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Experimental Analysis for Determination of Longitudinal Friction Coefficient Function in Braking Tractor Semi-trailer

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ABSTRACT

The longitudinal friction coefficient is a very important parameter to calculate vehicle dynamics. The theoretically longitudinal friction coefficient is often used to investigate the vehicle dynamics. However, the longitudinal friction coefficient depends on many factors and changes when the vehicle moves on the actual road. This paper presents the experimental method to determine the longitudinal friction coefficient function when braking the tractor semi-trailer on the road. The results of this study can be used as an input to dynamic survey model for the tractor semi-trailer and to verify the theoretical model. The experimental results showed that when braking the tractor semi-trailer on the dry asphalt, the maximum longitudinal friction coefficient is φ_{xmax}=0.89 and the minimum longitudinal friction coefficient is φ_{xmin}=0.72. Matlab-Simulink software was used to investigate and compare the longitudinal friction coefficient determined by experiment and the theoretically longitudinal friction coefficient according to Ammon tire model. The survey results showed that the average error between experiment and theory was about 17%.

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1. INTRODUCTION

The movement of the vehicle depends on the tire-road forces F_x, F_y, F_z. The tire-road forces F_x, F_y, F_z are usually determined by the tire model and they depend on the tire-road friction coefficient [1-3].

$$F_x(t) = F_z(t)\varphi_x(t) \tag{1}$$

$$F_y(t) = F_z(t)\varphi_y(t) \tag{2}$$

Therefore, the longitudinal friction coefficient function by time can be determined:

$$\varphi_x(t) = \frac{F_x(t)}{F_z(t)} \tag{3}$$

Thus, in order to determine the longitudinal friction coefficient function $\varphi_x(t)$, $F_x(t)$ and $F_z(t)$ should be known [4].

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2. THEORETICAL BASES

The method of separating structure of the multi-object system for the vehicle dynamic model ¼ is used as shown in Figure 1, the equation of vehicle movement is as follows [5]:

$$\begin{cases} m\ddot{z} = F_C + F_K \\ m_A\ddot{\xi} = F_{CL} - (F_C + F_K) \\ (m + m_A)\ddot{x} = F_X + F_W \\ F_Z = F_G + F_{CL} \end{cases} \tag{4}$$

Or $$\begin{cases} F_X = (m + m_A)\ddot{x} - F_W \\ F_Z = F_G + m\ddot{z} + m_A\ddot{\xi} \end{cases} \tag{5}$$

The longitudinal slip coefficient of the wheel by time is determined by the following Equations (6) and (7).

The longitudinal slip coefficient of the wheel when braking [6, 7]:

$$s_x(t) = \frac{r_d\dot{\varphi}(t) - \dot{x}(t)}{\dot{x}(t)}; r_d\dot{\varphi}(t) < \dot{x}(t); -1 < s_x < 0 \tag{6}$$

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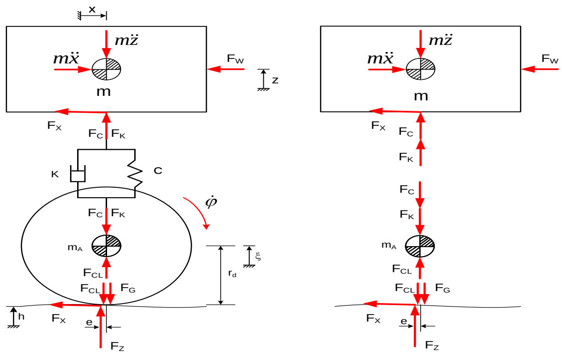


Figure 1. Model of vehicle dynamics ¼

The longitudinal slip coefficient of the wheel when accelerating [5, 6, 8]:

$$s_x(t) = \frac{r_d\dot{\varphi}(t) - \dot{x}(t)}{r_d\dot{\varphi}(t)}; r_d\dot{\varphi}(t) > \dot{x}(t); 0 < s_x < 1 \qquad (7)$$

So in order to determine the longitudinal friction coefficient function of the wheel according to the longitudinal slip coefficient $\varphi_x(s_x)$, the longitudinal friction coefficient function by time $\varphi_x(t)$ should be known as in formula (3) and the longitudinal slip coefficient function by time $s_x(t)$ as in formula (6,7). The longitudinal friction coefficient function according to the longitudinal slip coefficient is shown in Figure 2 [9, 10].

3. EXPERIMENT AND SIMULATION

3. 1. Experiment In this paper, a 6-axle tractor semi-trailer was chosen for experiment. During the experiment, the braking systems of the axles I, II, III, IV, V were adjusted to stop working. The diagram for installation of the experimental sensor is shown in Figure 3.

