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ABSTRACT

In recent years, concerns about local and global pollution have intensified. In some countries, they have already led to stricter and stricter environmental legislations. CO emissions from automobiles are responsible for two thirds of total CO emissions.

On today's vehicle driven by gasoline or diesel engines, a hydraulic power steering of which the power source is an engine- driven hydraulic pump is generally mounted.

In this power steering system, a hydraulic pump is rotated in proportion with a revolution speed of the engine and runs at high revolution speed even during a straight ahead position and high speed driving, even when no steering operation is needed. Therefore it always consumes some amount of energy that is always wasted. An energy consumed by such a power steering system is approximately 3% of all vehicle fuel consumption. Therefore energy saving in such power steering system should be more intensified.

Electrically Powered Hydraulic Steering (EPHS) Systems is one such pioneer technology that helps in reducing the overall emissions from automobiles annually.

This Project Report contains the development of a prototype of EPHS system for an after -market product development. The report deals with the selection of the components for a test bench, the testing of the prototype and validation of results obtained from the tests.

OBJECTIVE

- To develop a prototype of EPHS system:
  Indent is a company that looks for greener alternatives for automobiles. The projects carried out here are mainly based on improving the way automobiles run. One such way is to adopt EPHS system for heavy vehicles.
  Looking at the potential and scope of the system, we were given a project to develop a prototype of the system to obtain various desired parameters.

- Market survey and analysis:
  A small part of the objective was also to do a market survey of the product(s) currently available in the market. Also a market research was to be conducted for selection of the pump, motor, reservoir and hydraulic steering rack to make a prototype.

- To get readings of flow rate, hydraulic pressure of the fluid in the system:
  Any hydraulic steering system works on the flow of fluid, which is displaced by the pump at a desired pressure. On literature review of the EPHS systems, we discovered that the systems available run at 100 bars pressure and 8l/min flow for a given motor torque. So the main objective was to develop a lesser expensive prototype and obtain the readings of fluid flow rate and pressure in the system.

- Suggest Indent suitable data for selection of motor, pump and reservoir:
  To validate the calculations carried out with the results obtained. This would ensure the success of the prototype. These results can be then applied to suggest Indent Pvt. Ltd. for a suitable type of Motor-Pump-Reservoir unit (MPRU) as per the requirements.

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1. STEERING

1.1. Background:

Steering is the term applied to the collection of components, linkages, etc. which will allow a vehicle (car, motorcycle and bicycle) or a vessel (ship, boat) to follow the desired course [1].

The steering system is the key interface between the driver and the vehicle. The main aim of a steering is to steer the vehicle in the desired direction and desired rate. Also, the steering has to be precise. In addition, the steering system should be smooth, compact and light. It must also provide the driver with a perfect feel for the road surface and help the wheels return to the straight-ahead position.

The most conventional steering arrangement is to turn the front wheels using a hand–operated steering wheel, which is positioned in front of the driver, via the steering column, which may contain universal joints, to allow it to deviate somewhat from a straight line [2].

1.2. Functions of steering system:

- To convert the rotary motion of steering wheel into angular displacement of front wheel.
- Maintain straight ahead motion of vehicle while it encounters potholes and bumps.
- To operate with minimum effort. Should be light and easy to operate.
- Should not transmit road shocks to the steering wheels [3]

2. GEOMETRY PARAMETERS INVOLVED IN STEERING AND SUSPENSION:

The basic aim of steering is to ensure that the wheels are pointing in the desired directions. This is typically achieved by a series of linkages, rods, pivots and gears. Apart from these mechanisms, the steering geometry is a key factor that determines the overall steer-ability and straight ahead recovery of the vehicle.

The steering and road holding of a car depend to some extent on the layout and orientation of the stub axles on which the front wheels are mounted. The suspension geometry is defined by the traditional terms camber angle, toe-in, and the swivel angles called castor and king pin inclination. These terms are explained below.

2.1. Camber Angle:

Camber angle is regarded as the inclination of the wheel plane to the vertical [5]. Negative camber inclines the top of the tyre toward the centreline of the vehicle as seen in fig 1 and positive camber inclines the top of the tyre away from the centreline.

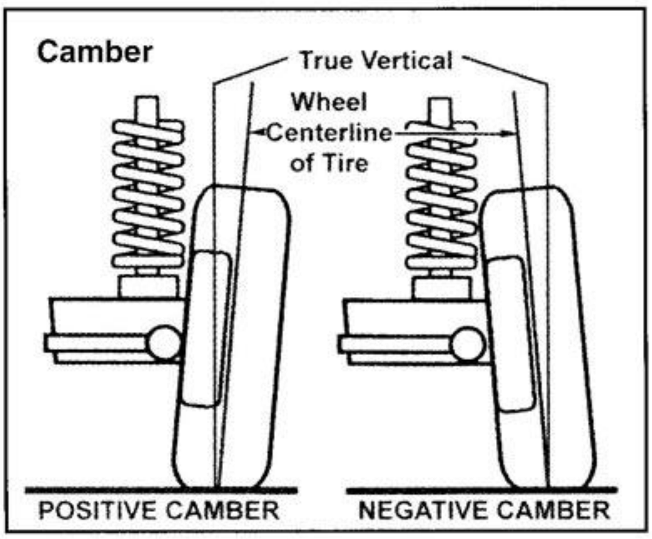


Figure 1: Camber angle (Front view) [1]

A small amount of negative camber of up to 1.5 degrees is recommended in order to induce camber thrust. However, changes in camber should be kept at minimum during chassis roll in order to reduce the loss of camber thrust and the change in wheel track load distribution during cornering.

2.1.1. Effect of Camber:

Negative camber improves grip when cornering. This is because it places the tire at a better angle to the road, transmitting the forces through the vertical plane of the tire rather than through a shear force across it. Another reason for negative camber is that a rubber tire tends to roll on itself while cornering. The inside edge of the contact patch would begin to lift off of the ground if the tire had zero camber, reducing the area of the contact patch. This effect is compensated for by applying negative camber, maximizing the contact patch area.

On the other hand, for maximum straight-line acceleration, the greatest traction will be attained when the camber angle is zero and the tread is flat on the road [1].

2.2. Caster Angle:

Caster angle is the angle in side elevation between the steering axis and the vertical. It is considered positive when the steering axis is inclined rearward (in the upright direction) and negative when the steering axis is inclined forward [5]. Caster angle can be visualised on fig 2.

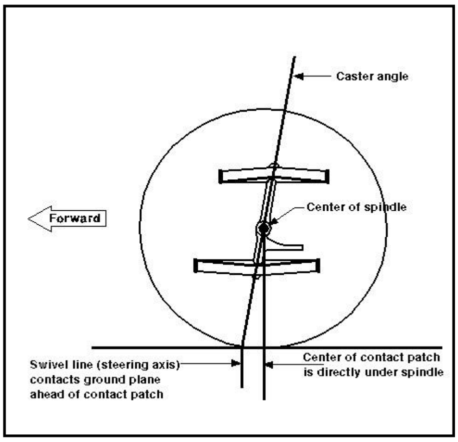


Figure 2: Caster Angle [2]

2.2.1. Effect of Caster angle:

When a vehicle's front suspension is aligned, caster is adjusted to achieve the self-centring action of steering, which affects the vehicle's straight-line stability. Improper caster settings will cause the driver to move the steering wheel both into and out of each turn, making it difficult to maintain a straight line. The pivot points of the steering are angled such that a line drawn through them intersects the road surface slightly ahead of the contact point of the wheel. The purpose of this is to provide a degree of self-centring for the steering; the wheel casters around so as to trail behind the axis of steering. This makes a car easier to drive and improves its directional stability. Excessive caster angle will make the steering heavier and less responsive [1].

2.3. Kingpin Geometry:

2.3.1. Kingpin inclination

The angle in front elevation between the steering axis and the vertical is regarded as kingpin inclination [5]. It is also known as steering axis inclination (SAI) and can be seen in Figure 4.

It is used to reduce the distance measured at the ground between steering axis and tyre’s centre of pressure in order to reduce the torque about the steering axis during forward motion. A right kingpin inclination will reduce the steering effort and will provide the driver with a good ‘road feel” [1].

2.3.2. Kingpin offset

Kingpin offset measured at the ground is the horizontal distance in front elevation between the point where the steering axis intersects the ground and the centre of tyre contact.

Kingpin offset it is also known as scrub radius. It is positive when the centre of tyre contact is outboard of the steering axis intersection point on the ground.

Kingpin offset is usually measured at static conditions (zero degree camber) [1].

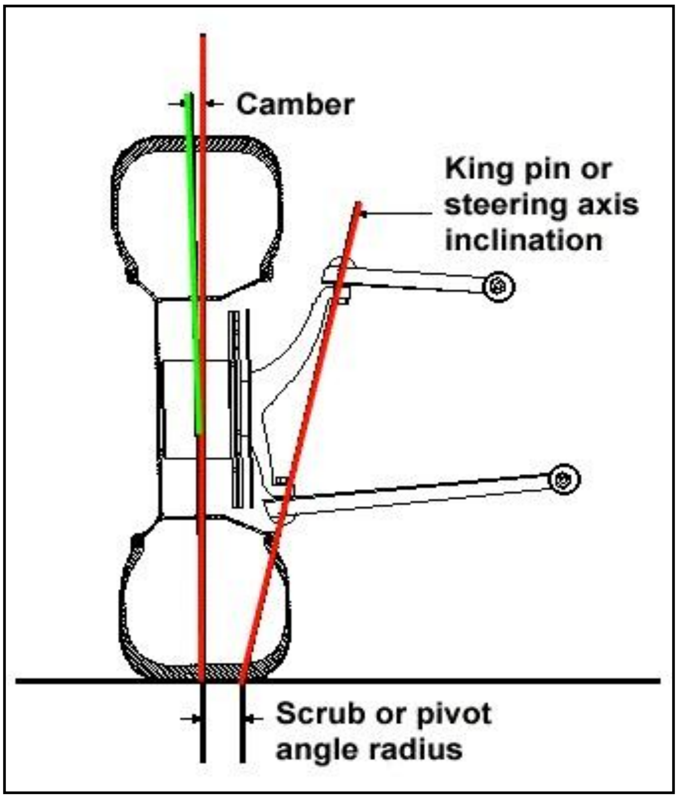


Figure 3: Kingpin angle and Scrub radius [3]

2.4. Wheel Toe:

2.4.1. Static toe angle:

Static toe angle is measured in degrees and is the angle between a longitudinal axis of the vehicle and the line of intersection of the wheel plane and the road surface. The wheel is “toed-in” if the forward position of the wheel is turned toward a central longitudinal axis of the vehicle, and “towed-out” if turned away.

2.4.2. Static toe:

Static toe-in or toe-out of a pair of wheels is measured in millimetres and represents the difference in the transverse distance between the wheel planes taken at the extreme rear and front points of the tyre treads. When the distance at the rear is greater, the wheel is “toed-in” by this amount; and where smaller, the wheels are “toed-out” [5] as illustrated in fig4.

