Improved Four Wheel Steering System

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***Abstract*—This paper discusses the advantages of four-wheeled steering system in automobiles and proposes a new mechanism that is simple and easy to control. Different variations of steering such as in-phase and out-of-phase steering is simulated and compared with regular two-wheel steering. These variations was found to reduce the turning radius during U-Turns and during high speed lane change and cornering, there is an increase in stability and reduction in roll of the car. The kinematics of the steering is briefly explained that uses Ackerman geometry.**

***Index Terms*—four-wheel steering, two-wheel steering, in-phase steering, out-of-phase steering, ackerman geometry,**

I. Introduction

The majority of current vehicles are manufactured with two-wheel steering systems, and the world is unaware of the safety and stability standards a four-wheel steering system can bring. Excellent handling makes passengers feel safe and in control, making panic swerves and steering corrections as controlled as possible. Even the driver's slightest touch on the wheel directs the steering system precisely and accurately. A well-designed suspension handles the excellent quality of the steering system. It is challenging for a typical four-wheel system to take a U-turn Alternatively, to have stability while taking turns with high speed.

There is a lot to be improved in the two-wheel steering system,but the issues are more or less solved by introducing the four-wheel steering system. With such a steering system, these problems can be minimized, and they can take turns easily with minimum space consumed. In this project, the primary concern is to design a four-wheel steering system with a different steering mechanism incorporated in phase and out-phase methods, and we intend to reduce the turn radius while taking curves.

The direction of steering the rear wheels relative to the front wheels depends on the operating conditions. At a low-speed wheel,movement is pronounced so that the rear wheels are steered in the opposite direction to that of the front wheels. At high speed, when steering adjustments are minute. The front wheels and the rear wheels turn in the same direction; by changing the direction of the rear wheels, there is a reduction in the turning radius of the vehicle, which is efficient in parking, low-speed cornering, and high-speed lane change [1]. Most cars use front-wheel driving with a Rack and Pinion steering system in the present scenario. So basically, it converts rotary motion into linear motion. This system is occupied with a circular gear which is the pinion, which locks teeth on a bar which is the rack.

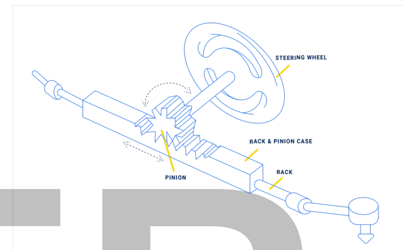


Fig. 1. Rack and pinion

In the typical front-wheel driving system, rear wheels do not turn in the direction of the curb, and it reduces the efficiency of steering. This problem generally arises in the case of high-speed monitoring. When a driver turns the wheel of typical front-wheel steering when it is at high speed, the car's forward momentum produces powerful sideways or cornering force at the front axle because the front tyres immediately begin to pivot during that situation. However, it will take time for the rear wheel to generate the corresponding required force at the rear axle, which will only begin when the car starts turning. This time delay is the main reason behind cars with two-wheel steering fishtails while they change lanes; in short, the vehicle's back end is trying to catch up with the front end. In extreme cases, or under slippery conditions, the car's rear may fishtail out of control [2].

A. Advantages of Front-wheel driving

- Wheels are slipping, it provides enough tactile feedback for the driving wheels.
- It has fewer components which results in enhancing its gasoline mileage, and it makes the vehicle lighter.
- While driving through slippery roads or while climbing hills, it can provide better traction since its engine and transmission are located above the driving wheels.

B. Disadvantages of Front-wheel driving

- They tend to understeer mostly.
- Due to torque steer, these vehicles tend to change direction suddenly, either to the right or left, while applying sudden acceleration
- Have the lower towing capacity
- Less stability while taking turns at high speed

