Steering Effort Calculation & Optimization Study on Mechanical Steering (Agri Machinery)

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Abstract: The steering efforts significantly influences vehicle handling and driver comfort, making it a critical parameter in automotive design. This research focuses on analyzing and optimizing steering effort in both mechanical and hydraulic power steering systems. The study investigates the relationship between steering effort and factors such as vehicle speed, steering angle, and axle load. Emphasis is placed on differentiating the effort required during low-speed maneuvers, such as parking, versus high-speed driving conditions. Mechanical steering systems are assessed in terms of direct driver input and torque requirements, while hydraulic systems are evaluated for their assistance mechanism through pumps and fluid pressure. Experimental and simulation-based methodologies are used to quantify steering effort, followed by optimization strategies to reduce physical demand on the driver without compromising steering feel or vehicle control. The results highlight the advantages and limitations of each system, offering insights into design improvements for enhanced performance and driver ergonomics.

Keywords: *Steering Effort, Mechanical Steering, Hydraulic Power Steering, Torque Optimization, Vehicle Dynamics.*

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I. INTRODUCTION

In the agricultural and automobile sector, steering effort plays a crucial role in determining operator comfort, vehicle control, and productivity during field operations. Tractors, in particular, operate under highly variable load conditions, uneven terrain, and low-speed maneuvers, all of which place significant demand on the steering system. The steering effort, defined as the torque required by the operator to turn the steering wheel, is influenced by factors such as front axle load, tire road interaction, steering geometry (specially angles), and the type of steering employed.

Both mechanical steering (MS) & hydraulic power steering (HPS) systems are commonly used in tractors, depending on the vehicle size, application, and cost constraints. Mechanical steering continues to be relevant due to its simplicity, robustness, and ease of maintenance, particularly in smaller or utility- class tractors. However, it typically demands higher steering effort, especially during stationary or low-speed operations. Hydraulic power steering, on the other hand, provides operator assistance using hydraulic pressure generated by an engine-driven pump, significantly reducing manual effort and improving comfort.

This study aims to quantify the steering effort in mechanical steering configurations under typical tractor loading conditions. Parameters such as front axle weight, steering arm length, scrub radius, and tire-road friction are analyzed to evaluate their influence on steering torque. optimization of steering effort of mechanical steering without compromising its simplicity.

By addressing these factors, this work contributes to enhance the ergonomic, efficiency, and performance of tractor steering systems, thereby supporting broader goals of mechanized farming and operator well-being.

II. STEERING EFFORT & REVOLUTION CALCULATION INPUTS (MS)

➢ *To Calculate the Steering Effort, we Require Inputs as Listed*

- Tire patch width
- Front Axle Reaction Weight
- Coefficient of friction
- King Pin Off-set at ground (Scrub radius)
- Steering Arm Length (CD)
- Tie-rod arm length (CD)
- Drop-arm/Pitman-arm length (CD)
- Steering wheel diameter
- Drop arm angular travel
- Tie-rod and tie-rod arm angles
- Drag-link and drop arm
- Drag-link and steering arm
- Gear ratio

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- Constant gear ratio (CGR)
- Variable gear ratio (VGR)

➢ *Refer Below Considerations Used for Study.*

- Considering tire 6x16 bias tire.
- Taking coefficient of friction 0.7 (worst case).
- Front axle reaction is 800kg (*approx. 40% of total weight*).
- Considering recirculating ball type SDA Steering with RH side mounted drop-arm considered.
- *Refer below table for other reference-*

Table 1 Parameter Against Symbol and Value Considered

S.No.	PARAMETER	SYMBOL	SCENERIO TAKEN
1	Front axle reaction	W	800 Kg
2	coeff. Of friction	μ	0.7
3	Tyre Patch width (*ref fig. 01*)	B	134mm
3	scrub radius (*ref fig. 02*)	E	51.2mm
4	steering arm length *(ref fig. 03)*	l	165mm
5	Tie-rod arm length *(ref fig. 03)*	x	120mm
6	Drop arm length *(ref fig. 04)*	L	210mm
7	King pin torque	T	-
8	Gear ratio	G	CGR-24.7:01 VGR-27.3~32:01
9	LH Tie-rod arm & tie-rod angle (ref fig. 07)	a°	*refer table 01*
10	RH Tie-rod arm & tie-rod angle (ref fig. 07)	b°	*refer table 01*
11	steering arm drag link angle (ref fig. 07)	C°	*refer table 01*
12	Drop-arm draglink angle (ref fig. 05)	D°	*refer table 01*
13	Drop arm travel (*ref fig. 06*)	Y	*refer table 01*
14	steering wheel dia. (*ref fig. 08*)	J	*420mm*

