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The effect of parallel steering of a four-wheel drive and four-wheel steer electric vehicle during spinning condition: a numerical simulation

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Abstract. X-by-wire technology is an advancement in automotive industry and is recognized by many countries in recent years. The in-wheel motor system is a type of drive-by-wire technology and it will be the main focused for the vehicle model in this paper. The steer-by-wire is a kind of by-wire technology in the automotive industry for the electric vehicle. [1] Steer-by-wire technology can be divided into two types which are two-wheel steering (2WS) and four-wheel steering (4WS). As we know, 2WS system is used in most of the vehicles.[2] However, the lower maneuverability will be shown in this type of vehicle during the vehicle spinning. The dynamic equation of motion was used for the simulation of vehicle movement.[3] The software of MATLAB Simulink was used to imitate that the effect of 4WD and 4WS EV during cornering.[4,5] The passive control was used in this simulation. As the result, the simulation indicated that 2WS EV is easy oversteered. After applied 4WS system, the vehicle oversteer problem was successfully solved by use parallel steering mode.

1. Introduction

The by-wire technology in the automotive industry is the use of electrical or electro-mechanical systems for performing vehicle functions traditionally achieved by mechanical linkages.[6] In general, it was divided into two different types which are the central motor system and in-wheel motor system. The central motor is motor put at the internal combustion engine position for a normal vehicle.[7] It will be supplied the electric power to every drive wheel.[8] The in-wheel motor is placed inside the hub of each wheel. It only provides power to the wheels on which it is located.[9] In-wheel motor is more independently. And it let the vehicle reduce the weight due to is can be reducing the many mechanical part. Such as, transmission shaft, power shaft and so on.[10]

For the driving system, there are two drive types of the vehicle which are 2WD and 4WD. The word meaning shows that 2WD is the vehicle that drives with two wheels and the rest wheel just follow.[11] 4WD is a type of the full-wheel drive system, it means that the vehicle will drive with four wheels. If the vehicle only has four wheels, the 4WD also can be called full-wheel drive.[2] Normally, the FWD can be changed to all types of the drive system.[12] Such as two wheels mode and a part-time system.

The steer-by-wire is another by-wire technology. Most of the vehicles use 2WS because the normal

vehicle has mechanical restrictions.[13] From the perspective of controlling the vehicle, the 2WS system is easier to let the driver control the vehicle.[14] 4WS system is more complex than 2WS because it has many steering types based on the specific objective and function.[15] For the 4WS, it can be divided into four modes which are 2WS, Opposite, Crab Steer (also called Parallel Steer) and Zero Turn. Due to the 4WS system is flexibility work as a 2WS by restricting the rear wheel moment. For the opposite steering mode, front wheel directions are opposite to rear wheel directions. This helps to take a sharp turn with least turning radius. And often used at lower speed. For the parallel steering mode, both the front and rear wheels face in the same direction.[16] It will decrease the yaw rotation speed, make vehicle have a slower turning. For the Zero turn, the angle of front and rear wheels is 45° inward and 45° outward, and the vehicle revolves around the center of the chassis. The path of the wheel is a circle.

Nowadays, every day will have many kinds of traffic accident happen. A kind of the accident is because of the vehicle occur oversteering during high speed cornering condition.[17] It is very dangerous if the vehicle can not have a steady cornering.

In this paper, completed an electric vehicle that simulated the parallel steering and four-wheel drive.[3] Firstly, calculate the time (t=2.3s) required for the simulated vehicle to reach a constant speed (V=5.75m/s) by simulation. Second, simulating the effect of 2WS on the vehicle when the front wheel steering angle θ_F = 10 deg at a constant speed. The results show that the vehicle will oversteer at that condition. Then, parallel steer mode was used for reducing the oversteer. In detail, the rear wheel steering angle θ_R was be increased from 1 to 9 deg. When $\theta_F = 10°$ and $\theta_R = 9°$, the oversteer phenomenon has been alleviated and simulated vehicle can make a steady cornering.

