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Research Paper

Conventional Four-bar Linkage Steering System Adoption for Underslung Front Suspension

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ABSTRACT

Recirculating ball (RCB) steering gear with four-bar linkage steering system is widely used in commercial vehicles with rigid front axle and over slung suspension owing to their architectural arrangement. The usage of RCB steering gear with four-bar linkage steering system with underslung suspension is not commercialized globally due to complexity of packaging suspension and steering linkages. Few automotive OEMs have studied and implemented Y link steering system in place of four-bar linkage steering system for underslung suspension arrangement. Y link steering system has got its inherent disadvantages such as higher bump steer, poor self-centering, complex linkages, more number of parts and less tire life. Further this arrangement is comparatively costlier than four-bar linkage steering system owing to their higher number of parts.

In this paper, an extensive analysis has been made to implement the four-bar linkage steering system for underslung suspension vehicle. In this arrangement, the track rod (one of the links of a four-bar linkage system) is packaged above the leaf spring unlike in vehicles with overslung spring. Due to this unique arrangement, there exists some challenges in critical parameter optimization and packaging which are addressed in this paper. A mathematical model was developed to arrive at optimum steering and suspension geometry inorder to reduce the Ackerman error for better tire life and improve vehicle handling characteristics. By solving this mathematical model, optimum hardpoints can be arrived to achieve less Ackerman error, lower steering effort, lower bump steer, better steering returnability and best in class tire life. The present paper shows a possible approach to define the optimized steering and suspension linkages from the existing complex geometry with underslung suspension.

This attempt is first of its kind in automotive industry and if commercialized successfully will go a long way in improving steering performance and cost savings for the vehicles with underslung suspension.

KEYWORDS: Underslung suspension, four-bar steering linkage, Y link steering, Ackerman, bump steer, overslung suspension, self-aligning torque, trapezoidal steering, pitman arm, Steering gear ratio, Kingpin torque, Scrub radius, caster angle, Axle lift, King pin inclination, Wheel cut angle, Brake steer, wheel lock angle

Introduction

The demand for higher safety on our roads is constantly increasing and the trend within automobile industry is going in the same direction with more advanced safety features are being introduced to the market. Safety systems can be divided into passive and active safety systems. Typical active safety system[1] include antilock braking system (ABS), electronic stability system and steering system control. Among all the active systems, steering is considered to be one of the important system which directly affects the driver feel. Steering system to be properly designed for lane keeping assist, emergency lane assist collision avoidance, roll-over prevention, yaw disturbance attenuation to stabilise the vehicle and jackknife avoidance (trucks with semitrailers). To enable this functionality, the steering system or the steering gear must allow for a modification of the steering wheel torque to turn the wheels or the road wheel angle by means of an external signal. This is here referred to as active steering. Another aspect within the industry is to look at comfort functions that in some way could improve the steering feel or reduce the work load of the driver, e.g. by variable steering ratio. In a much wider perspective, active steering is a step towards automatic driving.

Though overslung suspension gives a better vehicle ground clearance, overloading ability and easy packaging. Underslung suspension is effective for better vehicle handling with less installation height (CG) and gives the driver “a better feel and response" with reduced effort to steer the wheels. The most widely used steering linkage in overslung suspension with RCB steering combination is trapezoidal or convention four-bar steering linkages. As on date, Y link steering mechanism coupled with RCB steering gear is widely used for vehicles with rigid axle and underslung suspension due to vehicle'sarchitecture and packaging constrains. This arrangement holds good only for fully forwarded cab vehicle. Also the cost of Y link steering mechanism is higher than that of four-bar steering linkage mechanism. Further vehicles fitted with Y link steering system has issues such as higher bump steer, poor self centering, higher steering kick back force and rapid tire wear when compared to four-bar steering system. At present no readymade solution exists for applicating RCB steering gear coupled with four-bar steering on underslung suspension vehicle.

In line with the above requirement, present work is an attempt to provide a cost effective and optimized conventional four-bar steering linkage for rigid front axle underslung suspension vehicles.

