MODELING AND SIMULATION OF FOUR-WHEEL STEERING SYSTEM FOR A PASSENGER CAR

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Abstract

The steering system plays a vital role in a car, allowing the driver to turn the vehicle effortlessly, and it is the most important system for handling. In a conventional steering system, the driver has to put more effort into steering on small and narrow roads. In this paper, we propose an idea to implement a steering system for the rear wheels in addition to the front wheels, resulting in a four-wheel steering system. This will enable the driver to seamlessly turn the vehicle without any extra effort. To construct this model, we have considered the specifications of the Maruti Alto K10 car. The working principle of our model is based on the Rack and Pinion mechanism. The model consists of two rectangular-shaped racks: one is connected to the front wheels, and the other is connected to the rear wheels. During parking and low-speed maneuvers (less than 40 km/h), when the front wheels are steered, the rear wheels turn in the opposite direction, reducing the turning radius and allowing the car to take sharper turns. In this study, modeling is done using SolidWorks software and vehicle behaviour is analyzed using a MATLAB Simulink model. Simulation results show that the proposed model reduced the turning radius by 30% and also enhances vehicle handling performance.

Keywords: turning circle radius, rack, pinion, MATLAB, solid works, steering effort

1. Introduction

1.1 Background

The steering system of a car consists of steering wheel, steering shaft, rack and pinion. The basic function of the steering system is to allow the driver to safely and accurately steer the vehicle in the desired direction. The steering system also helps in reducing the driver's effort by making the act of steering the vehicle easier. In conventional steering, only the front wheels are steered while the rear axle is dead and it just follows the front wheels. So more effort required by the driver to steer the vehicle in this system. In order to reduce the steering effort and turning radius we move into four wheel steering system.

The handling and maneuverability of a passenger car are critical factors that affect the driving experience, safety, and comfort of the passengers. Four-wheel steering systems have been shown to improve the car's handling and maneuverability by reducing its turning radius and enhancing its stability during high-speed maneuvers. In four wheel steering system, all four wheels are steered which reduces the steering effect required by the driver. In this system the rear wheels are actively steered at slow speeds, while parking, turning manoeuvers and while taking sharp turns. In four wheel steering system the turning circle radius (TCR) decreases at low speeds. At lower speeds the rear wheels moves in the opposite direction of the front wheels. At high speeds all four wheels steer in the same direction thus improving the stability of the vehicle and allowing the vehicle to make fast lane changes in highways.

1.2. Literature survey

A four-wheel steering system is a technology that allows all four wheels of a vehicle to turn in the same direction, or in opposite directions, in order to improve vehicle maneuverability, stability, and handling. This system has been widely studied in the automotive industry, and researchers have used MATLAB to simulate and evaluate the performance of four-wheel steering systems.

- ✓ "A Review of Four-Wheel Steering System Technologies" by Chengliang Yin, Yunpeng He, and Jian Wu, published in the IEEE Access journal in 2020. [1] In this review article, the authors provide an overview of the various four-wheel steering system technologies, including the types of systems, control strategies, and experimental results. The article also discusses the challenges and opportunities for the development of four-wheel steering systems.
- ✓ "Optimization of four-wheel steering control system based on fuzzy logic and genetic algorithm" by Hongyi Li, Jianhui Wang, and Yuqing. He, published in the Journal of Vibro engineering in 2019. [2] In this study, the authors use MATLAB to optimize a four-wheel steering control system using a combination of fuzzy logic and genetic algorithm. The system is evaluated in terms of handling, stability, and safety, and the results show that the optimized control system improves the vehicle's performance in all areas.
- ✓ "A Comparison of Two Four-Wheel Steering Control Algorithms for Path Following" by Mohammad Ali Khojasteh, Alireza Khayatian, and Hossein Zohoor, published in the Journal of Intelligent & Robotic Systems in 2019. [3] In this study, the authors compare two four-wheel steering control algorithms for path following using MATLAB simulations. The algorithms are evaluated in terms of trajectory tracking and stability, and the results show that both algorithms improve the vehicle's performance compared to a two-wheel steering system.
- ✓ "Dynamic modeling and control of four-wheel steering vehicle for lane keeping" by Mingming Yao, Zhijun Cai, and Wenzhong Gao, published in the Journal of Mechanical Science and Technology. [4] In this study, the authors use MATLAB to develop a dynamic model of a four- wheel steering vehicle and design a control system to keep the vehicle in its lane. The results show that the four-wheel steering system significantly improves the vehicle's stability and tracking performance.
- ✓ "Optimal controller design for a four-wheel steering vehicle with active front steering and direct yaw moment control" by Xiaobo Chen, Long Chen, and Junjie Wang, published in the Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering. [5] In this study, the authors use MATLAB to design an optimal controller for a four- wheel

steering vehicle with active front steering and direct yaw moment control. The results show that the optimal controller improves the vehicle's handling and stability in various driving conditions.

