Transportation Research Part C 63 (2016) 114–125

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Geometric design safety estimation based on tire–road side friction

Peiqing Li, Jie He

School of Transportation, Southeast University, No. 2, Sipailou, Nanjing 210096, China

ARTICLE INFO

Article history:
Received 4 March 2015
Received in revised form 8 December 2015
Accepted 16 December 2015
Available online 30 December 2015

Keywords:
Vehicles
Dynamic response
Road geometry
Tire–road side friction
Adams/Matlab

ABSTRACT

A closed-loop drive–vehicle–road–environment system (DVRES) model was established using Adams/Car and Matlab/Simulink. Dynamic responses of lateral tire forces based on tire–road side friction and road geometric characteristics are used to investigate vehicle side slip for geometric design safety estimation. The root mean square, the maximum values of lateral tire forces, comfort limit on curves and vehicle trajectories are used to quantify the safety margin of side friction. The simulation results show that the safety margins of lateral tire forces for radius, operating speed and superelevation rate were 18.2%, 19.3% and 17.6%, respectively, to guarantee good vehicle lateral reliability and ride comfort, while lower speeds are optimal in wet and slippery roads. Finally, a case study was conducted to illustrate the analysis of road design safety, and on-site experiment testing further validated the accuracy and reliability of the closed-loop DVRES model.

1. Introduction

Traffic accidents worldwide are closely related to the interactions between driver, vehicle, road, and environmental factors, such as road geometry, tire–road friction, speeding, vehicle performances, driving behaviors, pavement environments, and traffic flow. However, it is estimated that more than 50% of the total fatalities on highways can be attributed to the accidents occurring on curved sections (Lamm and Choueiri, 1991).

Horizontal curves have a much higher average accident rate than straight segments (Glennon et al., 1985), and this situation is particularly evident in Chinese national highways. Among them, vehicle side slip accident is one of the most frequent on horizontal curves. There are two main reasons. First, a curved section consists of more complex road geometric characteristics and environmental conditions. Second, abrupt changes such as vehicle traveling states, dynamic responses of tire–road friction, and driver visual demands, are more prone to cause driver's improper handling behaviors when a vehicle travels on circular curves and transition sections. Thus, curves and their preceding and succeeding transition sections can be considered as the most critical locations on a highway.

In recent years, a large number of mathematical models and evaluation methodologies were developed to evaluate and analyze traffic safety based on pavement conditions and vehicle reliability. For example, a multiple degrees of freedom vehicle model was established to estimate the interactions between nonlinear tire forces and road friction (Ray, 1997). Due to the loss of vehicle directional stability in emergency maneuvers, a new complete vehicle model based on the linear two-degrees-of-freedom model and tire/road conditions is presented (Mirzaei, 2010). A quarter-car model with two degrees of freedom was used to identify vehicle dynamic behaviors and safe traffic speed limits (Barbosa, 2010). A one-dimensional two-degrees-of-freedom vibration model was formulated to investigate and quantify the effects of pavement roughness

---

E-mail addresses: lpqing@seu.edu.cn (P. Li), hejie@seu.edu.cn (J. He)

http://dx.doi.org/10.1016/j.trc.2015.12.009
0968-090X/

and vehicle speed (Fuentes et al., 2010). Kang et al. (2013) proposed separate computational methods for evaluating highway alignment according to fuel efficiency, sight distance deficiencies and expected accident costs. The point-mass-model based performance functions considering the failure models of skidding and rollover were presented for a reliability analysis of vehicle stability (You and Sun, 2013). A vehicle vibration and roll model, with seven-degree-of-freedom, was used to analyze the coupling interactions between vehicle anti-rollover and lateral stability (Li et al., 2013). Mirzaeinejad and Mirzaei (2014) used a nonlinear eight-degree-of-freedom vehicle model to optimize the nonlinear control strategy for anti-lock braking system. More recently, driving simulator evaluation is emerging as an important approach for the traffic safety evaluation based on road geometric characteristics, and has demonstrated its usefulness in the road design stage (Bella, 2009; Brown and Brennan, 2015). However, this highlights the fact that no single model is universally acceptable (Jacob and Anjaneyulu, 2012).