Uniqueness of this work

Underslung suspension with four-bar steering mechanism is unique and first of its kind in the global automotive industry.

In conventional steering system, tie rod is placed below the leaf spring. In this research work, the tie rod is placed above the leaf spring, which is first of its kind in the global automotive industry

Literature Survey

Since 1970, researchers and automobile industries have been studying concisely on the usage of RCB steering system in rigid front axle with underslung suspension. OEMs like TATA, Mahindra & Mahindra, Maruti Suzuki bundled RCB Y linkage steering with under slung suspension in vehicles like Xenon Yodha, Bolero pick up and Gypsy respectively. Ashok Leyland have sucessfully applicated Rack and Pinion steering system on rigid front axle with underslung suspension in Dost vehicle models.

Various theoretical and physical models for the steering system have been developed to analyze different effects like stability, steering feel and tire wear.

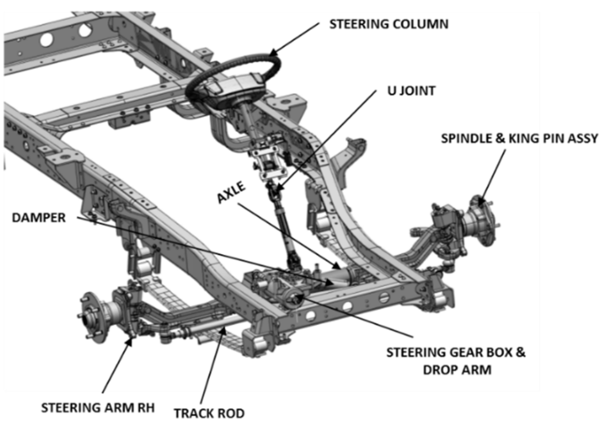

Fig. 1. Y link steering system layout.

Jing-Shan Zhao et al [3] had studied Design of an Ackermann-typesteering four-bar linkage, the number of points that a common four-bar linkage could precisely trace at most thereby pointing out the limits of a four-bar steering mechanism. Ranbir Singh et al [4] had studied design of an Ackermann-type steering four-bar linkage andanalysed the steering errors in a front wheel steered vehicle. Topac et al [5] had studied design of an Ackermann-type steering four-bar linkage of a multi-axle steering mechanism for a special purpose vehicle kinematic design and optimization. Ion Preda et al [6] had studied design of an Ackermann-type steering four-bar linkage approach for the vehicle's steering linkage fitted on rigid axle. Girish Rane et al [7] had studied the design of an Ackermann-type steering four-bar linkage for optimization for vehicle drift. In Four wheeler.com, [8] the design concept of an RCB with Y bar underslung suspension is clearly described. However there exists a research gap on implementing a four-bar steering linkage on rigid front axles with under slung suspension since none of the researchers have successfully implemented and productionized RCB steering system with four-bar linkage steering mechanism. The authors have tried to address this research gap in this paper.

Architecture Definition

Y link steering system on front rigid axle with underslung suspension (existing)

Underslung suspension with Y link steering system is commonly used by Mahindra & Mahindra in their pickup trucks. Arrangement of RCB steering gear with Y link steering system is shown Figure. 1. In this arrangement, one end of the drag link is connected to pitman arm and the other end is connected to the tie rod. The drag link goes all the way from RH side to LH side for RH drive and vice versa for LH drive. With this setup, the drag link angles down from the pitman arm and connects to the tie rod. The tie rod not only keeps the knuckles parallel, but also controls the movement of both knuckles. Refer Figure.2. for schematic Y link steering arrangement in a rigid front axle with an underslung suspension vehicle.

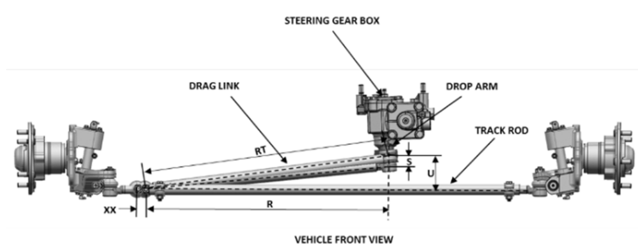

Fig. 2. Schematic arrangement of the Y link steering system in a rigid front axle with underslung suspension vehicle.