- ✓ "Modeling and analysis of a four-wheel steering system for a passenger vehicle using MATLAB" by Ankit Kumar, Manoj Kumar, and Shashikant Gupta, published in the International Journal of Automotive Engineering and Technologies. [6] In this study, the authors use MATLAB to model and analyze a four-wheel steering system for a passenger vehicle. They evaluate the system's performance in terms of maneuverability, stability, and cornering ability, and compare it to a conventional two-wheel steering system. The results show that the four- wheel steering system significantly improves the vehicle's performance in all areas.

These studies provide further insights into the design, modeling, and control of four-wheel steering systems using MATLAB, and demonstrate their potential for improving vehicle performance and safety.

1.3. Objectives

The main objectives of this project are as follows:

Maneuverability in Tight Spaces: One of the main objectives of reducing the turning radius is to improve the car's maneuverability in tight spaces. This is particularly important for city driving, where parking and navigating through narrow streets can be challenging.

Safety: Another objective is to improve the safety of the car by reducing the risk of collisions in tight spaces. By reducing the turning radius, the car can more easily navigate through tight corners and avoid obstacles, reducing the risk of accidents.

Comfort and Convenience: A third objective is to improve the comfort and convenience of the car's occupants. A smaller turning radius means that the car can make tighter turns, making it easier to navigate through parking lots and other areas where space is limited. This can make the driving experience more comfortable and less stressful for passengers.

2. Designing the four wheel steering system

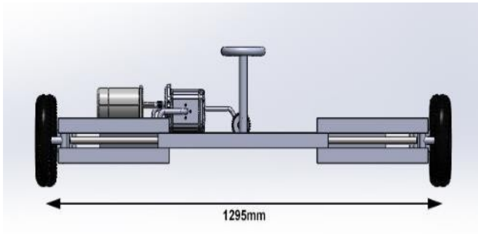
The specifications of Maruti Suzuki Alto K10 was considered for designing purposes which are listed below in Table 1.

Table 1. The specifications of Maruti Suzuki Alto K10

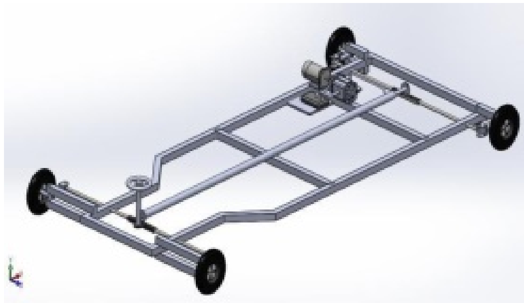
Top speed	145 kmph
Wheelbase	2360 mm
Wheel Size / Wheel Diameter	13 inch
Front Track width	1295 mm
Rear Track width	1290 mm
Turning Radius	4.6 m
Gross Weight	1210 kg

The model which is shown above was entirely done using SOLIDWORKS shown in fig.1. This model is based on Rack and Pinion mechanism for actuation. It consists of four wheels whose wheel diameter is 13 inch, connected to the vehicle chassis using control arms. The wheels are connected to the rack by a connecting arm. A shaft consisting of pinion on both the ends is attached between the two racks. There are two steering rack present - one for the front wheels and other for the rear wheels. The front rack is designed in such a way that gear teeth is provided on two sides - one on the top surface for meshing with the pinion of the shaft and other on the front surface for meshing with the pinion of the steering column. [9]

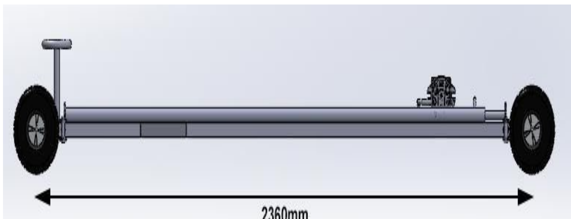
The rear rack is meticulously engineered, featuring gear teeth exclusively on its upper surface to seamlessly engage with the pinion positioned at the opposite end of the shaft. Simultaneously, a steering column integrates with the front rack's frontal surface, while its other end connects to a steering wheel, facilitating the transformation of rotational motion into linear motion along the front rack. This sophisticated translation mechanism enables precise manipulation of the front wheels. A shaft, equipped with pinions on both ends, forms an essential linkage between the two racks, creating an inseparable connection. As the front rack initiates movement, the rear rack follows suit in perfect synchronization. This coordinated action governs the precise steering of the rear wheels in the opposite direction, creating a counter-directional response. For example, when the front wheel turns left, the rear wheel elegantly sways to the right, and vice versa. This engineering marvel bestows upon the system an extraordinary degree of steering finesse and control, ensuring a harmonious and responsive driving experience.