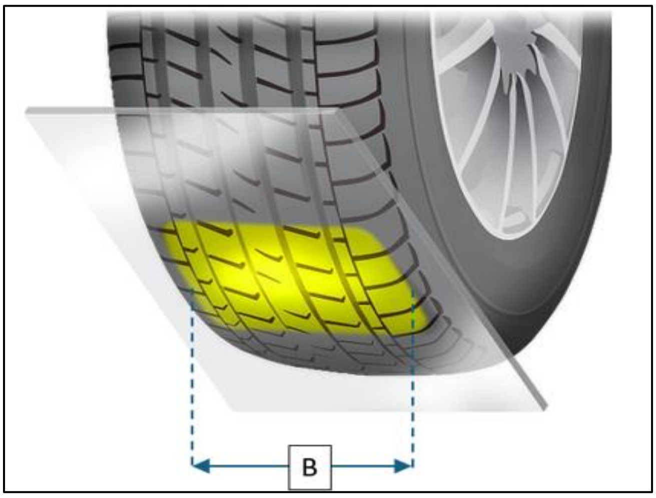

Fig 1 Tire Patch Width

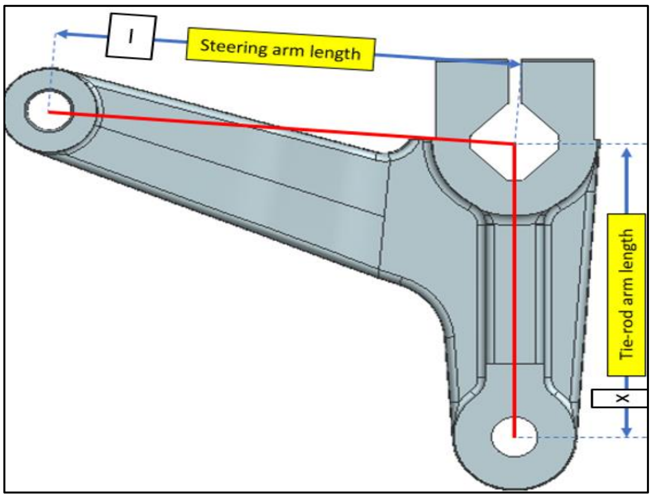

Fig 3 Steering Arm Tie-Rod Arm

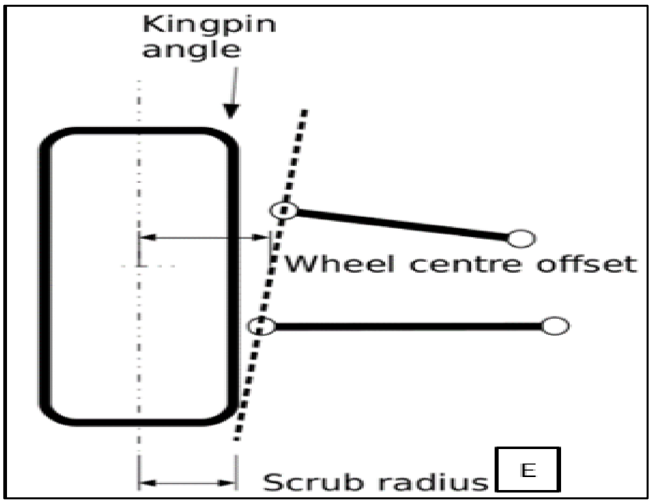

Fig 2 Scrub Radius

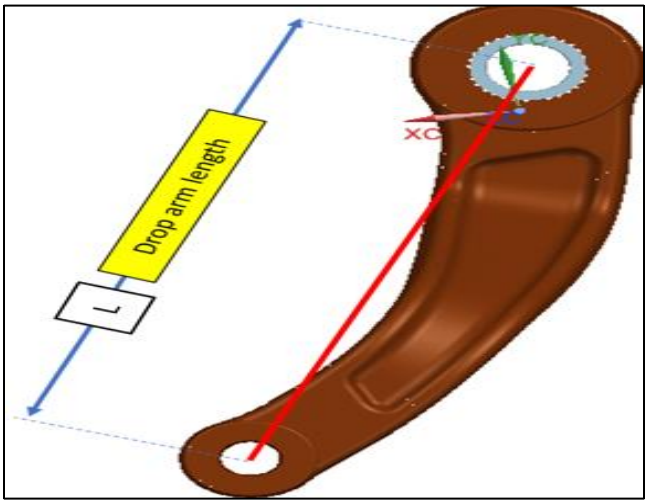

Fig.04; Drop-Arm

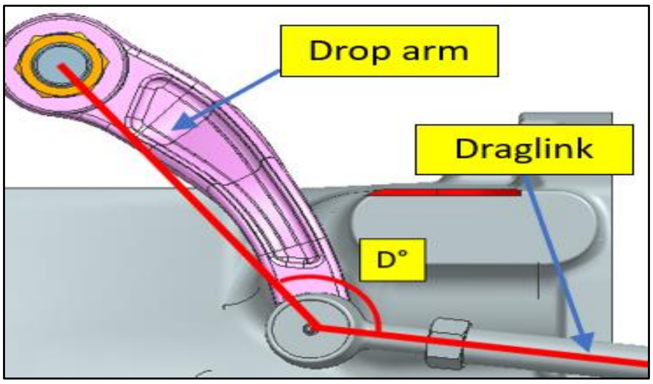

Fig.05; Drop-Arm Draglink Angle

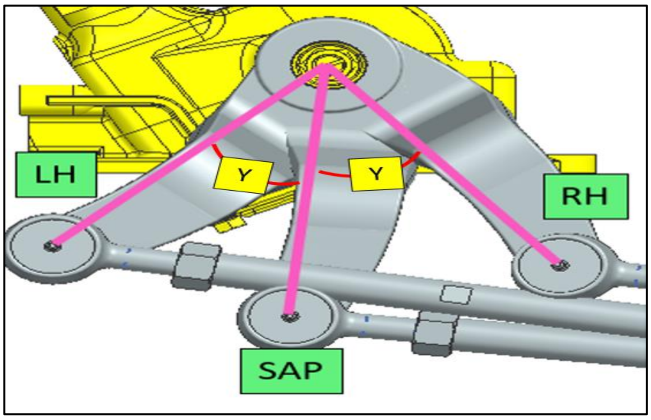

Fig.06; Drop-Arm Angular Travel

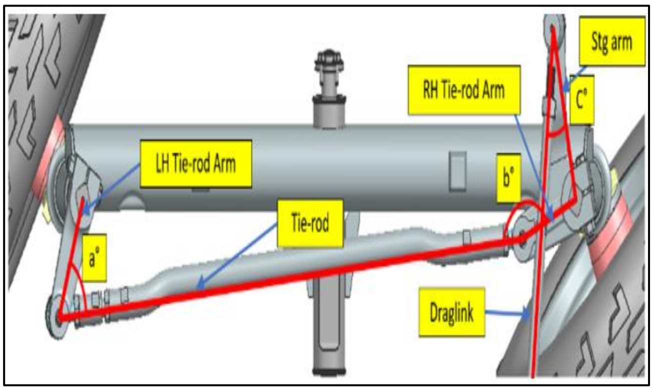

Fig 7 Tie-Rod and Tie-Rod Arm Angles

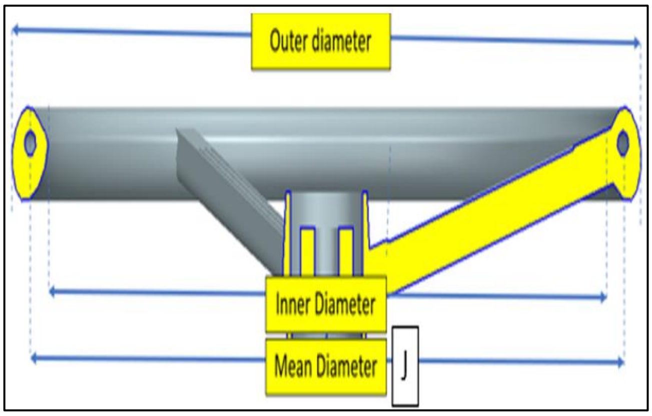

Fig 8 Steering Wheel Dia

➢ *Refer Table Below for Required Angles: -*

Table 2 Tie-Rod Drop-Arm Draglink and Steering Arm Angles

CONDITIONS	a°	b°	C°	D°	Y°
SAP	105°	105°	74.4°	92.5°	-
RH TURN	60°	160°	23.4°	129°	35°
LH TURN	160°	60°	113°	63.4°	36°

Fig.5,6 & 7 Shown for Reference

Gear ratio is the derived reduction ratio from steering gear,

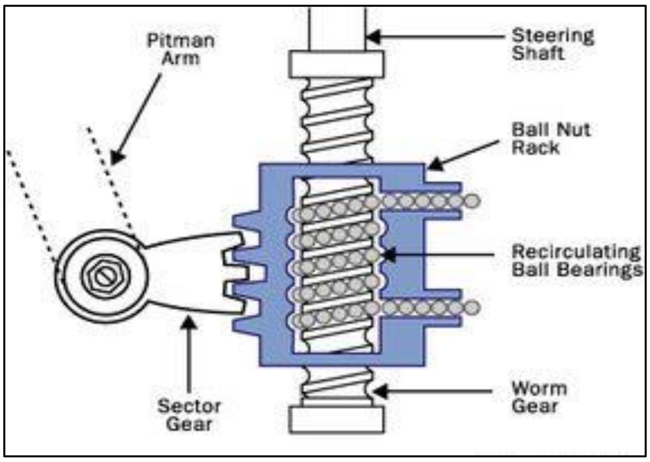

Fig 9 Recirculation Ball Type Steering Gear Mechanism

VGR & CGR are the varieties comes by changing the pitch of worm gear.

