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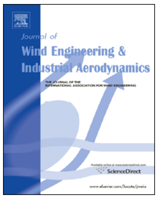

A simple static analysis of moving road vehicle under crosswind

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ABSTRACT

This article is devoted to vehicle safety in the crosswinds. A static model to determine the critical wind speed for overturn-, sideslip- and rotation-type of accidents is considered. The basic equations were defined by assuming that the vehicle moves in a uniform straight line. Explicit formulas for the critical wind speed for all three possible wind-induced accidents are derived to provide the new critical wind speed formulas for rollover and rotation wind-induced accidents. Numerical examples are given and compared to field observations.

1. Introduction

Strong winds affect road transport by forcing reduced speed limits or actual road closings. These measures prevent possible wind-induced traffic accidents; however, the measures may also lead to major economic losses. Therefore, continuous research efforts have aimed to determine the critical wind speed and associated speed limits for vehicles as well as general traffic policies in areas where high winds frequently occur.

One of the first criteria for detecting an incident situation for a vehicle under crosswind was proposed by Emmelman (Emmelman, 1981), who introduced a degree of danger index based on the estimation of vehicle lateral deviation from the driving line during the first 0.8 s after the wind begins to blow. Another criteria was proposed by Baker (Baker, 1986). According to Baker, crosswind accidents may be classified into three types (Fig. 1):

- rollover accidents;
- sideslip accidents;
- rotating accidents.

In the first type of accident, a vehicle is blown over; in the second type, a vehicle is blown sideways for a significant distance; and in the third kind, a vehicle rotates around its vertical axis to a significant degree. The proposed criteria for detecting the risk of a possible accident of one of these types when a vehicle enters a sudden crosswind are

- the contact force reduces to zero within 0.5 s;
- the lateral displacement of the vehicle exceeds 0.5 m within 0.5 s;
- the absolute value of the yaw angle exceeds 11.5° (0.2 rad) within 0.5 s.

Note that Baker assumes that the typical driver reaction time is of the order of 0.2–0.4 s. Thus, he suggests that the driver should not alter the steering angle for 0.5 s to reduce lateral and angular deflection.

The behavior of a vehicle in a crosswind generally is very complex and depends on various factors, such as (Weir, 1982)

- the vehicle characteristics;
- the driving conditions; i.e. speed and the direction of straight line cornering;
- the crosswind characteristics (direction, velocity profile, steady or gusty wind);
- driver reactions.

The above factors included in the study of a vehicle in crosswind depends on the type of research, which affects the complexity of the experimental, analytical model or numerical models (Abe, 2009; Baker, 1988, 1991a,b,c; Blythe, 2008; Canale et al., 1997; Chel et al., 2006; Guo and Xu, 2003; Lemay, 2010; Sterling et al., 2010). Here, we note that while physical laws govern the first three of the above factors, they do not govern driver behavior. The latter may be significant because each driver reacts differently to different driver situations; however, we will not include a driver in the present discussion. [A detailed discussion (and future references) that considers driver reactions and their modeling may be found in Baker (1988), Oraby and Crolla (2001) and Wagner and Wiedemann (2002).]

The main objective of this paper is to determine the critical wind speed that may cause a particular type of Baker's crosswind

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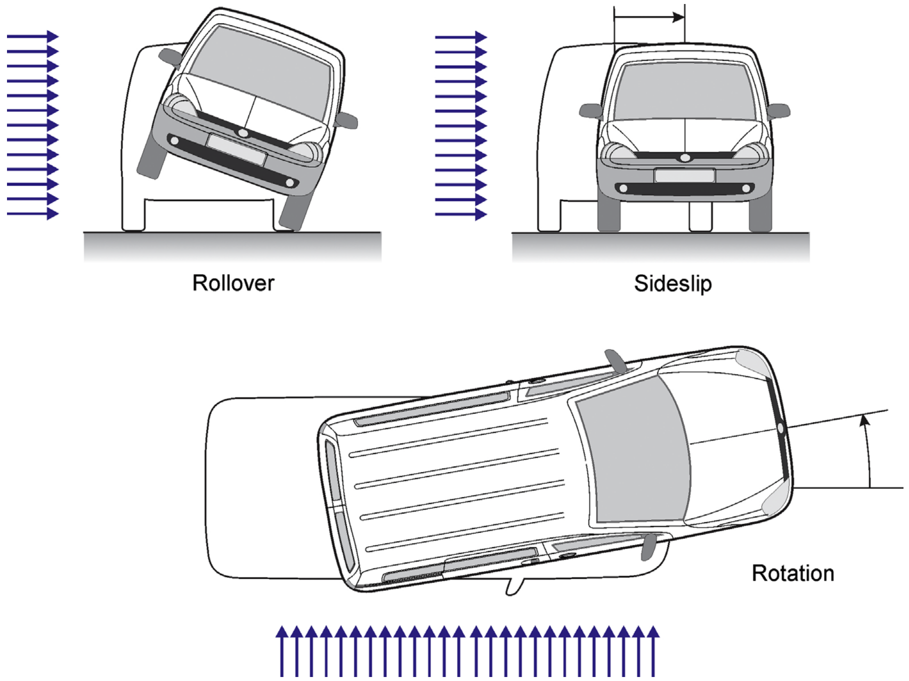

