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Original Research Paper

Research on the horizontal curve's radius under coupling effects of uneven adhesion coefficient and crosswind

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ABSTRACT

In order to study the effects of uneven adhesion coefficient and crosswind on alignment design indexes, a six-axle semi-trailer is selected as the typical vehicle model to investigate the effects of uneven adhesion coefficient caused by superelevation under the condition of rainfall on the truck's lateral stability, quantifying the crosswind using TruckSim. Based on the basic theory of vehicle dynamics, vehicle safety driving model is established. Also, the minimum radius is calculated with the consideration of uneven adhesion coefficient and crosswind. The results show that the effects of uneven adhesion coefficient and crosswind on the truck's lateral stability increase with the increasing of the truck's speed. Truck's lateral slide instability begins to appear when crosswind grade grows up to 9 or above. According to sensitive analysis, speed, rainfall, crosswind, and the interaction of the speed and rainfall have significant influences on the truck's lateral stability. The results quantify the effects of uneven adhesion coefficient and crosswind on truck's lateral stability. The advised index for horizontal curve design control is proposed, which provides a good reference for road safety design and safety protective measures. It can also provide theoretical basis and guidelines for highway safe operation in the windy and rainy areas.

1. Introduction

The traditional design standard of highway engineering only takes safety, economy, easy manipulation, and comfort factors into consideration for the lateral force coefficient, while ignoring the influence of crosswind and uneven road adhesion coefficient caused by rainfall on truck's lateral instability. Recent years, as the global environment deterioration, extreme weather events like strong winds and heavy rain are very frequent. The low technical standards of mountain roads in China and poor stability of trucks can easily lead to truck skidding, rollover, and other severe accidents under the conditions of strong winds and heavy rain. Moreover, the road traffic capacity and service level are greatly reduced (Baker, 1991, 1994; Coleman and Baker, 1992; Pang et al., 2006; Schlosser, 1977).

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The importance to understand the performance of crosswind and rainfall in the truck's lateral stability has become apparent. As early as 1990, Hight et al. (1990) and Pei et al. (1998) studied the stress distribution of the tire at different speeds and thicknesses of water film, then put forward the cause of the high accident rate for friction and water skiing on the rainy day. Peters (1993) and Start et al. (1998) carried out a wind tunnel test which chose vehicles' model ratio from 1:1 to 1:6 and the wind heading from 0° to 90°. Moreover, he put forward the changing rule of the aerodynamic force and the corresponding torque. Ryan and Dominy (1998) and Amundsen and Ranes (2000) obtained the passenger car model's aerodynamic force value with rollover in the wind heading of about 30°. Fang (2000) set up a vehicle dynamics simulation and high-speed aerodynamic characteristics model, and analyzed the speeding, side wind effects on vehicle handling stability. Maruyama and Yamazaki (2006) and Snæbjörnsson et al. (2007) came up with an accident risk method based on the vehicle weight, tire load, aerodynamic force and driving behavior, including the strong subjectivity driving behavior and other factors which were difficult to quantify. Wu (2011) studied the highway safety which affected by the typhoon weather, and developed a cars skid model. He also calculated the safety driving speed of the car under the different grades of typhoon weather, but didn't give a quantitative reaction of wind in the paper. Rodriguez et al. (2014) used a driving simulator to quantify the crosswind influence on driver behavior and vehicle lateral displacement, and proposed a calculation model based on the cross culture power, driver behavior, and the vehicle lateral displacement. Xu et al. (2014) and Ueckermann et al. (2015) studied the effect of crosswind on alignment design indexes by wind tunnel test, but his article did not consider the influence of the aerodynamic torque caused by wind and uneven coefficient on trucks lateral stability. Therefore, this article focuses on uneven adhesion coefficient and crosswind to study truck's lateral stability. Wind force on trucks in simulated uniform wind field is obtained by TruckSim simulation software. Based on vehicle dynamics principle, a vehicle stability driving model is established. Also, the radius of the road is calculated with the consideration of crosswind and uneven adhesion coefficient. Moreover, the research can provide technical reference for road safety design in the future.

2. Research method

2.1. *TruckSim simulation test*

TruckSim is a vehicle dynamics simulation software package developed by the Transportation Research Institute at University of Michigan, which has engaged in vehicle dynamics simulation research for more than 20 years (Song et al., 2010). Due to use of the parametric modeling method and the characteristic of module parameter accurate setting, this software can be used to analyze the response of roads, environment, driving behavior, and the vehicle itself parameter input. Therefore, the software has been widely used. At present, scholars have started to use this software for vehicle dynamics simulation study in China. Li et al. (2009) and Kwon et al. (2011) imported a driver model by using the software TruckSim, and changed the parameters such as wind speed, wind heading, and speed of truck. It analyzed the effect of crosswind on handling and stability of truck driving in a straight-line. Zhang and Ding (2012) and Wang et al. (2014) used TruckSim software to study the stability of a tractor semi-trailer in crosswind. Digital simulations were carried out at different wind headings, wind speeds, and vehicle speeds with step steering input to analyze different vehicle responses of roll angle, yaw rate, and hitch angle, and then obtain the critical vehicle speed and critical wind speed for the tractor semi-trailer with stability driving. Therefore, it is worthwhile to use TruckSim simulation software to quantify crosswind effect on truck.

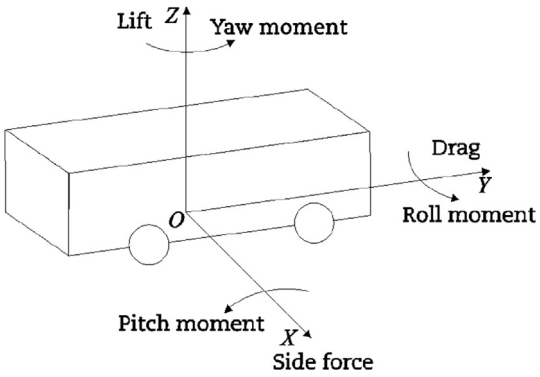

Fig. 1 – Wind force distribution on vehicle.

2.1.1. *Analysis of automotive aerodynamics*

According to the principle of aerodynamics, three directions of the aerodynamic force will act on wind pressure center of the truck where there is no pneumatic torque, but the wind pressure center and the vehicle mass center are always not at the same point (Rhonda and Joel, 2007). In order to facilitate the analysis of stress and kinematics equation, the vehicle mass center, which can add three pneumatic torques, is often used. This article uses the TruckSim software which transforms the reference point to the vehicle mass center automatically to reflect the influence of aerodynamics on vehicle dynamics in time. Under the action of crosswind, the vehicles' aerodynamic force is shown in Fig. 1.

2.1.2. *Calculation of the aerodynamic force*

In order to quantify the effects of crosswind on truck, a six-axle semi-trailer (Fig. 2) with no-load weight 14 t, center of

Fig. 2 – Test model.