To determine the longitudinal friction coefficient function of the wheel according to the longitudinal slip coefficient $\varphi_x(s_x)$, the following 6 parameters were experimentally determined: Measurement of the longitudinal velocity of the tractor semi-trailer ($\dot{x}$) by

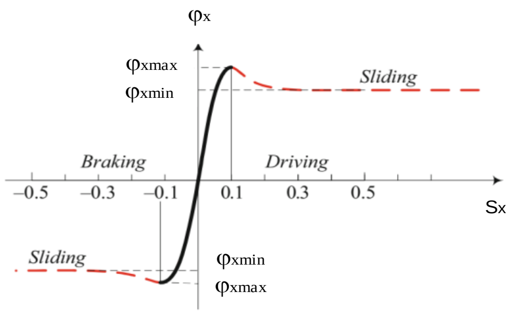
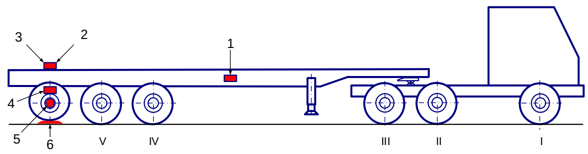


Figure 2. Longitudinal friction coefficient as a function of slip ratios



1. Sensor for measuring the body longitudinal velocity;
2. Sensor for measuring the body longitudinal acceleration;
3. Sensor for measuring the body vertical acceleration;
4. Sensor for measuring the axle vertical acceleration;
5. Sensor for measuring the wheel angular velocity;
6. Weigh the axle weight

Figure 3. Sensor installation diagram on the experimental tractor semi-trailer

Kistler GPS sensor (1); measurement of the longitudinal acceleration ($\ddot{x}$) and vertical acceleration ($\ddot{z}$) of the tractor semi-trailer by MMA7361LC-XYZ sensor (2,3); measurement of the vertical acceleration ($\ddot{\xi}$) of the axle by MMA7361LC-XYZ sensor (4); measurement of the wheel angular velocity ($\dot{\varphi}$) by Sharp Rotary Encoder sensor (5); weighing the un-sprung mass (m_A) and the sprung mass (m) with ULSTRALIM electronic balance (6). Diagram of the measurement system, signal reception and braking experimental result processing of the tractor semi-trailer are shown in Figure 4 [11, 12].

Let the tractor semi-trailer moved steadily on the dry asphalt at a speed of 50 km/h and then braked to let the tractor came to a complete stop. Based on 6 parameters determined by the experiment, the computer processed and output graphs $F_z(t)$, $F_x(t)$, $\varphi_x(t)$, $s_x(t)$ as shown in Figures 5, 6, 7 and 8. The longitudinal friction coefficient function of the wheel according to the longitudinal slip coefficient $\varphi_x(s_x)$ is shown in Figure 9.

The experimental results show that the value and shape of the graphs $F_z(t)$, $F_x(t)$, $\varphi_x(t)$, $s_x(t)$, $\varphi_x(s_x)$ are consistent with the theoretical rules. When braking the tractor semi-trailer on the dry asphalt, the maximum longitudinal friction coefficient is φ_{xmax}=0.89 and the minimum longitudinal friction coefficient is φ_{xmin}=0.72,