Fig. 1. Vehicle accidents in crosswind according to Baker (Baker, 1986).

accident when Baker's dynamic criteria are replaced with static criteria, which are the following:

- the contact force on a wheel(s) reduces to zero (rollover);
- all wheels reach the friction limit (sideslip);
- one of the vehicle axes reaches the friction limit (rotation).

We will explore the simplest possible vehicle model to identify these situations. Namely, a two-axis vehicle will be considered as a single rigid body with given mass and dimensions. The vehicle model is thus the same as the one used by Baker (Baker, 1986), with the difference being the assumed vehicle motion. While Baker assumes that the vehicle accelerates in a lateral direction and rotates around its vertical axis in the presence of wind, the present approach assumes that the vehicle executes a straight steady motion until one of the incident conditions is reached. This assumption results in the following differences between Baker and the present model. First, the present model does not include the driver reaction time. This omission could be an advantage. As demonstrated by the Baker solution for sideslip- and rotation-type accidents, when the sideslip friction coefficient is small, the vehicle limit speed is roughly inversely proportional to the driver reaction time, which results in large differences in the speed limit for an assumed driver reaction time between Baker's 0.5 s and Emmelman's 0.8 s. The second difference is the model of tire side force used. While Baker assumes that vehicle tire side forces are proportional to the sideslip angle, which is given as the ratio between the vehicle lateral and longitudinal component of velocity for a small angle, we will assume that tire side force is governed by the Coloumb friction law (Gillespie, 1992; Snæbjönsson et al., 2007). This approach is mainly motivated by Lemay's observation (Lemay, 2010), who noted a problem in Baker's approach for rollover accidents because it assumes that the vehicle begins sideslip in the presence of any wind side force. This situation is not observed in reality. Conversely, if a vehicle does not sideslip, tire side forces vanish. Thus, the tires cannot balance a side wind force. We note that both Baker and Lemay assume that that the value of the sideslip angle is the same for all tires; however, the paper will show that this assumption is not necessary because the equilibrium and the constitutive equations of the present model allow the sideslip angle to be different for the front and rear tires.

In what follows, the basic equation for the above-described model will be set up and the critical wind speed formulas will be derived for all three possible types of wind induced accidents. The theoretical consideration is then followed by numerical examples and a description of the field observations. Before proceeding, we note that the derivation of the rollover critical wind speed formula for both windward vehicle wheels losing contact is well known, and its derivation is elementary (Blythe, 2008; Lemay, 2010; Pritchard, 1985; Snæbjönsson et al., 2007). The same can be said about the derivation of the sideslip critical wind speed formula when all vehicle tires reach the friction limit. However, the present model also includes the cases in which only one vehicle wheel loses contact and cases when tires on only one vehicle axis reach the friction limit.

2. Basic equations

2.1. Equilibrium equations

We consider a two-axle vehicle subject to a uniform crosswind that moves in a steady, straight line. To maintain a constant speed and remain on a straight path under the aerodynamic loads produced by wind, friction forces should be generated from the contact between the vehicle wheels and road (see Fig. 2). If a vehicle is treated as a rigid body, the equilibrium conditions of the forces and moment with respect to vehicle center of gravity (COG) yield six equilibrium equations. If we take x-axis to be the driving direction and the z-axis to be directed upward, the equilibrium of forces in coordinate directions x, y and z respectively are

$$-F_D-F_{x1}-F_{x2}-F_{x3}-F_{x4}+i_1(T_1+T_2)+i_2(T_3+T_4)=0 \tag{1}$$

$$F_S-F_{y1}-F_{y2}-F_{y3}-F_{y4}=0 \tag{2}$$

$$-mg+F_L+F_{z1}+F_{z2}+F_{z3}+F_{z4}=0. \tag{3}$$