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Effect of Rack Friction, Column Friction and Vehicle Speed on Electric Power Steering (EPS) of Vehicle-A Methodology

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Abstract - *In Passenger vehicle industry, Steering performance is of utmost importance in determining the vehicle dynamic behavior for active vehicle safety and crucial to understand the performance well before its deployment on the vehicle. In current scenario, with the introduction of advanced driver assistance system (ADAS), which comes with many add on features in the steering system such as pull drift compensation, lane keep assist, auto park assist etc., this requirement becomes more stringent for the accurate delivery of the programmed algorithms. In this paper, the complete wheel-to-wheel steering model is developed for the simulation in Amesim platform with all the associated components. With the validated model, the variation of the total torque required at the pinion gear at different vehicle speeds (0 to 160 kmph) is plotted. The friction torque at column, steering rack and motor is plotted to closely understand the change behavior with respect to time for the given input of steering angle and vehicle speed. At last, results are analyzed to develop the understanding between steering system's components so that the necessary power can be requested from the system in order not to compromise with the desired force to turn the wheel on road.*

Key Words**: Electric power Steering, *Amesim*, Friction, Vehicle, Simulation etc.**

1. INTRODUCTION

According to the report of fortune business insight, the global market for automobile steering systems which is divide into four categories: manual steering, electric power steering (EPS), electro-hydraulic power steering (EHPS) and hydraulic power steering (HPS) as mentioned in Fig-1 was valued at USD 17.1 billion in 2018, and it is anticipated to reach USD 25.4 billion by 2026 [1]. Because manufacturers are increasingly integrating EPS into vehicle models, the electric power steering category is expected to dominate the market.

Furthermore, government restrictions for fuel efficiency have prompted a rise in the use of fuel-efficient vehicles which requires efficient steering systems. In addition, the consumer demand for fuel-efficient vehicles is anticipated to fuel the growth of the automotive steering system market.

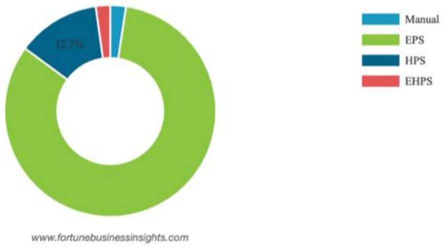

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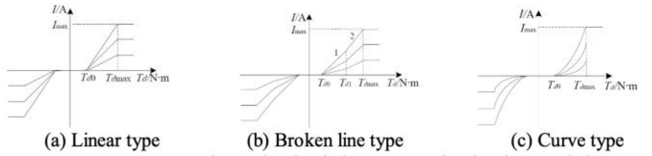
Fig -1: Global Automotive steering system market share, by type, volume 2018

To cater this requirement, other than many solutions on the engine and transmission etc. one promising solution is EPS system that only activates when the steering wheel is turned resulting in 3% better fuel efficiency than that of the vehicle equipped with an equivalent hydraulic system. The EPS system is therefore uses less energy and result in fuel saving and decreases the amount of carbon dioxide released into the atmosphere and thus making it more environmental friendly and energy-efficient [2]. To improve the efficiency within EPS system further, the friction which arise at different part of the steering system has to be at a value that gives the improved performance in terms of steering feel. Therefore, when it comes to the improvement, knowing the actual values and change behaviour over a range of driving manoeuvre is important to understand.

To understand and monitor the performance of the steering system, many researchers have put their efforts right from the design, simulation to testing setups. The design requirement of EPS has been covered by A. Isah et al. [3] for pinion type assist configuration (P-EPS), column type assist configuration (C-EPS) and rack assist configuration (R-EPS). Botti et al. [4] in their paper has included wheel to wheel steering system model in the early design stages of a power steering system while Hao Chen et al. [5] developed 15 degree of freedom(DOF) vehicle model consisted of, wheels- 4DOF, vehicle body-6DOF, suspension-rear-2DOF, suspension-front-2DOF, and steering wheel-1DOF. For this work, entire system was divided into three sections. (1) Brush-Direct Current motor, which supplies assist torque; (2) Mechanical system, which includes the steering wheel, steering column and steering rack; and (3) Electronic Control Unit (ECU), which includes related sensors like steering angle sensor, steering torque sensor and motor current sensor etc.

The control mechanism is a crucial part of the EPS system through which it offers more assistance as a vehicle slows down and less assistance as it travels faster. When no steering assistance is needed, system operates with very little power [6]. Many researchers have contributed in this domain. Lina Feng et al. [7] did investigations into control mechanisms of brushless DC motors and discussed three distinct kinds of fundamental assist characteristics—liner type, broken line type, and curve type—are depicted in Fig. 2. Out of these, linear type of assist characteristics are widely used for the development of power steering motor's torque control strategy.