2. Main Symbols

Table 1. The main symbols

Symbol	Description	value	unit
l_F	length from front wheel axle to gravity	0.756	m
l_R	length from rear wheel axle to gravity	0.534	m
d_F	front tread	0.84	m
d_R	rear tread	0.815	m
r	radius of the tire	0.23	m
m	mass of the vehicle	421.81	kg
b	width of wheel interact surface	0.1	m
l	length of wheel interact surface	0.15	m
k	road coefficient	0.8	
I	yaw inertia moment at gravity point of vehicle	1470	kgm^2
K_X	longitudinal tread rubber stiffness	3.33×10^6	N/m^3
K_Y	lateral tread rubber stiffness	3.33×10^6	N/m^3
F_Z	wheels load subject to load transfer	1034.5	N
$\omega_{FL}, \omega_{FR}, \omega_{RL}, \omega_{RR}$	tire rotational speed of each tire		Rad/s
$X_{FR}, X_{FL}, X_{RR}, X_{RL}$	friction force for each tire		N
θ_F, θ_R	front and rear wheels steer angle		°
$\gamma:$	yaw rotational speed		Rad/s
ρ	slip ratio		
β	side slip angle		°
$\beta_{FR}, \beta_{FL}, \beta_{RR}, \beta_{RL}$	tire side slip angle		°

3. Vehicle model

3.1 Toyota COMS

Figure 1. Toyota COMS[18]

Table 2. Specification of Toyota COMS [12]

Specification	Volume
Price	10,000(USD)
Mileage	50 km
Versions	Two (P.COM&B.COM)
Weight	≈ 408.2 kg
Speed	60 km/h (Max)
Charging	6 hours

The Toyota COMS is an ultra-small electric vehicle with a range of approximately 50 kilometers. The maximum speed of this vehicle is 60km/h. Regenerative braking helps to replenish the battery and charging the COMS to 100% using a standard Japanese 100 volts home socket is said to take about 6 hours. This compact single-seater weighs only 900 pounds and is designed to pass urban parking and road space restrictions. The specification of this model is used as a test model for the simulation. The Toyota COMS is a 2WD in wheel EV and it only equipped with 2WS system. However, it was considered as a 4WD and 4WS EV during simulation.

4. Dynamics Equation of Motion

4.1 Vehicle Dynamics
The main research object of vehicle dynamics is how the vehicles respond to driver input on a given road. The derivation of the dynamic equation of motion comes from the application of Newton's law in the inertial reference frame. The dynamic equations were used for longitudinal velocity, lateral velocity, and yaw rotational speed.[3,19–21] The equations are shown as below:

$$m\left(\frac{du}{dt} - v\gamma\right) = (X_{FR} + X_{FL})\cos\theta_F + (X_{RR} + X_{RL})\cos\theta_R - (Y_{FR} + Y_{FL})\sin\theta_F - (Y_{RR} + Y_{RL})\sin\theta_R \tag{1}$$

$$m\left(\frac{dv}{dt} + u\gamma\right) = (X_{FR} + X_{FL})\sin\theta_F + (X_{RR} + X_{RL})\sin\theta_R + (Y_{FR} + Y_{FL})\cos\theta_F + (Y_{RR} + Y_{RL})\cos\theta_R \tag{2}$$

$$I\frac{d\gamma}{dt} = l_F[(X_{FR} + X_{FL})\sin\theta_F + (Y_{FR} + Y_{FL})\cos\theta_F] + l_R[(X_{RR} + X_{RL})\sin\theta_R + (Y_{RR} + Y_{RL})\cos\theta_R] + \frac{d_F}{2}[(X_{FR} + X_{FL})\cos\theta_R + (Y_{FR} + Y_{FL})\sin\theta_F] + \frac{d_R}{2}[(X_{RR} + X_{RL})\cos\theta_R + (Y_{RR} + Y_{RL})\sin\theta_R] \tag{3}$$

4.2 Tire Characteristics

The wheel is an important factor in the simulation.[22] Therefore, during the modeling process, slip ratio, tire side slip angle, and weight distribution are all taken into account in calculating the friction force and the side lateral force. The deformation of the tire tread rubber is also used to derive these shown below equations.