When the vehicle with Y link steering system traverse through a bump, draglink and tierod undergoes conflicting movement as the wheel rebounds. The draglink movement thus causes the drop arm to rotate leading to an undesirable steering motion at the steering wheel without any input from the driver. This phenomenon is explained in Figure.1. using the parameter 'XX'. Optimizing this conflict in Y link steering system is difficult when compared to four-bar steering linkage which is explained in detail in the subsequent chapters. As the drop arm rotation for given suspension travel is higher in Y link steering system, following issues would occur affecting the steering performance of the vehicle.

Higher bump steer - Unintended rotation of steering wheel as the vehicle traverses through a bump or pot hole.

Higher steering kickback force - Higher steering wheel kick back (sharp movement of steering wheel) due to bumpsteer are not favourable as it increases driver fatigue and cause discomfort.

Poor self aligning torque - The tendency of the steering wheel to turn back to its original position inorder to drive straight ahead after maneuvering a corner depends upon the self aligning torque developed by the tire. With poor self aligning torque, driver has to do constant steering wheel correction causing him fatigue.

Considering the above drawbacks with Y link steering system, there is a need for integrating four-bar steering linkage mechanism for vehicles with front rigid axle and underslung suspension.This will ensure better pilot feel and comfort along with improved vehicle handling and tire life.

Four-bar steering linkage on front rigid axle with underslung suspension (proposed)

The oldest and simplest steering mechanism is a four-bar steering linkage mechanism, also called steering trapezoid or trapezoidal steering mechanism.Four-bar steering linkage architecture is most commonly used in all the overslung suspension vehicles. In this research work, it is proposed to integrate four-bar steering linkage on rigid front axle with underslung suspension vehicle.

Refer Figure 3. for the proposed architecture where four-bar steering linkages are integrated to an underslung suspension vehicle. In this arrangement, one end of the draglink is fitted with pitman arm and the other end is connected to a steering lever in longitudinal direction. Unlike Y link steering mechanism, the draglink doesnot crossover but stays longitudinally along the same side of the driver viz. along RH side for RH drive and LH side for LH drive.

One of the important feature with respect to four-bar steering linkage on overslung suspension is that the tie rod is placed below the leaf spring whereas this arrangement calls for the tie rod to be placed above the leaf spring due to its unique architecture.

Even with the four-bar steering linkage mechanism, suspension deflections could cause undesirable steering linkage movements as shown in Figure.4. However this movement can be optimized to the lowest possible value when compared to Y link steering mechanism. [9] & [10]

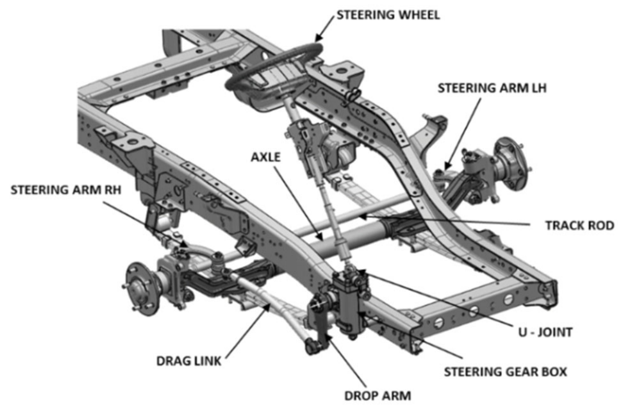

Fig. 3. Schematic arrangement of four-bar steering linkage on front rigid axle with underslung suspension.