(a) Linear type (b) Broken line type (c) Curve type

Fig -2: Assist characteristics

To predict the steering effort precisely, some work has been done on the prediction and calculation of friction torque in the past such as Kim et al. [8] has proposed an analytical method to take tire friction torque into consideration for the evaluation of steering effort. In his test setup, he used strain gauge, linear displacement indicator, non-spinning torque sensor for the measurement of rack force, rack displacement, steering effort and tire friction torque respectively. However he neglected the friction within the steering system and thus the calculated value of steering efforts are smaller than actual measurement. M. M. Skarzynska [8] highlighted the importance of reduction in friction and studied that steering friction is contributed from different parts of the system such as steering shaft friction, column friction, and steering rack friction. They concluded that to estimate steering wheel torque accurately, the steering column is one of the key contributors.

Given this contexture, this study focuses on development of steering system model in *Amesim* environment with the detailed focus on friction contributing component of the EPS system. The rest of the paper proceeds in following sections: Section2 covers the objective of this present work. In Section3, the modeling methodology with the introduction of *Amesim* tool is covered. Section 4 explains the working of the 1Dim EPS model. The results are explained in section5 and lastly the paper is concluded in section6 by providing future scope and limitations of the work.

2. OBJECTIVE

To understand the steering system's modeling methodology in 1D *Amesim* environment.

To know the impact of vehicle speed on the required pinion torque.

To know the impact and change behavior of component's friction (column, rack and motor) for a given set of steering angle and vehicle speed.

3. MODELING METHODOLOGY

The steering system is responsible to turn the vehicle as per driver's input. It contains the following parts: steering wheel, steering column, rack - pinion mechanism and assistance law. The parameters used as input, output and for the modeling of the steering system are as follow:

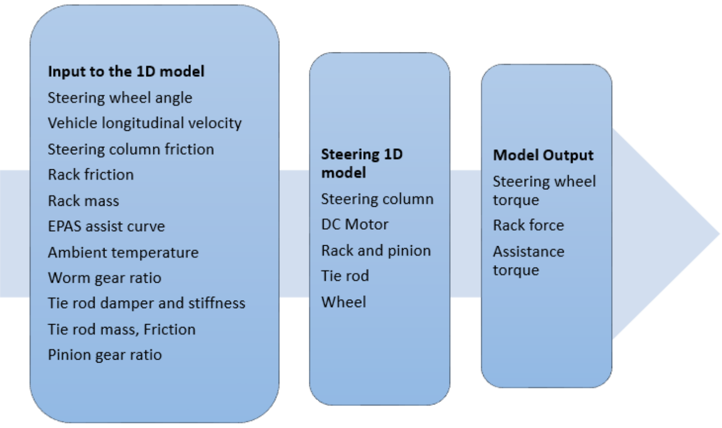


Fig -3: Parameters involved in steering system

3.1 INTRODUCTION OF *Amesim* TOOL

Amesim stands for Advanced Modelling Environment for Engineering System Simulation. This platform is used to model, analyze and predict the performance of the mechatronics system. In this work 1D mechanical and vehicle dynamics library of Simcenter *Amesim* platform is being used for model setting and to perform the simulation of the EPS logic. A brief understanding of the steering system components, principle of working and the corresponding library block to model in *Amesim* environment are explained here as follows:

3.1.1 Steering column and Torque Sensor

Torsion bar is used as the torque sensor in the column steering system connected between the driving source i.e. steering wheel from where the driver will provide input to the system and load i.e. the tire at the road surface such that its perfectly align with the axis of rotation. Torsion bar can be a simply metallic bar for measuring the torque transmitted from driver to load or load to driver with circular cross section.

The principle involved in measuring the torque is the twist or the deflection in the shaft. A torsional mechanical input is transformed into an electrical output signal using torque sensors and sent to the controller as an input.

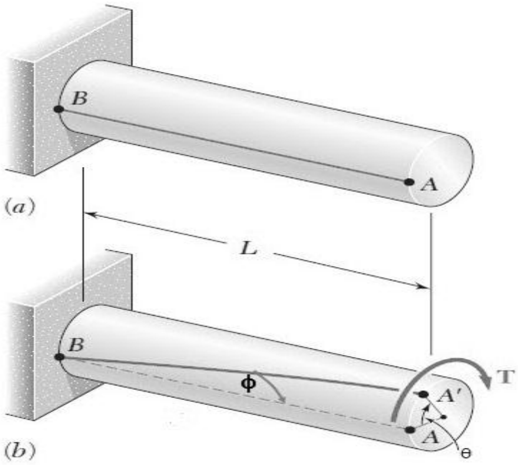


Fig -4: Torsion bar (a) before deflection (b)after deflection

The angular twist, the difference between the angle at both the end is directly proportional to the torque developed in the torsion bar between input and output shaft, and that is a direct measure of the torque value in the sensor.

