Original Research

Design and Manufacturing of Mechanical Steering System for Parallel Parking, Zero Turning Radius, Minimum Turning Radius with Traditional Turning

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Abstract	Article Information
Many existing cities in the world were not built according to population of cars. Therefore drivers find it difficult to park their car on crowded streets and to turn in small spaces. However it is possible to design cars to suit traffic conditions of the cities. Two wheel steering system has a drawback of demanding wide area because of comparatively larger turning radius. Currently most cars are using traditional steering system, but this system is difficult comparing to parallel parking method. Zero turning radius helps the vehicle rotating about an axis passing through the centre of gravity of vehicle rather than describing a circular path as in conventional turning. The aim of this research is to develop a combined mechanism of parallel parking, zero turn radius, minimum turning and traditional turning for automobiles. All the parts of the steering system are designed so as to meet all the configuration of steering system and to be well-matched to the power train, suspension system and body of the car. The steering system is designed for the car which is designed and manufactured at Bahir Dar Institute of Technology, Bahir Dar University which has the overall dimension of 1200 X 1450mm. After manufacturing of the parts, it had been assembled and ready for testing. The testing results showed that zero turning radius will reduce the turning radius up to 70% and parallel parking also make our life easy and reduce time consumption during parking and to pullout car from traffic jam. Minimum radius turn configuration will reduce the turning radius of vehicle about 36% compare to traditional steering mechanism.	

INTRODUCTION

Steering is the collection of components, linkages, etc., which allow vehicle (car, motorcycle, bicycle) to follow the desired course. The basic aim of steering is to ensure that the wheels are pointing in the desired direction. This is typically achieved by a series of linkages, rods, pivots and gears. Many modern cars use rack and pinion steering mechanisms, where the steering wheel turns the pinion gear; which in turn moves the rack, converting circular motion into linear motion along the transverse axis of the car (side to side motion) (Arun Singh, 2014).

The commonly employed system in current vehicles is a traditional steering in which only two wheels (front or rear) steer at a time. Now-a-days, four wheel steering system is also applicable in few cars. In most active four wheel steering system, the guiding computer or electronic equipment play a major role.

In this research an attempt has been made to design and manufacture the combined steering mechanism made of mechanical parts which are easy to manufacture and feasible design involving a double rack and pinion system for rear and front wheels enclosed within a casing, connected to the steering column by universal joint with a combination of bevel and spur gear assembly.

Traditional Turning

The traditional steering is a commonly employed system existing in present day vehicles in which only front or rear wheels are steered (Figure 1)

Minimum Turn Radius

Direction of turn of rear wheels is opposite to that of the front wheels. With all four wheels steered thus, the vehicle has a smaller turning radius than only two wheels steering vehicles (rear or front wheels steering system) (Figure 2).
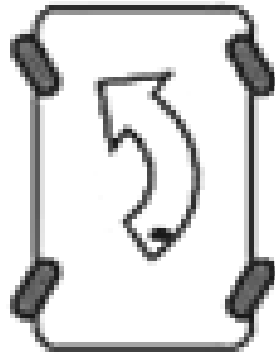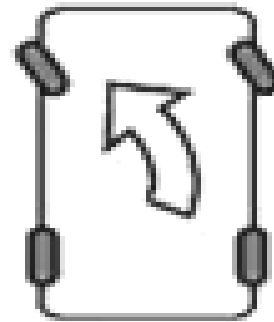
Figure1: Traditional Turning
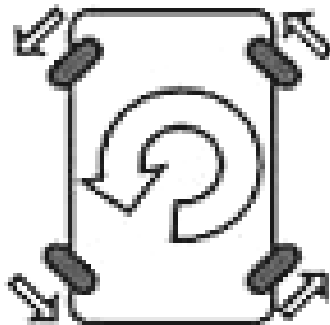

Figure 2: Minimum Turning Radius

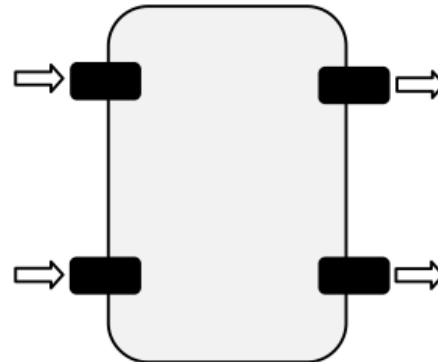**Figure 3:** Zero Turning Radius

Figure 4: Parallel Parking

Zero Turning Radius

Front wheels turn inward; rear wheels turn outward, enabling the vehicle to turn in its place (Figure 3).