When $\xi_s > 0$, then the longitudinal force and lateral force can be written as

$$F_x = -K_s s \xi_s^2 - 6\mu F_z \cos\theta \left(\frac{1}{6} - \frac{1}{2}\xi_s^2 + \frac{1}{3}\xi_s^3\right)$$

$$F_y = -K_\beta(1+s)\tan\beta\,\xi_s^2 - 6\mu F_z \sin\theta \left(\frac{1}{6} - \frac{1}{2}\xi_s^2 + \frac{1}{3}\xi_s^3\right)$$

(4)

And when $\xi_s \leq 0$, then

$$F_x = -\mu F_z \cos\theta$$

$$F_y = -\mu F_z \sin\theta$$

(5)

Where:

$$\tan\theta = \frac{K_\beta \tan\beta\,(1+s)}{K_s s} \qquad\qquad \cos\theta = \frac{s}{\lambda}$$

$$\sin\theta = \frac{K_\beta \tan\beta\,(1+s)}{K_s \lambda}$$

During the simulation, the point where the contact surface changes from the adhesive region to the slip region is found from the following:

$$\xi_s = 1 - \frac{K_s}{3\mu F_z}\lambda$$

Where:

$$K_s = \frac{bl^2}{2}K_x \qquad\qquad K_\beta = \frac{bl^2}{2}K_y$$

$$\lambda = \sqrt{s^2 + \left(\frac{K_\beta}{K_s}\right)^2 (1+s)^2 \tan^2\beta}$$

The equation for the side-slip angle to each tire is given as below:

$$\beta_{FL} = tan^{-1}\left(\frac{v + l_F\gamma}{u + d_F\frac{\gamma}{2}}\right) - \theta_F \quad , \qquad \beta_{RL} = tan^{-1}\left(\frac{v - l_R\gamma}{u + d_R\frac{\gamma}{2}}\right) - \theta_R$$

$$\beta_{FR} = tan^{-1}\left(\frac{v + l_F\gamma}{u - d_F\frac{\gamma}{2}}\right) - \theta_F \quad , \qquad \beta_{RR} = tan^{-1}\left(\frac{v - l_R\gamma}{u - d_R\frac{\gamma}{2}}\right) - \theta_R$$

$$(6)$$

Tire slip ratio s is used in calculating and expressing the slipping behavior of the wheel of an automobile. The equation as below:

$$s = \frac{u - r\omega}{r\omega} \tag{7}$$

The coefficient of tire friction μ can be approximated by the following equation:

$$\mu = -1.10k \times (e^{35\rho} - e^{0.35\rho}) \tag{8}$$

5. Control System
Passive control was used in the simulation for the rear wheel steer angle input. The main focus is to control the speed of the car and steering angle of the front and rear wheels.[23] In the simulation, first, select a suitable tire rotational speed. This speed will be used as the speed at which the car reaches a constant speed during simulation. The effect of this speed is to verify the results of the different 2WS angles in this case.[24] Finally, the appropriate steering angle is selected for the simulation of 4WS.

6. Simulation Procedures
The first stage of the simulation was to simulate the cornering of the vehicle. The simulation block diagram is shown in Figure 2. First, any suitable tire rotation speed ω=25 rad/s is selected, and the simulation time is selected as t=10 s, thereby determining the initial time t=2.3 s of the tire turns. Then continue to simulate 2WS, the simulation time is changed to t=100s, after the simulation starts, the speed V gradually increases until the speed reaches a constant speed after 2.3 seconds, the front wheel starts to turn with the steering angle is θ_F=10°.

The second stage is to simulate the mitigation effect of 4WS on oversteer. The rear wheel steering angle is from θ_R=0° ~ 9°, and the other parameters are the same as in the first stage [3].
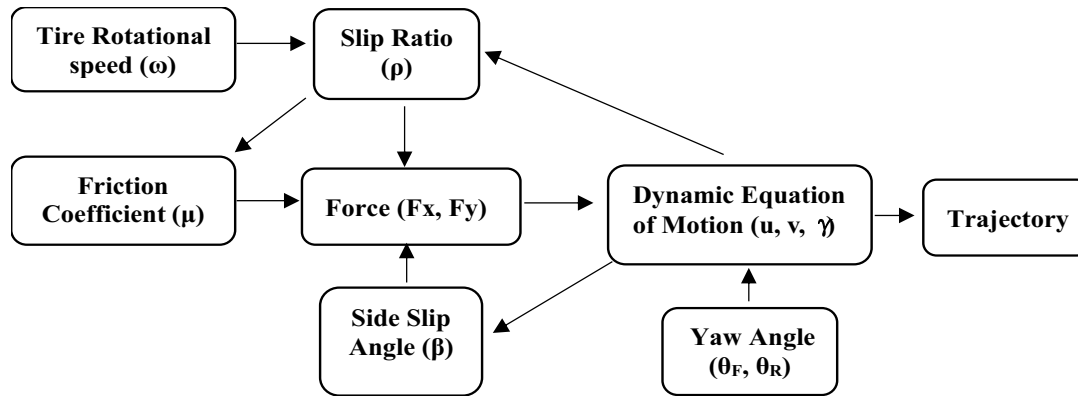