The mathematical expression involved:

$$T = \emptyset.(I_p.G)/L$$

After substituting the value of polar moment of inertia, I_p

$$\emptyset = \frac{2L.T}{\pi G({R_0}^4 - {R_i}^4)}$$

Where,
L=Torsion bar active length
T=Torque
G=Modulus of rigidity of the shaft material
R_0=Outer radius of the shaft
R_i=Inner radius of the shaft
∅=Angular displacement of the shaft
In case of solid shaft, $R_i = 0$

The modeling of the torsion bar is the important and crucial part in the entire electric power assist steering system. In the simulation model, it can comprise of a torsion spring connected to the steering column on one side and the pinion on the other as shown in the Fig-5.

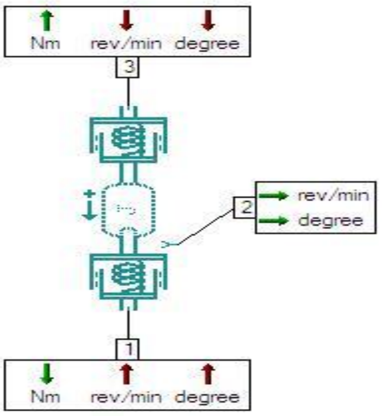


Fig -4: Torsion bar modeling in *Amesim*

3.1.2 Rack-Pinion Mechanism

The transformation ratio between the steering angle and the rack displacement is represented by the rack-pinion model. The ratio must be negative because of the sign conventions of expression frames: a positive steering angle (left turn) produces a negative rack displacement (rack goes to the right).

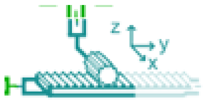


Fig -5: Rack and pinion symbol

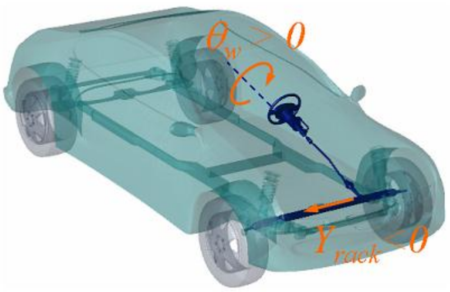


Fig -6: Steering motion mechanism

3.1.3 Assistance Law

In accordance with the steering torque at the torsion bar and the vehicle speed, the assistance law delivers a current intensity instruction. However, the electric motor's torque constant parameter, which converts the current instruction

into output torque, is all that is needed to model the electric motor.
The assistance law is the following:

$$Iassist = kassist * \frac{{T_{steer}}^{3}}{(V_{vehicle+\epsilon})}$$

Where
Iassist = motor current command in [A]
Kassist = assistance gain in [A.(km/h)/(Nm)3]
Tsteer = steering torque at torsion bar in [Nm]
Vvehicle = vehicle speed in [km/h]
ε is an offset to avoid division by zero in [km/h]

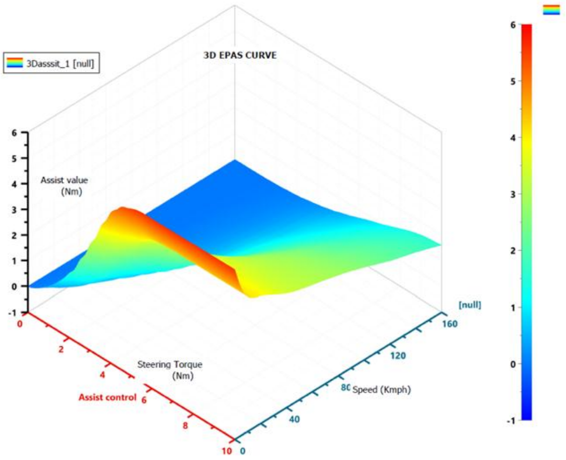


Fig 7 EPS 3D curve

the vehicle speed is given as the input for a range of 0 to 160 kmph while keeping the damper, stiffness, friction and other values unchanged for one set of simulation.