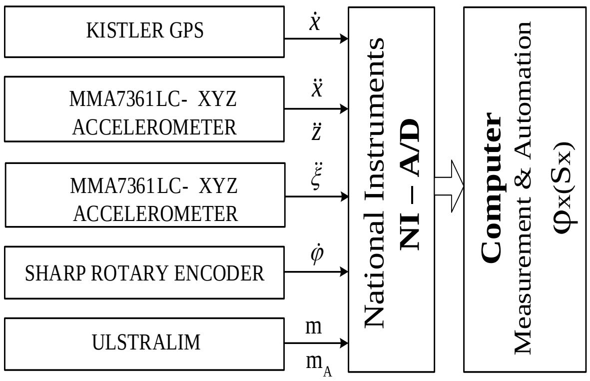


Figure 4. The longitudinal friction coefficient measurement system

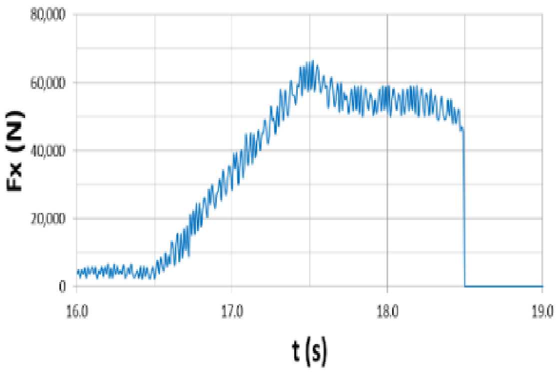


Figure 5. Tire longitudinal force

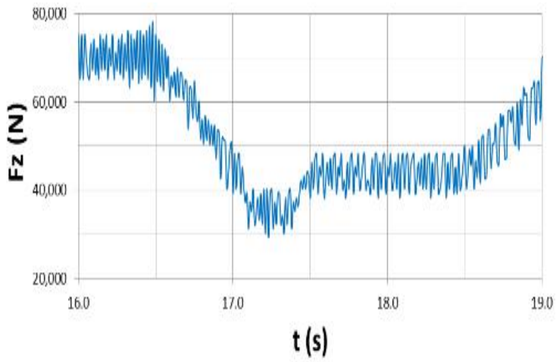


Figure 6. Tire vertical force

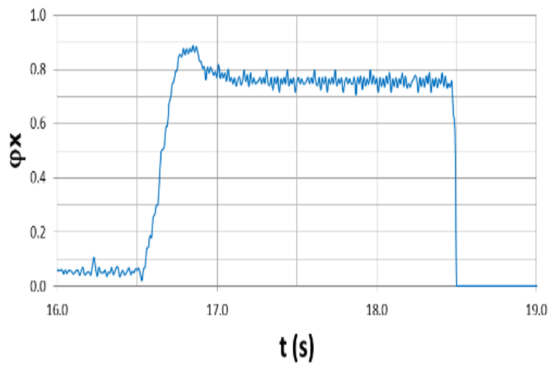


Figure 7. Longitudinal friction coefficient

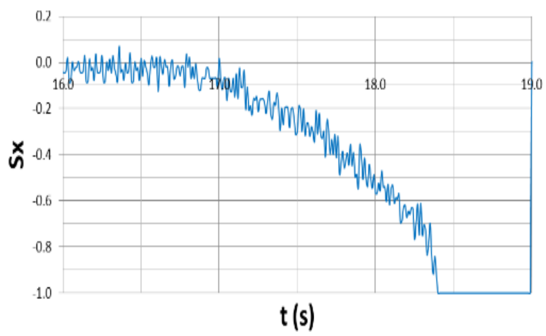


Figure 8. Longitudinal slip ratio

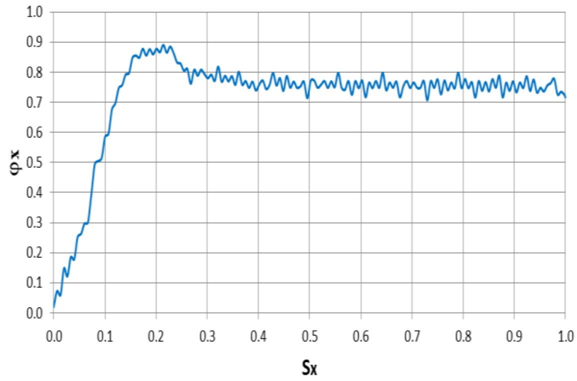


Figure 9. Function of longitudinal friction coefficient

the value of the longitudinal friction coefficient was determined by experiment equivalent to theoretical value.

3. 2. Simulation Matlab-Simulink software was used to investigate and compare the longitudinal friction coefficient function of the wheel according to the longitudinal slide coefficient $\varphi_x(s_x)$ determined by experiment and the function $\varphi_x(s_x)$ simulated according to Ammon tire model on the same type of road with the maximum longitudinal friction coefficient φ_{xmax}=0.89 and the minimum longitudinal friction coefficient φ_{xmin}=0.72 [4, 5]. The results of function simulation $\varphi_x(s_x)$ by experiment and according to Ammon tire model are shown in Figure 10. The survey results showed that the average error between experiment (the longitudinal friction coefficient function $\varphi_x(s_x)$ determined by experiment) and theory (the longitudinal friction coefficient function $\varphi_x(s_x)$ determined by Ammon tire model) was about 17%.

The function $\varphi_x(s_x)$ determined by experiment and function $\varphi_x(s_x)$ determined by Ammon tire model were used as an input to the dynamic survey model of the tractor semi-trailer as in Figures 11 and the system of dynamic equations of the tractor semi-trailer as fomulas (8-49).