Figure 2. Simulation block diagram

7. Result and Discussion

Figure 3 shown the longitude speed of 2WS and 4WS during the vehicle turning, the speed of longitudinal is decreased much for 2WS. The normal turning will not reduce longitudinal speed too much. And the longitudinal speed proved the vehicle drifted based on this figure. The longitude speed for 4WS during cornering at θ_F=10° and θ_R=9°. The speed after cornering just have a bit decrease. So, it means that the vehicle is moving steadily.

The Figure 4 showing the lateral velocity of 2WS and 4WS. For the 2WS, the speed starts with zero and increasing at positive speed side after that all speed is negative speed. The reason is that the direction for the velocity of the gravity is always as a tangent of turning circle. The lateral speed after two times increase and decrease become more stable and it is close to 0. The lateral speed at end of simulation time around negative 0.1m/s. This result proves that using four-wheel steering to reduce the oversteer is effective. That
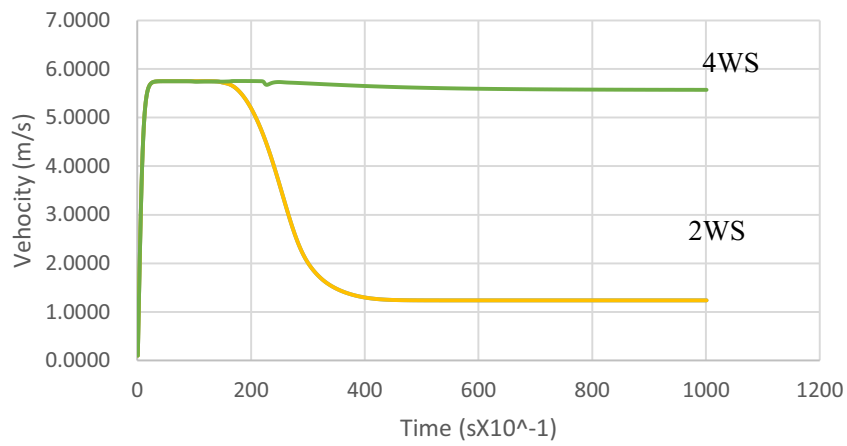
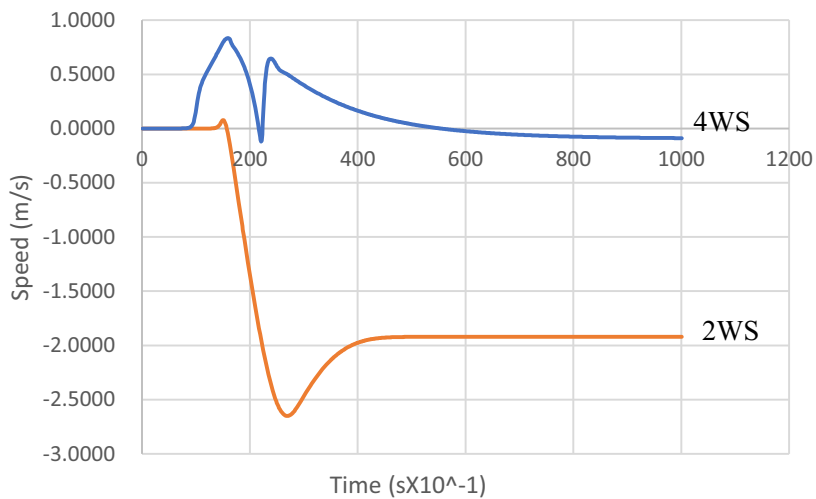**Figure 3.** Longitudinal speed at θ_F equal to 10°