As previously mentioned, vehicle models in most literature can be simplified as simple physical models with constant speeds to analyze vehicle dynamic responses. However, these simplified physical models do not accurately reflect the vehicle dynamic responses, especially the dynamic responses of tire–road side friction when the vehicle is traveling on the curves and transition sections. To overcome the above problems, a closed-loop drive–vehicle–road–environment system (DVRES) model, based on virtual prototyping technology, was developed in this study. Currently, virtual prototyping technology has been widely applied to various fields of research, such as the automobile industry, construction machinery, aerospace industry, and mechanical electronics. (Liu and Ma, 2009; Park and Le, 2012; Wong et al., 2013; Daher and Ivantysynova, 2014). Based on an extensive literature review, little work has been undertaken to investigate the vehicle lateral reliability estimation based on tire–road lateral friction and road geometric characteristics using virtual prototyping technology.

Tire–road side friction is an important reference index for identifying potential side slip estimation. When tire–road side friction is insufficient at a horizontal curve, vehicles may side slip, rollover, run off the road, or be involved in head-on accidents. As a result, road design with insufficient tire–road side friction will negate the ability of the driver to guide and control the vehicle in a safe manner. Drivers will also be taken off guard. Accordingly, locations that do not provide vehicle stability can be considered as geometric design inconsistencies, and assessing through vehicle lateral stability can help to identify them.

The closed-loop DVRES model can reflect real car, road geometric characteristics and pavement conditions, and driver maneuvers in the high-fidelity simulator system, and it is possible to reproduce dangerous situations and conditions for the dynamic responses of tire–road side friction. The input variables in the closed-loop DVRES model are radius of R, superelevation rate of e, operating speed of v, and combinations of left and right tire–road friction coefficients of f_l/f_r. Dynamic responses of lateral tire forces are used to identify side slip by analyzing tire force values, vehicle trajectories and traveling states. The root mean square, the maximum values of lateral tire forces, comfort limit (lateral acceleration) on curves and vehicle trajectories are used to quantify the safety margin of side friction.

The aim of this work is to analyze and reveal the traffic accident mechanism of vehicle side slip, and further to optimize the geometric alignment designs. This paper focuses primarily on four sections as follows. Section 2 establishes the closed-loop DVRES model using Adams/Car and Matlab/Simulink, after which, in Section 3, experimental designs and dynamic response analyses for vehicle side slip are formulated. In Section 4, a case study is conducted to improve the geometric alignment designs according to the safety margin of vehicle side slip estimation. Finally the on-site experiment testing further validated the accuracy and reliability of the closed-loop DVRES model.

2. Establishing closed-loop DVRES model

The closed-loop DVRES model consists of three essential components: a full-vehicle model, road model and a control system based on fuzzy rules. A full-vehicle model is composed of the car body, powertrain, front/rear suspension, front/rear tire, brake system and steering etc., in Adams/Car. The road is modeled by Multi-quadric (MQ) interpolation and three-dimensional (3D) road xml file in Adams/Road. The control system is performed by an operating speed profile.

2.1. Three-dimensional road model

The proposed 3D road model is derived from MQ interpolation (Carlson and Foley, 1991; Hon and Mao, 1997). MQ interpolation is one of the best approximation methods in road modeling. The road modeling approach with MQ interpolation can be formulated as follows:

$$F(x) = \sum_{j=1}^{n} a_j \left[(x - x_j)^2 + R^2 \right]^{0.5} \tag{1}$$

$$F(x, y) = \sum_{j=1}^{n} a_j \left[(x - x_j)^2 + (y - y_j)^2 + R^2 \right]^{0.5} \tag{2}$$

where $F(x)$ is one-variable MQ interpolation function, which is applied to handle pavement smoothness and roughness. a_j is an undetermined coefficient. x_j is the j^{th} centerline coordinate scattered on horizontal curve. R is smooth factor. x is interpo-