International Journal of
INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING
ISSN:2147-6799 www.ijisae.org Original Research Paper

Effect of Braking Force on Wheel Load and Braking Efficiency of Tractor Semi-Trailer on A Roundabout Using Machine Learning Techniques

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Submitted: 08/11/2022 **Accepted**: 11/02/2023

Abstract. If the vehicle is braked on the roundabout, the wheel load will be changed greatly, affecting the stability, braking efficiency, and durability of the vehicle and the road. This paper presents research results on the effect of braking force on wheel load and braking efficiency when a tractor semi-trailer is braked on a roundabout with a random road surface according to ISO 8608:2016. The results showed that, the maximum front wheel load is (1.43÷2.11)F_{z1st} and the maximum middle wheel load is (0.88÷1.07)F_{z3st} and the maximum rear wheel load (0.70÷0.95)F_{z6st}; The left middle tyres slip completely when the vehicle is braked at F_B=(70, 80, 90)%F_{Bmax}; The rear left tyres slip completely when the vehicle is braked at F_B=(50, 60, 70, 80, 90)%F_{Bmax}; The rear right tyres slip completely when the vehicle is braked at F_B=(80, 90)%F_{Bmax}.

Keywords: *Braking force, wheel load, braking efficiency, slip coefficient, machine learning*

1. Introduction

The braking force greatly affects the wheel load, braking efficiency, and durability of a tractor semi-trailer. The maximum wheel load ($F_{z,max}$) is determined by the following formula [1,2,3]:

$$F_{z,max} = F_{z,st} + F_{z,dyn,max} \le 2.5F_{z,st} \quad (1)$$

The braking efficiency of the vehicle is evaluated by the braking acceleration and the slip coefficient. The longitudinal slip coefficient of a driving tyre (S_D) and a braking tyre (S_B) are defined by the following formula [1,2,3]:

$$s_D = \frac{R_g\omega_w - V_x}{R_g\omega_w};\ R_g\omega_w > V_x;\ 0 < s_D < 1 \quad (2)$$

$$s_B = \frac{R_g\omega_w - V_x}{V_x};\ R_g\omega_w < V_x;\ -1 < s_B < 0 \quad (3)$$

2. The Dynamics Model

The tractor semi-trailer has six axles, including a three-axle tractor and a three-axle semi-trailer connected by a fifth wheel. A tractor semi-trailer is a complex structural system, it consists of many interconnected objects that are geometrically and physically nonlinear. The authors used the multi-body system method to establish a system of dynamic equations, force and torque diagrams of the vehicle as shown in Fig.1 [4,5,6].

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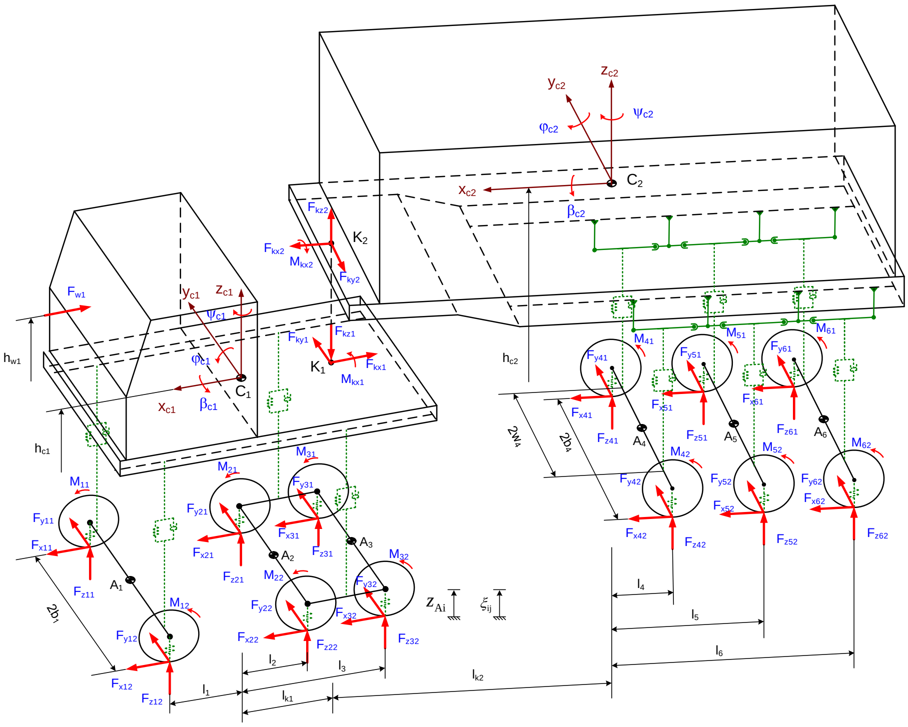