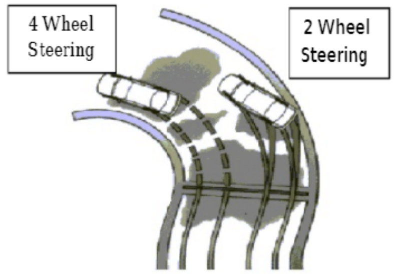


Fig. 2. Graphical comparison of 2WS and 4WS turning

As technology advances, four-wheel systems with fully electronic steer-by-wire systems, equal steering angles for front and rear wheels, and sensors to monitor the vehicle dynamics and adjust the steer angles in real time are in the process of development. Although such a complex four-wheel steering model has not been created for production purposes, several experimental concepts with some of these technologies have been built and tested successfully [1]. There have been proposed and developed four-wheel steering systems of vehicles of the type where a reference value of the rear-wheel steering angle is determined from the steering angle of the steering wheel and the vehicle speed. Even mechanisms to detect the angular speed of the steering wheel are also provided in the current inventions from which the reference value for rear-wheel steering is determined, and thus, by steering at the speed of reference value, rear-wheel steering without response delay can be obtained [3].

If all four wheels are steering the vehicle, then the vehicle requires very little input from the driver for steering; that is the main principle behind four-wheel steering. This reduction in the effort will help eliminate vehicles' fishtailing when they change lanes at high speed. When the rear wheels are turned simultaneously and in the same direction as the front wheels, the back end turns with the front, and the cornering forces occur at both axles simultaneously. The car slides smoothly to the side without sway or fishtail [1].

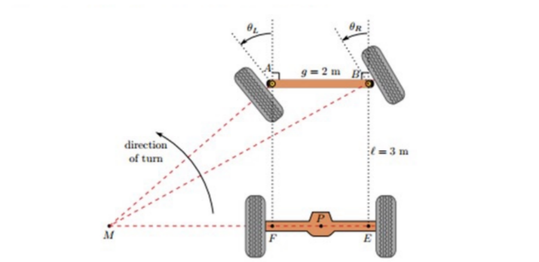


Fig. 3. FWS direction of turn

Usually, this turning radius will be larger in the case of the front wheel steering, as seen from Fig. 3, and it is not easy to turn the vehicle in a shorter radius. This makes many situations challenging for the driver to control and manage the vehicle, especially in traffic areas and parking. Also, the system has some instabilities and may lead to accidents in extreme conditions.

C. Vehicle behaviour

A vehicle's behaviour while taking a turn can be split into two: transient and steady-state responses. The steady-state response between Front-wheel sterling and Four-wheel steering will remain the same during the transition from driving to turning. However, the transient response is different for those between going straight and reaching the steady state [4].

D. Transient response of FWS vehicle to steering input

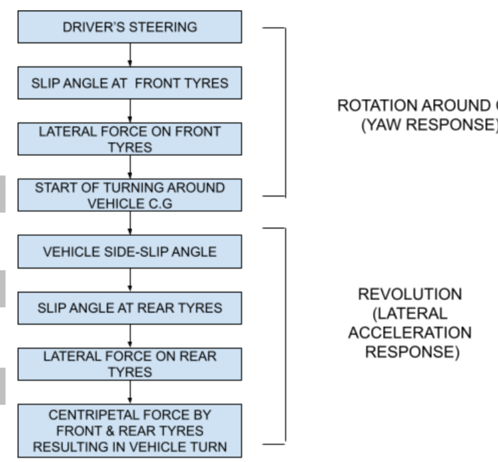


Fig. 4. Transient response of FWS to steering input

As shown in the Fig. 4, two phases of lateral force are generated even before the turning of vehicles starts. Of the two phases, one is created by the front wheels, which start rotation around the centre of gravity. This will result in yaw motion, as indicated in the above diagram. The second phase is created by a slip-side angle on the rear wheels, which results in turning the vehicle in the direction needed [4]

E. Transient response of 4WS vehicle to steering input

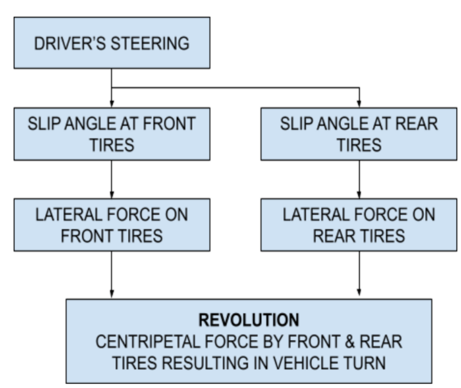


Fig. 5. Transient response of 4WS to steering input

Fig. 5 shows the transient response for four-wheel steering. The diagram shows that there is no time lag between the generation of cornering force between the front and back end. Also, there are no slip-angles and no rotation around the centre of gravity. Centripetal force provides a shorter time to start the turning of the vehicle in comparison with front-wheel steering. [4].