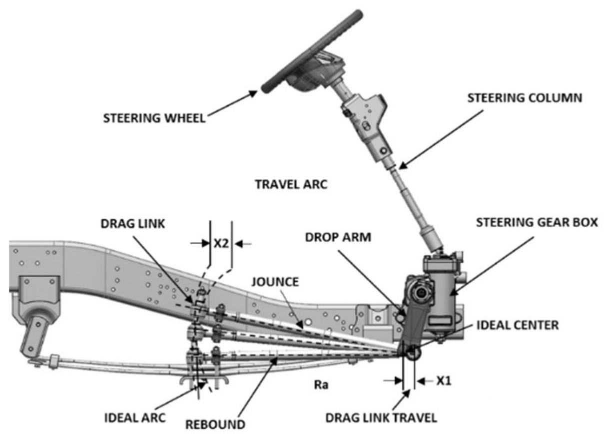

Fig. 4. Four-bar steering linkage mechanism layout

Mathematical Model for Four-Bar Steering Linkage and Y LinkSteering System

Ackerman Steering Geometry

Ackerman steering geometry is most widely used today in commercial vehicles. Ackerman condition is satisfied when 'I' centers of both front wheels meet at a point on rear axle which is turning point of the vehicle. Refer Figure 5. for typical Ackerman geometry representation of 2-wheel steering vehicle.

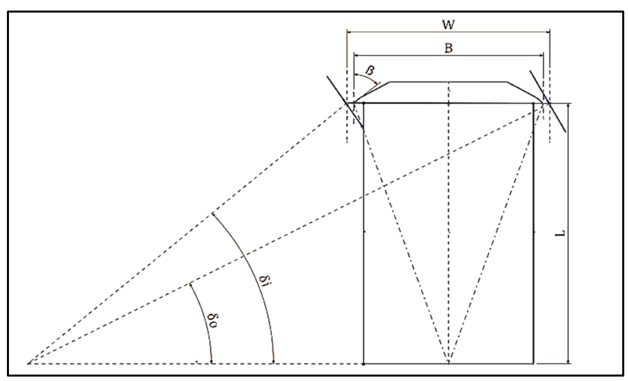

Fig. 5. Ackerman condition for commercial vehicle

Where,

δo - Outer wheel angle
δi - Inner wheel angle
W - Front track width of the vehicle
B - Distance between left and right kingpin centerline
L - Wheel base of the vehicle

Ideal Ackerman condition of typical steering system with RCB steering gear configuration can be expressed as follows :

$$\cot \delta o - \cot \delta i = \frac{B}{L} \quad .....(1)$$

Outer wheel cut angle ($\boldsymbol{\delta o}$) for a given certain inner wheel cut angle ($\boldsymbol{\delta i}$) can be calculated as follows:

$$\delta_0 = \cot^{-1}\left(\cot \delta_i + \frac{B}{L}\right) \quad .....(2)$$

Both four-bar steering linkage and Y link steering mechanisms must satisfy the above Ackerman condition.

Bumpsteer and pitman arm angle change during suspension travel in four-bar steering linkage

Bumpsteer is defined as a tendency of a wheel to steer itself without any input to the steering wheel. Bump steer causes a vehicle to turn itself when one wheel hits a bump or falls down into a pot hole. Excessive bump steer increases tire wear and makes the vehicle more difficult to handle on rough roads. For example, when a vehicle traverses through a bump, the front axle and all the parts attached to it moves due to deflection of the spring. This causes the draglink's fore and aft movement resulting in rotation of pitman arm and steering wheel associated to it. Thus the car turns itself left or right momentarily without any input to the steering wheel.

Refer Figure 6. for schematic layout drawn in vehicle side view to demonstrate pitman arm angle change for conventional four-bar mechanism.

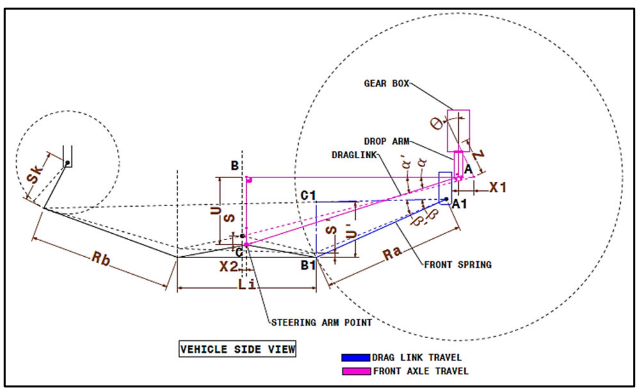

Fig. 6. Schematic layout for pitman arm angle change in four-bar steering linkage mechanism.