3.2 PART DECRIPTION

Table1: Steering system-Part description

Bullet number	**Part Description**	**Relevant Parameters**
1	Upper column	Friction value
2	Steering torque sensor Torsion Bar	Torque display (Nm) Spring, damping value
3	Worm and worm wheel of assist motor	Worm gear ratio
4	Intermediate shaft	Friction
5	Pinion shaft	Friction value
6	Tie rod	Friction, length
7	Universal joint	Friction
8	Rack and pinion	Pinion radius Gear ratio Rack mass

Fig9 shows how various components such as steering column, Electric motor, Torque sensor, Intermediate shaft, pinion shaft, Tie rod, Universal joints Rack and Pinion etc. of Electric power assist steering model are connected in an EPS system.

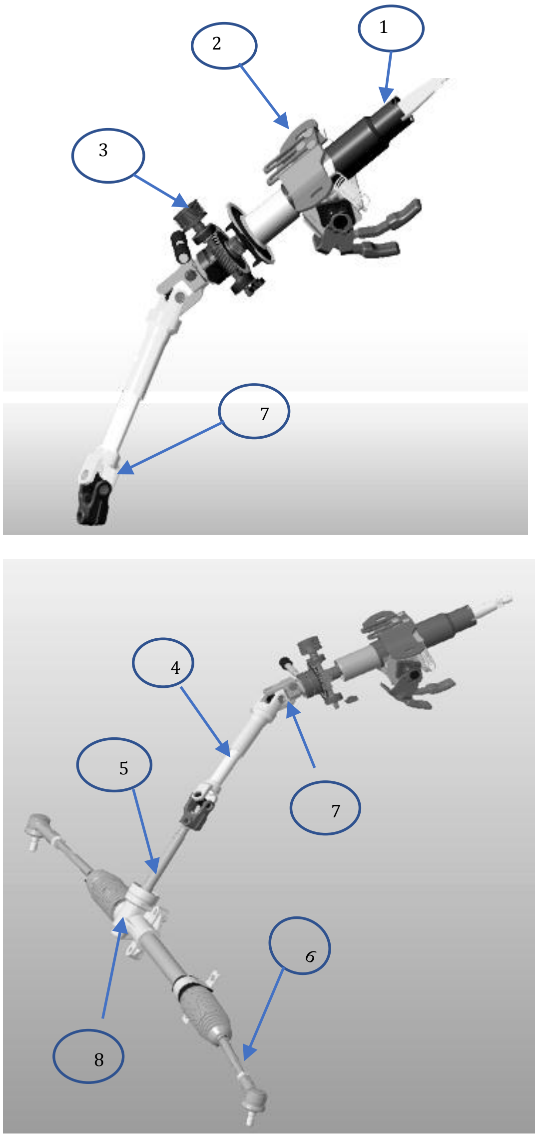


Fig -8*:* Steering system- Creo Model

4. *Amesim* EPS MODEL WORKING

The 1 Dimension line diagram is used to build the Electric power assist steering logic in Simcenter *Amesim* platform. The sinusoidal wave type input of 50 degree amplitude is provided as the steering profile. Steering column provides the friction in rectangular pattern.

Torque sensor is used to measure the resulting torsion bar torque. Assistance curve is used to calculate the corrective command based on vehicle speed and torque value measured by torque sensor.

For each set of vehicle, the 3D assist curve is available that will be used for the respective current /voltage calculation, the output from the assistance law will be treated as the input to the electric motor which will provide the compensation torque command.

To amplify the torque command value, worm and worm wheel is used, where as per the gear law *(G=26 for this study)* torque increases at the larger gear. The amplified torque value and the torque applied from driver's side is given to the pinion of the rack-pinion set where the rotary motion is transferred to the linear motion of the rack.

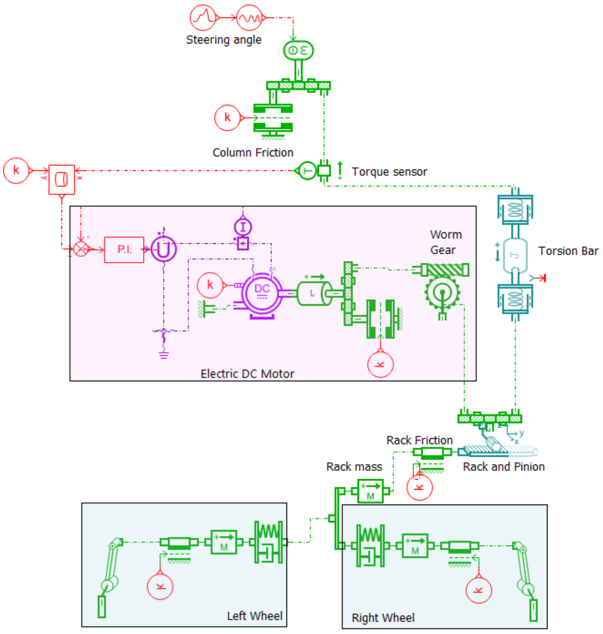


Fig -1: EPS-1Dim Model

Because of the rack inertia and friction of the component and joint, the value of the force that will actually come on the tie rod and wheels will be less.