II. Calculation of Turning Radius

A. Turing circle measurement

As per Indian standards 12222, a turning circle is created by drawing a circle, as shown in Fig 6. The outer wheels move when the steering wheel is turned to the maximum lock, and the vehicle moves at a speed below 5km/h. This measurement is done on both sides of the steering wheel lock, and the average of these two circles' diameter is represented as the turning circle diameter and half of this value is termed as the turning radius of the circle [5].

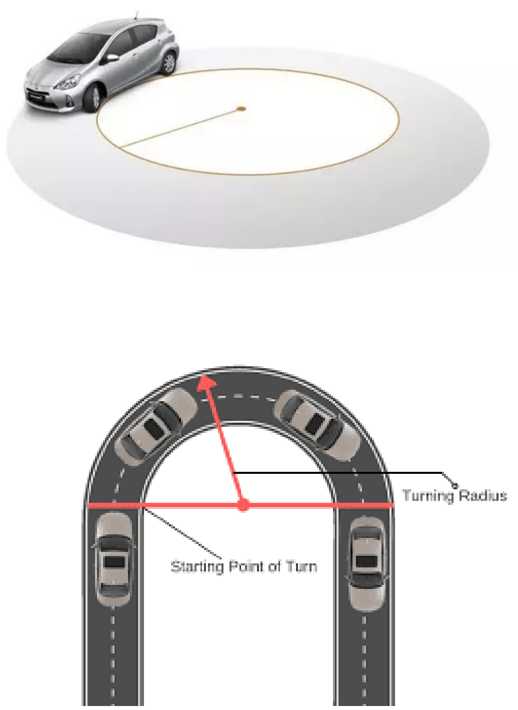


Fig. 6. Turning radius measurement

B. Turning radius calculation

For the kinematic analysis of a steering system, we must know the basic kinematics of the steering. For this, the basic steering system is studied. According to Ackerman's condition for a front-wheel steering system, the difference of the cotangents of the angles of the front outer to the inner wheels should be equal to the ratio of width and length of the vehicle being considered. The turning radius of a vehicle is calculated as follows [6].

$$\begin{aligned} R &= \sqrt{a_2^2 + l^2 \cot^2 \delta} \\ \cot \delta &= \frac{\cot \delta_0 + \cot \delta_i}{2} \end{aligned} \tag{1}$$

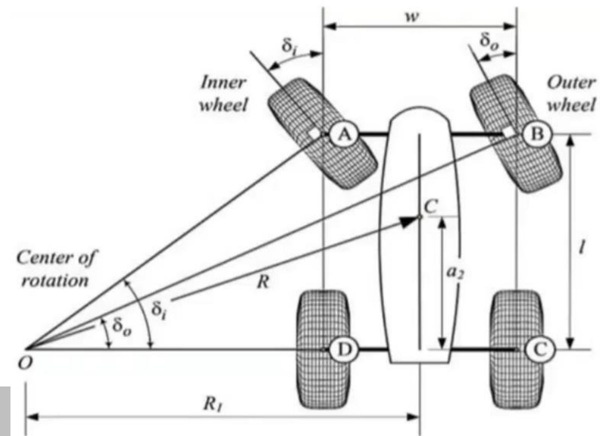


Fig. 7. Turning radius measurement of a vehicle

1) Calculation method for positive four-wheel steering:

$$\cot \delta_{of} - \cot \delta_{if} = \frac{w_f}{l} - \frac{w_r}{l} \frac{\cot \delta_{of} - \cot \delta_{if}}{\cot \delta_{or} - \cot \delta_{ir}} \tag{2}$$