Where,
W - Drag link length for four-bar steering linkage mechanism
Z - Drop arm length
α- Initial drag link angle
α'- After drag link angle based on suspension travel
β- Spring angle
β'- After spring angle based on suspension travel
Ra - Spring inactive length
X1 – Draglink travel
X2– Front axle travel
θ– Drop arm travel
X - Drag link lateral movement when suspension moved vertically
Θ - Pitman arm angle
Gr – Steering gear ratio

Considering triangles ABC and A_1 B_1 C_1, following equations can be derived.

$$X = \left[\frac{U}{\tan\alpha} * \frac{1}{\cos\alpha}[\cos\alpha' - \cos\alpha]\right] - \left[\frac{U'}{\tan\beta} * \frac{1}{\cos\beta}[\cos\beta' - \cos\beta]\right] \quad .....(3)$$

$$\alpha' = \sin^{-1}\left[\left[1 - \frac{S}{U}\right] * \sin\alpha\right] \quad .....(4)$$

$$\beta' = \sin^{-1}\left[\left[1 - \frac{S\prime}{U\prime}\right] * \sin\beta\right] \quad .....(5)$$

By substituting equation (4)&(5) in equation (3), we get

$$X = \left[\frac{U}{\sin\alpha} * \left[\cos\left[\sin^{-1}\left[\left[1 - \frac{S}{U}\right] * \sin\alpha\right]\right] - \cos\alpha\right]\right] - \left[\frac{U'}{\sin\beta} * \left[\cos\left[\sin^{-1}\left[\left[1 - \frac{S'}{U'}\right] * \sin\beta\right]\right] - \cos\beta\right]\right] \quad .....(6)$$

Drop arm angle change for suspension travel of S,

$$\Theta = \tan^{-1}\left[\frac{Y}{X}\right] \quad .....(7)$$

Bumpsteer can be expressed as:

$$Bump\ Steer = \Theta * \left[\frac{Gr}{360°}\right] \quad .....(8)$$

Bumpsteer and pitman arm angle change during suspension travel in Y link steering mechanism

Refer figure 7 and 8 for schematic layouts shown in vehicle front and top view respectively to demonstrate change in draglink length and pitman arm angle when the vehicle traverses through a bump.

Where,

RT - Draglink length for Y bar mechanism

Ø - Initial drag link angle

Ø' - Draglink angle based on suspension travel

Y - Drop arm length

XX - Drag link lateral movement when suspension moved vertically

B - King pin center to center distance

Considering the triangles EFG and E_1 F_1 $G_1$from Figure.7, following equation shall be derived.

$$XX = \left[\frac{U}{\sin \emptyset} * \left[\cos\left[\sin^{-1}\left[\left[1 - \frac{S}{U}\right] * \sin \emptyset\right]\right] - \cos \emptyset\right]\right] \quad \text{.....(9)}$$

Considering triangles of J K L of Figure.8. drop arm angle change for suspension travel of S,

$$\theta = \tan^{-1}\left[\frac{XX}{Y}\right] \quad \text{.....(10)}$$

Bumpsteer can be expressed as:

$$Bump\ Steer = \theta * \left[\frac{Gr}{360°}\right] \quad \text{.....(11)}$$

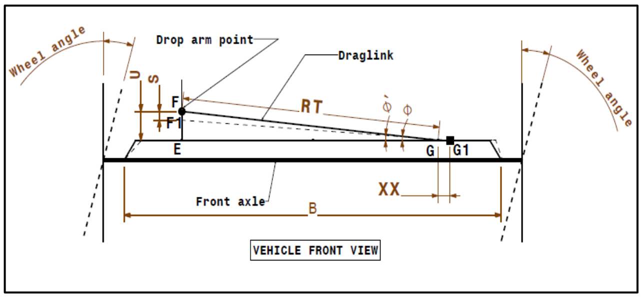

Fig. 7. Schematic layout for draglink length change in Y link steering mechanism - Vehicle front view.