We considered CGR present is 24.7:1 and VGR is 27.3~32:1, considering the variation in ratios in VGR further formula will be derived in calculation section for the same.

III. STEERING EFFORT & REVOLUTION CALCULATION (MS)

➢ *Evaluating Individual King Pin Torque*

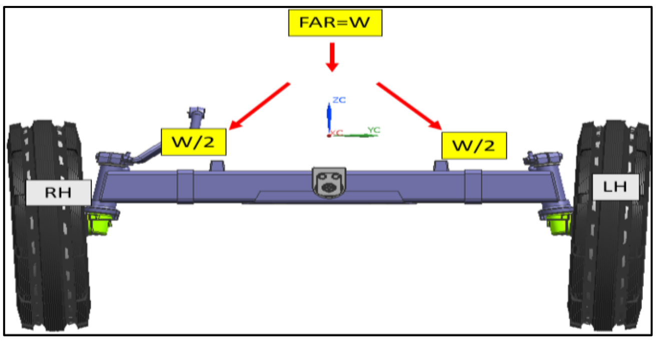

Fig 10 Front Axle Reaction Distribution

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Fig 10 represents equal distribution of FAR on both the tyres.

$$T = \frac{W}{2} \cdot \mu \sqrt{\frac{B^2}{8} + E^2}$$

where T is individual king pin torque (*reaction torque that acts against the motion ref fig 11).*

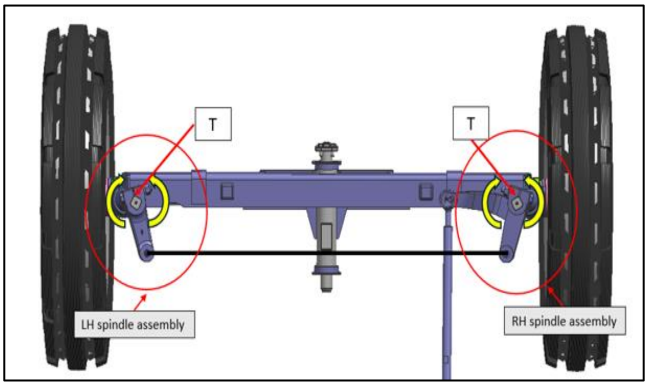

Fig 11 Torque Generation Representation

- *Evaluating Force on Tie Rod Due to LH King Pin Torque:*

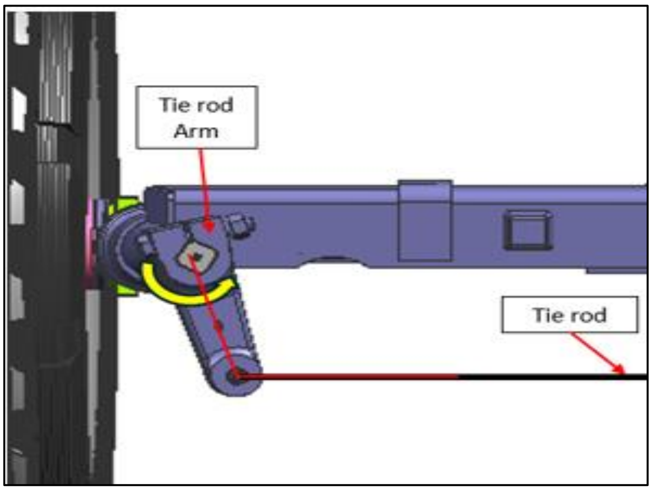

Fig 12 LH Tie-Rod Arm

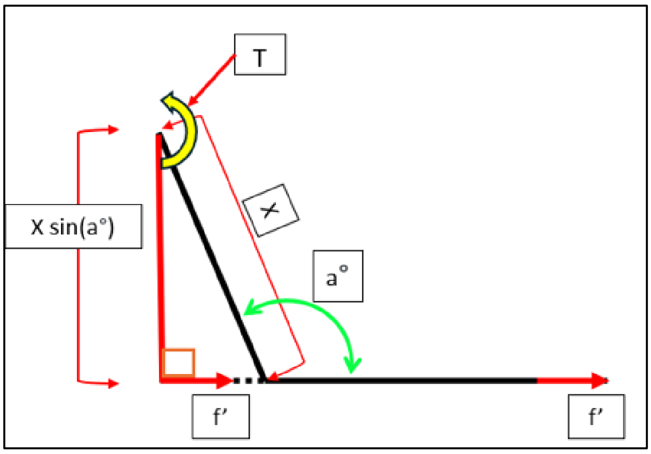

Fig 13 Vector Components for LH Tie-Rod Arm & Torque

- Where a° is the angle between Tie-rod-arm and Tie-rod,
- f' is the reaction force on tie-rod (force generated by individual king pin torque)
- Xsin(a°) is effective CD (⊥ distance between tie-rod arm and Tie-rod) of tie-rod arm.