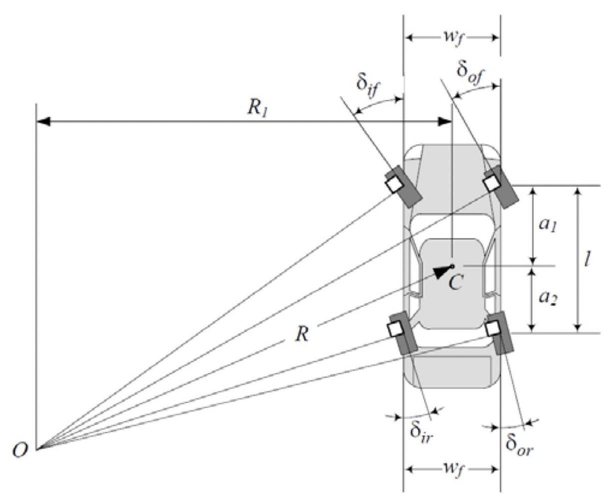


Fig. 8. Positive four wheel steering system

$$\begin{aligned} \tan \delta_{if} &= \frac{C_1}{R_1 - \frac{w_f}{2}} \\ \tan \delta_{of} &= \frac{C_1}{R_1 + \frac{w_f}{2}} \\ \tan \delta_{ir} &= \frac{C_2}{R_1 - \frac{w_r}{2}} \\ \tan \delta_{or} &= \frac{C_2}{R_1 + \frac{w_r}{2}} \end{aligned} \tag{3}$$

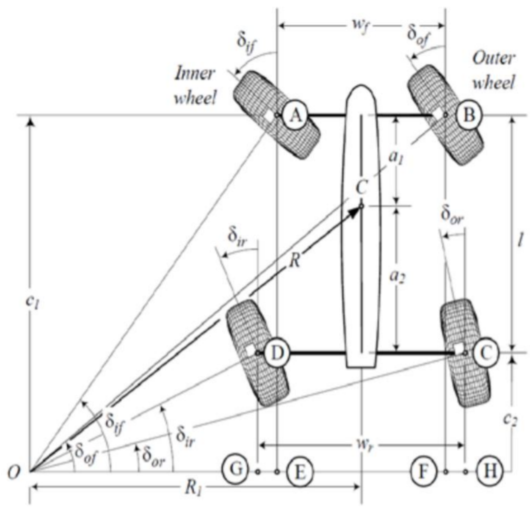


Fig. 9. Positive four wheel steering system angles

$$\cot\delta_{of} - \cot\delta_{if} = \frac{w_f}{C_1}$$
$$\cot\delta_{or} - \cot\delta_{ir} = \frac{w_r}{C_2} \quad (4)$$
$$C_1 - C_2 = l$$
$$\frac{w_f}{\cot\delta_{of} - \cot\delta_i f} - \frac{w_r}{\cot\delta_{or} - \cot\delta_{ir}} = l$$

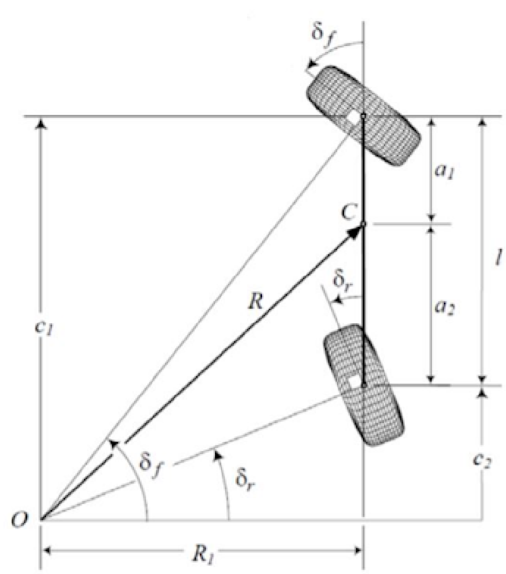


Fig. 10. Bicycle model of four wheel steering system

Considering the above-mentioned relations, the turning radius can be obtained as follows [5].

$$R = \sqrt{a_2^2 + l^2 \cot^2\delta} \quad (5)$$

C. Theoretical comparison between FWS and 4WS

Apply the concept of Four-wheel steering to the existing model of a car with front-wheel steering. For that, use the standard data of the car Maruti Suzuki Baleno as a reference [7]–[9].