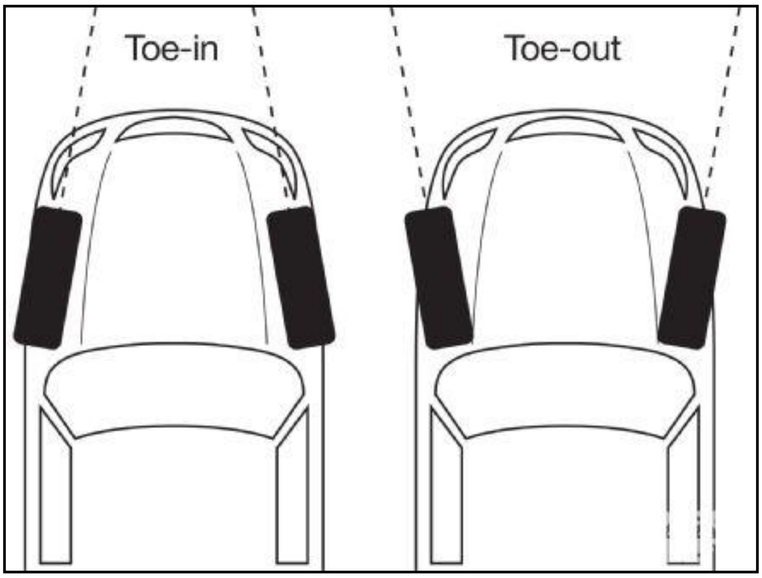


Figure 4: Toe-in and Toe-out [4]

2.4.3. Effect:

It is necessary to set the static toe such way to prevent the tyres to become toe-out during maximum bump and roll in order to prevent the outboard tyre to steer the vehicle to the outside of the turn when cornering.

Toe-in produces a constant lateral force inward toward the vehicle centreline during forward motion that will enhance the straight line stability.

3. ACKERMANN STEERING GEOMETRY:

Ackermann steering geometry is a geometric arrangement of linkages in the steering of a car or other vehicle designed to solve the problem of wheels on the inside and outside of a turn needing to trace out circles of different radius.

The intention of Ackermann geometry is to avoid the need for tyres to slip sideways when following the path around a curve. The geometrical solution to this is for all wheels to have their axles arranged as radii of a circle with a common centre point. As the rear wheels are fixed, this centre point must be on a line extended from the rear axle. Intersecting the axes of the front wheels on this line as well requires that the inside front wheel is turned, when steering, through a greater angle than the outside wheel [5].

The fig 5 below illustrates the Ackermann steering geometry.

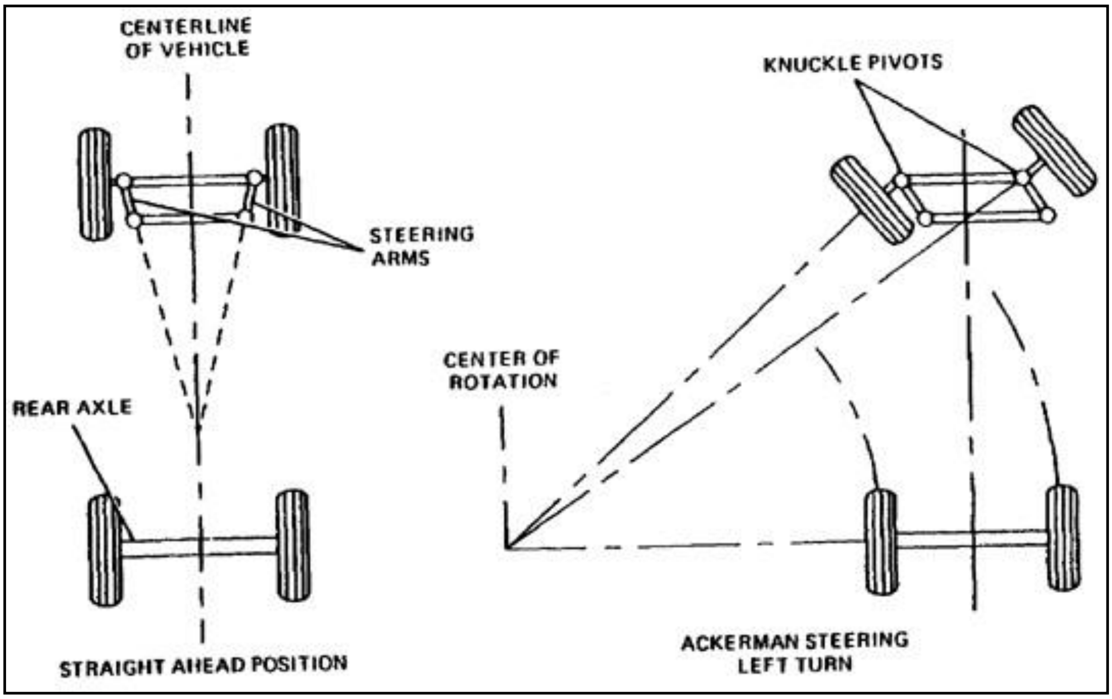


Figure 5: Ackermann Steering Geometry [5]

4. TYPES OF STEERING SYSTEM:

4.1. Manual Steering:

4.1.1. Rack and Pinion system:

A rack and pinion is a pair of gears which convert rotational motion into linear motion. The circular pinion engages teeth on a flat bar - the rack. Rotational motion applied to the pinion will cause the rack to move to the side, up to the limit of its travel.

Rack-and-pinion steering is quickly becoming the most common type of steering on cars, small trucks and SUVs.

A rack-and-pinion gear set is enclosed in a metal tube, with each end of the rack protruding from the tube. A rod, called a tie rod, connects to each end of the rack [6].

The pinion gear is attached to the steering shaft. When you turn the steering wheel, the gear spins, moving the rack. The tie rod at each end of the rack connects to the steering arm on the spindle. It can be seen in fig. 6 below.

The rack-and-pinion gear-set does two things [2]:

a) It converts the rotational motion of the steering wheel into the linear motion needed to turn the wheels.

b) It provides a gear reduction, making it easier to turn the wheels

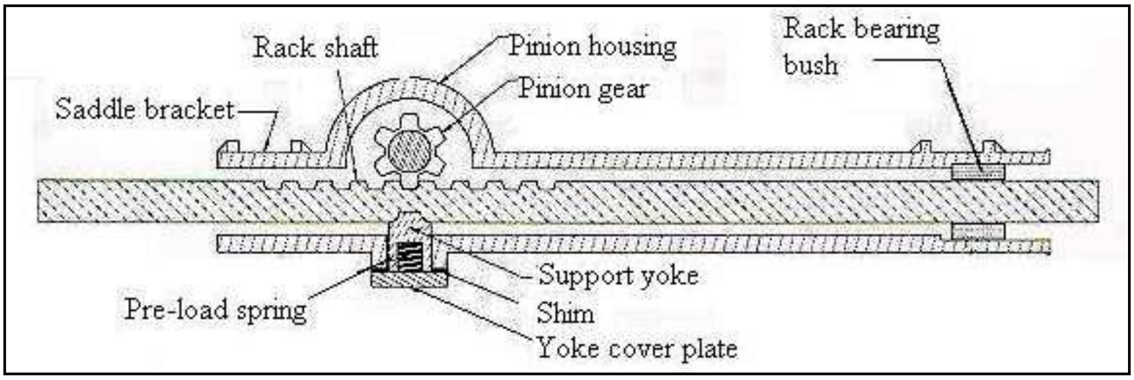


Figure 6: Rack and Pinion steering system [6]

4.1.2. Recirculating Ball Mechanism:

The recirculating ball steering mechanism contains a worm gear inside a block with a threaded hole in it. This block has gear teeth cut into the outside to engage the sector shaft (also called a sector gear) which moves the Pitman arm. The steering wheel connects to a shaft, which rotates the worm gear inside of the block. Instead of twisting further into the block, the worm gear is fixed so that when it spins, it moves the block, which transmits the motion through the gear to the pitman arm, causing the roadwheels to turn.

Bearing balls: The worm gear is similar in design to a ball screw the threads are filled with steel balls that recirculate through the gear and rack as it turns. The balls serve to reduce friction and wear in the gear, and reduce slope [1].

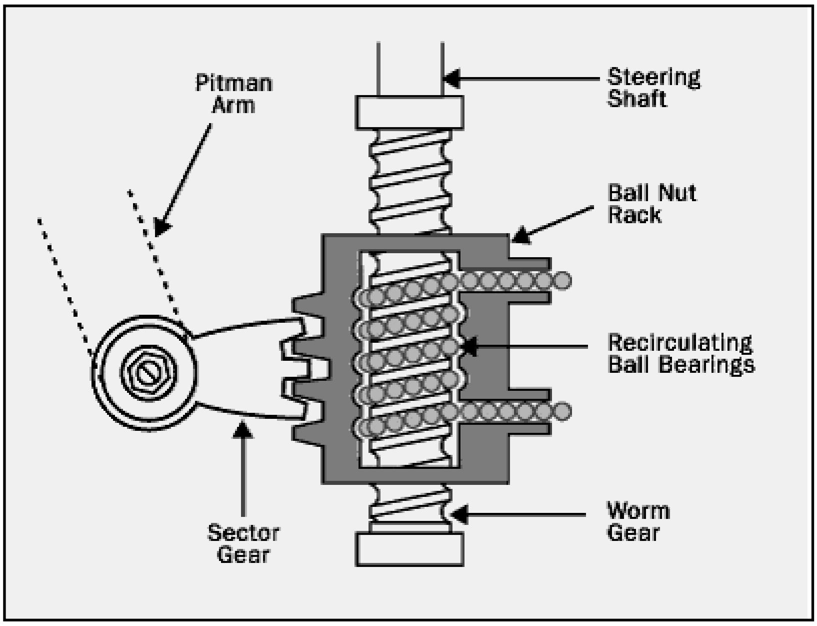


Figure 7: Re-circulating ball mechanism [6]

4.2. Power Steering:

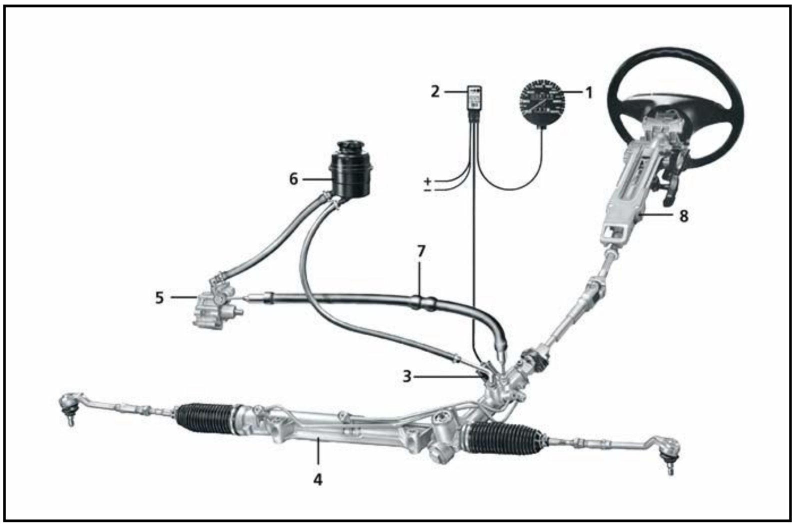
As vehicles have become heavier and faster along with an increase in tire width and diameter, the effort needed to manually turn the steering wheel has increased. Therefore power steering (or rather power-assisted steering) was introduced to assist the driver. A specific advantage of power steering is speed adjustable steering, where the steering is heavily assisted at low speed and lightly assisted at high speed [2].