Fig.1 The force and torque diagrams of the tractor semi-trailer

The system of dynamic equations of the tractor semi-trailer is established by the Newton-Euler method as follows [4,5,6]:

$$m_{ci}(\ddot{z}_{ci} - \dot{\varphi}_{ci}\dot{x}_{ci}) = F_{Cij} + F_{Kij} - F_{kz} \quad (4)$$

$$J_{yci}\ddot{\varphi}_{ci} = -(F_{Cij} + F_{Kij})l_i + F'_{xij}(h_{ci} - r_i) + F_{kxi}(h_{ci} - h_{ki}) + F_{kzi}l_{ki} + M_{ij} \quad (5)$$

$$(m_{c1} + \sum_{1}^{3} m_{Ai})(\ddot{x}_{c1} - \dot{\psi}_{c1}\dot{y}_{c1}) = F_{x11}cos\delta_{11} + F_{x12}cos\delta_{12} - F_{y11}\sin\delta_{11} - F_{y12}\sin\delta_{12} + (F_{x2j} + F_{x3j}) - F_{wx1} - F_{kx1} \quad (6)$$

$$(m_{c1} + \sum_{1}^{3} m_{Ai})(\ddot{y}_{c1} + \dot{\psi}_{c1}\dot{x}_{c1}) = F_{x11}\sin\delta_{11} - F_{ky1} + F_{x12}\sin\delta_{12} + F_{y11}cos\delta_{11} + F_{y12}cos\delta_{12} + (F_{y2j} + F_{y3j}) \quad (7)$$

$$J_{zc1}\ddot{\psi}_{c1} = [F_{x1j}\sin\delta_{1j} + F_{y1j}cos\delta_{1j}]l_1 + (F_{x12}cos\delta_{12} - F_{x11}cos\delta_{11})b_1 + F_{ky1}l_{k1} + (F_{y11}\sin\delta_{11} - F_{y12}\sin\delta_{12} - F_{y2j}l_2 - F_{y3j}l_3 + (F_{x22} - F_{x21})b_2 + (F_{x32} - F_{x31})b_3 \quad (8)$$

$$(m_{c2} + \sum_{4}^{6} m_{Ai})(\ddot{x}_{c2} - \dot{\psi}_{c2}\dot{y}_{c2}) = F_{x4j} + F_{x5j} + F_{x6j} + F_{kx2} \quad (9)$$

$$(m_{c2} + \sum_{4}^{6} m_{Ai})(\ddot{y}_{c2} + \dot{\psi}_{c2}\dot{x}_{c2}) = F_{ky2} + F_{y4j} + F_{y5j} + F_{y6j} \quad (10)$$

$$J_{zc2}\ddot{\psi}_{c2} = (F_{x42} - F_{x41})b_4 + (F_{x52} - F_{x51})b_5 + (F_{x62} - F_{x61})b_6 + F_{ky2}l_{k2} - F_{y4j}l_4 - F_{y5j}l_5 - F_{y6j}l_6 \quad (11)$$

$$J_{xci}\ddot{\beta}_{ci} = \sum_{i=1}^{i=6}(F_{C2i} + F_{K2i} - F_{C1i} - F_{K1i})w_i + \sum_{i=1}^{i=6}F_i(h_c - h_{Bi}) - M_{kx} \quad (12)$$

$$m_{Ai}(\ddot{z}_{Ai} + \dot{\beta}_{Ai}\dot{y}_{Ai}) = F_{CLij} + F_{KLij} - F_{Cij} - F_{Kij} \quad (13)$$

$$m_{Ai}(\ddot{y}_{Ai} - \dot{\beta}_{Ai}\dot{z}_{Ai}) = F_i + F_{yij} + F_{yij} \quad (14)$$

$$J_{Axi}\ddot{\beta}_{Ai} = (F_{Ci1} + F_{Ki1} - F_{Ci2} - F_{K12})w_i + (F_{CLi2} + F_{KLi2} - F_{CLi1} - F_{KLi1})b_i - F_{yij}(r_{ij} + \xi_{Aij}) + F_i(h_{Bi} - r_i) \quad (15)$$