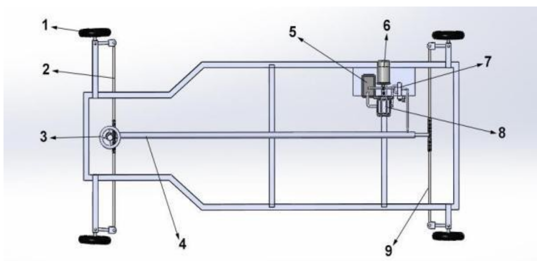
Front view



Topview



Sideview



isometric view

Fig.1. Design of Four Steering Mechanism in Solid works.

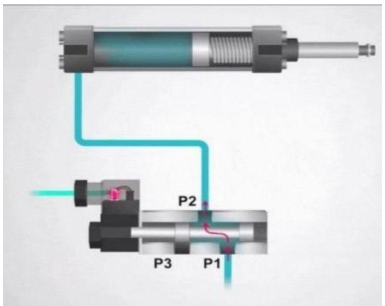
1 Wheel
2 Front rack
3 Steering wheel
4 Shaft
5 Oil reservoir
6 DC motor
7 Solenoid actuated spool value
8 Hydraulic pump
9 Rear rack

3. Switching mechanism solenoid actuated 3/2 spool valve

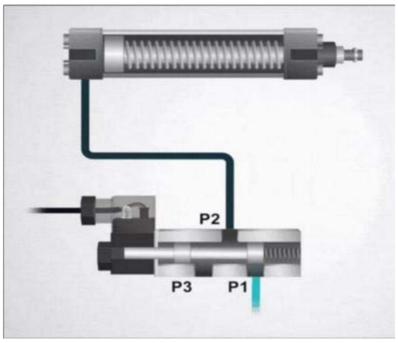
The spool valve is used to actuate the hydraulic cylinder. It is connected to the pump through which the oil is pumped from the reservoir. This mechanism consists of 3 ports namely inlet, outlet and exhaust. There is a spool present inside the cylinder with these 3 ports. The function of the spool is either to close or open the available ports by moving back and forth. This spool can be actuated by a solenoid which is controlled by a PIC microcontroller. When the solenoid is energized it actuates the spool and pushes it forward. When the solenoid is not energized, the spool is pushed back to its original position by the action of the spring present in the cylinder.

3.1 Working

The basic working of the solenoid actuated 3/2 spool valve is, the oil supply from the pump is connected to the inlet port shown in diagram. The outlet port is connected to the shaft vent. The exhaust port is connected to the oil reservoir so that the same oil is used again. Initially the inlet port is closed, when the spool is actuated, the inlet port opens and the oil flows through the outlet port into the shaft vent while the exhaust port is closed by the spool. This is called the working position. Now when the solenoid is de-energized, the spool returns to its rest position and the inlet port is closed so that the exhaust port is opened and the oil from the shaft returns back to the reservoir. This is called the normal position shown in fig.2.



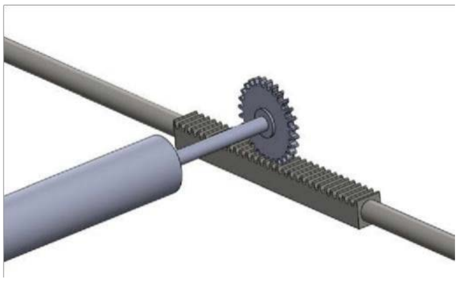
Spool valve working position



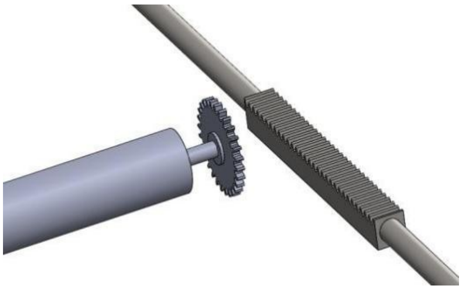
Spool valve normal position
Fig.2. Spool valve working