Figure 4. Lateral speed at θ_F equal to 10°

fluctuates result happen because of when rear wheel starts turning the vehicle already spin. So, from here we can get even four-wheel steer can reduce spinning, but it will take a time
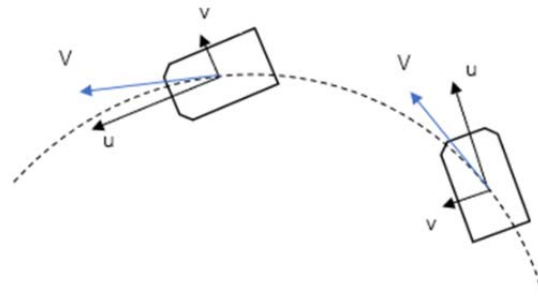
Figure 5. Vehicle turning

As Figure 5 shows that when the direction of longitudinal velocity is inside of turning circle. Then the direction of lateral velocity will be outward. This figure also showed that when the vehicle turns in any direction if consider this longitudinal direction is the positive direction. Then the speed of the lateral will be in a negative direction.
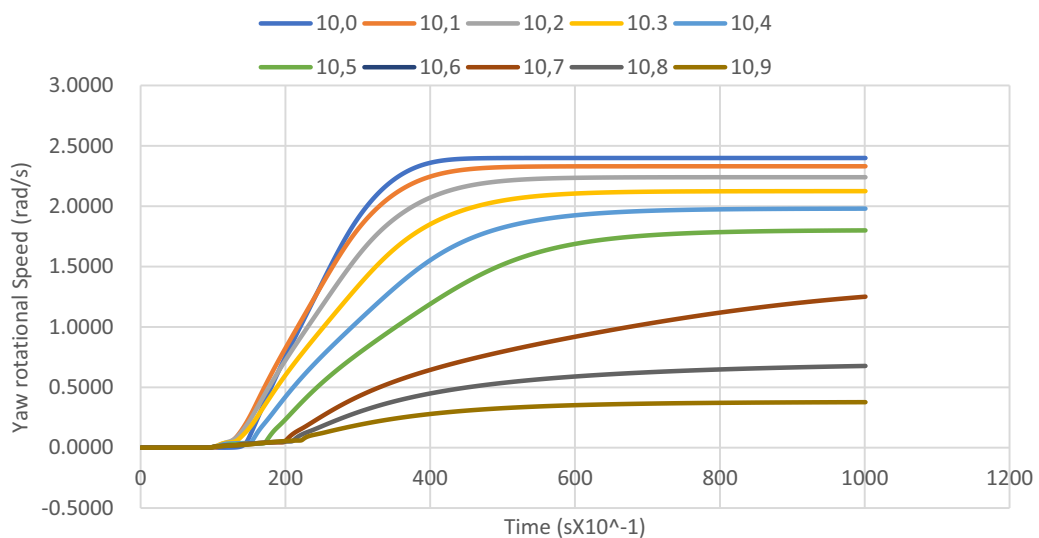

Figure 6. Yaw rotational speed for 2WS and 4WS

Figure 6 showed the yaw rotational speed at 2WS and 4WS conditions. In order to have a good cornering performance, the yaw rotation speed cannot be too higher and also cannot be very lower around zero. During the 2WS, the vehicle will spin was proved from the figure shown on 20s to 40s. So, for the 4WS electric vehicle cannot have much yaw rotational speeds. From the figure, as the steering angle of the rear wheel increases, the yaw rotational speed is gradually reduced. The "10,0", means that the front wheel steering angle is 10 degrees and the rear wheel steering angle is 0 degree. The meanings of the following numbers are the same. For example, "10,1" means that the front wheel has a steering angle of 10 degrees and the rear wheel has a steering angle of 1 degree.
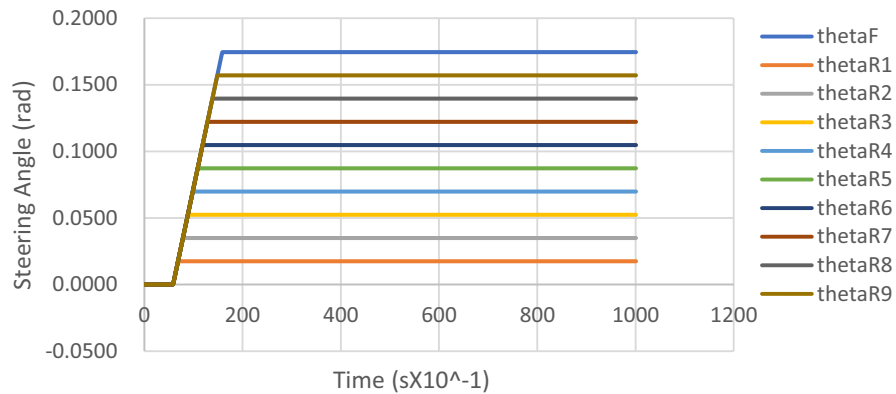
Figure 7. Steering angle for front and rear wheel