$$J_{Ayij}\ddot{\varphi}_{ij} = M_{Aij} - M_{Bij} - F_{xij}r_{dij} \quad (16)$$

Table 1. The special symbols and explanations

Symbols	Definition
S_D	The longitudinal slip coefficient of a driving tyre
S_B	The longitudinal slip coefficient of a braking tyre
i = 1÷3	Axle number of the tractor
i = 4÷6	Axle number of the semi-trailer
j = 1÷2	j = 1 is left wheel; j = 2 is right wheel;
x_c, y_c, z_c	Displacement in the $B(Cx_cy_cz_c)$ coordinate system
r_{dyn}	Dynamic radius of the tyre
δ_{1j}	Front wheel turn angle
l_i	Longitudinal distance of axle i from mass center
h_{c1}, h_{c2}	Height of mass center from the ground
b	Lateral distance of tyre from longitudinal x-axis
w	Lateral distance of suspension from longitudinal x-axis
φ	Rotation angle of the tyre
β_c, φ_c, ψ_c	Rotation angle of the tractor body around the x_c, y_c, z_c axis
m_c, m_A	Sprung mass and un-sprung mass of the tractor semi-trailer
J_x, J_y, J_z	Moment of inertia about the x, y, z axis of the sprung mass
J_{Ay}	Moment of inertia about the y-axis of the tyre
F_C, F_K	The suspension elastic force, damping force of the tyre
F_{CL}	The tire elastic force of the tyre
F_x, F_y, F_z	The longitudinal force, lateral force, wheel load of the tyre
F_{st}	The static weight
M_A, M_B	Driving torque and braking torque of the tyre

3. Survey results and discussions

A tractor semi-trailer was surveyed in the left roundabout with a radius of 100m at a speed of 50km/h [7], on a random road surface of class B according to ISO 8608:2016 [8]. A tractor semi-trailer was surveyed at six different braking force levels F_B=(0, 50, 60, 70, 80, 90)%F_{Bmax}. The black solid line (1) corresponds to F_B=0%$F_{Bđm}$; the black dashed line (2) corresponds to F_B=50%$F_{Bđm}$; the red solid line (3) corresponds to F_B= 60%$F_{Bđm}$; the red dotted line (4) corresponds to F_B=70%$F_{Bđm}$; the green solid line (5) corresponds to F_B=80%$F_{Bđm}$; the blue dashed line (6) corresponds to F_B=90%$F_{Bđm}$.

Fig.2 is the wheel load graph of the left and right front tyre F_{z11} and F_{z12}. Studying the graph, we see that when the vehicle is turned to the left (t=1÷4s), the left front wheel load has a reduced value of F_{x11}=(2.8÷1.7)kN, in contrast to the right front wheel load has an increasing value F_{x12}=(2.8÷3.8)kN. When the vehicle is braked (t=4÷10s) the maximum left front wheel load is F_{z11max}=(4.0÷5.2)kN=(1.43÷1.86)F_{z11st} and the maximum right front wheel load is F_{z12max}=(4.2÷5.9)kN=(1.50÷2.11)F_{z12st}.

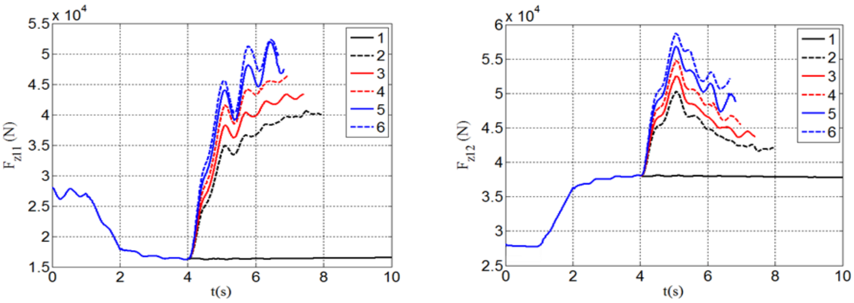

Fig.2 The wheel load of the front axle

The wheel load graph of the left and right middle tyre F_{z31} and F_{z32} is shown in Fig.3. When the vehicle is turned to the left (t=1÷4s), the left middle wheel load has a reduced value of F_{x31}=(4.2÷2.0)kN, in contrast to the right middle wheel load has an increasing value F_{x32}=(4.2÷6.4)kN. When the vehicle is braked (t=4÷10s) the maximum left middle wheel load is F_{z31max}=(3.7÷4.3)kN=(0.88÷1.02)F_{z31st} and the maximum right middle wheel load is F_{z32max}=(4.0÷4.5)kN=(0.95÷1.07)F_{z32st}.