3.2 Engaging and Disengaging of the Four wheel steering system

At the end of the piston, we have connected the pinion to be meshed with the rear rack which causes the rear wheels to be steered along with the front wheels thus making it a four-wheel drive. So when the speed of the vehicle is less than 40 km/hr, the fluid flows into the cylinder thereby the piston in the single acting hydraulic cylinder moves forward thus the pinion at the end of the rod moves forward and is meshed with the rack at the rear axle. When the speed of the vehicle is more than 40 km/hr, the pressure is released and the fluid flows back into the reservoir through the port thus the piston is retracted back thereby the piston disengages the rear rack shown in fig.3.



Pinion meshed with the rack



Pinion unmeshed from the rack

Fig.3. Engaging and Disengaging Mechanism

3.3 Actuation of Motor and Solenoid

The actuation of the motor and solenoid depends upon the input which is received from the wheel rpm. The wheel RPM is measured using Hall Effect sensor which generates a square wave from which the voltage value for the corresponding RPM is determined. Here the RPM value for 40 km/hr is 643. The top speed of Maruti Suzuki Alto k10 is 145 km/hr whose corresponding RPM value is 2330. The maximum voltage for PIC microcontroller is 5V from which it is found that the corresponding voltage value for 643 RPM is 1.38V. Here the speed of the vehicle is compared to the potentiometer so when the voltage is brought below 1.38V using potentiometer, the microcontroller powers the motor and the solenoid. Thus it provides a linear actuation in the hydraulic cylinder which in turn causes the pinion to get meshed with the rear rack. When the voltage is above 1.38V, the microcontroller cuts off the power supplied to the motor and the solenoid which in turn causes the pinion to get unmeshed from the rear rack. The simulation is done using PROTEUS software shown in fig.4 and also working flow of the entire system is shown in fig.5.[10]

ON condition OFF condition

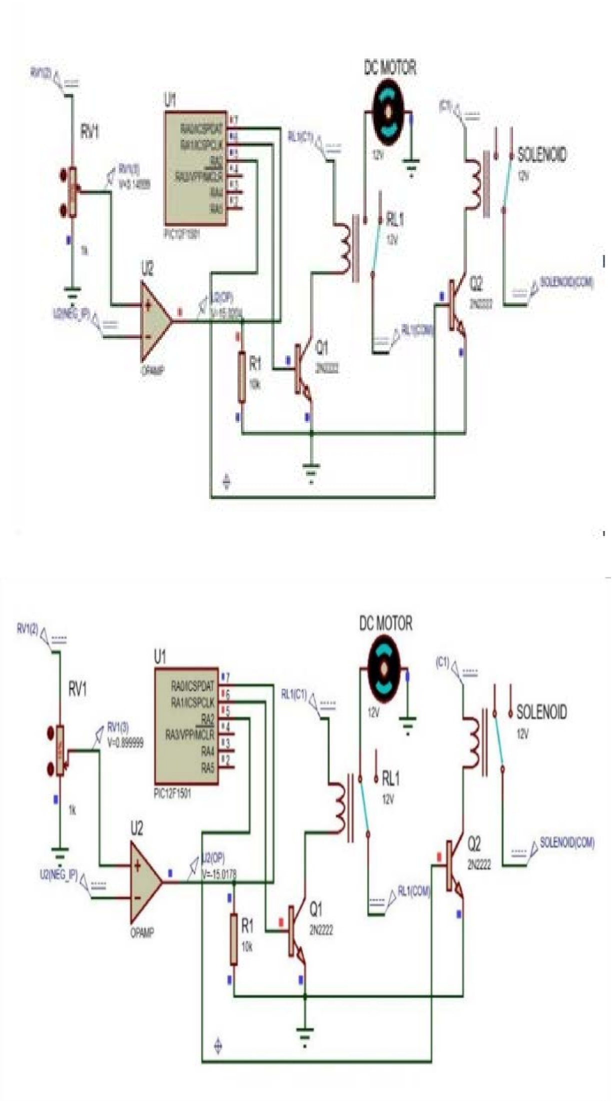


Fig.4. The simulation in PROTEUS software.

