Analysis of Steering Performance of the Wheeled Vehicles with the Influence of Centrifugal Force

Fei Yang¹, Qiang Wang¹, Xinmin Shen¹, *, Xiaohui He¹

¹College of Field Engineering, Army Engineering University, No. 1 Haifu Street, Nanjing, Jiangsu 210007, P. R. China
Email: shenxmjfjlgdx2014@163.com

Abstract. The steady-state steering characteristics of a vehicle directly affect its work efficiency and safety. The traditional steering mechanical model of the wheeled vehicle does not take into consideration the influence of centrifugal force. Thus, in order to accurately calculate the various steering performance parameters during the actual steering of the vehicle, a mathematical model for steering of a wheeled vehicle is established based on an in-depth study of the wheeled vehicle steering mechanism, in which the influencing factors are taken into account, such as centrifugal force and tire slip/slip. Meanwhile, the specific vehicle model is used as an example to solve the numerical model. The results show that the centrifugal force generated during the steering of the vehicle will affect its steering performance. With change of the steering radius and vehicle speed, the slip radius and the amount of steering centerline movement increase or decrease accordingly, which affect the steering stability of the vehicle.

1. Introduction

Different from the common geometric steering method of the wheeled vehicles [1-3], the slip steering is to change the driving direction by giving different speeds to the wheels on both sides [4-6], which can realize the in-situ steering and center steering with better steering flexibility, simple structure, low cost, space-saving, and other advantages. Therefore, in recent years, a variety of military and civilian wheeled vehicles at home and abroad have adopted the slip steering.

Although there have been many reports on the steady-state steering performance of wheeled vehicles [4-6], most of them ignore the slip between grounded tires and the ground during steering when it has a large impact on steering performance [7]. At the same time, the vehicle’s steering centerline (the vertical line between the vehicle’s steering center and the body centerline) is subject to a centrifugal force that causes a longitudinal offset, which also directly affects the vehicle’s steady-state steering characteristics [8]. Therefore, a mathematical model of the vehicle’s steady-state steering was established and it was numerically solved in this research. The changing trend of the inner and outer wheel slip radius and the deviation of the steering centerline with the turning radius and vehicle speed were investigated, and their effect on vehicle steering and impact of stability were analyzed as well.

2. Kinematic analysis

2.1 Tire Kinematics Analysis

In order to simplify the analysis, it is assumed that the entire vehicle turns with a constant speed at a level and flat ground, and the tire roll angle is zero and the influence of the tire width is ignored. In the actual steering process, it is always accompanied by the tire slippage. Generally, for a wheeled vehicle,
during the large-radius steering, the driving force acts on the outer driving wheels and the braking force acts on the inner driving wheels, which is prone to slip.

The sliding of the tire relative to the ground can be divided into lateral sliding and longitudinal sliding. Figure 1 is an exploded view of the ground contact speed of the tire in a slip situation. \( v_c \) is the speed of the car body involved, \( v_r \) is the speed of the rotational movement relative to the wheel center, \( v_s \) is the tire ground speed, and forms an angle \( \alpha \) with the \( Y \) axis. It can be known from the above analysis that the slip velocity \( v_s \) exists on the ground contact surface of the tire, that is, the instant center of the speed of the ground contact surface is offset instead of at the geometric center.

![Figure 1. Decomposition of the slip speed.](image)

### 2.2 Vehicle Kinematics Analysis

Figure 2 is a schematic diagram of the vehicle’s slipping steering motion analysis on a horizontal road surface. A coordinate system is established with \( O \) as the origin of coordinates, \( X \) as the transverse direction, and \( Y \) as the longitudinal direction. In the Figure 2, \( O \) is the steering center, \( R \) is the steering radius, \( R_g \) is the distance between the steering center and the vehicle’s center of gravity \( N \). The center of gravity coincides with the geometric center of the vehicle. The ground pressure is uniform, and \( W \) is the steering angular velocity.