There are three types of power steering, as follows:

1) Hydraulic Power Steering.
2) Electric Power Steering.
3) Electro-Hydraulic Power Steering (EPHS).

4.2.1 Hydraulic Power Steering:

The dominating steering solution for today's vehicles is rack and pinion- hydraulic steering. In a hydraulic power steering system, a part of the rack contains a cylinder with a piston in the middle. The piston is connected to the rack. Supplying a higher pressure fluid to one side of the piston forces the piston to move, which in turn moves the rack. The hydraulic power steering system uses hydraulic pressure supplied by an **engine-driven pump** to assist the turning motion of the steering wheel. This system offers good value and functionality, a high level of reliability, and has a proven safety record. Major components, aside from the rack and pinion, include the pump providing the hydraulic pressure, the valve assembly, the rack tube housing as well as flexible bellows and pressure lines [2]. Fig 8 below shows a HPS & its components.



1. Electronic Speedometer, 2. ECU, 3. Electro hydraulic transducer, 4. Rack and pinion power steering gear, 5. Engine driven pump, 6.Oil reservoir, 7. Hose pipe

Figure 8: Hydraulic Power Steering [7]

4.2.2. Electric Power Steering:

4.2.2.1. Electric Power Steering with servo unit on Steering Column:

For small to medium cars, where the steering efforts are relatively low, the servo unit and its electronic control unit are integrated in the steering column. They are connected to the mechanical rack and pinion steering gear via the intermediate shaft with universal joints. The torque produced by the electric motor is converted, via a worm gear, into an assistance torque and transmitted to the intermediate shaft. The result is an extremely lightweight design that requires very little space. The location of the servo unit and the electronic control unit in the passenger compartment saves space in the closely packed engine compartment and enables reduced temperature as well as sealing requirements compared with systems situated under the hood [2].

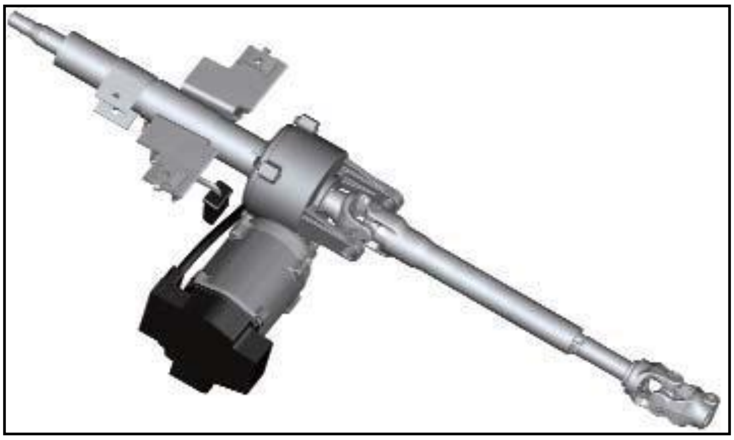


Fig 9: Electric Power Steering with servo unit on Steering Column [7]

4.2.2.2. Electric Power Steering with Servo Unit on a Second Pinion:

Electric power steering systems with the servo unit on a second pinion are designed for mid-size or upper midsize cars. The assist power is applied directly to the rack. This design allows for lower inertia, lower friction and more direct steering feel, as well as superior response. The physical separation of the sensor and the drive unit offers the opportunity for a performance-optimized configuration and improved crash safety thanks to optimum use of the available installation space [2].

Fig 10: Electric Power Steering with Servo unit on a second Pinion [7]

4.2.3. Electrically Powered Hydraulic Steering System (EPHS):

Hydraulic-electric hybrid systems allow a conventional hydraulic steering system to run without an engine-driven hydraulic pump. The hydraulic pressure is supplied instead by an electric motor pump unit independent of the engine. This concept is particularly useful in vehicle platforms that utilize conventional hydraulic steering as a base technology, but are also offered for hybrid electric vehicle variants [2].

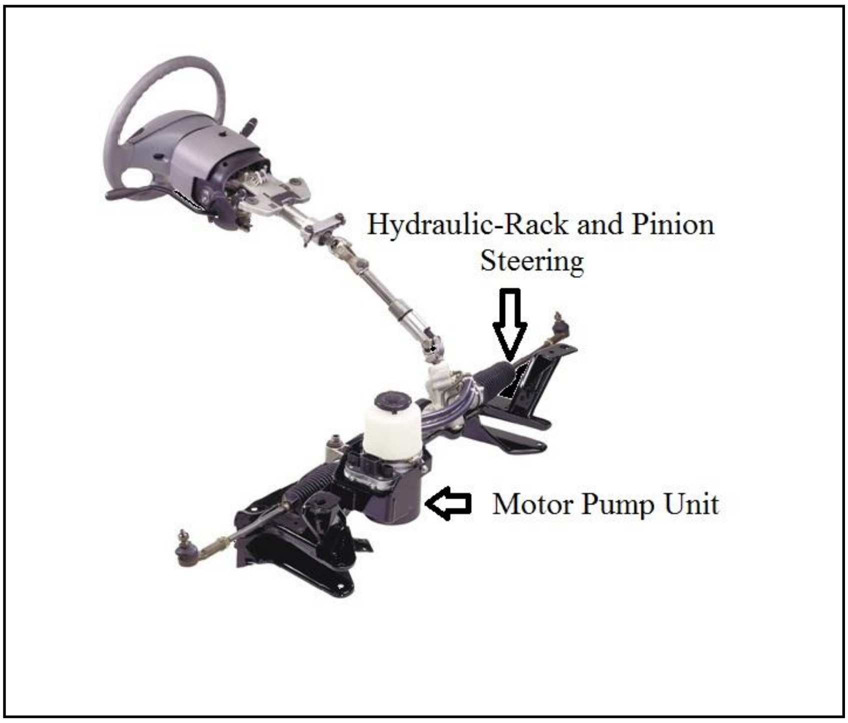


Fig 11: Electrically Powered Hydraulic Steering System [7]

5. ELECTRICALLY POWERED HYDRAULIC STEERING SYSTEM:

5.1. Overview:

The power steering system of an automobile serves two main functions basically:

- It allows the driver to make the vehicle follow the desired path or trajectory without requiring excessive physical effort.
- It assists the driver to judge the driving conditions by allowing some feedback.

The hydraulic steering system of present day which appears so natural and appropriate, took nearly 50 years to mature after first introduction. Prior to this time drivers struggled to manoeuvre the vehicles for parking, at low speed. At high speed, there was also a problem of finding the right sensitivity and stability. As engine power increased and vehicles grew larger, the effort required of driver to steer the vehicles satisfactorily became difficult [7].

5.1.1. Need for a new steering system:

- Using the engine power to drive the pump increases the load on engine and thus reduces the efficiency of engine.
- Hydraulic power steering extracts power from engine, so it increases the fuel consumption of the engine.
- Stringent emission norms are being rolled out. Emissions from the engine increases due to use of conventional hydraulic power steering.
- At lower speeds, the engine runs at lower RPM thus driving the pump at less speed and supplying lesser fluid in the hydraulic circuit. But the assistance required is much more.
- Similarly, at higher speeds, the engine drives the pump at a greater speed and thus supplying fluid more in amount than needed.
- Above two reasons make it mandatory to include a Flow control valve in the system, which increases the overall cost of the system.

5.2. Working Of Electrically Powered Hydraulic Steering System:

Electrically Powered Hydraulic Steering System (EPHS) is an steering system that eliminates the connection between the engine and the steering system.

The EPHS system consists of a conventional rack and pinion power gear and a very compact Motor Pump Reservoir Unit (MPRU). The MPRU or Power Pack normally combines a electronically commutated brushless DC motor, a gear wheel pump, a tank/reservoir for the hydraulic fluid and electronic control unit (ECU) with the control electronics and power electronics in one housing.

Unlike ordinary hydraulic steering systems, EPHS can be delivered as a fully tested, ready-to-install unit, providing a cost-effective fuel saving solution that requires a minimum of redesign to the vehicle platform. By optimizing various system related variables, the EPHS technology enables cost savings that are not available to traditional steering [8].

5.3. State Machine:

A state machine is a mathematical model of computation used to design both computer programs and sequential logic circuits. It is conceived as an abstract machine that can be in one of a finite number of states. The machine is in only one state at a time; the state it is in at any given time is called the current state. It can change from one state to another when initiated by a triggering event or condition, this is called a transition. A particular state machine is defined by a list of its states, and the triggering condition for each transition.

5.3.1. Explanation of State Machine:

- The fluid flow to the rack and pinion piston gallery is regulated by a Positive displacement pump, which in turn is controlled by a motor.
- The motor is driven by a DC power source, depending on the type of motor.
- Motor is being controlled by a Proportional Integral (PI) controller.
- The PI controller takes input from the feedback motor given by the hall element sensor, and the motor driving speed calculated by the CAN bus data.
- The motor driving speed is calculated by acquiring data from the following sources:

  - The steering angle sensor feeds in the steering angle, rate of steering and torque applied on the torsion bar. The CAN bus supplies this data to the motor control element, which determines the amount of current to be supplied to the motor. If the steering angle and rate is low, the current supplied will be low and proportional to the amount of hydraulic fluid to be supplied to the rack and vice versa.
  - The vehicle speed sensor feeds in the speed of the vehicle at fixed intervals to the CAN bus. The vehicle speed is then fed, that determines the motor speed required. If the speed of vehicle is high, the fluid supply required is less and hence the motor speed is low and vice versa.
  - The amount of current driving the motor is fed back to a sensor which determines whether to STOP the motor or keep the motor running i.e STANDBY, which ultimately results in energy saving.

5.3.2. Simplified View of the State Machine:

In fig 13below the working of state machine is illustrated. The figure shows that the data from the steering angle sensor, engine speed sensor and the vehicle speed sensor are constantly fed into the CAN bus. The MPR unit can access this data from CAN bus as and when required, for motor control as per the steering rate and vehicle speed.