Parallel Parking

Parallel parking enables the driver to park a vehicle in a smaller space. The idea is to turn all the wheels perpendicular to the edge of the road. Then driver engages the reverse gear or forward gear and car will be driven to the parking lot (Figure 4) (Anish Kulkarn and Kshitij, 2011).

Nowadays, there are two types of steering system that are commonly used, front/rare wheel steering (two wheel steering) and four wheel steering. In a typical front wheel steering system the rear wheels do not turn in the direction of curve and thus restrict efficiency of the steering. Few cars like Honda Prelude, Nissan Skyline GT-R have been available with four wheel steering systems, where the rear wheels turn only 2 or 3 degrees to aid the front wheels in steering rather than steer by themselves (Lohith, Shankapal, Monish Gowda, 2013).

Design, simulation and demonstration of a parallel parking mechanism for a city car were developed by M.S. Ramaiah School of advanced studies, Bangalore. The concept is to lift the car on additional four wheels and park the car without using a steering mechanism (Varun Gopinath, Shankapal, Prakash Unakal, 2009).

Indian Automotive and Aeronautical Engineering (FT-2012) students designed and fabricated an all-wheel steer (AWS) platform capable of zero turn radii (Anil Kumar, 2014).

Saket Bhishikar *et al.* (2014) developed an innovative four wheel steering design to implement a mechanism that can serve the purpose of changing in-phase and counter-phase steering of rear wheels depending upon the conditions of turning and lane changing with respect to front wheels, thus enhancing the manoeuvrability of a vehicle in accordance with its speed.

This research focuses on designing of mechanical steering system all-wheel steer, which is capable of achieving traditional turning, minimum turning radius, zero turning radius and parallel parking.

DESIGN AND ANALYSIS

Working Principle of Proposed Combined Steering System

The steering column (shaft) (1) and universal joint (2) the steering wheel (3) is connected to the pinion of the first rack (4) and the motion is transmitted to the next rack by using spur gear attachments of pinions (5). The second spur has an attachment of bevel gear (6) which is used to connect the front steering system to rear steering.

The importance of using two rack and pinion systems for front steering is to have opposite direction movement of the wheel during parallel parking and zero turning radius steering configurations.

The selector (7) is used to select between rack one (8) and rack two (9). When the tie rod (10) is engaged to rack one traditional turning and minimum turning radius system are used and when it is engaged to rack two parallel parking and zero turning radii are applied.

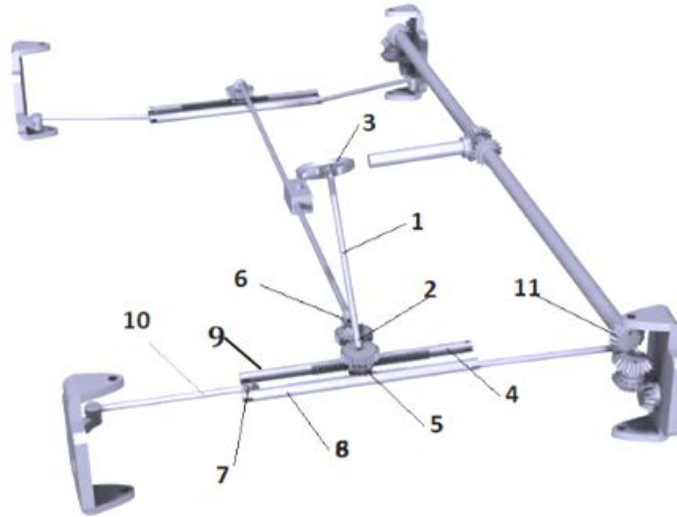To transmit power from engine to the wheels bevel gears (11) are used.

Figure 5: Designed Combined Steering model in CATIA V5

System Analysis

The selected specifications are taken from the previous work (Abinet Abera *et al.*, 2015).

