Proc. Schl. Eng. Tokai Univ., Ser. E
40 (2015) 71-75

Research on Steering Control of a 4 Wheel Steering Electric Vehicle with Intelligence Steering Control System

by

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(Received on Mar. 30, 2015 and accepted on Jul. 14, 2015)

Abstract

Due to small roads and slippery conditions, driving in urban areas can be dangerous for most vehicles because the tires will easily slip. However, the risk can be reduced if the vehicles have improved performance and controllability. Here, 4 Wheel Steering (4WS) Small Electric Vehicle (SEV) control for driving is addressed as a solution for the problem. Here, we proposed the Intelligence Steering Control System (ISCS) on the 4WS SEV. ISCS will compare the drivers demand to the dynamics of the SEV and the circumstances surrounding the vehicle, road conditions and vehicle stability. Then, ISCS will control all 4 wheels driving or braking torque and steering angles independently. This enables the vehicle to move under the safest conditions. In normal steering, only front wheel is used to make cornering. In opposite steering, both front and rear wheels will turn in opposite direction for cornering. With the results, we prove that the usage of opposite steering in the 4WS SEV can increase the cornering performance.

Keywords: Four wheel steering (WS), Two wheel steering (WS), Electric vehicle (EV), Intelligence steering control system (ISCS), Normal steering, Opposite steering

1. Introduction

Due to the growing urge to reduce the fuel consumption, world concern over the vehicle's green technology has risen to a remarkably high level. Manufacturers have started to research on the innovation of green technology vehicles such as fuel cell EV (FCEV) and hybrid vehicles (HEV). On the other hand, there are many narrow roads in urban area. This is due to limited land size to accommodate a lot of people. With this concern in mind, a small mobility is seen as a solution to the problem. We predict that the usage of small mobility vehicle will be increased in the future[1)]. For small mobility vehicle, manufacturers and researchers are focusing on the development of Small Electric Vehicle (SEV).

There are 2 types of motor system used in SEV. Type 1 is centralized motor system which replace combustion engine to a motor. Type 2 is in-wheel motor system, which means there is an electric motor attached to every driving tire. In comparison to centralized motor system, in-wheel motor system has many advantages such as low amount of energy loss, quick torque response and ability to measure the torque applied on each tire[2)].

When driving in urban area, the road can be narrow and sometimes slippery due to snow or rain. In slippery road, the friction coefficient between tire and the road is greatly reduced. However, for SEV with in-wheel motor, an antilock brake system (ABS) is very difficult to install due to space limitation. ABS is a basic skid control system to prevent the wheels from locking up and avoid uncontrolled skidding. The lack of ABS system in SEV makes it very dangerous during emergency braking. To overcome this problem, mechanical braking system is installed at the driving tire as a replacement for ABS.

In recent years, many studies have been made regarding in-wheel motor SEV. A study on dynamic motion of opposite and parallel steering showed the effect of steer angle to vehicle movement[3)]. In safety aspect, the research on skid control EV have been made. It used direct yaw moment control (DYMC) to control the tire steering in braking to increase vehicle`s

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Table 1 Specifications of analysis model

Vehicle mass, *m*	422 [kg]
Height of center of gravity	0.105 [m]
Tread length d_f, d_r	0.84 [m]
Length of tire interacted surface l_f, l_r	0.64 [m]
Moment of inertia *I*	1470 [kgm^2]
Inertia of tire	2.530 [kgm^2]
Driving system	4 in-wheel motors

stability[4]. For control system, traction control method was proposed to generate appropriate driving force based on the acceleration pedal[5]. Traction control based on optimal slip was proposed to control the skid braking and slip acceleration. A sliding mode controller is designed for tracking the optimal wheel slip, where the optimal value of the wheel slip is obtained from the tire model[6].

To replace ABS and enhance the control system in SEV, we propose the Intelligence Steering Control System (ISCS) on 4WS SEV. ISCS is a system that automatically change the vehicle's tire angle according to the circumstances surrounding the vehicle. ISCS will compare the drivers demand to the dynamics of SEV and the circumstances around the vehicle, road conditions and vehicle stability. Then, ISCS will control all four wheels driving or braking torque and steering angle independently. This enables the vehicle to move on the safest condition.