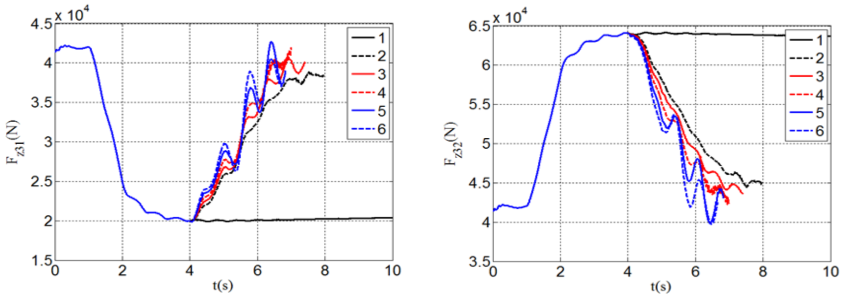

Fig.3 The wheel load of the middle axle

Fig.4 is the wheel load graph of the left and right rear tyre F_{z61} and F_{z62}. If the vehicle is turned to the left (t=1÷4s), the left rear wheel load has a reduced value of F_{x61}=(4.0÷0.8)kN, in contrast to the right rear wheel load has an increasing value F_{x62}=(4.0÷7.1)kN. If the vehicle is braked (t=4÷10s) the maximum left rear wheel load is F_{z61max}=(2.8÷3.5)kN=(0.70÷0.87)F_{z61st} and the maximum right rear wheel load is F_{z62max}=(2.8÷3.8)kN=(0.70÷0.95)F_{z62st}.

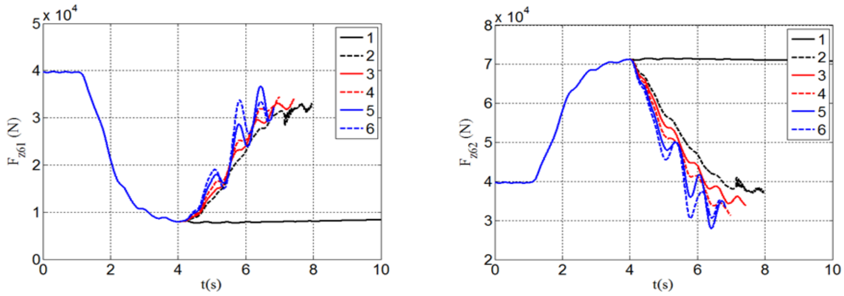

Fig.4 The wheel load of the rear axle

The slip coefficient of the front axle is shown in Fig.5. When a tractor semi-trailer is braked at six different braking force levels F_B=(0, 50, 60, 70, 80, 90)%F_{Bmax} on a random road surface of class B according to ISO 8608:2016 [8], the slip coefficient of the left front tyre has the value S_{11}≈2÷4%, the slip coefficient of the right front tyre has the value S_{12}≈2÷3%, and the tyres are working stably.

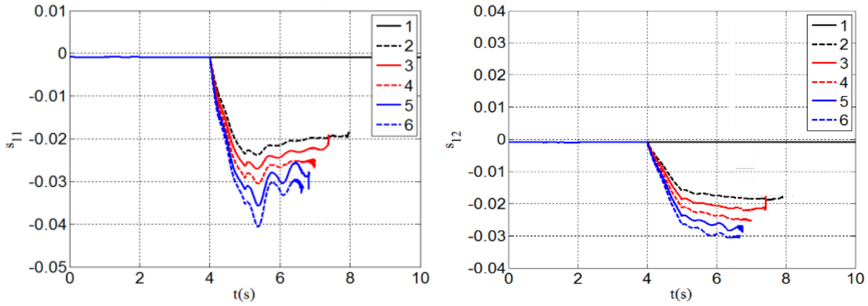

Fig. 5. The slip coefficient of the front axle

Fig.6 is a graph of the slip coefficient of the middle axle when a tractor semi-trailer is braked at six different braking force levels on a random type B road surface, the slip coefficient of the right middle tyre is $S_{32} \approx (2.5 \div 8)\%$. For the left middle tyre, if the braking force $F_B = (0, 50, 60)\% F_{Bmax}$, the slip coefficient is $S_{31} \approx 5\%$, the tire is working stably; If the braking force $F_B = (70, 80, 90)\% F_{Bmax}$, the slip coefficient is $S_{31} \approx 100\%$, the tyre is completely skidded, and the vehicle is unstable.