From the Figure 7, the angle is increasing slowly in order to have a good performance for this project. "ThetaF" means that angle is for front wheel angle. The front wheel angle was used as 10 degrees. "ThetaR1" means that angle is for rear wheel angle. "1" means turn 1 degree during that condition.
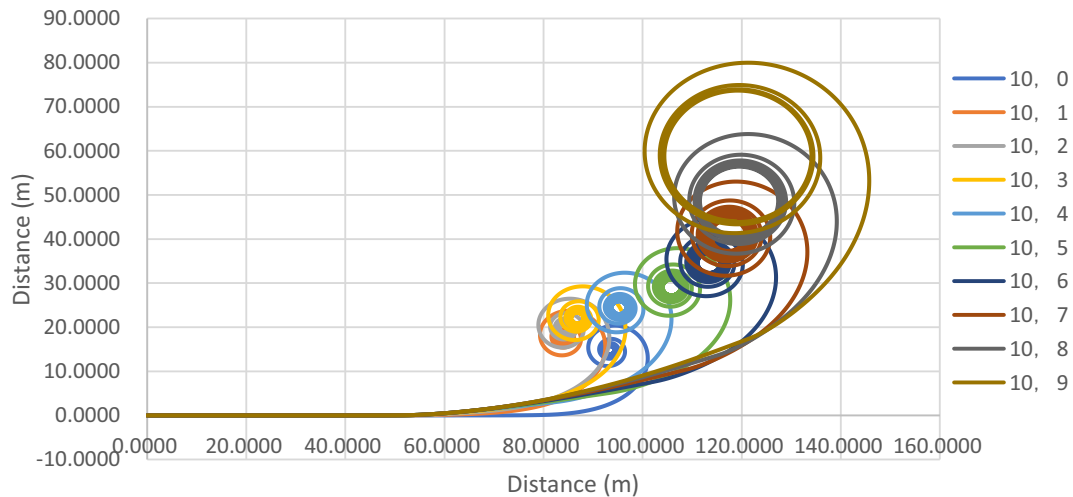

Figure 8. Trajectory for 2WS and 4WS

The Figure 8 shown that the trajectory at 2WS and 4WS condition. The "10, 0" means front wheel angle is 10 degrees, rear wheel angle is 0 degree. Which means that the first one "10, 0" is two-wheel steering, and the rest is four-wheel steering. From the figure, we can see that since start turns the rear wheel the trajectory changed more and bigger. This thing happened because the rear wheel is turned for reduce spinning. So, in this condition, the distance will become longer. From the first line, we can see that the

trajectory line is going to the middle of the circle. With the increase of the rear steering angle, the trajectory almost became a real circle.

8. Conclusion

This paper studies the vehicle dynamics of 4WD and 4WS electric vehicles through numerical simulation. In the first phase of the study, the process of turning the EV was simulated. The results show that the simulated vehicle will spin when the tire rotation speed ω=25rad/s and θ_F=10°. In the second phase, the 4WS mode was used. The oversteering of the EV is alleviated by turn the rear wheel. During the simulation processing, the steering angle of the front wheels be constant at 10°, and the steering angle of the rear wheels is increased from 1° to 9°. During the gradual increase of θ_R, the mileage used by the vehicle to turn increase but the phenomenon of oversteering is alleviated. Therefore, if the EV oversteering when turning at a constant speed, the 4WS EV using Parallel Steer mode will solve this problem.

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