The objective of this research is to apply ISCS in 4WS SEV. In this paper, we reported the first step of ISCS where it control a model vehicle in 2WS (normal steer) and 4WS (opposite steer) driving. We did a comparison for the cornering using normal steer and opposite steer. The experiment was made using both computer numerical analysis and model test.

2. Application of ISCS

By understanding the characteristics of tire steering condition, we can decide which condition to be used on various type of road. For example, opposite steer system gives great advantages when driving on narrow road. Thus we can set ISCS to enable opposite steer system when the vehicle enter narrow road or making sharp turning.

Intelligence Steering Control System (ISCS) will act as an assist to the driver. It will automatically decide the best steering condition to be used when driving. In order for ISCS to make better judgement, a proper study on each steering condition is needed.

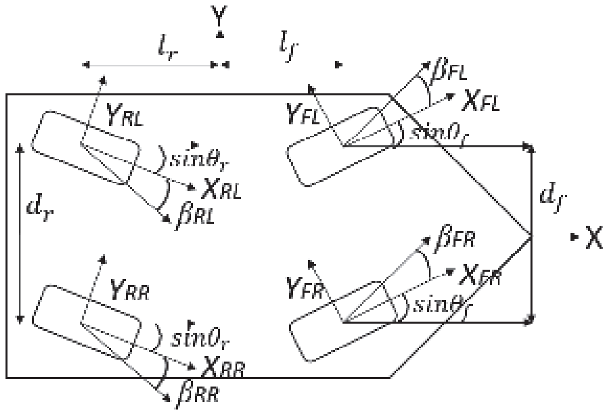


Fig. 1 Analysis model

3. Analysis

3.1 *Main symbols*

b: width of tire interacted surface [m], *F*: Friction force [N], *g*: Gravitational acceleration [m/s^2], *I*: Moment of inertia [kgm^2], *l*: length of tire interacted surface [m], *m*: Body mass [kg], *R*: Tire radius [m], *T*: Torque [Nm], *u*: Vehicle longitudinal speed [m/s], *v*: Vehicle lateral speed [m/s], *W* : Wheel load [N], *X*: Driving force on frontal direction [N], *Y*: Driving force on lateral direction [N], β: Side slip angle [rad], ρ: Slip ratio, *r*: Yaw angular velocity [rad/s], μ: Driving friction coefficient, ω: Tire angular velocity [rad/s]

Suffix:

D : driving, F : front, R : rear, L : left, R : right, *x* : coordinate in *x*-axis, *y* : coordinate in *y*-axis, *z* : coordinate in *z*-axis

3.2 *Analysis Model*

Figure 1 shows the analysis model. The specification of our analysis model is shown in Table 1. In this analysis, we assumed the following points:

1) Rotation on *x*-axis of the vehicle is ignored
2) Rotation on *y*-axis of the vehicle is ignored
3) The movement on *z*-axis of the vehicle is ignored

The model and its specifications was made using Toyota COMS as a reference.

3.3 *Basic equations of motion*

Vehicle velocity and location in *x*-axis and *y*-axis was obtained using the following equations.

$$m\left(\frac{du}{dt} - vr\right) = (X_{FL} + X_{FR})cos\theta_f + (Y_{FL} - Y_{FR})\sin\theta_f + (X_{RL} - X_{RR})\cos\theta_f + (Y_{RR} - Y_{RL})\sin\theta_r \quad (1)$$

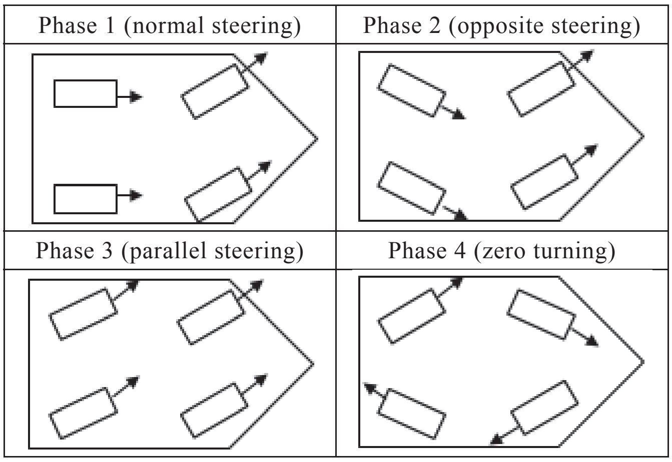


Fig. 2 4 different types of cornering

$$m\left(\frac{dv}{dt}+ur\right)=(Y_{FL}+Y_{FR})\cos\theta_f-(X_{FL}+X_{FR})\sin\theta_f$$
$$+(Y_{RL}+Y_{RR})\cos\theta_r+(X_{RL}+X_{RR})\sin\theta_r \quad (2)$$