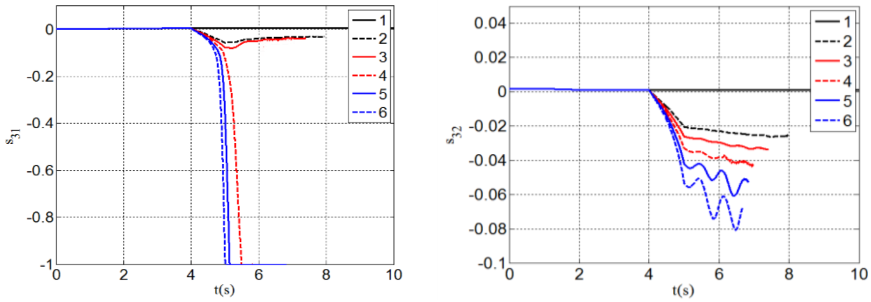

Fig. 6. The slip coefficient of the middle axle

The slip coefficient of the rear axle when a tractor semi-trailer is braked at six different braking force levels on a random type B road surface, the slip coefficient of the left rear tyre is $S_{61} \approx 100\%$, the tyre is completely skidded, and the vehicle is unstable. For the right rear tyre, if the braking force $F_B = (0, 50, 60, 70)\% F_{Bmax}$, the slip coefficient is $S_{62} \approx 5\%$, the tire is working stably; If the braking force $F_B = (80, 90)\% F_{Bmax}$, the slip coefficient is $S_{62} \approx 100\%$, the tyre is completely skidded, and the vehicle is unstable.

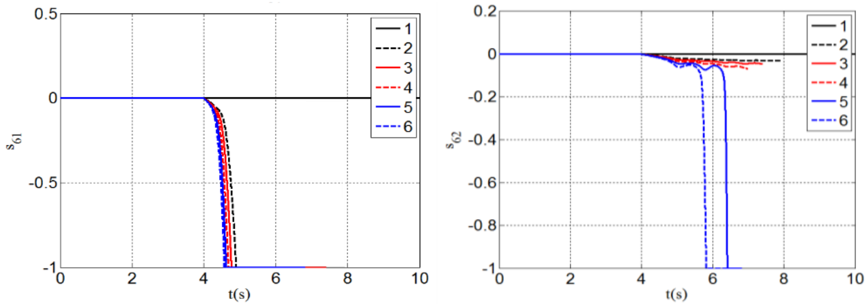

Fig. 7. The slip coefficient of the rear axle

The braking acceleration of the tractor a_{x1} and the semi-trailer a_{x2} is almost the same, as Fig.8. When the braking force $F_B = (50, 60)\% F_{Bmax}$, the braking acceleration of the vehicle is $a_{x1} \approx a_{x2} \approx (4 \div 5) m/s^2$. If the braking force $F_B = (70, 80, 90)\% F_{Bmax}$, the braking acceleration of the vehicle is $a_{x1} \approx a_{x2} > 5 m/s^2$, the brake system meets the requirements of the ECE-R13 standard [1].

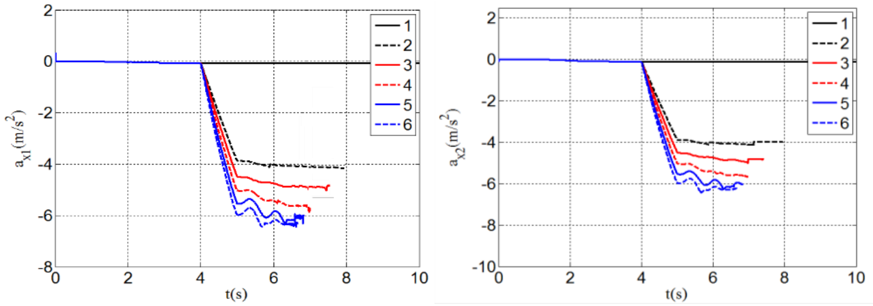

Fig. 8. The braking acceleration of the vehicle

4. Conclusions

When a tractor semi-trailer is running on the left roundabout with a radius of 100m at a speed of 50km/h on a random road surface of class B according to ISO 8608:2016 and is braking at six different braking force levels F_B=(0, 50, 60, 70, 80, 90)%F_{Bmax} the maximum front wheel load is (1.43÷2.11)F_{z1st} and the maximum middle wheel load is (0.88÷1.07)F_{z3st} and the maximum rear wheel load (0.70÷0.95)F_{z6st}; The left middle tyres slip completely when the vehicle is braked at F_B=(70, 80, 90)%F_{Bmax}; The rear left tyres slip completely when the vehicle is braked at F_B=(50, 60, 70, 80, 90)%F_{Bmax}; The rear right tyres slip completely when the vehicle is braked at F_B=(80, 90)%F_{Bmax}.

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