthermore, Coleman and Baker (1994) carried out wind tunnel tests to measure the mean and fluctuating values of the aerodynamic force coefficients and surface pressure coefficients on

* Corresponding authors.
E-mail addresses: ce_hanyan@163.com (Y. Han), cscai@lsu.edu (C.S. Cai).

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a 1/50 scale articulated lorry model on a bridge deck and revealed the flow mechanisms involved.

The review of all the previous studies reveals that a scheme of reliable estimation of aerodynamic loads on road vehicles is still far from established. This is due to the complicated nature of the problem related to scaling rules, flow simulation, the effects of local topography and infrastructure, as well as the limitations of wind tunnel technology. This situation will be more complicated when considering vehicles operated on long span bridges due to the interaction between the vehicles and bridge. Chen and Cai (2004); Guo and Xu (2006) demonstrated that for the same wind velocity the risk of vehicle instability is higher if a vehicle is crossing a long span bridge as opposed to traveling on a road. For extending the existing data, Dorigatti et al. (2012) investigated the aerodynamic properties of high sided vehicles over long span bridges by carrying out a series of wind tunnel experiments to measure the aerodynamic forces of three 1:40 scale model vehicles placed on the bridge: a Van, a Bus and a Lorry. Zhu et al. (2012) measured aerodynamic coefficients of four types of road vehicles over a typical bridge deck in low turbulence fields in wind tunnel and investigated the effects of the bridge deck on aerodynamic coefficients. Han et al. (2011, 2013) investigated the aerodynamic characteristics of road vehicles on a bridge by using the CFD method and by carrying out a series of wind tunnel tests considering the interaction of the aerodynamic forces between the road vehicles and the bridge. In their studies, only one type of vehicles is included and the vehicle is simplified for the measurement of pressure distributions.

As responders to the accident, emergency vehicles, such as fire trucks and ambulances, are desired to continue to operate provided that their own safety is not compromised. One of the motivations for this study is the concern over the safety of the emergency vehicles and other high-side vehicles under strong wind conditions on long span bridges. Some studies (Cai and Chen, 2004; Chen and Cai, 2004; Xu and Guo, 2003; Li et al., 2005; Han and Chen, 2007) have made good progress on setting up feasible framework to numerically study the performance of vehicles under wind actions on long span bridges. The success of these analytical approaches no doubt relies upon an accurate description of the aerodynamic loads on the corresponding vehicles. Since aerodynamic force data on emergency vehicles is scarce, and the information on the vehicle geometry and dimensions are often missing, even if some wind tunnel test data are available, making reference to these data inherently causes large uncertainties. In this study, a wind tunnel study was conducted to fill this void and provide necessary information for analytical work.

Section 2 gives the definition of force coefficients for wind loads on vehicles. Section 3 describes the experimental apparatus and measurement techniques. The experimental results and discussions are presented in Section 4. Finally, some conclusions are drawn in Section 5. It is found that the flow conditions did have effects on the variation of wind loads; the smooth flow case is a conservative estimation in general. The height of the center of gravity of the vehicle will significantly affect the results of the aerodynamic moment coefficients, which causes the significant difference between different studies. The results under the boundary layer flow also provide a good reference guide for the context of applications such as stability problem of still vehicles under extreme wind events.

2. Definition of force coefficients for wind loads on vehicles

A coordinate system with the *x*, *y*, and *z* axes as shown in Fig. 1 is adopted for the definition of the aerodynamic forces and moments, following the most frequently used convention. The mean

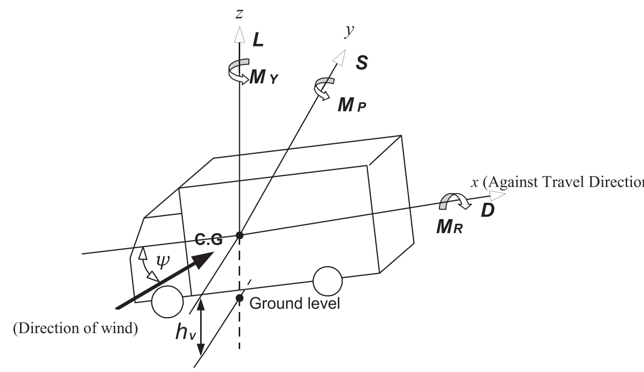

Fig. 1. Sign conventions for aerodynamic forces of the vehicle.

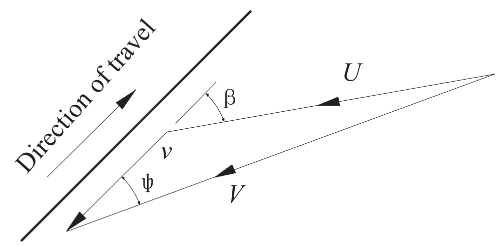

Fig. 2. Velocities and directions.

aerodynamic drag force (D), side force (S), and lift force (L) are in the positive x, y, and z directions, respectively, acting at the center of gravity (CG). The mean aerodynamic rolling moment (M_R), pitching moment (M_P), and yawing moment (M_Y) follow the right-hand screw rule about the x, y, and z axes, respectively. All the mean force coefficients are referred to the frontal area of the vehicle, and the moment coefficients are referred to the frontal area times the height of the CG from the ground, h_v. Mean aerodynamic force and moments coefficients are then defined as:

$$C_S(\psi) = S/0.5\rho V^2 A \tag{1a}$$

$$C_L(\psi) = L/0.5\rho V^2 A \tag{1b}$$

$$C_D(\psi) = D/0.5\rho V^2 A \tag{1c}$$

$$C_P(\psi) = P/0.5\rho V^2 A h_v \tag{1d}$$

$$C_Y(\psi) = Y/0.5\rho V^2 A h_v \tag{1e}$$

$$C_R(\psi) = R/0.5\rho V^2 A h_v \tag{1f}$$

where S, L, D, P, Y and R are the mean side force, lift force, drag force, pitching moment, yawing moment, and rolling moment, with their sign conventions shown in Fig. 1, which are measured by the force balance and averaged over the required time period of 60 s; $C_S(\psi)$, $C_L(\psi)$, $C_D(\psi)$, $C_P(\psi)$, $C_Y(\psi)$ and $C_R(\psi)$ are their corresponding coefficients; ψ is the yaw angle, which can be produced by changing the vehicle speed or changing the wind angle β by rotating the vehicle, as shown in Fig. 2, if no vehicle movement is considered; A is the frontal area of the vehicle; h_v is the distance from the gravity center of the vehicle to the road surface; and V is the relative wind speed to the vehicle as shown in Fig. 2. Meanwhile, in Fig. 2, U is wind velocity, v is the vehicle speed, β is the wind angle between the wind direction and the vehicle direction of travel, and $\beta = \psi$ and $V = U$ in this study since no vehicle movement is considered.