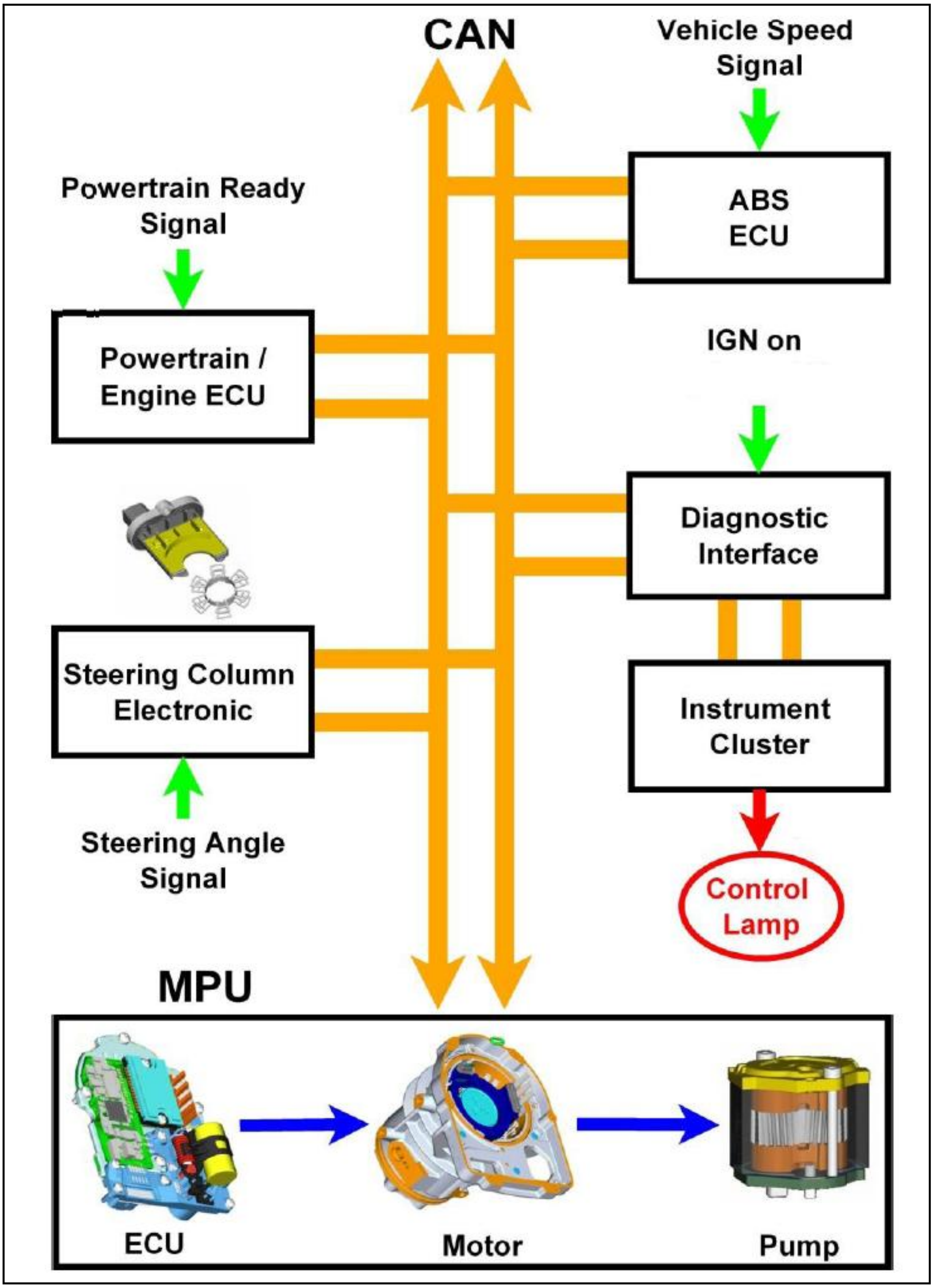


Fig 13: State Machine [8]

5.4. Working of EPHS system:

Fig 14 below shows the working of the EPHS system. It shows a cross section diagram of the MPRU and the steering rack along with the fluid flow inside the system. The way the data from different sensors is mapped into the system is also shown in the figure.

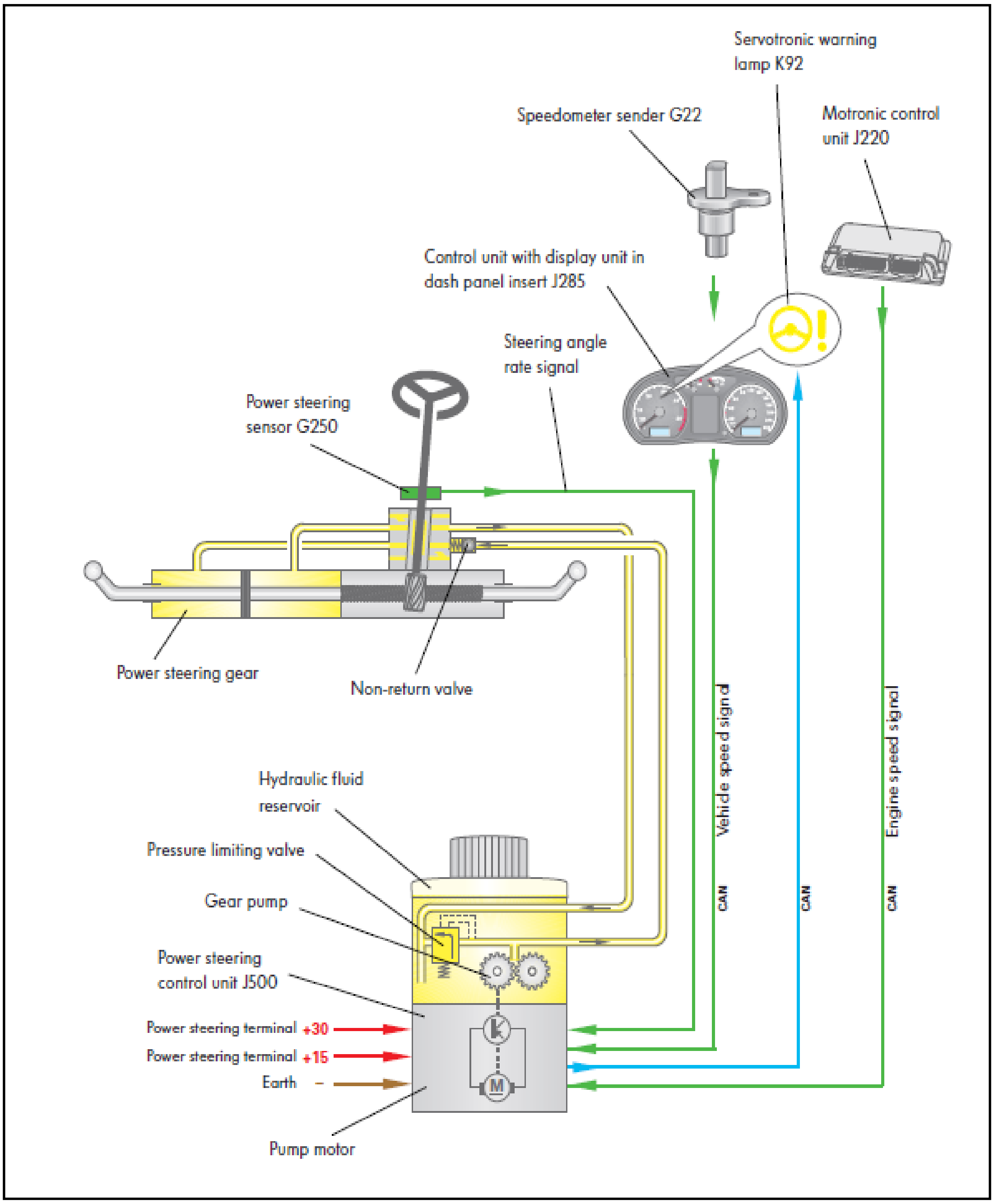


Fig 14: Working of EPHS [9]

5.5. Components of EPHS system:

5.5.1. Hydraulic Powered Rack and Pinion Steering and Rotary valve:

A power-steering system should assist the driver only when he is exerting force on the steering wheel (such as when starting a turn). When the driver is not exerting force (such as when driving in a straight line), the system shouldn't provide any assist. The device that senses the force on the steering wheel is called the rotary valve.

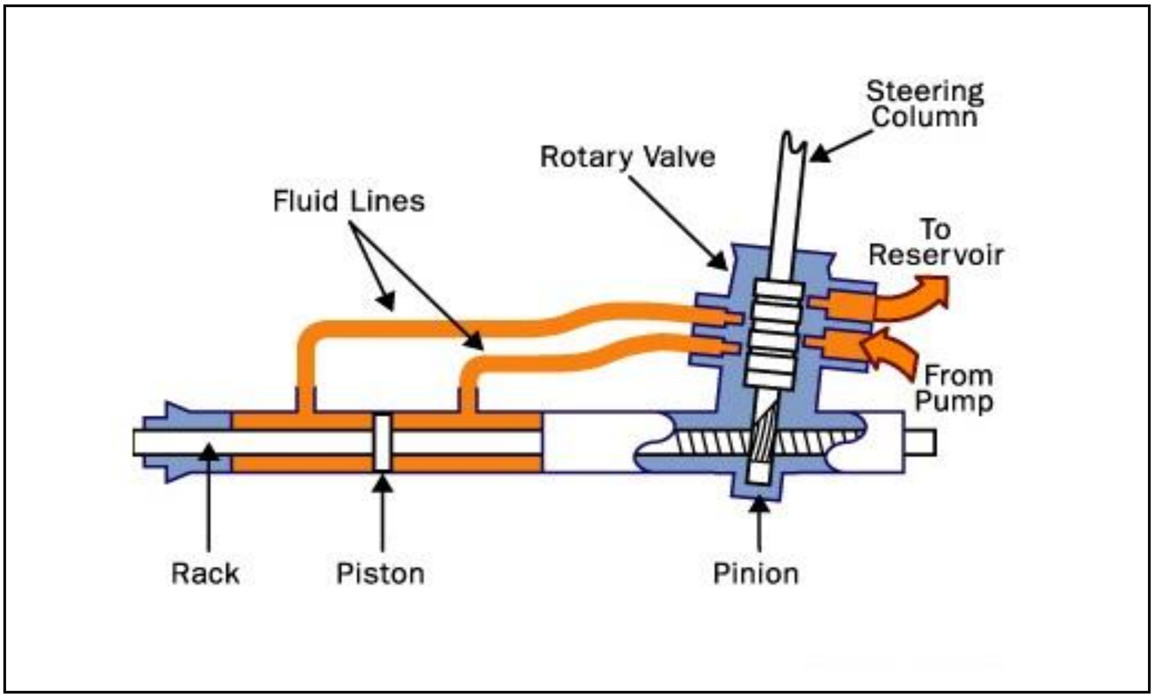


Fig 15: Hydraulic Steering Rack [10]

The key to the rotary valve is a torsion bar. The torsion bar is a thin rod of metal that twists when torque is applied to it. The top of the bar is connected to the steering wheel, and the bottom of the bar is connected to the pinion or worm gear (which turns the wheels), so the amount of torque in the torsion bar is equal to the amount of torque the driver is using to turn the wheels. The more torque the driver uses to turn the wheels, the more the bar twists.

The input from the steering shaft forms the inner part of a spool-valve assembly. It also connects to the top end of the torsion bar. The bottom of the torsion bar connects to the outer part of the spool valve. The torsion bar also turns the output of the steering gear, connecting to either the pinion gear or the worm gear depending on which type of steering the car has.

As the bar twists, it rotates the inside of the spool valve relative to the outside. Since the inner part of the spool valve is also connected to the steering shaft (and therefore to the steering wheel), the amount of rotation between the inner and outer parts of the spool valve depends on how much torque the driver applies to the steering wheel.

When the steering wheel is not being turned, both hydraulic lines provide the same amount of pressure to the steering gear. But if the spool valve is turned one way or the other, ports open up to provide high-pressure fluid to the appropriate line [12].