The rack will be distributed to the left and right wheel in proportion to the wheel inertia and stiffness value. In ideal case this distribution is exactly same on both the side.

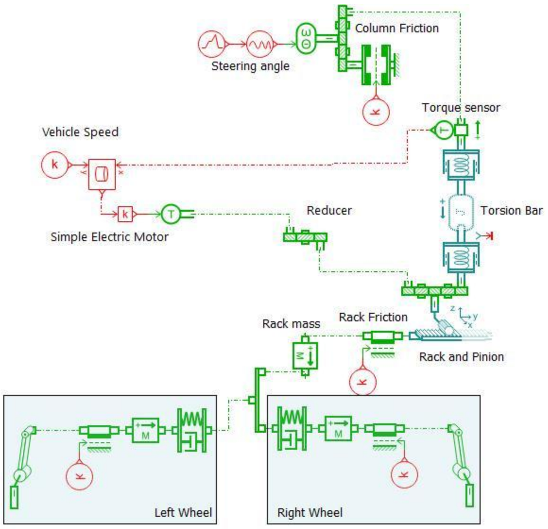


Fig -2: EPS-1Dim model with simplified Electric motor

Flow Diagram:

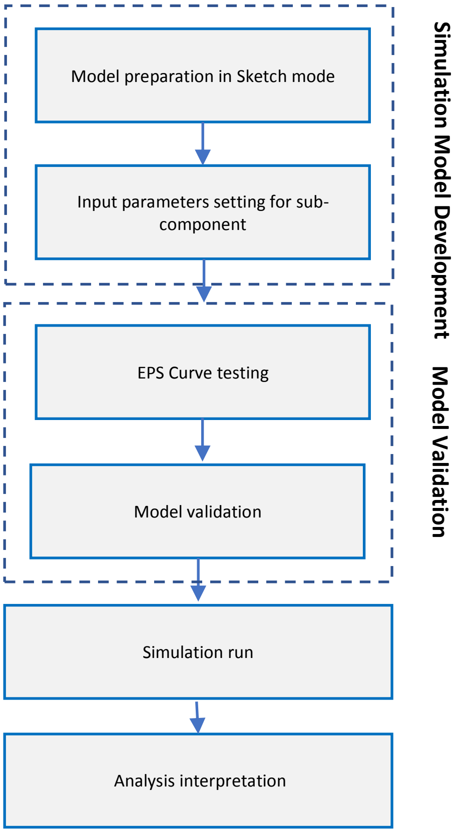
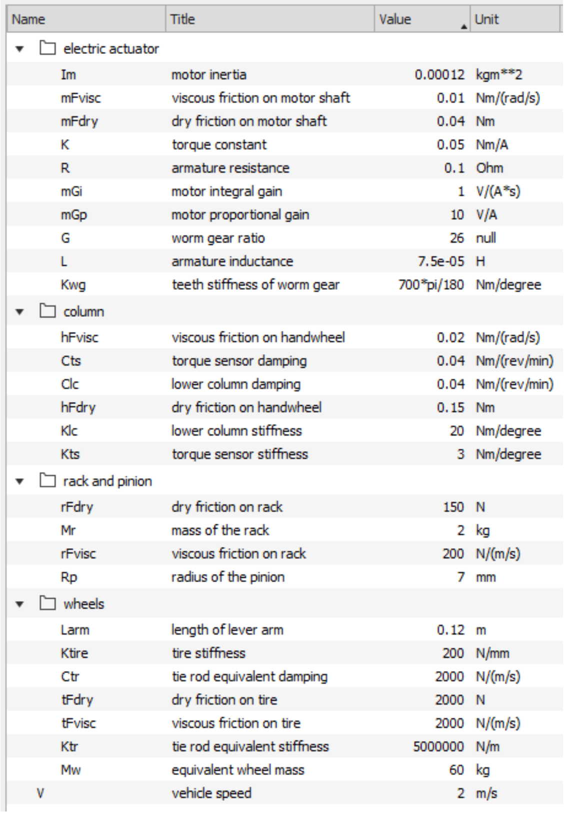