Standard Parameter	Dimensions
Wheel base(L)mm	2520
Front track width(w_f)mm	1515
Rear track width(w_r)mm	1525
Turning radius (R)mm	4900
Weight of car(W)kg	935
Weight distribution (Front : Rear)	60:40
Load on front axle(W_f)kg	561

TABLE I
STANDARD SPECIFICATIONS OF MARUTI SUZUKI BALENO

To find a_2

$$W_f = \frac{W \times a_2}{L}$$
$$a_2 = 1512$$

From which calculate R_1

$$R^2 = a_2^2 + R_1^2$$
$$R_1 = 4660.88$$

For illustration take inner angle of the rear tyre, δ_{if} as 27.4^0. Take the value of δ_{if} such that the value of C_1 does not exceed the wheelbase L. Usually this value will be less than 30^0. The distance of instantaneous center from front axle axis, C_1 is as follows

$$\tan\theta_{if} = \frac{C_1}{R_1 - \frac{w_f}{2}}$$
$$C_1 = 2023.32$$

Distance of instantaneous center from front axle axis, C_1 and Distance of instantaneous center from rear axle axis, C_2 is described by the relation

$$C_1 + C_2 = L$$
$$C_2 = 496.68$$

To find δ_{of}

$$\tan\delta_{of} = \frac{C_1}{R_1 + \frac{w_f}{2}}$$
$$\delta_{of} = 20.3$$

To find δ_{ir}

$$\tan\delta_{ir} = \frac{C_2}{R_1 - \frac{w_r}{2}}$$
$$\delta_{ir} = 7.23$$

To find δ_{or}

$$\tan\delta_{or} = \frac{C_2}{R_1 + \frac{w_r}{2}}$$
$$\delta_{or} = 5.14$$

Now, considering the same steering angle for the front and rear wheel, we reduce the vehicle's turning radius but keep the wheelbase and track width the same as the reference vehicle. ie $\delta_{if} = \delta_{ir} = 27.4^0$ and $\delta_{of} = \delta_{or} = 20.3$

$$\delta_i = \delta_{if} + \delta_{ir} \quad = 54.8$$
$$\delta_o = \delta_{of} + \delta_{or} \quad = 40.6$$

To find $\cot \delta$

$$\cot \delta = \frac{\cot \delta_i + \cot \delta_o}{2} = 0.9355$$

To find turning radius R

$$R^2 = a_2^2 + L^2 \cot^2 \delta = 2800$$

From the above results, it is evident that introducing a Four

Turning radius	Four-wheel steering	Front-wheel steering
By calculation	2.8m	4.9m

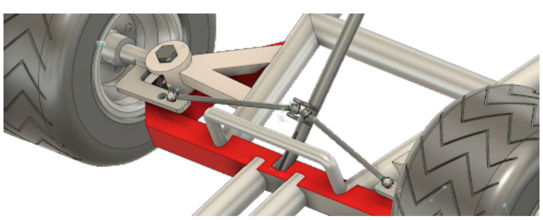
TABLE II
COMPARISON OF TURNING RADIUS OF BALENO BY CALCULATION

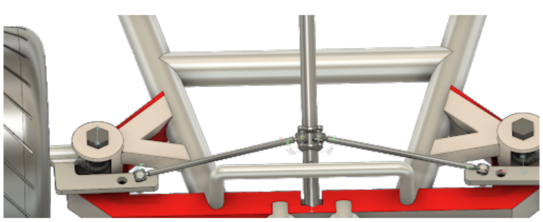
wheel steering system to an existing Front wheel steering system would effectively reduce the turning radius taken by the vehicle while taking a curve. Here the reduction brought was about 42 percent.

III. Proposed Mechanism

Design a four-wheel steering system that specifically emphasizes the stability of the vehicle while steering. Also, we intend to develop a system with the following features :

- Superior cornering stability.
- Improved steering response and precision.
- High-speed straight-line stability.
- Improved lane-changing maneuver
- Smaller turn radius.
- Relative wheel angles and their control.