![Figure 2. Steering motion analysis.](image)

During the steady-state steering, the vehicle makes a uniform circular motion at a speed \( V_o \) around \( O \), and the angle between \( V_o \) and the \( Y \) axis is \( \beta \), as shown in the Eqs. (1) and (2).

\[
V_g = \omega R_g \tag{1}
\]

\[
R = R_g \cos \beta \tag{2}
\]

Therefore, the relationship between the vehicle speed \( V_g \) and the turning radius \( R \) is obtained, as shown in the Eq. (3).
3. kinetics analysis

Figure 3 shows the analysis of the steering force of the vehicle. From the above analysis, it can be known that $O_1$ and $O_2$ are the instantaneous steering centers of the inner and outer tires respectively, $A_1$ and $A_2$ are the lateral offsets respectively. The magnitude of the longitudinal offset $e$ of the steering center can characterize the stability of the vehicle when steering. A larger value indicates a larger distance from the centroid of the steering centerline and the worse steering stability. On the contrary, a smaller value indicates more stable steering. The distances from the instantaneous steering centers $O_1$ and $O_2$ to the longitudinal symmetry planes of the tires are $A_1$ and $A_2$ respectively. Their values reflect the degree of tire slippage, and mean the steering maneuverability. The larger the value is, the more the actual steering path deviates from the expected steering will be. The smaller the value of path is, the smaller the speed loss will be, and the closer the steering expectation is to the steering process in the theoretical state.

$$V_o = \frac{\alpha R}{\cos \beta}$$

3.1 The external force acting when turning

It can be seen from the Figure 3 that the external force received by the vehicle at this time is mainly the rolling resistance of each tire, the supporting force of the ground on each driving wheel, the reaction force of the ground against tire sliding when turning, and the centrifugal force generated by the vehicle during steering. The vertical force balance of the vehicle and the moment balance of the ground point can be used to obtain the support force of each wheel, as shown in the Eq. (4).

$$N_1 = N_2 = N_3 = N_4 = \frac{1}{4} G$$

Take tire 1 as an example of the force analysis. To facilitate the analysis, the steering center $O$ is the coordinate origin. The line connecting steering center $O$ and $O_1$ is designated as the $X$ axis, and the coordinate system is established parallel to the vehicle longitudinal direction as the $Y$ axis. The friction force $F_1$ is opposite to the direction of $V_1$, and is perpendicular to the line connecting the steering center and the center of the ground plane. Its components in the $X$-axis direction and the $Y$-axis direction are shown in the Eqs. (5) and (6) respectively. In the same way, the forces of the ground acting on other tires along the $X$-axis and $Y$-axis can be obtained.
Moreover, the rolling resistance of the tire 1 can be obtained by the Eq. (7). Here $f_c$ is the rolling resistance coefficient. Similarly, the rolling resistance of other tires can be obtained.

\[ F_{r,1} = \frac{1}{4} f_c G \]  

Furthermore, the components of the centrifugal force $F_c$ at the center of gravity of the vehicle in the $X$-axis direction and the $Y$-axis direction can be obtained, as shown in the Eqs. (8) and (9).

\[ F_{cx} = \frac{mV^2 \sin \beta}{R_g} = \frac{meV_c^2}{R^2 + e^2} \]  
\[ F_{cy} = \frac{mV^2 \cos \beta}{R_g} = \frac{mRV_c^2}{R^2 + e^2} \]  

3.2 External torque acting when turning

When the vehicle is turning at a constant speed, the longitudinal force and the lateral force received by the vehicle take a torque on the vehicle’s turning center $O_c$ to form three external torques when turning. The steering driving torque $M_{q,1}$ formed by the force $F_1$ in the tire 1 is calculated by the Eq. (10), and the calculated steering resistance torque $M_{z,1}$ is shown in the Eq. (11).

\[ M_{q,1} = \frac{B}{2} F_{ly} = \frac{1}{8} \mu GB \frac{A_i}{\sqrt{A_i^2 + \left(\frac{L}{2} + e\right)^2}} \]  
\[ M_{z,1} = \left(\frac{L}{2} - e\right) F_{lx} = \frac{1}{4} \mu G \frac{\left(\frac{L}{2} + e\right)^2}{\sqrt{A_i^2 + \left(\frac{L}{2} + e\right)^2}} \]  

Steering driving torque and steering resistance torque of other tires can be obtained in the same way.

The torque generated by the centrifugal force during the steering of the vehicle is shown as the Eq. (12).

\[ M_c = eF_{cs} = \frac{me^2V_c^2}{R^2 + e^2} \]  

3.3 Traction and braking required for steering

When the vehicle turns, the outer tire is subjected to traction and the direction is the same as the forward speed; the inner tire is subjected to the braking force and the direction is opposite to the forward speed. Assuming that the outer traction is $P_o$ and the inner braking is $P_i$, that is, the vehicle
must provide such large traction and braking force to overcome rolling resistance and provide the driving torque required for steering, as shown in the Eqs. (13) and (14).