Yaw angular velocity was obtained by following equation.

$$I\frac{dr}{dt}=l_f\left[(X_{FL}+X_{FR})\sin\theta_f+(Y_{FL}+Y_{FR})\cos\theta_f\right]$$
$$+l_r[(X_{RL}+X_{RR})\sin\theta_r-(Y_{RL}+Y_{RR})\cos\theta_r]$$
$$+\frac{d_f}{2}\left[(X_{FR}-X_{FL})\cos\theta_f+(Y_{FR}-Y_{FL})\sin\theta_f\right]$$
$$+\frac{d_r}{2}[(X_{RR}-X_{RL})\cos\theta_r-(Y_{RR}-Y_{RL})\sin\theta_r] \quad (3)$$

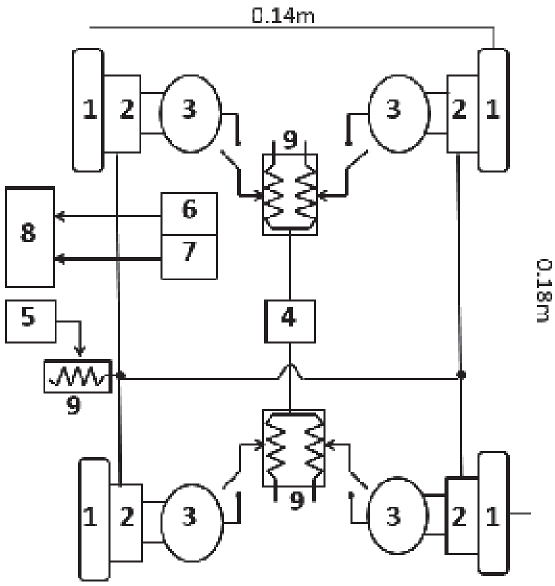
In vehicle dynamics, side slip angle, β is the angle between a rolling wheel's actual direction of travel and the direction towards which it is pointing. Side slip angle can be calculated using following equation.

$$\beta_{FR}=tan^{-1}\left(\frac{v+l_f\omega}{u+\frac{d_f\omega}{2}}\right)-\theta_f\ ;\ \beta_{FL}=tan^{-1}\left(\frac{v+l_f\omega}{u-\frac{d_f\omega}{2}}\right)-\theta_f$$

$$\beta_{RR}=tan^{-1}\left(\frac{v-l_r\omega}{u+\frac{d_r\omega}{2}}\right)-\theta_r\ ;\ \beta_{RL}=tan^{-1}\left(\frac{v-l_r\omega}{u-\frac{d_r\omega}{2}}\right)-\theta_r \quad (4)$$

3.4 *Tire Characteristics*

To solve the dynamic equation shown in section 2.3, we need to calculate the Forces *X* and *Y*. Forces *X* and *Y* is calculated using brush model[7-8]. In brush model, the value of sideslip angle, slip ratio and friction coefficient is needed to complete the calculation. Sideslip angle value was obtained from eq. (4) in section 2.3. Slip ratio ρ and friction coefficient μ was obtained using the following equations



1: Tire, **2**: Driving motor, **3**: Steer motor, **4**: Steer battery, **5**: Driving battery, **6**: Acceleration sensor, **7**: Gyro sensor, **8**: Data logger, **9**: Variable resistance

Fig. 3 Experiment model

$$\rho=\frac{V-r\omega}{V} \quad (5)$$

$$\mu=-Croad\times 1.05\times(e^{-35\rho}-e^{-0.35\rho}) \quad (6)$$

Dry Asphalt : *Croad*=0.8
Icy Road : *Croad*=0.12

Slip ratio is the difference between vehicle velocity and tire speed. Next, using magic formula equation[5)], approximation of the friction coefficient μ was calculated.