Table -2: Parameters considered in 1D EPS model



Name	Title	Value	Unit
electric actuator			
Im	motor inertia	0.00012	kgm**2
mFvisc	viscous friction on motor shaft	0.01	Nm/(rad/s)
mFdry	dry friction on motor shaft	0.04	Nm
K	torque constant	0.05	Nm/A
R	armature resistance	0.1	Ohm
mGi	motor integral gain	1	V/(A*s)
mGp	motor proportional gain	10	V/A
G	worm gear ratio	26	null
L	armature inductance	7.5e-05	H
Kwg	teeth stiffness of worm gear	700*pi/180	Nm/degree
column			
hFvisc	viscous friction on handwheel	0.02	Nm/(rad/s)
Cts	torque sensor damping	0.04	Nm/(rev/min)
Clc	lower column damping	0.04	Nm/(rev/min)
hFdry	dry friction on handwheel	0.15	Nm
Klc	lower column stiffness	20	Nm/degree
Kts	torque sensor stiffness	3	Nm/degree
rack and pinion			
rFdry	dry friction on rack	150	N
Mr	mass of the rack	2	kg
rFvisc	viscous friction on rack	200	N/(m/s)
Rp	radius of the pinion	7	mm
wheels			
Larm	length of lever arm	0.12	m
Ktire	tire stiffness	200	N/mm
Ctr	tie rod equivalent damping	2000	N/(m/s)
tFdry	dry friction on tire	2000	N
tFvisc	viscous friction on tire	2000	N/(m/s)
Ktr	tie rod equivalent stiffness	5000000	N/m
Mw	equivalent wheel mass	60	kg
V	vehicle speed	2	m/s

Simulation model development and validation is done as mentioned in the flow diagram with the given input of steering angle profile, assist curve and vehicle velocity.

Steering angle profile

In this work the steering angle considered as the input which varies sinusoidally with an amplitude of 50 degree on each side as shown in the chart1

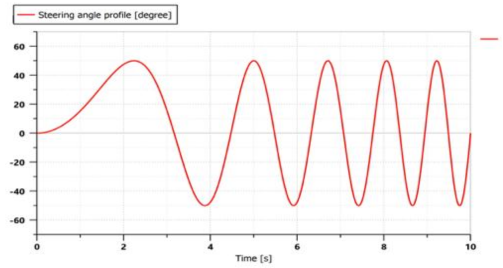


Chart -1: Steering angle profile

Assist curve

Assist curve is the another input to the EPS model, where based on the vehicle speed and steering effort, the current value is there which is fed into the DC electric motor to get the assist torque input which then multiplied by the worm gear ratio and the amplified torque then applied to the pinion to assist the driver.

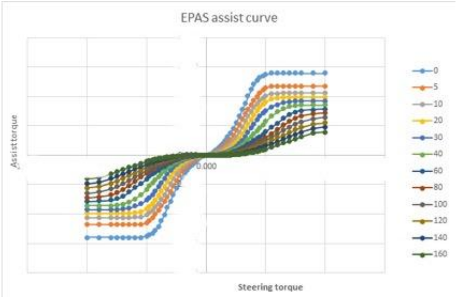


Chart -2: EPS Assist curve

Vehicle velocity

The prepared model is capable to analyse the model for a range of vehicle speed from 0 to 160 kmph. However, for the model validation, vehicle speed is maintained to 100kmph as per ISO 7401:2011 with 2% of maximum allowed fluctuation as mentioned in the chart3.

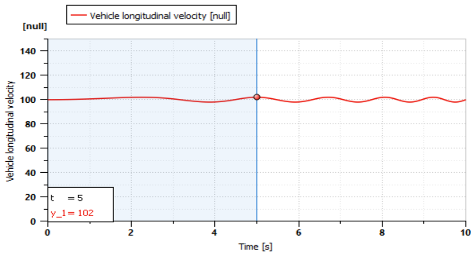


Chart -3: Vehicle longitudinal velocity profile

5. SIMULATION RESULTS AND DISCUSSION

The detailed steering EPS model is analysed against the above mentioned boundary conditions and parameters.