$$f' = T/(X\sin(a°))$$

- *Evaluating Torque on Steering Arm on RH Side:*

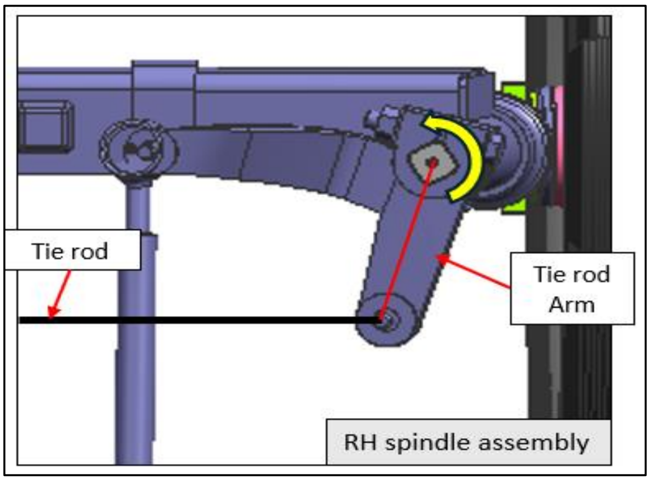

Fig 14 RH Tie-Rod Arm

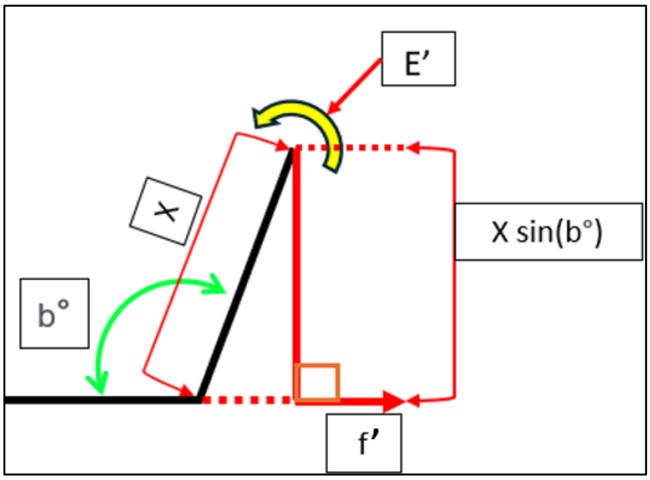

Fig 15 Vector Components for LH Tie-Rod Arm & Torque

- b° - angle between Tie-rod-arm and Tie-rod.
- f' - reaction force on tie-rod (force generated by individual king pin torque).
- Xsin(b°) - effective CD (⊥ distance between tie-rod arm and Tie-rod) of tie-rod arm.
- E' - torque generated due to f'.

$$E' = f' * X\sin(b°)$$

$$E' = T*(\sin(b°)/\sin(a°))$$

- *Evaluating Net Torque on King pin axis RH side:*

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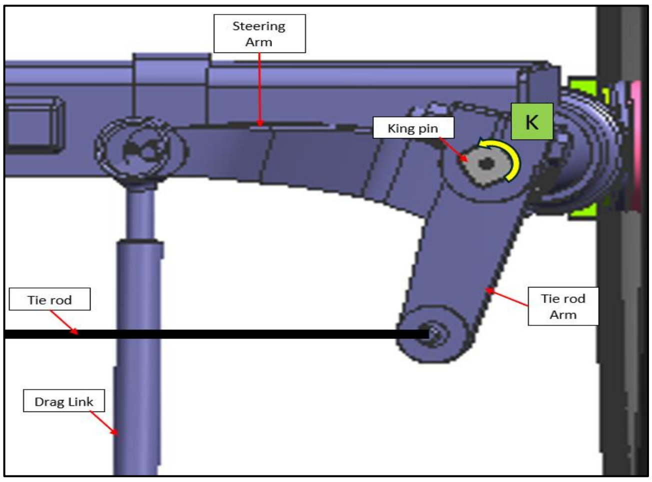

Fig 16 Net Torque on RH Steering Arm

K is net king pin torque on RH side (Summation of Torque due to ground reaction on RH king pin and torque generated by reaction force coming from LH wheel)

$$K = E' + T$$

➢ *Evaluating force on Drag-Link Rod:*

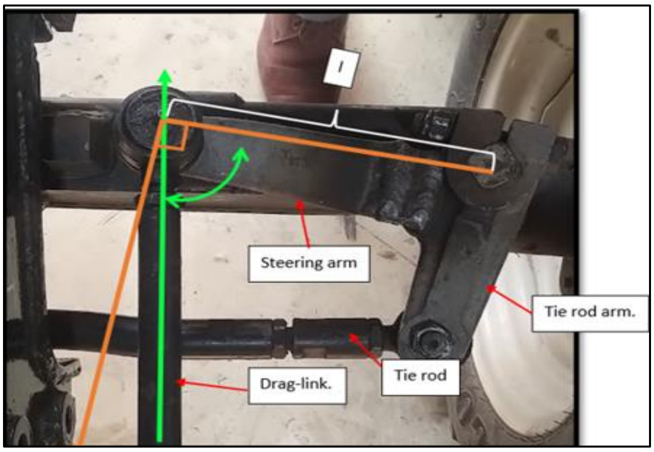

Fig17 RH Stg Arm with Draglink

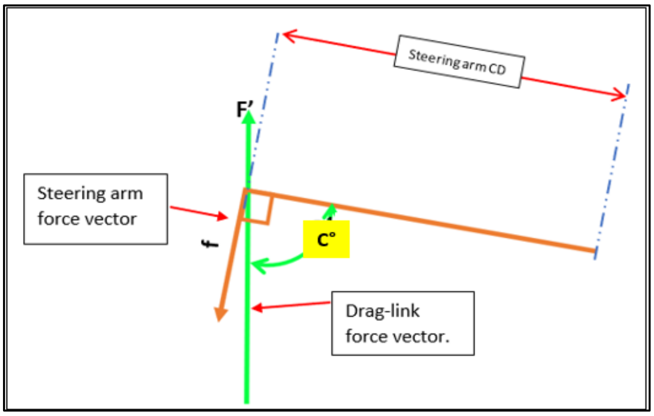

Fig 18 RH Stg Arm Vector Components

- F' - draglink force.
- C° - the angle between draglink.
- l - steering arm CD and