To calculate the slip ratio value, we need to know the value of tire angular speed. Tire angular speed was calculated using the following equation.

$$I_T\frac{d\omega}{dt}=T_D-T_f \quad (7)$$

3.5 *Simulation condition*

Figure 2 shows 4 different types of cornering avaiable in 4WS system. However, in this paper, we only compared the cornering performance between normal steering and opposite steering. The simulation was done in slippery road condition, where friction coefficient of road is set to 0.12. During simulation, the initial velocity of vehicle and steering angle was set to 0 degree. Vehicle will then accelerate until it reached desired velocity (15 km/h). Once the velocity reached 15 km/h, it will maintain constant velocity and the tire steering angle will increase. Input driving torque was maintained at certain value to keep the constant velocity during cornering.

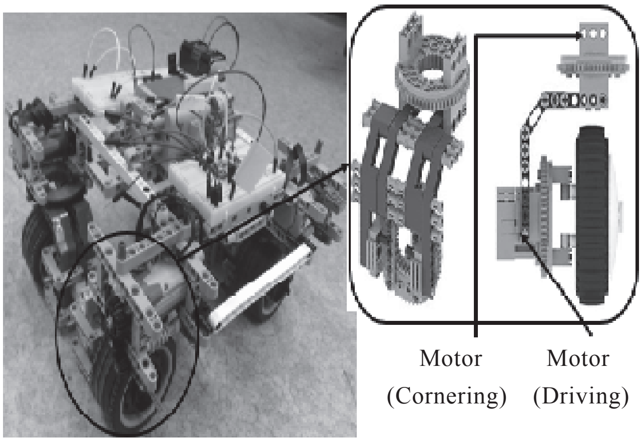


Fig. 4 Experiment model & steering system

Table 2 Specifications of experiment model

Parameter	Model	Unit
Body mass	1	kg
Length of tire interacted surface	0.18	*m*
Tread length	0.14	*m*
Tire radius	0.035	m

4. Experiment

4.1 *Experiment model*

Based on the result obtained from numerical analysis, we proceed to model experiment to verify the result. To verify the numerical analysis result, we did an experiment with LEGO model which is 10 times smaller size than real SEV (1:10). Figs. 3 and 4 shows our experiment model and its steering system. In the model, we use 2 types of sensor which is acceleration sensor and gyro sensor. We attached the sensor at the middle of the model (center of gravity) to calculate the model's acceleration, speed and yaw angle.

By using 2 motor in each tire, we can control the speed and turning angle of all tire independently. This enables the usage of 4 different types of cornering as shown in Fig. 4. This model was made according to the scale of Toyota COMS. However, the similarity features between the model and real EV had not yet been tested. The specifications for the experiment model is shown in Table 2.

4.2 *Model experiment condition*

The objective of this experiment is to compare the cornering performance between normal steering and opposite steering. Tire angle was set to 15 degree. The time taken to finish the experiment is 20 seconds. After 20 second, we record the location of the model and plot it into a graph. The difference between normal and opposite steering is shown below:

Normal steering : Front tire= 15° ; Rear tire = 0°
Opposite steering : Front tire = 15° ; Rear tire = 15°

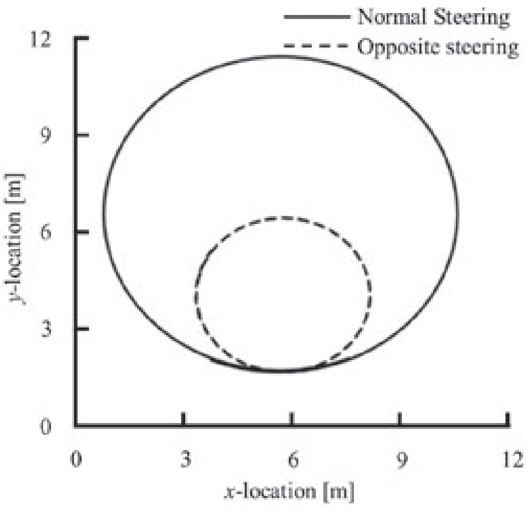


Fig. 5 Vehicle location (simulation)