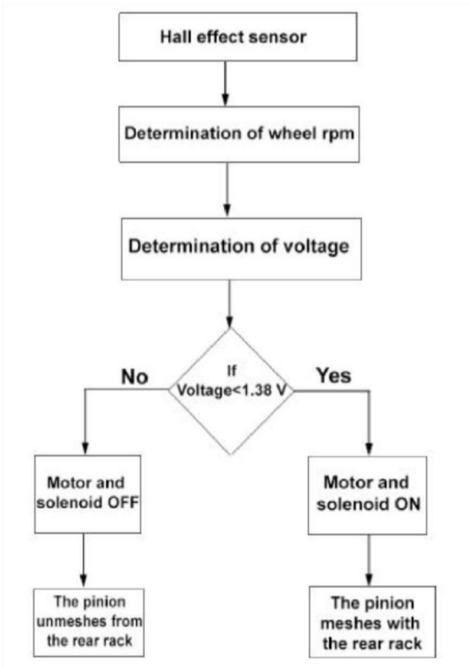


Fig.5. Working flowchart

4. Design Calculation for Four wheel Steering Mechanism

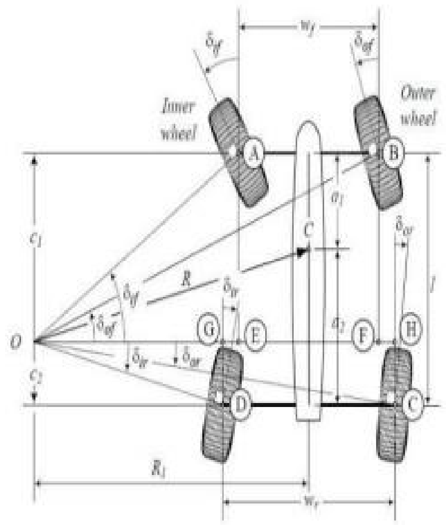


Fig.6. Four Wheel Steering Mechanism

L - Wheelbase (mm)
R - Turning radius (mm)
C_2 - Distance between rear wheel and instant center (mm)
a - Distance between front axle and CG (mm)
b - Distance between rear axle and CG (mm)
c- Distance between right wheel and CG (mm) d - Distance between left wheel and CG (mm) δi - total inner angle of the car (º)
δo - total outer angle of the car (º)
C_1 – Distance between front wheel and instant center (mm)
R_r - Reaction force on rear axle (N)
R_f - Reaction force on front axle (N)
R_1 - Distance between instantaneous center and the axis of the vehicle (mm)
W - Total weight of car (kg)
Δ - Total steering angle of the vehicle (degree)
wf - Front track-width [8]

4.1. Side view calculation:

Wheel base (l) = 2360 mm
Weight (w) = 1210 kg
R_r = Reaction force on rear axle.
R_f = Reaction on front axle.
Rr = 4840 N R_f = 7260 N
b= Distance between CG and rear axle a= Distance between CG and front axle L = a + b
$\Sigma Fy = 0$
$W = R_r + R_f$
$\Sigma Mr = 0$ (M= Total Moment about rear wheel)
$R_f * L = W * b$
a= 1416 mm b = 944 mm

4.2. Front view calculation:

Track width (T) = 1295 mm
$\Sigma Fy = 0$
$W = R_r + R_l$
$\Sigma Ml = 0$
$W*c = R_r * T$
c=Distance between CG and right wheel d= Distance between CG and left wheel So, c = d = 647.5 mm
Turning radius = 4.6 m (Given in the specification)
$R^2 = a^2 + R^2$
$(4.6)^2 = (1.416)^2 + R^2$
$R_1 = 4.37663$ m

C_1 = Distance between front wheel and instant center (mm)
C_2= Distance between rear wheel and instant center (mm)
Inner Angle Of Front Tire θ_{if} = 24.5°
Wf = Front track width
$\tan \theta = C_1/(R_1 - W_f/2)$
tan 24.5° = C_1 = 1699.5 mm
C_1 = 1699.5 mm
C_2 = 661.8 mm

In fig. 6, present an illustrative depiction of the Four-Wheel Steering Mechanism, a pivotal component of our study. Additionally, fig. 7 provides crucial side and front views of the vehicle model employed for our comprehensive calculations and analyses, offering valuable insights into our research methodology and experimental setup.