Maximum speed (V_{max}) = $40 \ km/h$
Minimum speed (V_{min}) = $20 \ km/h$
Maximum power (H)   = $4.2 \ kW$
Gross load (m) = $400 \ kg$
Wheel base (l) = $1450 \ mm$
Track width(w) = $1200 \ mm$

Steering Dynamics

Consider a front wheel steering vehicle that is turning to the left as shown in Fig. 6. When the vehicle is moving very slowly, there is a kinematic condition between the inner and outer wheels that allows them to turn slip-free [8]. This condition is said to be Ackerman condition and is expressed by,

$$cot\delta_o - cot\delta_i = \frac{W}{l} \quad (1)$$

Where, δ_i- steer angle of the inner wheel; δ_o- steer angle of the outer wheel; l -wheel base; W- track width
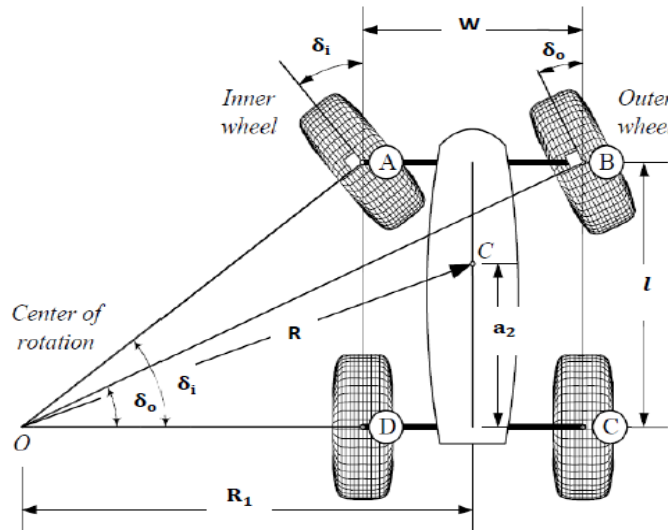

Figure 6: Front wheel steering vehicle and Ackerman condition (Jitesh Kumar Singh, 2015).

The mass center of a steered vehicle will turn on a circle with radius R

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

Where, δ - cot average of the inner and outer steer angles

$$cot\delta = \frac{cot\delta_o + cot\delta_i}{2} \quad (3)$$

Most of the time it is recommended that steering angle of the inner wheel is between $25^0 - 45^0$. Taking the average value $\delta_i = 30°$,

Substituting the given values to find δ_o and R

$$\delta_o = cot^{-1}(w/l + cot\delta_i) \quad (4)$$

$$\delta_o = 21.33°$$

$$R = \sqrt{a_2{}^2 + l^2 cot\delta}$$

$$R = 3.164m$$

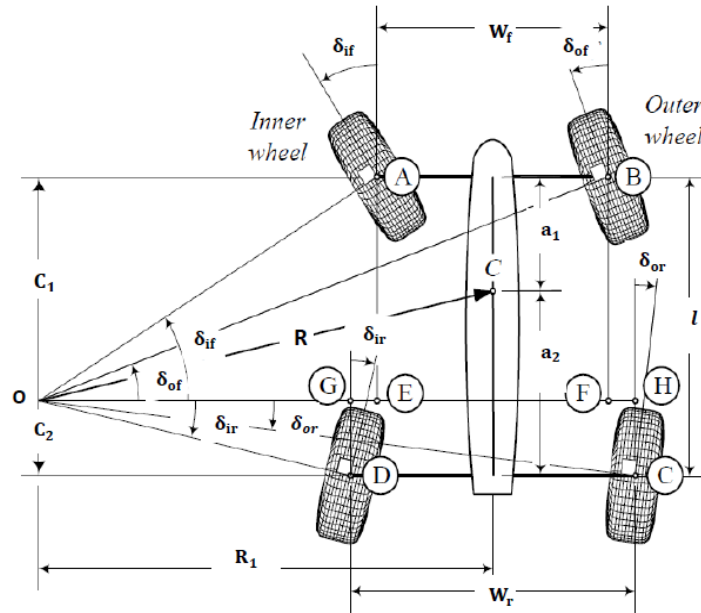In case of minimum turning radius configuration,

Figure 7: Symmetric four wheel steering vehicle (Jitesh Kumar Singh, 2015).