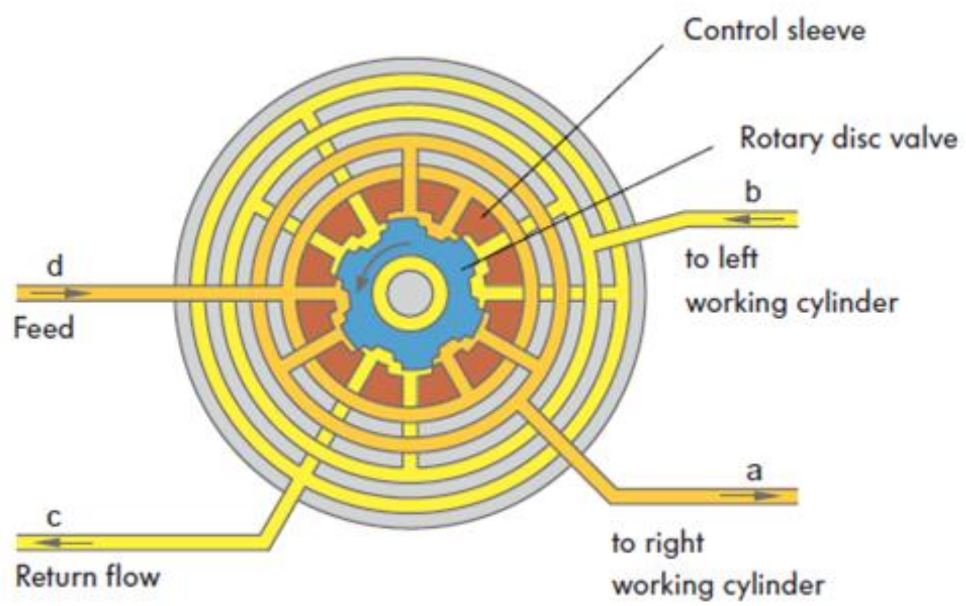


Fig 16: Rotary/Spool Valve [9]

5.5.2. Motor Pump Reservoir Unit

5.5.2.1. Electric Motor:

An electric motor is an electromechanical device that converts electrical energy into mechanical energy. Electric motors operate on the physical principle behind production of mechanical force by the interactions of an electric current and a magnetic field, Faraday's law of induction. [15]

There are two major types of motors depending on the type of power source, AC motors and DC motors.

The DC motors are powered by direct current, e.g. a battery powered portable device or motor vehicle, the AC motors are powered by alternating current from a central electrical distribution grid or inverter.
As the EPHS system is fitted in the vehicles, where the power source is the battery system. So the choice of motor that is best for the system is DC motor. In DC motors, there are two different kind of motors i.e. Brush motor and Brushless motor.

5.5.2.1.1. Brush DC Motor

The brushed DC electric motor generates torque directly from DC power supplied to the motor by using internal commutation, stationary magnets (permanent or electromagnets), and rotating electrical magnets. Like all electric motors, torque is produced by the principle of Lorentz force, which states that any current-carrying conductor placed within an external magnetic field experiences a torque or force known as Lorentz force [16].

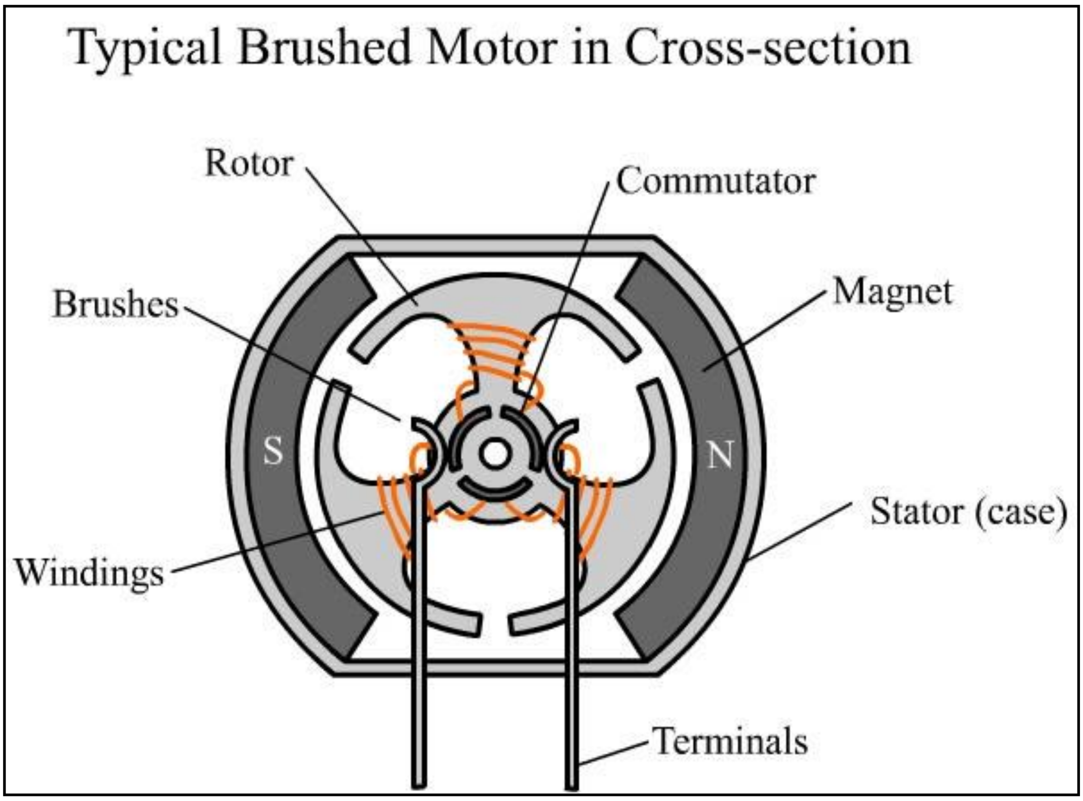


Fig 17: Brush DC Motor cross section [11]

Brushed Motor Pros

- Two wire control
- Replaceable brushes for extended life
- Low cost of construction
- Simple and inexpensive control
- No controller is required for fixed speeds
- Operates in extreme environments due to lack of electronics

Brushed Motor Cons

- Periodic maintenance is required
- Speed/torque is moderately flat. At higher speeds, brush friction increases, thus reducing useful torque
- Poor heat dissipation due to internal rotor construction
- Lower speed range due to mechanical limitations on the brushes

5.5.2.1.2. Brushless DC Motor

A Brushless DC Motor (also known as a BLDC Motor), is a synchronous electric motor powered by a direct current. As the name implies, the Brushless DC Motor does not operate using brushes; rather it operates with a controller via electronic commutation. A Brushless DC Motor is operated by means of an electronic six-step commutation system. Unlike its Brush DC Motor counterparts, the Brushless DC Motor does not contain any carbon brushes. Instead, the electromagnets within the motor remain stationary along with the armature, while the encased permanent magnets rotate, generating torque.

An electronic Brushless DC Controller (also known as a Driver, or Electronic Speed Controller), replaces the mechanical commutation system utilized by a Brush DC Motor, and is required by most Brushless DC Motors to operate.

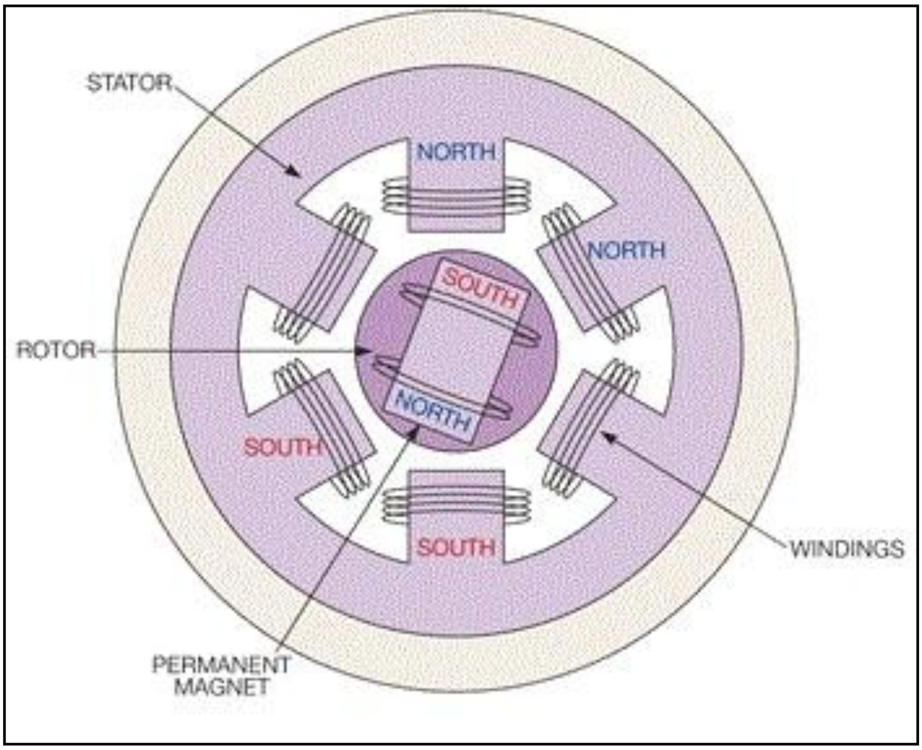


Fig 18: Brushless DC Motor cross section [12]

5.5.2.1.2.1. BLDC Motor Control:

In a Brushless DC Motor controller, either a Hall Effect Sensor or Back EMF (Electromotive Force) is used to identify the position of the rotor. Understanding the orientation of the rotor is crucial to operating the Brushless DC Motor.

The Hall Effect uses three hall sensors within the Brushless DC Motor to help detect the position of the rotor. This method is primarily used in speed detection, positioning, current sensing, and proximity switching. The magnetic field changes in response to the transducer that varies its output voltage. Feedback is created by directly returning a voltage, because the sensor operates as an analogue transducer. The distance between the Hall plate and a known magnetic field can be determined with a group of sensors, and the relative position of the magnet can be deduced. A Hall sensor can act as an on/off switch in a digital mode when combined with circuitry.

Six step commutation:

Six-step commutation is a cost-effective means of electronic commutation, due to the simple and relatively inexpensive feedback and drive devices. In six-step commutation, only two out of the three Brushless DC Motor windings are used at a time. Steps are equivalent to 60 electrical degrees, so six steps make a full, 360 degree rotation. One full 360 degree loop is able to control the current, due to the fact that there is only one current path. Six-step commutation is typically useful in applications requiring high speed and commutation frequencies [14].

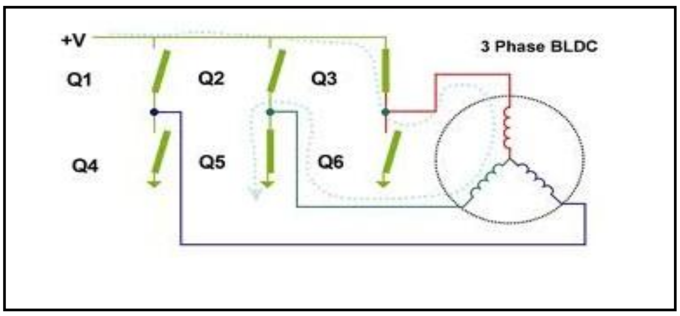


Fig 19: Six step commutation [13]

BLDC Motor Pros

- Long life span, little or no maintenance
- Less required maintenance due to absence of brushes
- Speed/Torque- flat, enables operation at all speeds with rated load
- High efficiency
- High output power
- Reduced size due to superior thermal characteristics. Because BLDC has the windings on the stator, which is connected to the case, the heat dissipation is better
- Higher speed range - no mechanical limitation imposed by brushes/commutator
- Low electric noise generation

BLDC Motor Cons

- Higher cost of construction
- Motor Control is complex and expensive
- Electric Controller is required to keep the motor running.

As the system is to have a long life span, less maintenance and high power output; so from above comparison we see that the Brushless DC motor is more preferable according to our system.