F'sin(C°) is effective perpendicular component of force to CD of steering arm hence,

$$F'(\sin(C°)) = K/l$$

$$F' = K/(l*\sin(C°))$$

➢ *Evaluating Torque on Sector Shaft:*

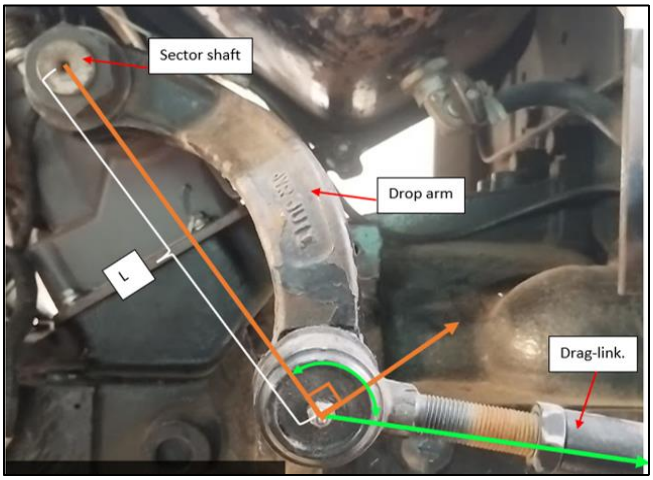

Fig 19 Drop-Arm and Draglink

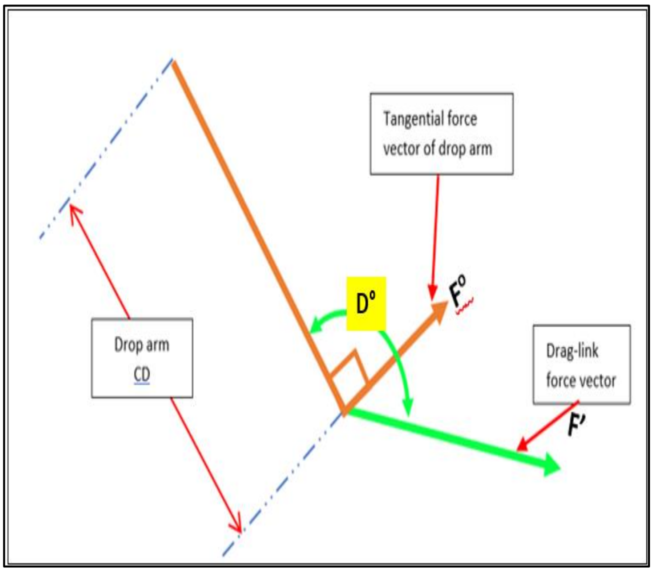

Fig 20 Drop Arm Vector Components

- D° - angle between drop-arm and drag-link.
- F' - represents the draglink force,
- L - Drop arm CD

F'*sin(C°) is effective perpendicular component to CD of drop arm

$$T' = L.\ F'*\sin(D°)$$

Where T' is the torque on sector shaft

➢ *Evaluating Net Steering Effort:*

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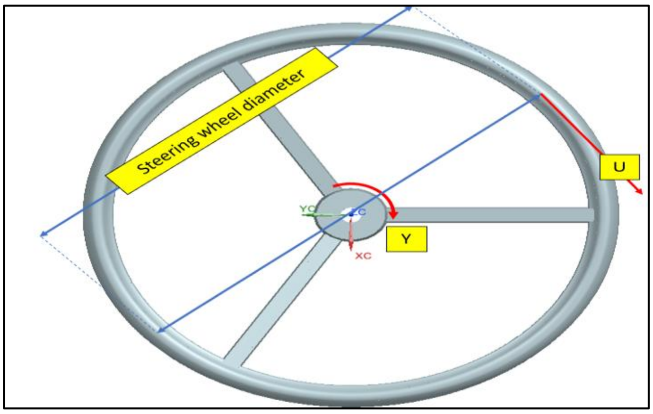

Fig 21 Steering Wheel Dia, Torque and Effort Representation

Here “Y” is the reduced torque due to steering gear reduction and “U” is the final effort faced by driver.

As gear ratio is G

$$\text{Gear Ratio(G)} = \frac{\text{Torque on sector shaft(T)}}{\text{Torque on steering wheel(Y)}}$$

$$Y = T'/G$$

$$\text{Hence } U*(J/2) = Y$$

$$U = Y/(J/2)$$

Where “J” is steering wheel diameter and “U” is the force on steering wheel (steering effort)

To meet the actual conditions dividing steering effort with efficiency
i.e. steering effort= U/(Z)

where “Z” is net efficiency.

Z= (tie rod eff.) x (draglink eff.) x (gear box eff.) x...(others)

- *Finalizing the Formula by Putting all Variables: -*

- Stg effort = (U)/(Z)
- = ((Y)/(J/2))/(Z)
- = ((T’/G)/(J/2))/(Z)
- = (((F’* L *sin(D°))/G)/(J/2))/(Z)
- = ((((K/(l*sin(C°))) * L *sin(D°))/G)/(J/2))/(Z)
- = (((((E’+ T)/(l*sin(C°))) * L *sin(D°))/G)/(J/2))/(Z)
- = ((((((f’*X sin(b°)) + T)/(l*sin(C°))) *L *sin(D°))/G)/(J/2))/(Z)
- = ((((((((T/ (X sin(a°))) *X sin(b°)) + T)/(l*sin(C°))) * L *sin(D°))/G)/(J/2))/(Z)

Where T is king pin torque

Putting inputs

$$T = \frac{W}{2} \cdot \mu \sqrt{\frac{B^2}{8} + E^2}$$

Refer below table for data

Table 3 King Pin Torque Output

Parameters	Formula/Symbol	Unit	DATA
Front Axle Weight	Wf	Kg	800
	Wfx9.81	N	7848
Tyre contact width on ground	B	m	0.134
King pin offset at Ground	E	M	0.0512
Coefficient Of Friction	µ	-	0.7
King pin torque	$T_k = (\mu \times Wf \times \sqrt{(B^2/8+E^2)})/2$	N-m	191.61

$$T = 191.61 \text{ Nm}$$

Note: - gear ratio in CGR is constant but in VGR it changes with respect to drop arm travel.