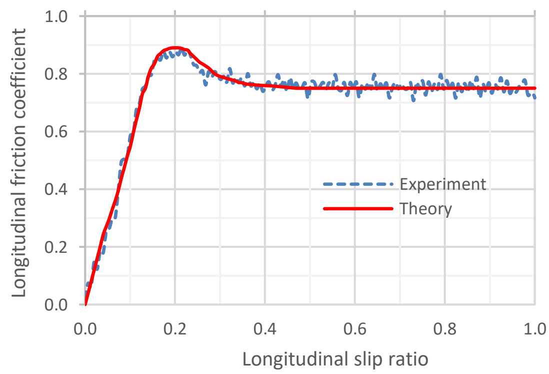


Figure 10. Function $\varphi_x(s_x)$ determined by experiment and Ammon tire model

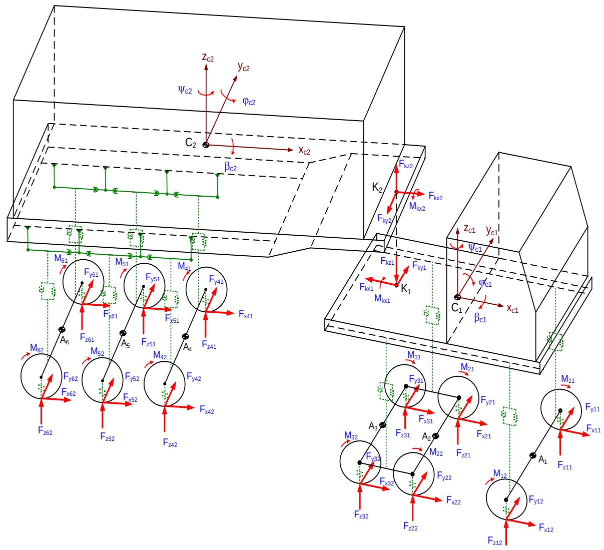


Figure 11. Dynamic model of the tractor semi-trailer

The system of dynamic equations of the tractor semi-trailer are as follows [5]:

$$m_{c1}\ddot{x}_{c1} = F_{xij} - F_{wx1} - F_{kx1}(i = 1-3) \quad (8)$$

$$m_{c1}\ddot{y}_{c1} = F_{yij} - F_{wy1} - F_{ky1}(i = 1-3) \quad (9)$$

$$J_{zc1}\ddot{\psi}_{c1} = F_{x1j}l_1 + F_{x1j}b_1 + F_{ky1}l_{k1} - F_{yij}l_i + (F_{xi2} - F_{xi1})b_i \quad (10)$$

$$m_{c2}\ddot{x}_{c2} = F_{xij} + F_{kx2}(i = 4-6) \quad (11)$$

$$m_{c2}\ddot{y}_{c2} = F_{ky2} + F_{yij}(i = 4-6) \quad (12)$$

$$J_{zc2}\ddot{\psi}_{c2} = (F_{xi2} - F_{xi1})b_i + F_{ky2}l_{k2} - F_{yij}l_i(i = 4-6) \quad (13)$$

$$m_{c1}\ddot{z}_{c1} = F_{Cij} + F_{Kij} - F_{kz1}(i = 1 \div 3) \quad (14)$$

$$J_{yc1}\ddot{\varphi}_{c1} = (F_{C1j} + F_{K1j})l_i + F_{kz1}l_{k1} - F_{kx1}(h_{c1} - h_{k1}) + M_{ij}(i = 1 \div 3) \quad (15)$$

$$m_{c2}\ddot{z}_{c2} = F_{Cij} + F_{Kij} + F_{kz2}(i = 4 \div 6) \quad (16)$$

$$J_{yc2}\ddot{\varphi}_{c2} = -(F_{Cij} + F_{Kij})l_i + F_{kx2}(h_{c2} - h_{k2}) + F_{kz2}l_{k2} + M_{ij}(i = 4 \div 6) \quad (17)$$

$$J_{xc1}\ddot{\beta}_{c1} = (F_{Ci2} + F_{Ki2} - F_{Ci1} - F_{Ki1})w_i + M_{kx1} \quad (i = 1 \div 3) \quad (18)$$

$$J_{xc2}\ddot{\beta}_{c2} = (F_{Ci2} + F_{Ki2} - F_{Ci1} - F_{Ki1})w_i - M_{kx2}(i = 4 \div 6) \quad (19)$$

$$m_{Ai}\ddot{z}_{Ai} = F_{CLij} + F_{KLij} - F_{Cij} - F_{Kij}(i = 1 \div 6) \quad (20\text{-}25)$$

$$m_{Ai}\ddot{y}_{Ai} = F_i + F_{yij}(i = 1 \div 6) \quad (26\text{-}31)$$

$$J_{Axi}\ddot{\beta}_{Ai} = (F_{Ci1} + F_{Ki1} - F_{Ci2} - F_{Ki2})w_i + (F_{CLi2} - F_{CLi1})b_i - F_{yij}(r_{ij} + \xi_{Aij}) \quad (32\text{-}37)$$

$$J_{Ayij}\ddot{\varphi}_{ij} = M_{Aij} - M_{Bij} - F_{xij}r_{dij} \quad (38\text{-}49)$$