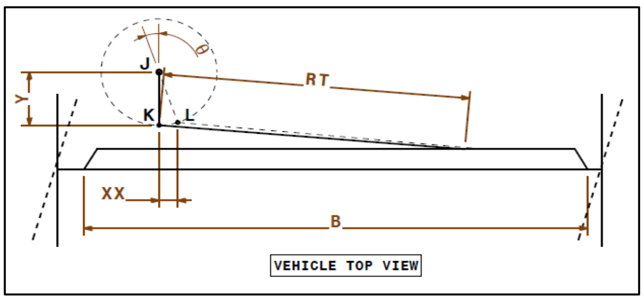

Fig. 8. Schematic layout for pitman arm angle change in Y link steering mechanism - Vehicle top view

Steering wheel kickback force

Steering wheel kickback force relates to the sharp and rapid movement of steering wheel as the front wheels encounter a significant obstruction or imperfection in the road. The amount of kickback is directly proportional to bump steer.

Steering wheel kickback force can be expressed as:

$$Fdr = \frac{Tk}{ls} \quad \text{.....(12)}$$

$$le = \frac{ld}{\cos\theta} \quad \text{.....(13)}$$

$$Ts = Fdr * le \quad \text{.....(14)}$$

$$Ti = \frac{Ts}{Gr} \quad \text{.....(15)}$$

$$Fkb = \frac{Ti}{rw} \quad \text{.....(16)}$$

Where,
Fdr - Drag Link force
Tk- Kingpin torque
ls - steering arm length
le - Effective drop arm length
ld- Drop arm length
Ts - Torque at shaft
Gr- Gearbox ratio
Ti- Torque on input shaft
rw - Steering wheel radius
Fkb- Steering wheel kick back force
θ- Pitman arm angle

Net Aligning Torque

Net aligning torque is the torque developed by the tire when vehicle is turned.

$$Rc = Fc * sr * \sin\varphi * \cos\lambda \quad \text{.....(17)}$$

$$Lk = Fk * sr * \sin\psi * \cos\lambda \quad \text{.....(18)}$$

$$Tn = \sqrt{(\psi^2 + \varphi^2)} * (Rc + Lk) \quad \text{.....(19)}$$

Where,
Rc – Axle roll effect due to Caster & Steer angle
sr – Scrub Radius
φ – caster angle
λ – Wheel angle
ψ – King pin Inclination Angle
Lk – Axle Lift effect due to KPI & Steer angle
Fk – Front Axle Weight
Tn – Net aligning torque

The net aligning torque helps vehicle to become stable in straight ahead position without any external effort by driver after completing the turn. Net aligning torque will be affected by overall weight of a vehicle, the speed at which a turn is approached, tire's shape, tread pattern and the actual road surface being driven on. Net aligning torque can be calculated through conventional method using FAW, KPI, scrub radius, wheel lock angle and tire parameters.

Results and Discussion

The vehicle considered for results discussion is a SCV having a gross vehicle weight (GVW) of 3490 kg. Following are the major vehicle level parameters considered for comparison purpose :

Where,
W - 689mm (Drag link length of four-bar steering mechanism)
S - 50mm (Suspension travel considered)
Y - 190mm (Pitman arm length)
Sk -80mm (Shackle pitch)
Ra - 399mm (Spring front active length)
Rb - 399mm (Spring rear active length)
Li - 100mm (Inactive length of spring)
RT - 727mm (Draglink length of Y link steering mechanism)
WT- 1580mm (Wheel track)
WB- 2600mm (Wheel base)

The linkage dimensions of four-bar and Y link steering mechanisms are maintained similar to the maximum possible extent for the purpose of comparison of results between two steering mechanisms.