- *Determining Gear Ratio for VGR (27.62~32.06:1) for Steering Effort*

Below data is taken as reference input

LH side drop arm angular travel represented by -ve symbol and vice-versa for RH side drop arm angular travel

Table 4 Travel vs Gear Ratio Input

Travel	Gear Ratio	Travel	Gear Ratio
-39	32.06	0	27.62
-36	31.40	3	27.65
-33	30.80	6	27.73
-30	30.25	9	27.86
-27	29.75	12	28.04
-24	29.30	15	28.28
-21	28.91	18	28.57
-18	28.57	21	28.91
-15	28.28	24	29.30
-12	28.04	27	29.75
-9	27.86	30	30.25
-6	27.73	33	30.80
-3	27.65	36	31.40
		39	32.06

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Plotting this into graph via. Table 04

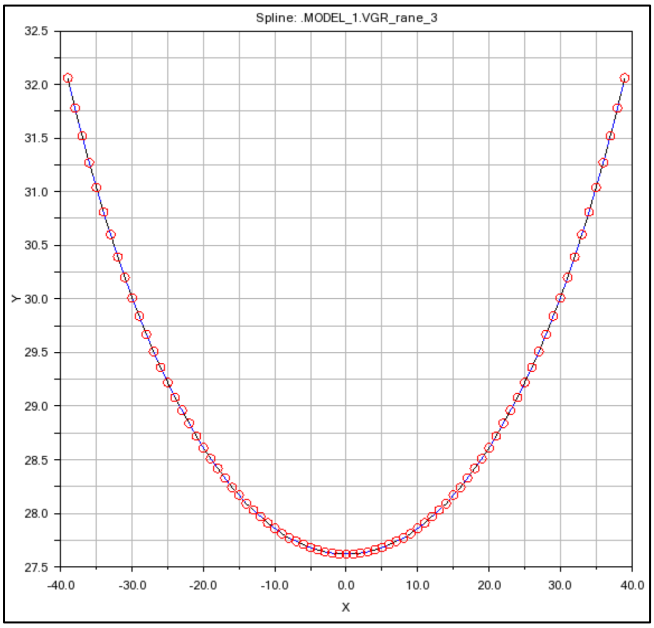

Fig 22 Table 04 Plotted to Graph

Where X axis determines drop-arm travel and Y axis represents Gear ratio.

The graphs appear parabola

Typical parabolic equation is

$Y = a (X - h)^2 + k$

where (h, k) is vertex

a > 0 is a constant

now determining the inputs

at an instance

case 1

Y=27.62

h =0

k=27.62

X=0

a=?

case 2

Y=32.06

h =0

k=27.62

X=39

Putting in equation

$32.06 = a (39 - 0)^2 + 27.62$

$a= (32.06-27.62)/ (39)^2$

a=0.002919

hence with value of a we can now determine value of Y at given value of X by equation

$Y \approx 0.002919(X)^2 + 27.62$

$X=\sqrt{((Y-27.62) / (0.002919))}$

Where X [-39,39] & Y [27.62,32.06]

Value of Y and X are as following

SAP condition Y=0, derived X≈27.62

RH Turn condition Y=36, derived X≈31.2

LH Turn condition Y=31.3, derived X ≈30.3

- *Determining Steering wheel Revolution for VGR (27.62~32.06:1)*

As the formula for the steering wheel revolution for CGR is

(angular travel of stg wheel) = (Angular Drop-arm travel) x (gear ratio)

(F)=(X) x (G)

Where, "F" is angular travel of steering wheel

"X" is angular travel of drop arm And "G" is gear ratio

The stg wheel revolution will be = F/360°

But in VGR the steering wheel revolution defer due to un equal travel of drop arm for same interval of stg wheel revolution

To determine the revolution for VGR we will follow the steps as following: -

Step 1

As derived equation for drop-arm travel and gear ratio

i.e. $Y \approx 0.002919(X)^2 + 27.62$

finding gear ratio for short intervals

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Table 05; Travel vs gear ratio

Travel	Gear Ratio
0	27.620000
0.01	27.620000
0.02	27.620001
0.03	27.620003
0.04	27.620005
0.05	27.620007
0.06	27.620011
0.07	27.620014
0.08	27.620019
0.09	27.620024
0.1	27.620029

Now finding steering wheel revolution for each 0.01 ° travel of drop-arm.
By

(F)=(X)x (G)

Where stg wheel revolution is F/360

Table 6 Revolution Per 0.01° Rev Till 39°

Droparm Travel (x)	Gear Ratio (Y)	Stg wheel Rev for each .01° drop-arm travel
0	27.620	0.000000000
0.01	27.620	0.000767222
0.02	27.620	0.000767222
0.03	27.620	0.000767222
0.04	27.620	0.000767222
0.05	27.620	0.000767222
0.06	27.620	0.000767223
0.07	27.620	0.000767223
0.08	27.620	0.000767223
0.09	27.620	0.000767223
0.1	27.620	0.000767223
:	:	:
:	:	:
:	:	:
:	:	:
39	32.060	0.00089

In order to find the net revolution, we need to add all previous intervals for the particular travel

For example, we need to find steering wheel revolution at 31.3° of drop arm travel

Table 7 Revolution Per 0.01° Rev Till 31.3°

Travel	Gear Ratio	Stg wheel Rev for each .01° drop-arm travel
0	27.620	0.000000000
0.01	27.620	0.000767222
0.02	27.620	0.000767222
0.03	27.620	0.000767222
0.04	27.620	0.000767222
0.05	27.620	0.000767222
0.06	27.620	0.000767223
0.07	27.620	0.000767223
0.08	27.620	0.000767223
0.09	27.620	0.000767223
0.1	27.620	0.000767223
:	:	:
:	:	:

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:	:	:
:	:	:
31.3	30.48.0	0.000847

Let steering wheel revolution for each (n- 0.01) ° to n° of drop-arm travel be P(n)

Stg wheel revolution for 31.3° drop arm travel be

=P (.01) + P (.02) + P (.03) + … + P (31.3)

=0.000767222 + 0.000767222 + …. + 0.000847

=2.49 revolution

For 36° of drop-arm travel the steering wheel revolution will be=2.89 revolution

Now to get the steering wheel effort

Putting value of T and G in derived formula the efforts comes out are mentioned below

SAP condition= 8.3/Z

RH turn condition=8.9/Z

LH turn condition=11.6/Z

Considering net efficiency Z=77%

Table 8 Effort and Revolution Output

PARAMETERS	SAP CONDITION	RH TURN	LH TURN
effort	10.8Kg	11.5 Kg	15.1 Kg
revolution	NA	2.89 Rev	2.49 Rev

IV. STEERING EFFORT OPTIMIZATION

As per the derived formula for steering effort

= ((((((((T/ (X sin(a°))) *X sin(b°)) + T)/(l*sin(C°))) *L *sin(D°))/G)/(J/2))/(Z)

There are several parameters which can help optimizing the steering effort, but with change in every parameter may impact on other parameters like number of steering wheel rev, TCD, etc. Hence, we should balance all parameters as per requirement.