The output parameters such as angle at wheel, torque required at pinion, steering torque, motor friction, rack friction, column friction findings are as follows:

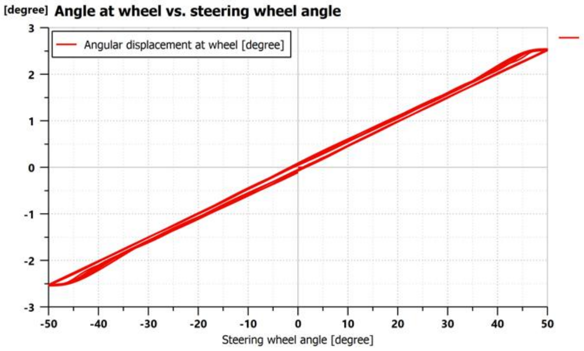


Chart –4: Angle at wheel vs steering angle

In chart4, the graph plotted between the steering angle and angle at the wheel. This graphs gives the information about one of the geometric parameter i.e. the steering ratio. Steering ratio measures how much the steering wheel turns in relation to wheel turns in total and is defined as the ratio between the steering wheel angle and wheel angle on road.

$$\text{Steering ratio} = \frac{\theta_{Steering\ wheel}}{\theta_{Wheel}} \simeq \frac{30-0}{1.5-0} \simeq 20$$

5.1 Effect of Vehicle Velocity

Table -2 Vehicle velocity vs torque requirement

Vehicle Velocity (kmph)	Total torque required at pinion with simplified model	Total torque required at pinion with Electric model
0	1.78553	1.96849
75	1.57493	1.80816
100	1.52488	1.79233
125	1.47183	1.77146
160	1.41354	1.75173

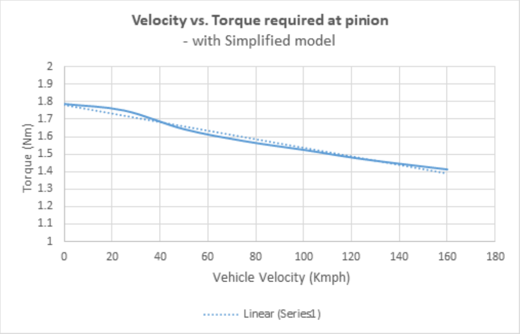


Chart -5: Velocity vs pinion torque with simplified model

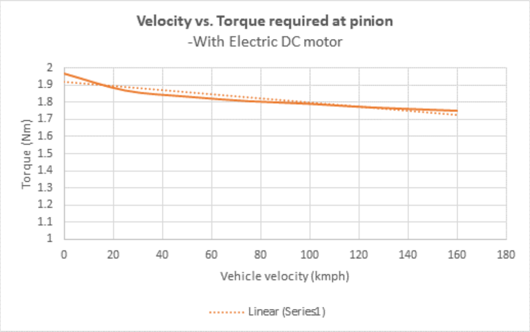


Chart -6: Velocity vs pinion torque with Electric Motor model

Table2, shows the numerical output of the total torque required at different velocity which explains that as the velocity of the vehicle increases, the total torque (steering effort +electric assist torque) keeps on decreasing for both the model irrespective to the detailing as mentioned EPS-1D sketch.

Chart1 and chart 2 show that there is downward slope for velocity vs pinion torque for both simplified and Electric DC motor model. However, because of the added friction in detailed model, the required torque values are on higher side. To explain the above statement, chart 7 shows the hysteresis loop for steering angle vs steering torque for both the model. It is clearly evident that the area covered with the detailed electric model is greater than that the area covered in simplified model which signifies that because of the added friction, more torque is required.

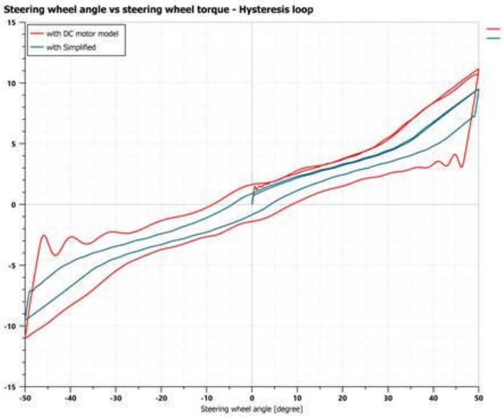


Chart -7: Steering wheel vs steering torque-Hysteresis loop

5.2 Effect of Motor Friction

Chart 9 represents the variation in the torque profile at the motor. The red color line represents the available torque for amplification at the worm and worm gear, which is the resultant from friction torque and the torque corresponding to the assist current as per the assist curve provided in the model.

The torque applied on the rack and pinion comes from both the electric machine assistance and the driver through steering wheel. The magnitude of these two torque contributions are compared in chart 8, where the motor torque is multiplied by the worm gear ratio and the amplified torque is the electric assistance torque applied on the pinion gear.