5.5.2.2. Positive Displacement Pump:

The operating principles of positive displacement (PD) pumps differ from centrifugal pumps. This basic difference is evident in the pump's response to a system's head/flow curve

PD pumps create flow, centrifugal pumps create pressure. Fluids with large gas fractions or high viscosities cannot be moved with standard centrifugal designs. PD pumps allow a wider range of liquids, slurries and foams to be transported without product degradation.

In a PD pump, flow is created by enclosing a volume at suction, moving it to discharge, and releasing it. Pressure is created by the system's response to flow. If there was no connection at the discharge flange, the flow would exit the pump at atmospheric pressure. Centrifugal pumps create pressure by first imparting velocity to the fluid with the impeller, then converting the velocity to pressure with the volute. If there was no discharge flange connection, the flow would exit the pump with that developed pressure [9].

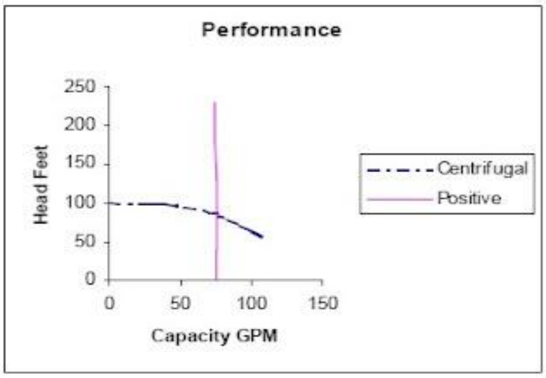
5.5.2.2.1. Criteria for Pump selection:

Pump selection plays an important role taking into account the required application.

Following are the key points that distinguish between gear pumps and centrifugal pumps on the basis of their performance while comparing their head pressure, flow rate, viscosity of the fluid flowing, etc.

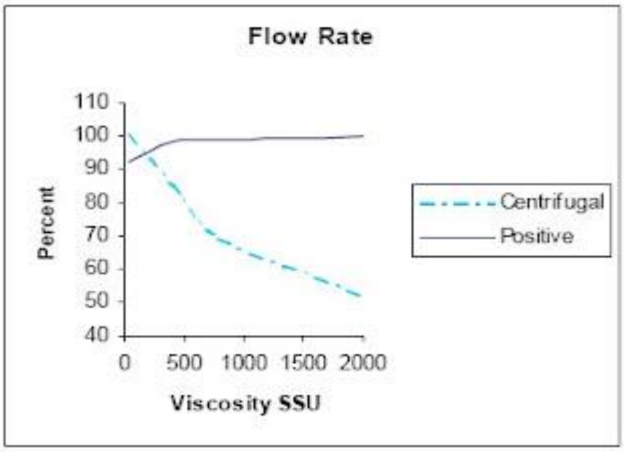
Flow rate versus pressure:

By looking at the performance chart below we can see just how different these pumps are. The centrifugal has varying flow depending on pressure or head, whereas the PD pump has more or less constant flow regardless of pressure [10].



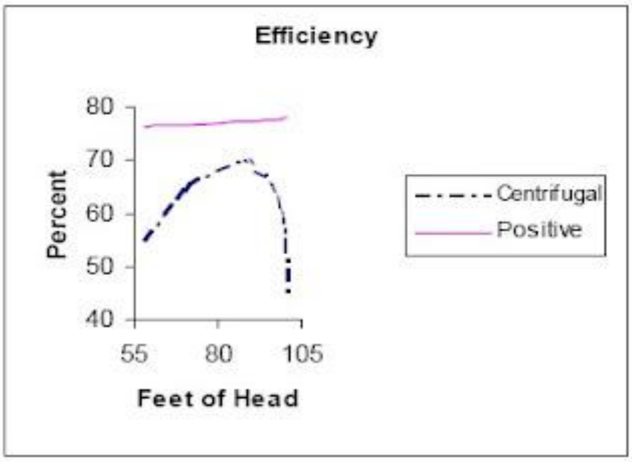
Flow rate versus viscosity:

Another major difference between the pump types is the effect viscosity has on the capacity of the pump. We notice in the flow rate chart how the centrifugal pump loses flow as the viscosity goes up but the PD pump's flow actually increases. This is because the higher viscosity liquids fill the clearances of the pump causing a higher volumetric efficiency [10].



Efficiency versus Pressure:

The pumps behave very differently when considering mechanical efficiency as well. By looking at the efficiency chart to the right we see the impact of pressure changes on the pump's efficiency. Changes in pressure have little effect on the PD pump but a drastic one on the centrifugal [10].



Owing to above reasons, a PD pump of external gear type is selected for the EPHS system.

Of all the PD pumps, gear pumps use a very simple mechanism to generate flow, and therefore have a minimum number of parts associated with the design. The simplicity of the gear pump design translates into higher reliability as compared to other positive displacement pumps that use a more complex design.

5.5.2.2.2. Gear Pump

Construction:

Figure below shows a cross-sectional view taken through the gears of a typical gear pump. The pump consists of two identical gears that are used for displacing fluid. Gears of different ratios may also be used under certain circumstances as per the requirement.

The gears are contained in a close-tolerance housing that separates the discharge port from the intake port. An external shaft is connected to gear 1 while the other gear is supported by an internal shaft and bearing [11].

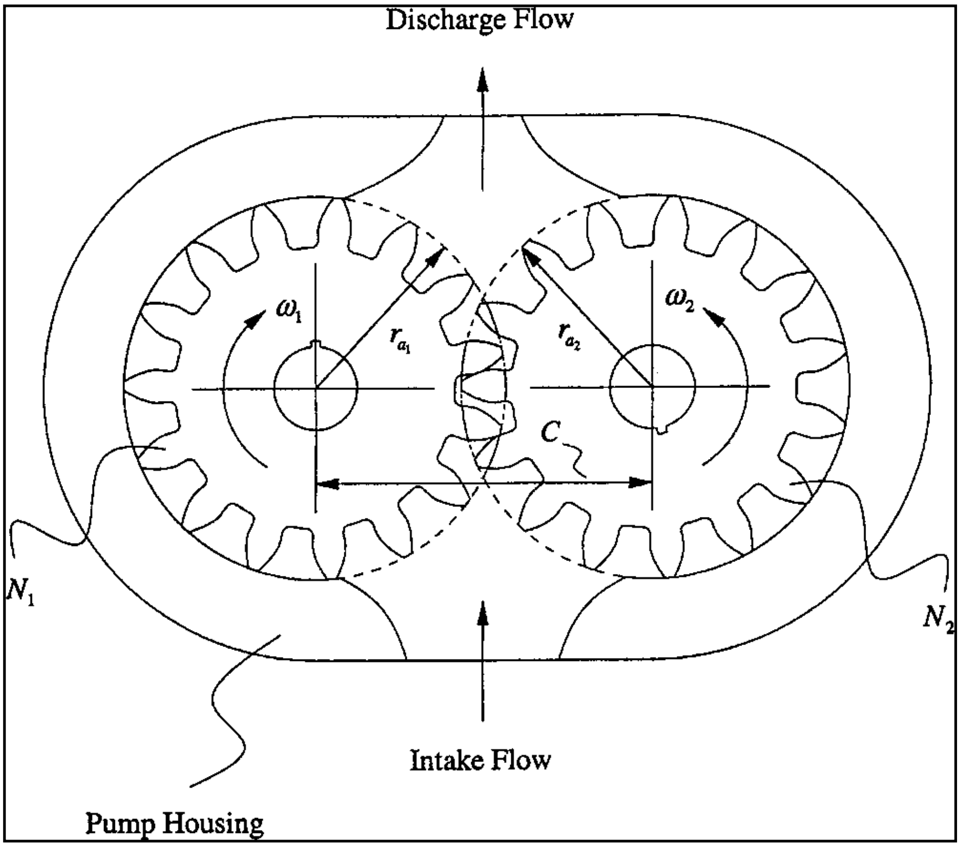


Fig 20: Gear Pump cross section [14]

Working:

On the suction side, the liquid to be pumped fills the gap between the meshing gears from the direction, opposite to that of rotation. The liquid entrapped between the gap in successive teeth of the gear, passes round the casing and finally finds its way on the delivery side. On the delivery side, the two streams of liquid come together, one from the driving gear and other from the driven gear. The major volume of liquid is pushed to the delivery port and a small portion finds it way back to the suction side from between the clearance between the gear and the casing.

The assumption that the liquid trapped in the gaps between the teeth of the gear, is pushed through the teeth of the opposite gears, is not correct and does not occur in actual practice [13]

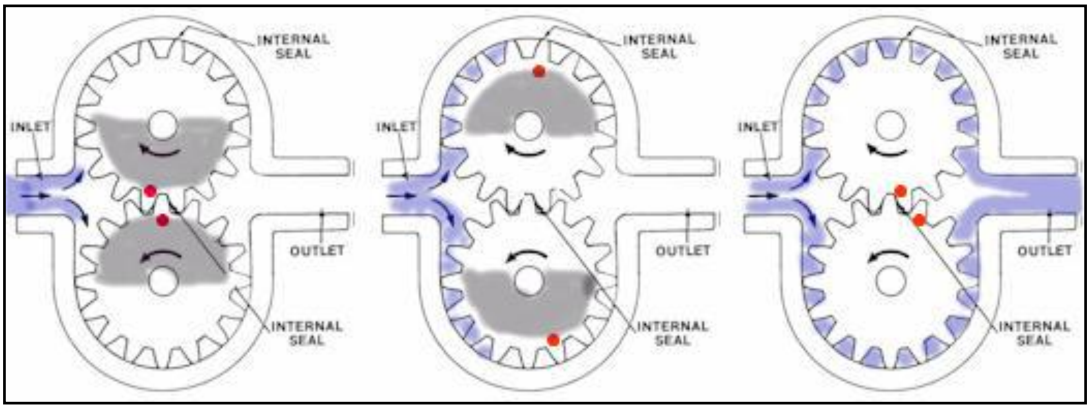


Fig 21: Fluid flow inside a gear pump [15]

5.5.2.3. Hydraulic Reservoir

All hydraulic systems have a reservoir. A reservoir is similar to an accumulator, except that the fluid pressure is constant over all fluid levels. A reservoir performs several functions. First and foremost, the reservoir holds fluid not required by the system under any given operating condition and accounts for fluid capacity needs over time in the system. Fluid volume needs will vary during different operational scenarios. Secondly, the reservoir provides for thermal expansion of the fluid over the operational temperature range of the system. Thirdly, the reservoir provides fluid to the inlet side of the hydraulic pump.

Reservoirs consist of a container or volume, fluid inlet port, fluid outlet port, fill/drain port, and a means to pressurize the fluid in the volume [17].

5.5.2.3.1. Material Selection for Reservoir:

The reservoir should be made of a material that is economically feasible. It should be easily mouldable for a high rate of production and should have good engineering properties. Based on these considerations, the material used for hydraulic reservoir is Poly Propylene (PP).

Polypropylene (PP) is a thermoplastic polymer used in a wide variety of applications. Polypropylene is normally tough and flexible, especially when copolymerized with ethylene. This allows polypropylene to be used as an engineering plastic. Polypropylene is reasonably economical, and can be made translucent when uncoloured. Polypropylene has good resistance to fatigue. Commercial PP has a melting point that ranges from 160 to 166 °C.