By considering above points below parameters are considered for optimization.

- drop-arm (length and preset angle)
- Steering arm (length and angle with drag-link)
- Tie-rod arm (length and angle with tie-rod)
- *Drop-Arm Modification (CD)*

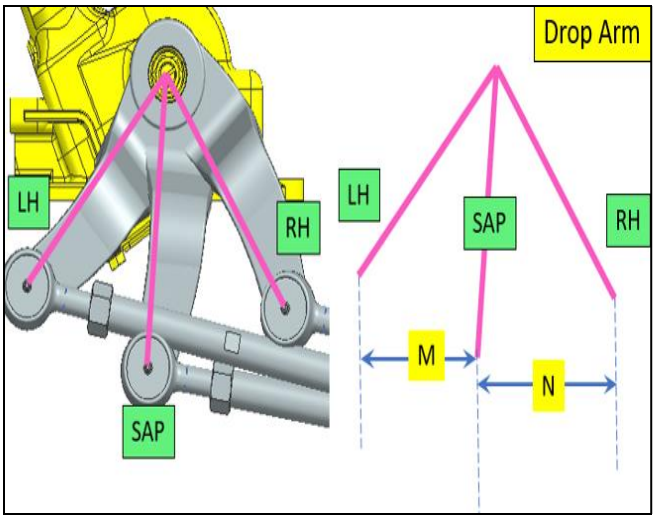

Fig 23 Drop-Arm Angular and Linear Travel

In fig 23. Pink line indicates the center line for drop arm along with the case (LH, RH, SAP)

Where M and N is the liner travel (linear travel required by steering arm to turn vehicle LH turn lock to RH turn lock condition)

Note : - M and N will remain constant till there's no change in steering arm

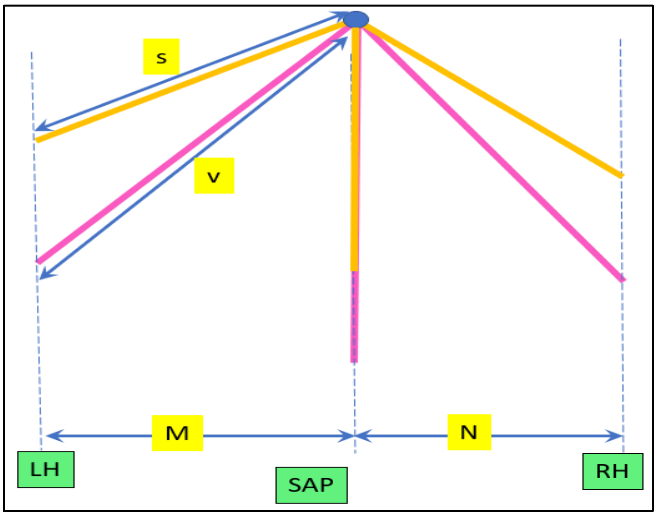

Fig 24 Linear Travel vs Angular Travel with Change in Drop-Arm CD

arm S<V, M and N remains constant. to cover required linear travel drop arm angular travel increases hence it results better steering effort but increases steering wheel revolution.

- *Drop-arm Modification (Pre-Set Angle)*

As per the observation in steering effort, if there is unequal steering effort, for example: - LH steering effort is more than RH steering effort, we need to balance the steering

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effort by changing drop arm only As per the previous observations the steering effort is directly proportional to drop arm effective CD which is CD*Sin(D°) where CD is drop arm Centre distance and D° is angle between draglink and drop arm.

By reducing drop-arm CD, decreases steering effort equally but doesn't make LH and RH steering effort equal or nearby Hence, in order to reduce effective CD of drop arm to **reduce the effort in LH turn we need to shift preset the angle of drop-arm towards the rear of vehicle, and vice versa for reducing effort at RH turn.**

- *The Drawbacks of this Method are as Following: -*
- ✓ Increase in steering effort on the opposite turn.
- ✓ Increase of steering wheel revolution

➢ *Steering-Arm Modification (CD)*

As per the derived formula for steering effort

= ((((((((T/ (X sin(a°))) *X sin(b°)) + T)/(l*sin(C°))) *L *sin(D°))/G)/(J/2))/(Z)

We can determine that to optimize steering effort the CD of steering-arm should be as max as it can Although there is no effect of CD of tie-rod arm in the formula.

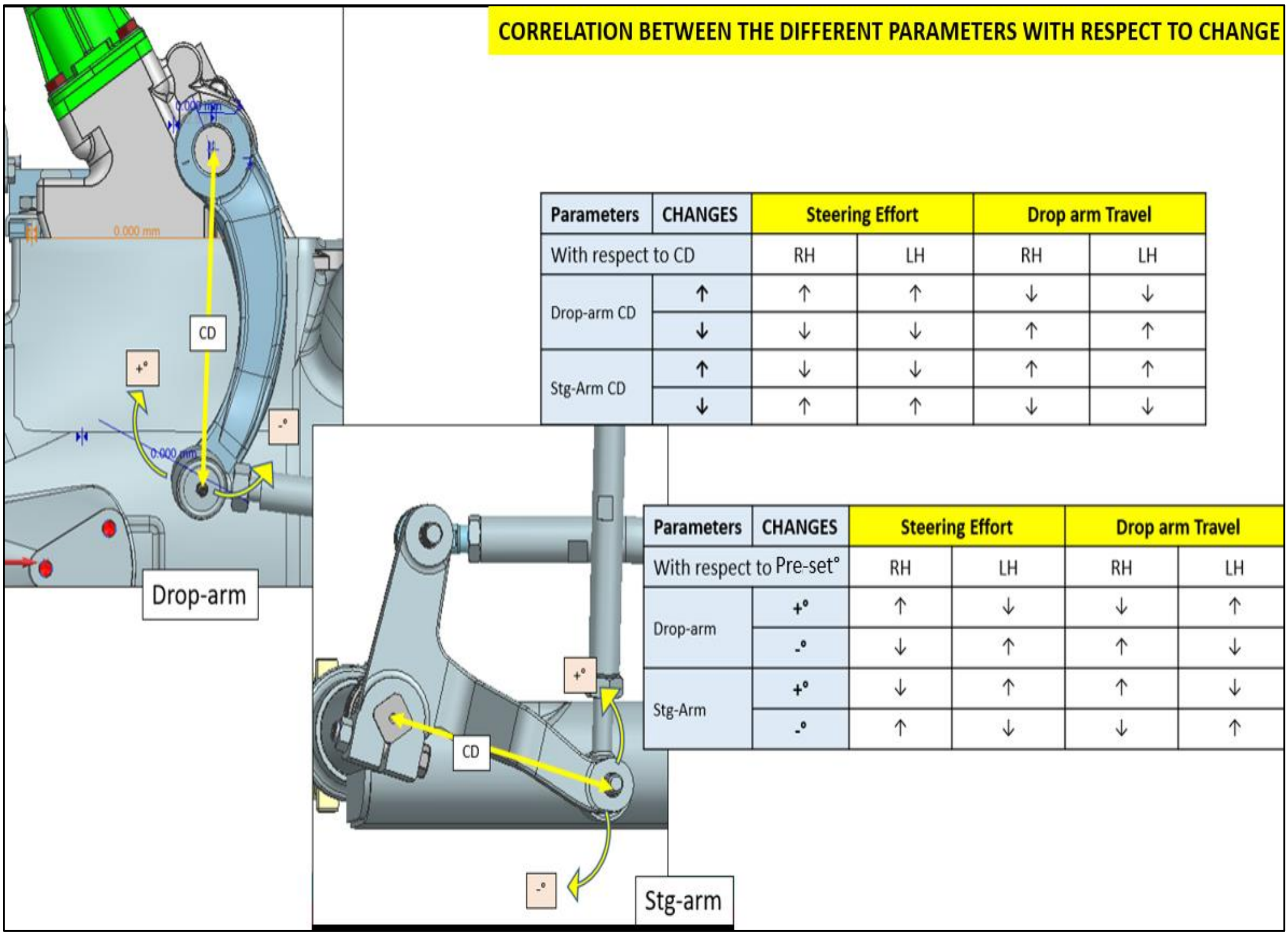
Hence increasing length of steering arm can result in lesser steering effort meanwhile it also increases the required liner travel of the drop-arm and the same wheel lock angle results in more steering wheel revolution.