Comparison of Ideal and Actual Wheel Cut Angles

The actual inner and outer wheel cut angles were simulated in layout and compared with theoretically calculated ideal wheel cut angles. Refer Figure 9. for actual and ideal wheel cut angles. Ideal wheel cut angle is same for both the steering mechanisms. The actual wheel cut angle closely follow the ideal wheel cut angle for both the steering mechanisms. This clearly demonstrates the fact that both Y link steering system and four-bar steering linkage meets the Ackerman condition.

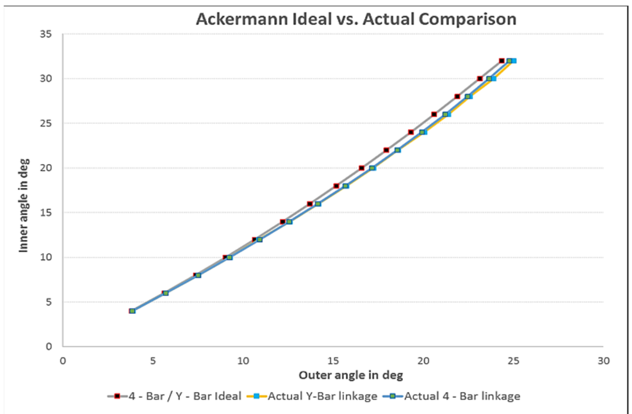

Fig. 9. Comparison of wheel cut angles – Ideal vs. actual wheel cut angle for four-bar and Y link steering mechanisms.

Comparison of Bump Steer Results

All the required vehicle level parameters were substituted inthe equations (6) to (11) to arrive at bump steer values for four-bar and Y linksteering mechanismsaccordingly. Figure 10 demonstrates bump steer variation for both the steering mechanisms as the suspension displaces from initial condition to 50mm. It is evident from the figure that, bump steer for four-bar steering linkage mechanism is 33% lesser than the Y linksteering mechanism for 50mm of suspension travel.

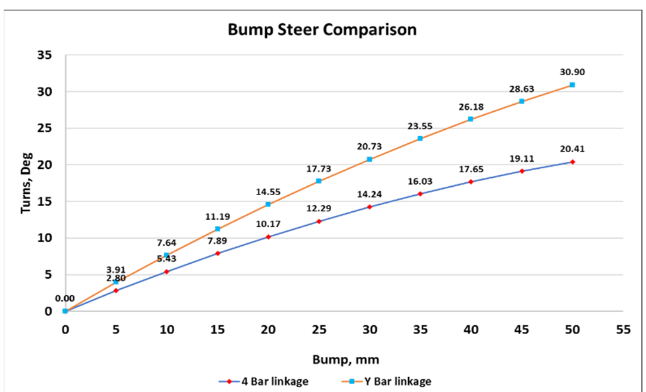

Fig. 10. Bump steer comparison for four-bar and Y link steering mechanism

With reduced brake steer in proposed four-bar linkage steering mechanism, constant steering wheel correction by the driver is not warranted thus improvingthe driver comfort and reducing his fatigue.

Comparison of Steering Wheel Kick Back Force

By Substituting the required vehicle level parameters on equation (16), steering wheel kickback force can be arrived considering pitman arm angle respectively for four-bar and Y link steering mechanisms. Figure.11. demonstrates the steering wheel kick back force variation for both the steering mechanisms as suspension travels from initial condition to 50mm. It is evident from the figure that, steering wheel kickback forcewithfour-bar steering linkage mechanism is 19.5% lesser than Y link steering mechanism for 50mm of suspension travel. This clearly implies that reduction in kick back force will results in significant improvement on pilot comfort and fatigue.

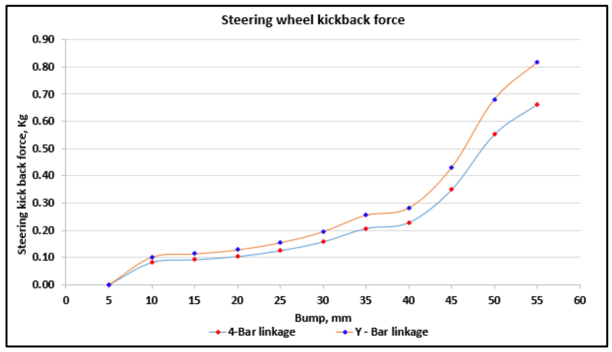

Fig. 11. Comparison of steering wheel kick back force for four-bar and Y link steering mechanisms.

