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Modeling free-flow speed according to different water depths—From the viewpoint of dynamic hydraulic pressure

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ABSTRACT

In this paper, we propose a method of modeling free flow speed from the viewpoint of hydroplaning. First, the lift forces for different water depths were estimated using Bernoulli's equation. Compared with the result of the experimental test performed by the Japan Automobile Research Institute, the hydrodynamic pressure coefficient was determined to be 0.03 (tf s^2/m^4). The validation of the predicted lift force is found in another published paper. A very good match is found between the computed values by the proposed numerical model and the data in other published papers. Then, the loss of contact force is considered to evaluate the hydroplaning performance of a tire. To simulate the hydroplaning speed, a tire-sliding model was utilized to obtain the traction and friction forces between the road surface and the tire. The observation data obtained in Japan in 2009 is compared with the physically computed hydroplaning speed, yielding the conclusion that the traction force at the measured desired speed is, on average, 23.4% of the traction force at hydroplaning speed. The analytical model offers a useful tool to quantitatively show that the free flow speed changes as the water depth increase.

Introduction

According to traffic regulation, the free speed or desired speed is defined as the speed driven when the driver is not influenced by other road users (Hoogendoorn, 2005). It will be influenced by lane width, weather, design speed, behavior, and the environment (Garber and Gadiraju, 1989; Oppenlander, 1966; Ottensen and Krammes, 2000; Rowan and Keese, 1962).

When a vehicle is driving on a wet road at high speed, the rainwater flows through the tire tread grooves and gives rise to hydrodynamic pressure. The occurrence of this hydrodynamic force causes the tire traction efficiency to deteriorate because it decreases the tire contact force, such that the driving controllability and the braking performance become worse than those on dry road. The risk of hydroplaning increases with the increase of the depth of the water and the driving speed of the vehicle (Glennon and Hill, 2004), and it will impact the free flow speed to a large extent.

Once hydroplaning occurs, the friction coefficient between tire and road surface decreases significantly; less experienced drivers are more vulnerable to making misjudgments regarding driving speed, which can lead to traffic accidents. Therefore, to determine the safe driving speed to guarantee the safe traffic environment in the rain, it is vital to study the water film's mechanism of influence between the tire tread and road surface.

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Tire hydroplaning was first noticed and demonstrated experimentally around 1957 during a tire treadmill study (Harrin, 1958). It was revealed in this investigation by the low values of tire-surface friction found during a large airplane's wheel spin-up when landing on a wet runway (Hall et al., 1958). The research in the Langley landing load tracks involving bogie and nose-gear studies (Horne, 1962; Horne and Leland, 1963) indicates that the relationship between tire hydroplaning speed V_p (km/h) and tire inflation pressure P_I (kPa) is in the form of Bernoulli's equation, as in Eq. (1).

$$P_I = 6.36V_p^2 \quad (1)$$

The tire inflation pressure P_I (kPa) is proportional to the square of the hydroplaning speed V_p (km/h). The experiments were conducted using aircraft and automobile tires on a relatively smooth concrete pavement with an average water depth of 7.62 mm. Although the empirical model is still in use today, it is appropriate to highlight the fact that numerous experimental studies (Horne and Dreher, 1963; Gallaway et al., 1979; Henry and Meyer, 1983; Huebner et al., 1986) have indicated that the thickness of a water film on a pavement surface and tire-related variables, for example, tire shape, would also significantly affect the hydroplaning speed. The NASA equation (Eq. (1)) does not include the effect of water film thickness and tire shape factors in the prediction of hydroplaning speed.

Analytical studies on the tire hydroplaning phenomenon have been conducted (Saal, 1936; Martin, 1966; Eshel, 1967; Grogger and Weiss, 1996; Nakajima et al., 2000; Okano and Koishi, 2001). Among the analytical studies, Grogger and Weiss first introduced a computational simulation for hydroplaning analysis. Nakajima et al., Okano and Koishi used DYTRAN, a commercial FEM code, to simulate tire hydroplaning. In the recent past, a number of studies have been conducted to model the hydroplaning phenomenon. However, few focused on on-road real-time emissions data, which is necessary for evaluating the impact of real-time driving conditions and quantitatively analyzing the perception of driving safety in wet conditions.

In this paper, research has been conducted to study the effect of water depth on roadway operation and traffic speed by using observed on-road data. A dynamics method from the view point of hydroplaning has been proposed to analyze the traction force, evaluate the lift and drag force produced by water, estimate the ground speed at which hydroplaning occurs, and quantitatively model the free flow speed considering the impact of different water depths.

Data collection

Measuring vehicle flow characteristics commonly involves the use of traffic counters, as they offer an effective method for obtaining large amounts of data. However, in this study, care was needed to separate the effects of water depth from those of free-flow speed. Therefore, camera data were used to obtain vehicle and water status data simultaneously for parsing. The survey was conducted in July 2009 when Fukuoka, Japan was experiencing a heavy rainfall. The site was the number 202 state road, which runs through Fukuoka, Itosima, Japan. It is a two-lane road and is shown in Fig. 1. Forty-five minutes of observations were taken at the site. The rainfall exceeded 100 mm/h, and the maximum depth of water reached 20 cm during the observation period.

Method for measuring a car's free-flow speed

When measuring the free-flow speed, sample data are collected when a car is by itself. The speed measuring method is demonstrated via Eqs. (2) and (3).

$$t_c = T_h - T_t \quad (2)$$

$$V_f = 3.6L_c/t_c \quad (3)$$

In the above equations, t_c (s) is the total time taken for the entire car to pass through the green[1] line shown in Fig. 1. T_t is the clock time when the front of the car (position of the yellow line) passes the location of the green line. T_h is the clock time when the rear of the car (position of the red line) passes though the location of the green line. V_f (km/h) is the free flow speed of the sample car, and L_c (m) is the length of the car. The data on car length was obtained from the internet. This information is shown in Table 1.

The values of L_c (m) (abbreviated values are shown in Table 1) are determined according to the specific type of car observed by the video. The study objects are the only types mentioned in Table 1. Therefore, the length range is from 3.5 to 5.0 (m).

Method for measuring water depth

The depth of water was estimated through visual observation. If the depth exceeded the lower rubber portion of the tire, it was judged as being more than 10 cm. If the depth was located within the lower rubber portion of the tire, it was judged as being less than 10 cm. The first situation was defined as the high water depth, and the value, 15 (cm), (for a range from 10 cm

[1] For interpretation of color in Figs. 1, 5, 6 and 8, the reader is referred to the web version of this article.