➢ *Steering-arm Modification (Pre-Set Angle)*

As per the observation in steering effort, if there is unequal steering effort, for example: - LH steering effort is more than RH steering effort and we need to balance steering effort by setting steering arm only As per the previous observations the steering effort is inversely proportional to steering arm effective CD which is [CD*Sin(D°)] where CD is stg arm Centre distance and C° is angle between drag link and stg arm.

By increasing steering-arm CD decreases steering effort equally but doesn't make LH and RH steering effort equal or nearby Hence; in order to increase effective CD of steering arm to **reduce the effort in LH turn we need to shift the preset angle of steering-arm towards the front of vehicle, and vice versa for reducing effort at RH turn.**

- *The Drawbacks of this Method are as Following: -*
- ✓ Increase in steering effort on the opposite turn.
- ✓ Increase of steering wheel revolution for the optimized turn.



Parameters	CHANGES	Steering Effort		Drop arm Travel	
With respect to CD		RH	LH	RH	LH
Drop-arm CD	↑	↑	↑	↓	↓
	↓	↓	↓	↑	↑
Stg-Arm CD	↑	↓	↓	↑	↑
	↓	↑	↑	↓	↓

Parameters	CHANGES	Steering Effort		Drop arm Travel	
With respect to Pre-set°		RH	LH	RH	LH
Drop-arm	+°	↑	↓	↓	↑
	-°	↓	↑	↑	↓
Stg-Arm	+°	↓	↑	↑	↓
	-°	↑	↓	↓	↑

Fig 25 Correlation b/w Different Parameters with Respect to Change

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Fig 25. represents all the observations and outcomes with respect to modifications in steering arm and drop arm (*right hand mounted drop arm & steering arm with center mounted steering gear).*

Although there's still an optimization procedure other than drop arm and steering arm that is **Tie-Rod.**

➢ *Tie Rod Optimization (Pre - Set Angle)*

As per the derived formula for steering effort

= ((((((((T/ (X sin(a°))) *X sin(b°)) + T)/(l*sin(C°))) *L *sin(D°))/G)/(J/2))/(Z)

We can determine that to optimize the steering effort there is no effect of CD of tie-rod arm in the formula.

But significance of the ratio of sin of angle a° and b° still validates and observed in formula.

Initially these angles are set to follow Ackerman geometry

Meanwhile for the effective kingpin torque at RH stg arm is compiled with ratio of sin components with respect to angle a° and b°

E'=T*(sin(b°)/sin(a°)) is the formula resolved previously

E'+T is net king pin torque on RH steering arm

E' is directly proportional to (sin(b°)/sin(a°))

Hence to reduce steering effort the ratio of sin components with respect to angle a° and b° should be minimized

Note: - a° and b° are symmetric to each other with respect to both RH and LH turn condition, for example

If a° = 60° and b° = 160° for RH turn it becomes a°160° and b°=60° for LH turn

If we optimize steering effort by changing the ratio to the minimum for RH turn it becomes Max in LH turn So, initially the angles a° and b° should be near 90° to optimize effort and maintain symmetricity in effort but the major drawback is a degrading Ackerman geometry (*an increase in Ackerman error*.

V. CONCLUSION

This study comprehensively evaluated the steering effort in mechanical steering systems used in agricultural machinery (Tractors), Particularly under variable operational conditions. By develop a detailed analytical model grounded in mechanical geometry and force distribution, key contributors to steering effort-such as king pin torque, arm lengths, steering angles, and gear ratios-were identified and quantified. The investigation into both constant gear ratio (CGR) and variable gear ration (VGR) configurations revealed the trade-offs between steering effort and steering wheel revolution.

Optimization strategies focused on critical components like the drop-arm, steering arm, and tie-rod geometry. There modifications demonstrated that meaningful reductions in steering effort are achievable without compromising fundamental advantages of mechanical steering, such as simplicity and reliability. However, the study also highlighted the importance of balancing improved ergonomics with geometric constraints and steering response characteristics.

Overall, the finding provides actionable insights for design engineers to enhance the driver comfort and performance of mechanical steering systems in tractor. Future work may extend to combined mechanical optimization with hybrid assist mechanisms to further reduce operator fatigue, especially in prolonged field applications.

LIST OF ABBREVIATIONS

➢ *Abbreviations Definition*

- SDA single drop arm
- RH right hand
- LH left hand
- SAP straight ahead position
- VGR variable gear ratio
- CGR constant gear ratio
- Rev. revolution
- Stg. steering
- CD center distance
- MS mechanical steering
- Coeff. coefficient

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