In a symmetric four wheel steering vehicle the front and rear wheels steer opposite to each other equally i.e $w_f = w_i$

The kinematic steering condition for a symmetric steering is expressed by,

$$cot\delta_o - cot\delta_i = \frac{w_{fi}}{l} + \frac{w_r}{l} \qquad (5)$$

Where,
$$W_{fi} = front\ wheel\ track\ width$$
$$W_r = rear\ wheel\ track\ width$$

$$c_1 = \frac{w_f}{cot\delta_i - cot\delta_o} \qquad (6)$$
$$c_2 = \frac{w_r}{cot\delta_i - cot\delta_o} \qquad (7)$$
$$tan\delta_o = \frac{c_1}{R + \frac{w_f}{2}} \qquad (8)$$

Hence, $\delta_o = 16.45°$, and $R = 1.8557\ m$

In case of zero turning radius since all the perpendicular lines from the four wheels meet at center point 'O' the turning radius $R = 0$

Steering System Part Design
In the proposed combined steering system there are many parts which will make the system functional, however for this paper presentation some of the critical machine element analysis is presented.

Design of Bevel Gear
Bevel gears are most often mounted on shafts that are at right angle, but can be designed to work at other angles as well. Bevel gear is selected in this design to transmit engine power from the shaft to the driving wheels.

Table 1: Bevel Gear Geometry

S.No	Parameters	Values
1	Number of teeth	23
2	Pressure angle	20°
3	Tooth form	Straight
4	Module	3mm
5	Circular pitch	9mm
6	Outer diameter (OD)	60mm
7	Face width	13mm
8	Bore diameter	30mm

Note: These calculations are applicable to all the bevel gears.

The resultant force acting at the center of the tooth has three components a tangential force (w_t), a radial force (w_r) and an axial force (W_a) (Khurmi and. Gupta, 2005)

Transmitted load
$$w_t = \frac{33000H}{V} = 7032\ N$$
$$w_r = w_t \tan \emptyset \cos \gamma = 1810\ N$$
$$w_a = w_t \tan \emptyset \sin \gamma = 466\ N$$

Where,
$$Presure\ angle(\emptyset) = 20^0$$
$$Pitch\ angle\ (\gamma)\quad = 45^0$$

The modified form of the Lewis equation for the tangential tooth load is
$$w_t = (\sigma_o * c_v)b * \pi * m * y'\left(\frac{L-b}{L}\right) \qquad (9)$$
Where,
Cone distance (L) $= 40\ mm$
Face width (b) $= 13.00\ mm$
Velocity factor (c_v) $= 0.91$
Static allowable stress (σ_{OG}) $= 78.00$ MPa
Tooth form factor (Lewis factor) for the equivalent number of teeth (y') = 0.572
$$w_t = 607\ N$$

i. Limiting Load for Wear

Then the dynamic load (w_D) on the gear

$$w_D = w_t + \frac{21 * v * (b * c + w_t)}{21 * v + \sqrt{b * C} + w_t} \tag{10}$$

Where,
Dynamic factor (C) = 583.10 N/mm (Richard Budynas and Keith Nisbett, 2006).

$w_D = 619\,\text{N}$
The maximum or limiting load for wear (w_w)

$$w_w = d_p * b * Q * k \tag{11}$$

Where,
Pitch diameter (d_p) = 56mm
Load stress factor (K) = 1.29
      Ratio factor (Q) = 1
$w_w = 954\,\text{N}$
Since w_w is greater than w_D, therefore the design is satisfactory from wear point of view.

ii. Gear Contact Stress (Richard and Keith, 2006)

$$\sigma_c = c_c \left(\frac{w_t}{F d_p I} * k_o * k_v * k_m c_s c_{xc} \right)^{1/2} \tag{12}$$

Where,
Contact geometry factor (I) = 0.065
Over load factor (k_o) = 1.750
Dynamic factor(k_v) = 1.200
Load distribution factor(k_m) = 1.000
Size factor for pitting resistance (c_s) = 0.50
Crowing factor for pitting (c_{xc}) = 2.00
Elastic coefficient(c_p) = 0.41
            $\sigma_c = 126.95\,\text{Mpa}$

Design of Shaft

The power transmission shaft is designed for the following parameters.

Maximum speed (N_{max}) = 406rpm
Minimum speed (N_{min})) = 203rpm
Power (H) = 4.2 kW

By considering this, the material selected is carbon steel of Indian standard designation of 45C8.