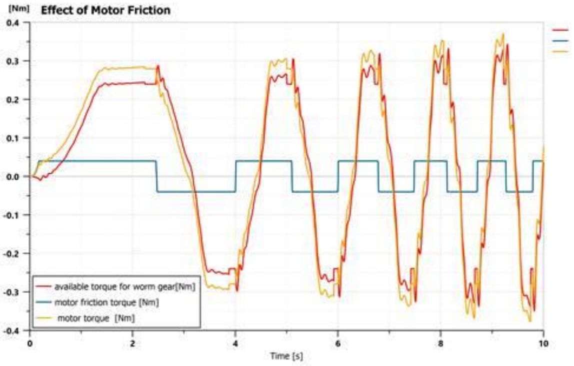


Chart -8: Effect of Motor Friction

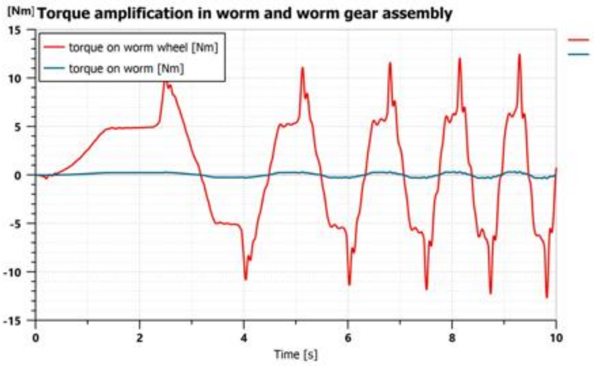


Chart -9: Torque amplification profile

5.3 Effect of Rack Friction

The summation of the steering effort and electric assist torque is applied at the pinion which converts the rotating motion at pinion into linear displacement of rack. The rack is itself having some inertia value which have an impact on the available rack force which further divides into the left and right wheel through tie rod.

Chart 10 shows the variation of the rack friction force and the available rack force with time.

The blue color line is the actual available rack force profile.

5.4 Effect of column Friction

The chart 11 is plotted at v=160 kmph in the detailed model. The red color line shows the variation of the column friction in rectangular pattern, changing its sign as per the steering angle profile and blue color line is for the steering effort. However, the total steering force (shown in yellow color) required at the steering wheel is the summation of the friction force and the one recorded by the torque sensor through torsion bar.

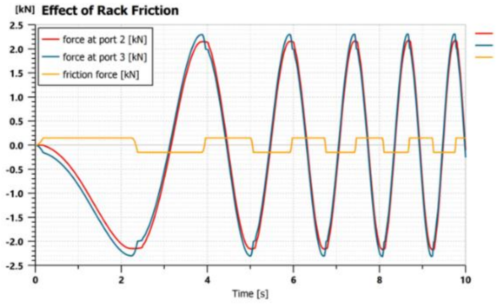


Chart -10: Effect of Rack friction

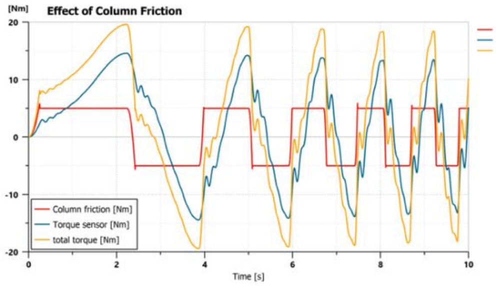


Chart -11: Effect of Column Friction

6. CONCLUSIONS

In this work, the electric power assist steering system's component are covered right from working principle to the modeling methodology. The law and mechanism of force and torque transferred are covered through 1Dimension model in *Amesim* environment with required set of input parameters.

The two different 1Dim model with simplified and detailed model are prepared and the hysteresis graph is plotted to know the comparison of added friction in the detailed model. However, the effect of the friction torque is evaluated at different point in the model to know the impact of motor friction, column friction and rack friction which can vary at different-different values to optimize the performance. Also, the performance of the dynamic behavior is evaluated with respect to vehicle longitudinal velocity which shows the decreasing pattern in total torque required with the increase in the vehicle speed.

The main focus of this work was to elaborate on the modeling Methodoly and highlight the way of evaluating the performance in the simulation environment. For this purpose, the dummy values of the passenger vehicle are taken into consideration. This work can be used as the benchmark to start modeling of the steering system and is capable to predict the performance of any new system with the slight change in the mass, stiffness, damping and CG values etc.

Furthermore, to know the performance at the vehicle level such as vehicle trajectory, roll, and pitch and yaw rate etc., the system has to be integrated with the complete vehicle model either 15DOF or 18DOF, where along with the EPS model, the detailed model of tire, suspension, brakes, transmission etc. are covered.

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