The only disadvantage of PP is that it is liable to chain degradation from exposure to heat and UV radiation such as that present in sunlight.

PP can be used for plastic moulding of reservoirs, wherein it is injected into a mould while molten, forming complex shapes at relatively low cost and high volume [18].

6. MARKET SURVEY:

A list of EPHS systems available in the International/ Indian market was made. Further details with our analysis are listed below in the form of a table.

The need for more driving comfort generated the trend towards power steering in the past –in Europe. Hydraulic Power Steering (HPS) had become a standard feature in the second half of the 1980s.

In the early 1990s, the first electrically driven hydraulic steering pumps were developed. High oil prices and a supply shortening helped the development of fuel saving technologies –EPHS is one of them.

TRW launched the first two major customer applications with EPHS in 1998 for the GM Opel Astra and VW Polo platforms, both million sellers.

VW is using on their Polo platform (PQ24) until today the same EPHS system in all derivatives from Seat, Skoda and Audi [20].

Another OEM for EPHS is Koyo-Jtekt. The Koyo group's participation began in 1989 when European company H as a member of the group first adopted an industrial power pack for use in vehicle as the 1st generation EPHS. In 2003, Koyo's EPHS system was first adopted for a mass-produced standard passenger vehicle marketed in Japan [22].

EPHS Company	Model	Car Company	Car Model	Price £
TRW	Generation-B	VW	Polo	300-375
		Skoda	Fabia	
		Fiat	Croma	
		Seat	Ibiza	
		Audi	A1	
		Saab	9 3	
		Opel	Zafira	
			Meriva	
		Volvo	V50	
			S40	
		Ford	Focus	
			Kuga	
			C-Max	
	Generation-C			375-500
		Buick	LaCrosse	
		Porsche	Cayenne	
		VW	Touraeg	
		Peugeot	308	
			Rcz	
		Citroen	C4	
			C5	
		Hyundai	Genesis	
			Equus	
		Ford	Galaxy	
			S-Max	
			Mondeo	
		Daimler	S-Class	
			CL-Class	
			M-Class	
			GL-Class	
			R-Class	
			GLK-Class	

JTEKT-HPI	7701470783	Renault	CLIO II	300-570
	4007ZE 9682527780	Peuguot	407	
	4007ST 9684713280	Peuguot	307	
	8200520790	Renault	Kangoo	
		Dacia	Logan	
		Nissan	Kubistar	
	4007CC	Citroen	Saxo	
	40079C	Peuguot	106	
	4007VH 1400752580	Fiat	Expert	
		Citroen	Dispatch	
		Scudo Fiat	Lancia	
		Ulysses	Phedra	
		Peuguot	807	
	YS613K514BF 1120754	Ford	Fiesta	
	7701466770	Renault	Clio I	
	4007XV 9670308780	Citroen	C4	
	4007S3	Citroen	C15	
	4007R2	Peuguot	205	
	4007NX	Peuguot	206	
	7701468590	Renault	19	
	8603159	Peuguot	306	

7. SWOT Analysis:

A SWOT Analysis looks at the strengths, weaknesses, opportunities and threats that are relevant to an organization in a new venture. A SWOT Analysis is a tool which allows users to look at the direction a company or organization may wish to move towards in the future. A SWOT Analysis is a useful tool, which in conjunction with others can help make informed decisions.

By specifying clear objectives and identifying internal and external factors that are either helpful or not, a short and simple SWOT analysis is a useful resource which may be incorporated into an organizations strategic planning model.

- Strengths- Internal attributes that are helpful to the organization to achieving its objective.
- Weaknesses – Internal attributes that are harmful to the organization to achieving its objective.
- Opportunities – External factors that help the organization achieve its objective.
- Threats - External factors that are harmful to the organization to achieving its objective.

After identifying the SWOT's, identification of the factors and their interdependence helps clarify the steps needed to achieve the ending objectives [21].

Strength	Weakness
✓ Fuel economy benefit: Up-to 0.35 l fuel saving per 100 km & related CO2 savings of approx. 8 g/km. ✓ Most powerful 12 V electrical steering system upto 18kN rack force due to high efficiency. ✓ Speed proportional assist- stable at high and comfortable at low speeds and parking. ✓ Best packaging flexibility due to free positioning of the Motor Pump unit. ✓ Premium steering feel.	✓ High degree of complexity involved in the hydraulic mapping of the system. ✓ Noise generation to some extent due to constant running of the gear pump. ✓ Prone to hydraulic leakages during extreme conditions.
Opportunities	**Threats**
✓ Simplified vehicle assembly: can be integrated into any vehicle with minimal changes. ✓ Simplified supply chain logistics. ✓ Low engineering costs for mass production. ✓ Excellent cost/benefit ratio as compared to other technical means. ✓ Lesser overall engine emissions, thus meeting stringent norms.	✓ Pressurised system if not relieved properly, will lead to detrimental consequences. ✓ If fit as an after-market product into a vehicle, might lead to misconceptions amongst mechanics and might result into undesirable consequences. ✓ Scope of market demand. ✓ Costlier than other available steering systems, which might lead to lesser market for the product.

8. DESIGN OF THE PROTOTYPE FOR TESTING:

8.1. Steering Rack:

The steering rack chosen is a direct rack and pinion- hydraulic steering of Skoda Fabia. Volkswagen is the OEM of the rack. The fig below shows the cross section of the steering rack.

As explained earlier, the rack consists of a rack & pinion gear along with a hydraulic gallery. There is a spool valve to direct the flow into the hydraulic cylinder as per the direction of the steering. There is an integrated steering angle sensor that comes with the unit, but is not used for validation of the prototype, as it requires extensive programming.

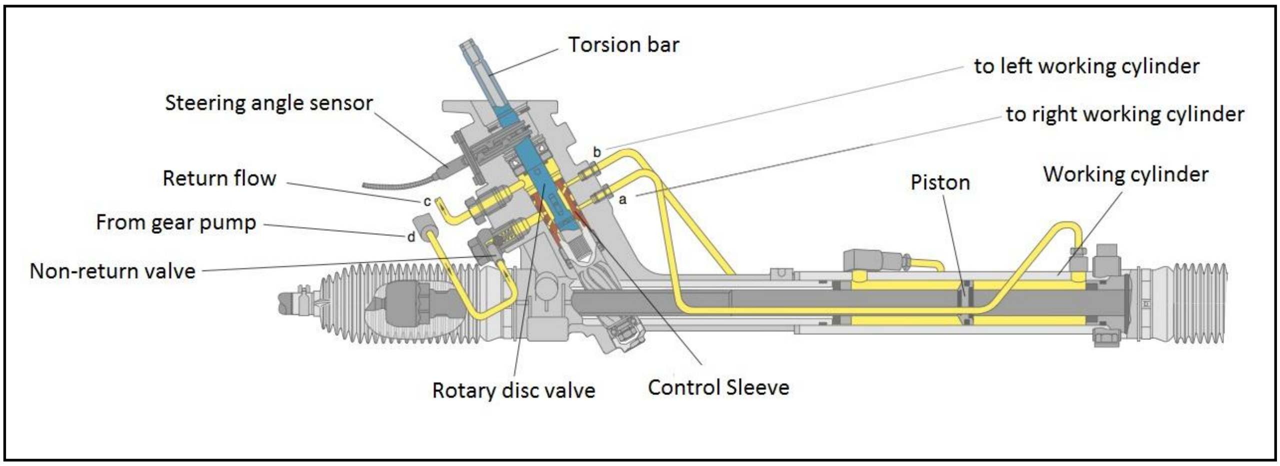


Fig 22: Cross section of selected Steering Rack [9]

8.2. Gear Pump:

The pump selected is an external gear pump of TRW. The following are the specifications of the gear pump [19]:

a) No. of teeth on driving gear: 12
b) No. of teeth on driven gear: 12
c) Pressure angle: 20°
d) Module: 1.15 mm
e) Operational Pressure: 3.5-100 bar
f) Angular speed range: 1500-3400 rpm

The figure below shows the gear pump used for the prototype.

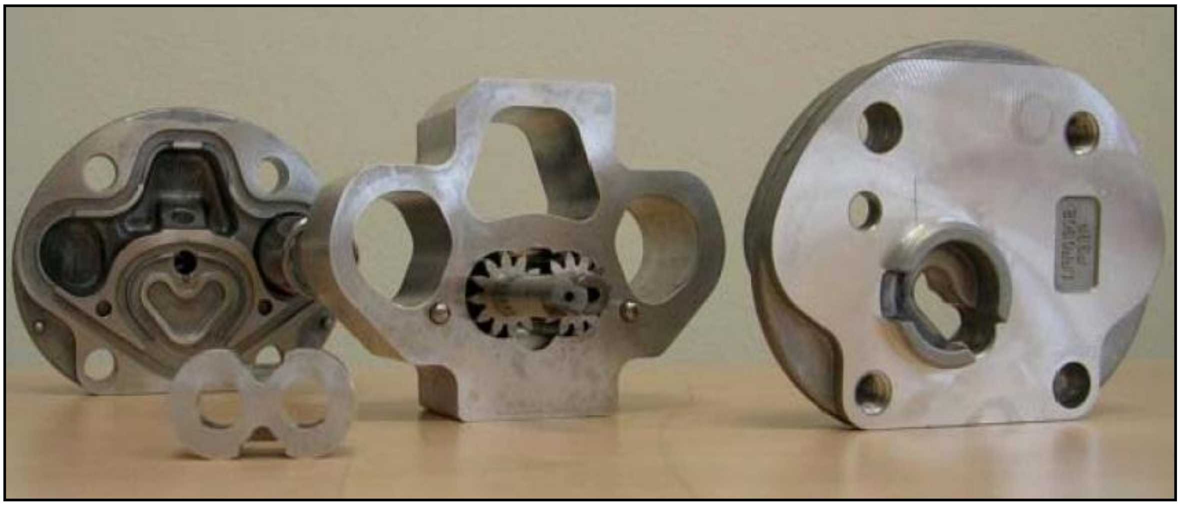


Fig 23: Gear Pump selected [16]

The gear pump consists of a set of meshing gears inside housing. The gear pump also has a pressure relief valve. It is a compact assembly of all these components into one unit. The explored view of the selected pump is shown below in fig 24.