The torque transmitted by the shaft (Khurmiv and Gupta, 2005)

$$T = \frac{p * 60}{2\pi N} \tag{13}$$

$T = 197.5\,Nm$

The equivalent twisting moment

$$T_e = \sqrt{M^2 + T^2} = \underline{1705\ \text{N-m}}$$

$$T_e = \frac{\pi}{16} * \tau * d^3 \tag{14}$$

$$d = 45\,mm$$

Design of Rack and Pinion

The rack and pinion is used to convert circular motion into linear motion along the transverse axis of the car (side-to-side motion).

Table 2: Rack and Pinion Geometry

No	Parameters	Values	
1	Number of teeth for pinion	18	
2	Circular pitch	6.3	mm
3	Outside diameter	40	mm
4	Pitch diameter	36	mm
5	Addendum	2.0	mm
6	Dedendum	2.314mm	
7	Number of teeth for rack	32	

The torque (T) which is produced by the friction (f) and moment radius (R) is,
$$T = f * R = 191\,Nm$$

Tangential force acting on the gear (Jitesh Kumar Singh, 2015)

$$F_t = \frac{H}{v} = 10{,}583\,N$$

The horizontal force acting on the pinion gear
$$F_r = F_t \tan \emptyset = 3{,}852\,N$$

i. Gear bending stress of pinion (Richard and Keith, 2006)

$$\sigma = w_t K_o K_v K_x \frac{P_d}{F} \frac{K_m K_b}{\tau} \tag{15}$$

Where,
    K_b(Rim thickness factor) = 1
           $\sigma = 388.79 Mpa$

ii. Gear contact stress (Richard and Keith, 2006)

$$\delta_C = C_P (w_t K_o K_V K_S \frac{K_m}{d_p F} \frac{C_f}{I})^{1/2} \tag{16}$$

$$\delta_c = 16.29 Mpa$$

iii. Gear Contact Endurance

$$\delta_{c,all} = \frac{S_C Z_N C_H}{S_H K_T K_R} \tag{17}$$

Where,
S_c(Allowable contact stress) = 1,896.06Mpa
Z_N(Stress cycle factor) = 1
   C_H(Hardness ratio factor) = 1

$$S_H = \frac{S_C Z_N C_H / K_T K_R}{\delta_C}$$

Wear factor of safety
      $S_H = 1.165 > 1$ So the design is safe

RESULTS AND DISCUSSION

The design developed by M.S. Ramaiah School of advanced studies, Bangalore, needs additional four wheels attachment to the bottom of the car to lift while parking and it works only for parallel parking.

The design and fabrication of an all-wheel steer (AWS) platform capable of zero turn radius has the drawback of not working for parallel parking and driven by manual pedal power. To overcome such limitation this research an attempt has been made to use all four steering configurations to happen together and develop a mechanism for power transmission through all wheels.

During testing of the car it is found that the turning radius of vehicle in case of traditional turning and minimum turning, R = 3.90 m and R = 2.5 m respectively, as it can be seen from the results the radius is less in case of minimum turning configuration.

Figure 8: Wheel Arrangement for Zero Turning (Photo taken during testing)

Figure 9: Wheel Arrangement for Parallel Parking (Photo taken during testing)

The test result and theoretical result has some acceptable variation, may be due to of measurement technique and manufacturing accuracy, which need further investigation to find out the reason. But the result has a consistent pattern of similarity in both theoretical and test result.

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Table 3: Comparison of theoretical and practical results

Configuration	Theoretical turning radius	Practical turning radius	% of reduction in area requirement
Traditional Turning	3.164 m	3.9 m	-
Minimum Turning	1.8557 m	2.5 m	36% w.r.t traditional turning
Zero turning	1.05 m	1.1 m	69.35% w.r.t. traditional turning

CONCLUSIONS

The system is designed to have four configurations together and all the system is mechanically operated. Hence the designed mechanical steering system which combines all the advantages of minimum turning, zero turning, and parallel parking can be applicable for light weight cars.

During the test it is found that the minimum radius turn configuration will reduce the turn radius of vehicle by 36% in comparison to traditional steering mechanism during test.

Zero turning radius and parallel parking configurations, have the space requirement is equivalent to the dimension of the car. These kinds of configuration have lots of advantages in daily life, such as:
- Better parking at home and constricted spaces
- Easy ride of vehicle during traffic jams
- Turning back at narrow roads

Application of the newly designed combined steering system for heavy duty vehicle requires further study.

Conflict of Interest
None declared.

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