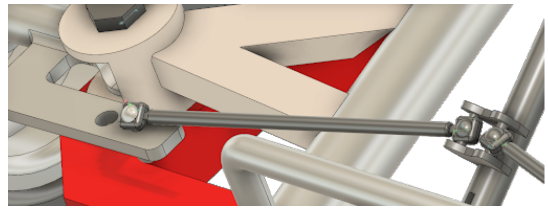


Fig. 11. Autodesk Fusion 360 model of Four WS - Close views of the Steering mechanism

Fig 11 shows how the various components of the steering system are connected. The steering wheel and the steering column are connected and can be rotated. The two ball bearings on the steering column help guide and move the tie rods, turning the wheel joints. All these connections are through spherical joints.

IV. Out of Phase Steering

This strategy aims not to allow the vehicle to slide sideways during a turn. Turning the rear wheels out of phase of the front wheels can achieve zero side-slip. This can reduce lateral movement and reduce the delay phase in lateral acceleration, which occurs in FWS and improves manoeuvrability by reducing the Turning Circle (TC). The negative side to this strategy is the increased yaw rate, which makes this strategy unsuitable at high speeds.

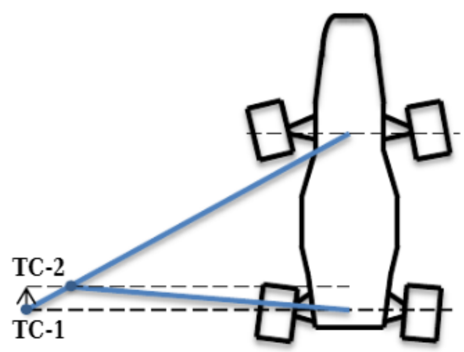


Fig. 12. Out of phase steering

Fig. 12 shows the rear wheels turning opposite to the front wheels.This system does have a higher construction and maintenance cost, and the mechanism is a little more complex than the standard system.

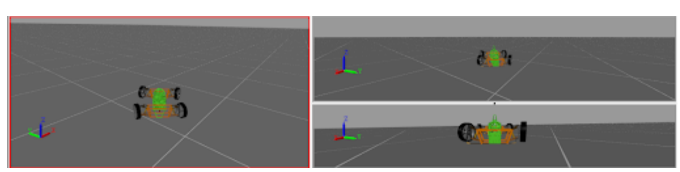


Fig. 13. 3D simulation of the car in out-of-phase steering during the turn

In Fig. 14 ,the car path along with vehicle roll magnitude with respect to time is given. The turning radius of the car is

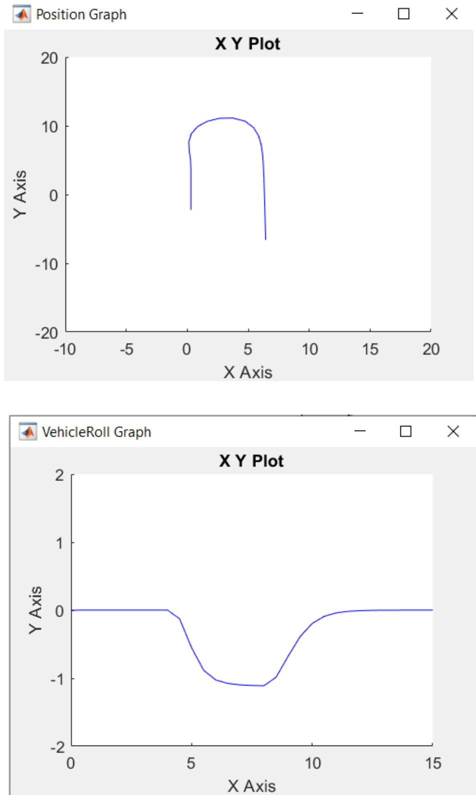


Fig. 14. Position and Vehicle Roll graphs for out-of-phase steering

measured to be 2.984 m. And the maximum magnitude of the roll is near 1. Comparing to two-wheel steering which had a turning radius of 6.0124m, and a maximum magnitude of the roll of 0.5, there is a reduction of approximately 50%.