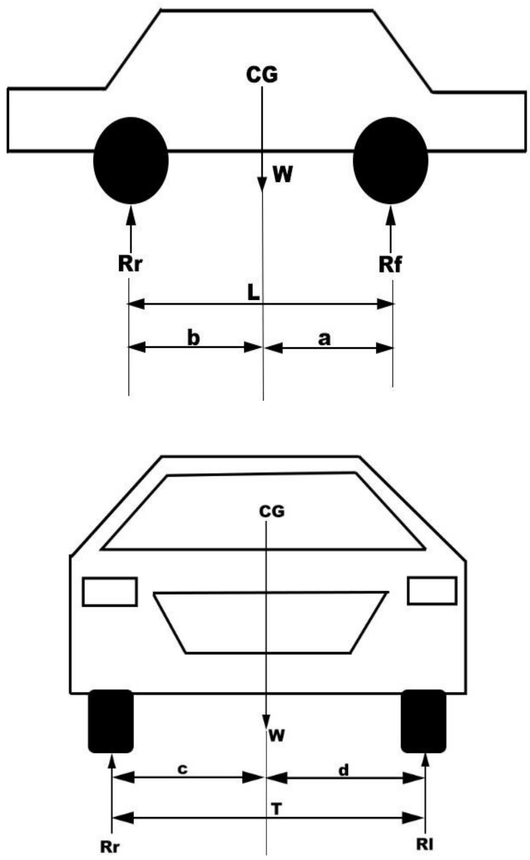


Fig.7.Side and Front view of the vehicle

5. Simulation in MATLAB Model

In this Simulation, vehicle turning circle radius is calculated using the Simulink model as shown in fig. 8. with the following cornering stiffness for front and rear wheel steering system. [12]
Cornering stiffness for front tire (kf) = 55 kN/rad.
Cornering stiffness for rear tire (kr) = 60 kN/rad.
Inner angle of the front tire = 24.5 degree.

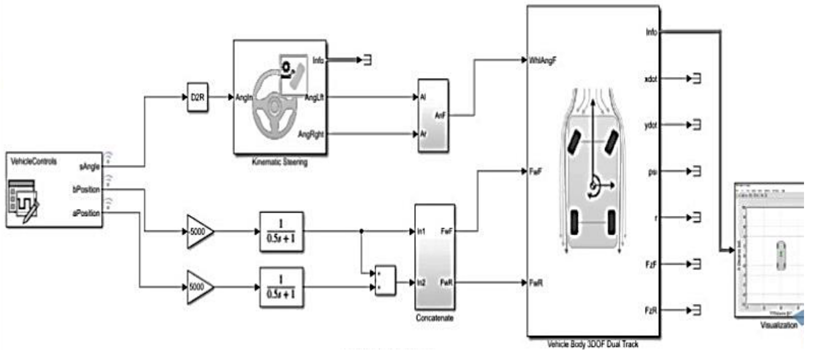


Fig.8. MATLAB Simulation.

The above Turning Radius (R) is found for inner front angle of 24.5 degrees when only front wheel is steered. (Conventional steering system). For different inner angle of front wheel (δi), we have found the corresponding Turning radius value for both four wheel steering system and conventional steering system and a graph is plotted shown in fig. 9. [7]

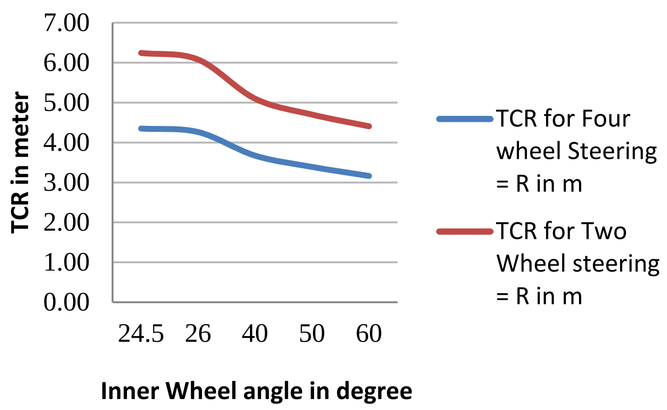


Fig. 9. TCR VS Inner Wheel Angle

6. Conclusions.

The validated mathematical model of the four-wheel steering system for a passenger car showed that the system improved the car's handling and maneuverability, reduced its turning radius, and enhanced its stability during high-speed maneuvers. The optimized design parameters of the four- wheel steering system included the inner angle of the front tire between 24.5 degrees and 60 degrees. The results shows that for the given inner angle of front wheel, the turning circle radius of four wheel steering system is less compared to conventional two wheel steering system. [11] Also the usage of PIC micro controller improves the efficiency and accuracy in steering the rear wheels when compared to mechanically controlled rear steering system. In future this concept can also be used in forklifts, earth movers, passenger cars etc.

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