Graphs of force F_x, F_z surveyed by Matlab-Simulink software with the input function $\varphi_x(s_x)$ determined by experiment and Ammon function are presented in Figures 12 and 13. The survey results showed that when the input function $\varphi_x(s_x)$ determined by experiment and Ammon function were used, the average error of force F_x was 11,81% and the average error of force F_z is 19 and 25%.

The obtained results determined by the experiment had shapes and values consistent with theoretical rules as well as research results of many other authors [8, 11, 12].

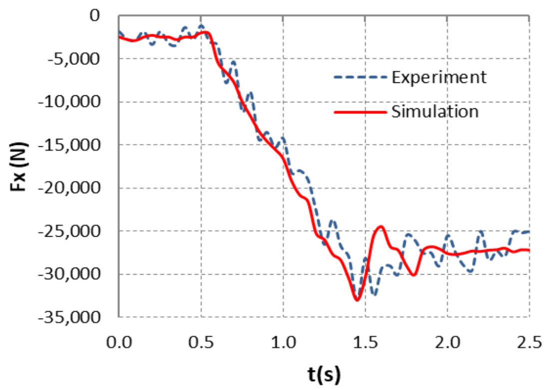


Figure 12. Tire longitudinal force F_x

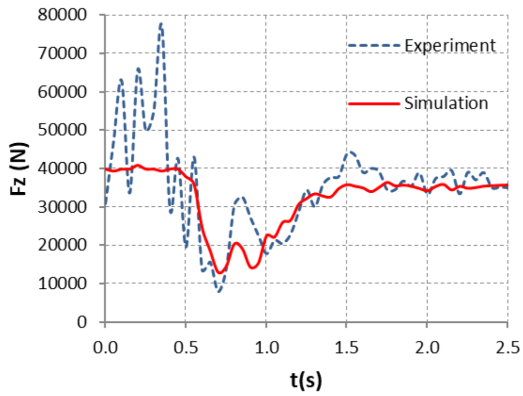


Figure 13. Tire vertical force F_z

4. CONCLUSION

The longitudinal friction coefficient function $\varphi_x(s_x)$ can be determined by measuring the longitudinal velocity of the vehicle ($\dot{x}$), the longitudinal acceleration of the vehicle ($\ddot{x}$), the vertical acceleration of the body ($\ddot{z}$), the vertical acceleration of the axle ($\ddot{\xi}$), the wheel angular velocity and weighing the vehicle weight. The experimental results can be used to study the dynamics of the tractor semi-trailer and other types of vehicles on actual roads.

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Persian Abstract

چکیده

ضریب اصطکاک طولی پارامتر بسیار مهمی برای محاسبه دینامیک خودرو است. از ضریب اصطکاک طولی نظری اغلب برای بررسی پویایی خودرو استفاده می شود. با این حال ، ضریب اصطکاک طولی به فاکتورهای زیادی بستگی دارد و هنگام حرکت وسیله نقلیه در جاده واقعی تغییر می کند. در این مقاله روش آزمایشی برای تعیین عملکرد ضریب اصطکاک طولی هنگام ترمزگرفتن نیمه تریلر تراکتور در جاده ارائه شده است. نتایج این مطالعه می تواند به عنوان ورودی به مدل بررسی پویا برای نیمه تریلر تراکتور و برای تأیید مدل نظری مورد استفاده قرار گرفته است. نتایج تجربی نشان داد که هنگام ترمز نیمه تریلر تراکتور روی آسفالت خشک ، حداکثر ضریب اصطکاک طولی φxmax = 0.89 و حداقل ضریب اصطکاک طولی minxmin = 0.72 می باشد. از نرم افزار Matlab-Simulink برای بررسی و مقایسه ضریب اصطکاک طولی تعیین شده با آزمایش و ضریب اصطکاک طولی نظری با توجه به مدل لاستیک آمون استفاده شد. نتایج بررسی نشان داد که میانگین خطای بین آزمایش و نظریه حدود ۱۷٪ بوده است.