V. In Phase Steering

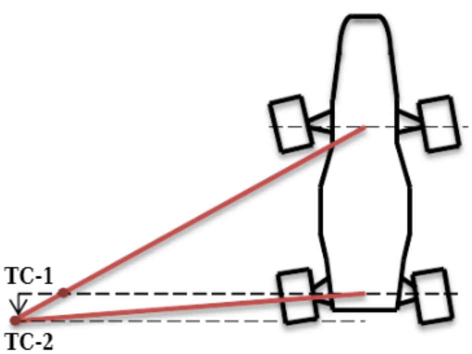


Fig. 15. In phase steering

This strategy aims to reduce the rotational motion around the centre of gravity and increase the lateral motion; this is more suitable for high speeds. This strategy works in opposition to a zero side-slip strategy. Turning the rear wheels in the phase of the front wheels can achieve zero yaw- rate. Fig 15 represents the direction of front wheels with respect to rear wheels

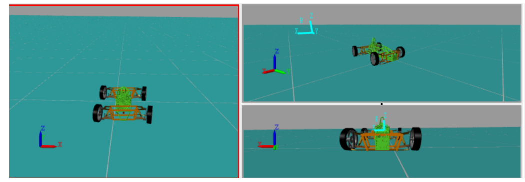


Fig. 16. 3D simulation of the car in in-phase steering during the turn

Fig. 17 shows the path taken during the lane change. The lane change is much more smooth and easy to make. Also, the vehicle roll is lower than two-wheel steering, giving more stability and comfort.

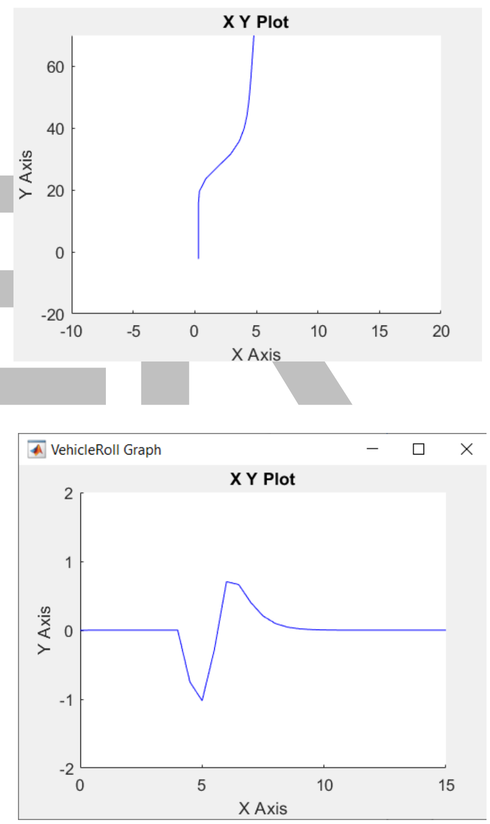


Fig. 17. Position and Vehicle Roll graphs for in-phase steering

Inference

- In the case of Front wheel steering, Lateral force on rear tyres develop only after the response is generated by the lateral force on front tyres, whereas in the case of four-wheel steering, the lateral force on both front and rear tyres develop at the same time which leads to shorter time to turn the vehicle which implies the shorter turn radius for the four-wheel steering system.
- The turning radius of the car during low speed using out of phase configuration was about 50 percentage lower than using front-wheel steering. Nevertheless, the roll was a bit higher than the standard case.

- During lane change in a high-speed scenario, the four-wheel in-phase steering configuration was able to take the lane changes quickly, and the roll is much lower than the usual case. This leads to more stability and less prone to accidents.
- The data from production car theoretical analysis suggested that by outfitting the four wheel steering system, the turning radius lowered by 42percentage compared to the front wheel steering system.

CONCLUSION

The results from this study suggest that a viable method for four-wheel steering for cars can be done. Furthermore, it is advantageous to use this system as the car's turning radius was brought down by 50 percentage. The stability in high-speed cornering and lane changes was increased. Concerning the implementation of the system, the mechanism designed was simple and hence easy to manufacture. This could lead to lower prices and hence could introduce this system in low-end cars.

The theoretical case study of making an actual production car(Suzuki Baleno) into a four-wheel steering system gave the results of reducing the radius by 42 percentage. Similar case studies conducted on other cars with varying dimensions and weight distributions could bring down the radius by 40-55 percentage.

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