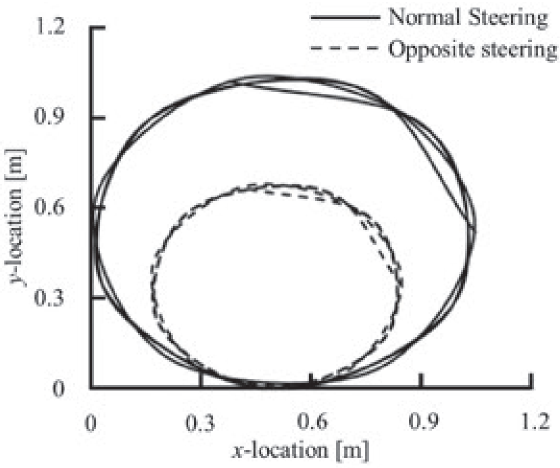


Fig. 6 Model location (model experiment)

5. Result and Discussion

Figures 5 and 6 shows the simulated trajectories in normal steering and opposite steering. The trajectories correspond by tire steering input. We use this result to make a comparison between normal and opposite steering cornering. From the results above, we confirmed that the turning radius of opposite steering is smaller than normal steering. Normal steering takes longer distance in a cornering. Hence, we can conclude that opposite steering has higher cornering performance.

In case of normal steering, cornering force is only produced at front tires. The rear tires will only follow the

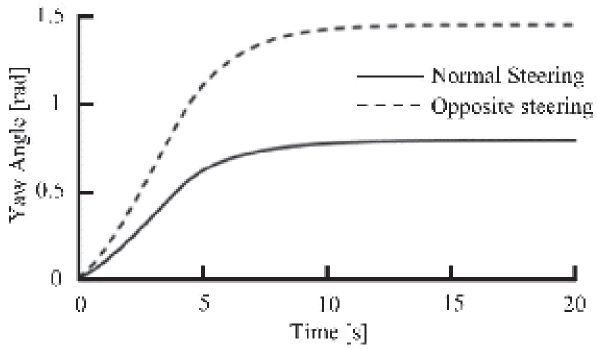


Fig. 7 Yaw angular velocity

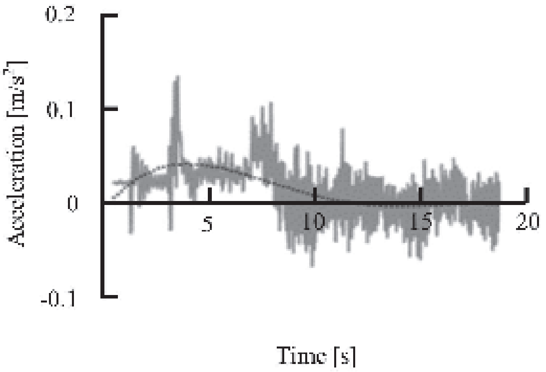


Fig. 8 Model acceleration

movement of front tires. However, for opposite steering, cornering force is produced at both front and rear tires.

Opposite steer produces excess cornering forces as an addition to the yaw moment control. This results in higher yaw angular velocity of the vehicle. The result value of yaw angular velocity is shown in Fig.7. Fig.8 shows the acceleration of the model during experiment. To match the experiment condition with simulation condition, we make the model to move at constant velocity (acceleration =0) after it reached desired velocity. In the simulation, the yaw angular velocity in opposite steer increase faster than normal steer. This is because opposite steer produced higher cornering force as explained before. From this result, we understand the relation between yaw angular velocity and cornering performance.

6. Conclusion

In this study, we aimed to increase the performance and stability of Electric Vehicles. Thus we constructed a simulation and experiment to compare the cornering performance normal steer and opposite steer. We controlled the tire position during cornering and recorded the vehicle condition. Based on the results, we had the following conclusions:

1) Opposite steering has higher cornering performance than normal steer.
2) Opposite steer has better response to steer angle change. This is because the yaw angular velocity of opposite steer increase faster than normal steer.

In the future, we plan to improve the model of this vehicle by adding more sensors for higher accuracy results. We also plan to design collision avoidance ability into this model by using infrared distance sensors and PIC control.

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