Comparison of Net Aligning Torque

Net aligning torque can be calculated through conventional method using FAW, KPI, scrub radius, wheel lock angle and tire parameters.

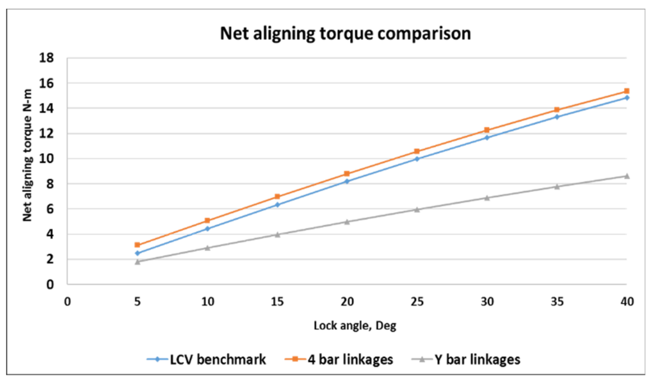

Fig. 12. Net aligning torque comparison for four-bar and Y link steering mechanism

Net aligning torque will be affected by the overall weight of a vehicle, the speed at which a turn is approached, tire's shape, tread pattern and the actual road surface being driven on. Refer Figure.12. for net aligning torque comparison for both the steering mechanisms for wheel lock angle of 40°.. It is evident from the figure that net self aligning torque for four-bar steering mechanism is 78% higher than Y link steering mechanism. To have better self aligning torque, Y link steering mechanism has got lateral damper attached between drag link and front axle beam.

Cost Comparison

Y link steering mechanism has got an additional damper to have better net aligning torque. Also the drag link in this arrangement iscomparatively longer due to its architecture. Further, track rod and drag link are comparatively thicker in Y link steering linkage than four-bar steering system. On the other hand, steering lever has got more material in four-barsteering linkage system. No of parts are on par in both the steering linkages. Considering equal FAW and vehicle parameters, the cost of Y link steering system with damperis around 20% cheaper than equivalent Y link steering system. Even after damper removal Y link steeringsystem costs 5% more than proposed four-bar steering linkage mechanism.

Conclusion

In this research work, an extensive study has been made for adopting four-bar steering linkage in underslung suspension vehicle which is first of its kind in the automotive industry. One uniqueness in this proposal is the location of tie rod, in which it is placed above the leaf spring whereas with conventional arrangement the tie rod of 4 link steering mechanism is placed below the leaf spring.

Both the steering mechanisms meet the Ackerman conditions. Following are the key benefits of implementing a four-bar steering linkage mechanism for an underslung suspension vehicle.

Reduced system cost - Cost savings of around 20% if four-bar steering linkage is used in place of Y link steering mechanism. This cost can be further reduced by optimizing linkages along with vehicle level testing, which will be taken up in subsequent days

Reduced bump steer - Bump steer with four-bar steering linkage mechanism is 33% lesser than the Y linksteering mechanism thusconstant steering wheel correction by the driver is not essentialthereby improving driver comfort and reducing driver fatigue.

Reduced steering wheel kick back force - Steering wheel kickback forcewithfour-bar steering linkage mechanism is 19.5% lesser than Y link steering mechanismwhich clearly indicates that pilot fatigue is reduced drastically in the proposed system.

Increased self aligning torque - Net self aligning torque for four-bar steering mechanism is 78% higher than Y link steering mechanism. This clearly indicates that the straight-line stability will be better in the proposed system when compared with Y link steering system.

The above advantages clearly demonstrate that proposed four-bar steering mechanism reduces driver fatigue and improves pilot feel and subsequently improving vehicle and road safety. Further all the above-mentioned vehicle level parameters will be fine-tuned in future through subsequent simulations and vehicle level testing.

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