\[ P_o = F_{3y} + F_{4y} \]  
\[ P_i = F_{1y} + F_{2y} \]  

4. Mathematical modeling

According to the force and torque balance during steady steering of the whole vehicle, the mathematical model of large radius steady steering can be obtained and summarized in the Eqs. (15), (16) and (17). When the expressions of various forces and moments are brought into the equations, the force balance equations are obtained when the vehicle is in steady-state steering.

\[ F_{1x} + F_{3x} + F_{ex} = F_{2x} + F_{sx} \]  
\[ P_o + F_{cy} = f_r G + P_i \]  
\[ M_e + M_z = M_q \]  

5. Simulation analysis

Taking a certain type of tactical vehicle as an example, its structural parameters and ground parameters are shown in the Table 1. The steady-state steering dynamics are analyzed according to the model in this research. The analysis results are shown in the Figures 4 and 5 respectively.

| Vehicle structural parameters | Ground parameters |
|-------------------------------|-------------------|
| Vehicle quality              | 1080kg            | Ground adhesion coefficient | 0.8 |
| Wheelbase                    | 1.72m             | Rolling resistance coefficient | 0.03 |
| Track                        | 1.54m             |                                |      |
| Tire radius                  | 0.37              |                                |      |

In Figure 4, when the speed is constant, along with increase of steering radius, the wheel slip radius gradually increases, and the amount of steering centerline movement gradually decreases. The increase of the slip radius is due to the increased braking force of the inner wheels, and the decrease of the steering centerline movement is caused through the reduction of the traction force of the outer wheels. The value decreases along with the steering radius increases, which indicates that the steering centerline becomes difficult to move along with the turning radius increases. At this time, the vehicle’s handling becomes worse, but its stability increases.

In Figure 5, when the steering radius is constant, as the vehicle speed increases, the slip radius of the wheels gradually decreases, because the braking force of the inner wheels becomes smaller; the amount of movement of the steering centerline gradually increases, and the traction of the outer...
wheels increases. Great cause. At this time, as the centrifugal force becomes larger, the moment of the force on the steering center also increases. In order to balance the moment, moment of the lateral force of the wheel ground contact surface on the steering center needs to be increased, and the steering centerline moves forward. The greater the amount of steering centerline movement is, the worse the stability of the tracked vehicle will be when turning in this state.

6. Conclusions
Taking the lateral offset and the longitudinal offset of the steering center as the evaluation indicators of the steady-state slip steering characteristics of a wheeled vehicle, a mathematical model of the vehicle’s steady-state steering is established and a solution method is proposed, which can be used to simulate the lateral analysis of inner and outer tires. Variation of offset and longitudinal offset of steering centerline with steering radius and vehicle speed and its impact on the vehicle steering stability. The mathematical model and numerical analysis method proposed in this paper can be used to analyze the effect of the slip phenomenon of the wheeled vehicle on the steady steering of the vehicle during slip steering.

References
[1] Cheng J W, Gao L H, Wang H Y 2006 Steering analysis of tracked vehicles based on skid condition Chinese Journal of Mechanical Engineering 26(5) 396-400.
[2] Wang H Y, Qin L, Rui Q 2014 Analyzing and testing verification the performance about high-speed tracked vehicles in steering process Chinese Journal of Mechanical Engineering 50(16) 162-171.
[3] Maclaurin B 2011 A skid steering model using the magic formula Journal of Terramechanics 48 247-263.
[4] An J, Zhou Z L, Cao F Y 2006 The effect on vehicle stationary turning performance of tracked slip and turning center line excursion Journal of Henan University of Science and Technology 27(5) 146-150.
[5] Qiao J L, Fan Y, Jin M 2017 Study on the Steering Characteristics of Four Wheel Steering Vehicle Journal of North University of China 38(04) 458-465.
[6] Dong C, Chen K, Gao X L 2017 Tracked Vehicle Skid Steer Performance Analysis Under the Influence of the Centrifugal Force Journal of Vibration, Measurement & Diagnosis 37(01) 76-83 + 200.
[7] Li A D, Li C S, Wang Y 2018 Kinematic Analysis and Trajectory Tracking Control for Skid-Steered Mobile Robots Machinery Design & Manufacture 11(1) 253-256.
[8] Cui M Y, Sun D H, Li Y F, Liu W N 2013 Adaptive tracking control of wheeled mobile robots in presence of longitudinal slipping Control and Decision 28(05) 664-670.

Figure 5. Relationship of $A_1$, $A_2$, $e$ and $V$ when $R = 30$m.