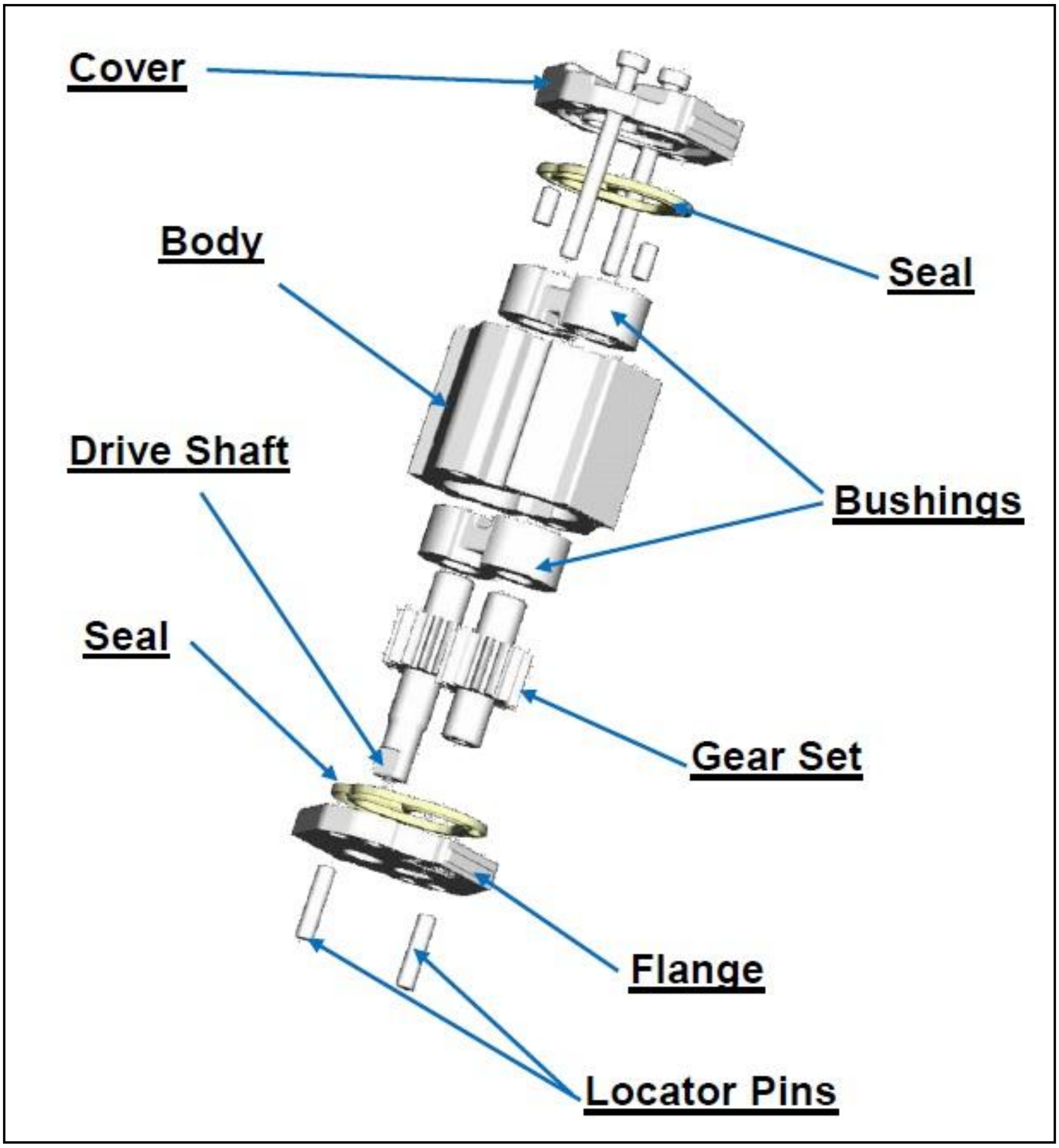


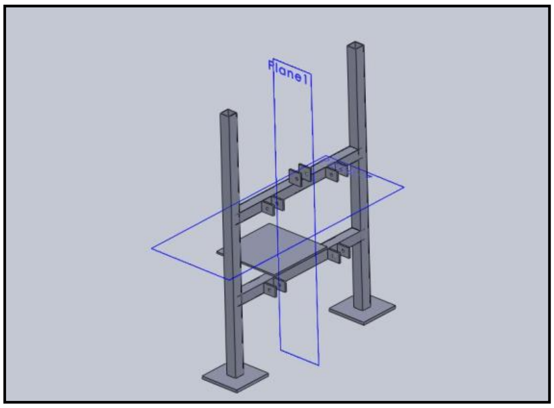
Fig 24: Components of the Gear Pump [8]

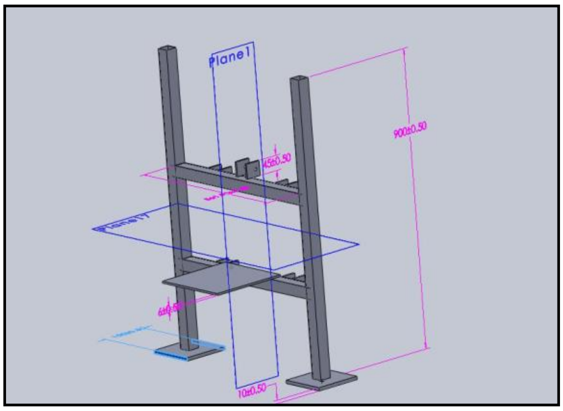
8.3. Motor:

The motor selected is a Yo-bike brushed motor of 240 W (0.3 hp). The motor runs on a 24 V DC power supply, with a maximum rpm of 3000. BLDC motors being costly and extensive level of programming is required, a brushed motor was selected for the initial testing of the prototype.

8.4. Testing jig:

A jig was designed in solid works for mounting the steering rack. The figures below show the jig design.

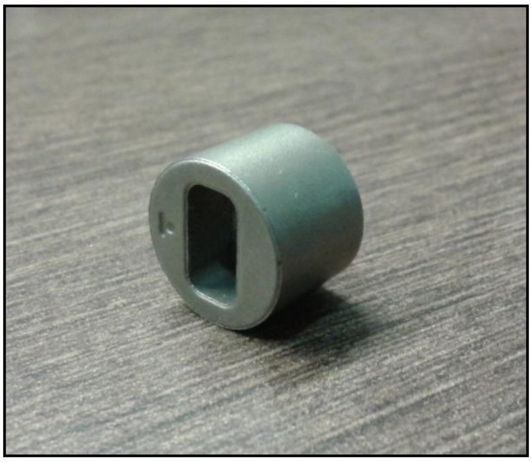




The jig was then welded as per the design. The material used for the jig was mild steel (MS). The figure below shows the welded jig.

8.5. Modifications made to the system:

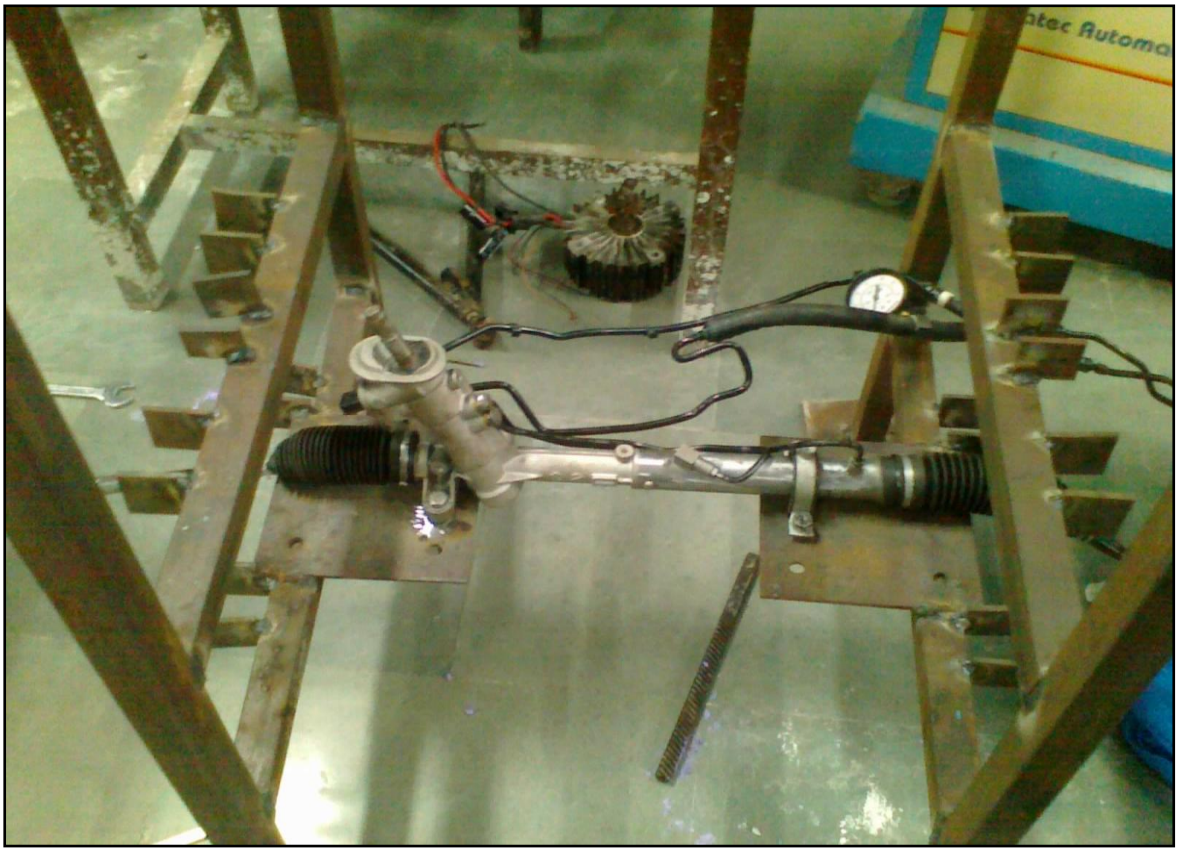
- A shaft and a coupling were machined in order to couple the motor and the pump.



- The hydraulic hoses were cut and a T-joint was fit in between, in order to fix a pressure gauge in the line and acquire the pressure reading.

8.6. Test bench:

After the welding of the test jig and acquiring all the required components for the system, the rack was mounted and the MPRU was connected to the system.



8.7. Analysis of the System considering ideal conditions:

Key Relations:

1 l/min = 0.264 gpm (i)

1 psi = 0.069 bar (ii)

Theoretical discharge of a gear pump:

$$Q_t = \frac{\Pi \times m^2 \times b \times N}{60} \times [2n + \{1 + (n/n')\}]\left[1 - \frac{\Pi^2 \cos^2 \alpha}{48}\right] \times 10^{-6}$$

where

m = module of gear = 1.15 mm

b = gear thickness = 12.1 mm

N = Pump RPM = 3000 rpm

n = number of teeth on driving gear = 12

n' = number of teeth on driven gear = 12

α = pressure angle = 20°

$$\therefore Q_t = \frac{\Pi \times 1.15^2 \times 12.1 \times 3000}{60} \times [2 \times 12 + \{1 + (12/12)\}]\left[1 - \frac{\Pi^2 \cos^2 (20°)}{48}\right] \times 10^{-6}$$

= 0.0535 litres/sec

$\therefore Q_t$ = 3.21 litres/ min

Theoretical Maximum Pressure generated by the pump:

The relation between the power that drives the gear pump and the pump flowrate & pressure is given by:

$$HP = \frac{\text{Pressure (in PSI) x Flowrate (in GPM)}}{1714 \text{ x Efficiency } (\eta_{pump})}$$

Now,

3.21 l/min = 0.847 gpm (from ii)

$$\therefore 0.3 = \frac{\text{pressure x } 0.847}{1714\text{x}80}$$

$\therefore$ pressure = 479.4 psi

$\therefore$ pressure = 479.4/0.069 bars = 33 bars (using relation ii)

8.8. Readings obtained:

(i) Max. Pressure obtained from the system: 26 bars.

Reasons for lesser pressure development:

- Lower efficiency of the pump: The gear pump bought was a second hand market product. Therefore, the mechanical efficiency of the pump was lesser than 80 % that was assumed.
- Less motor output: The motor being a second hand market product, the motor brushes have worn out to some extent. As a result, the motor power and hence the torque output is not to the expected level.
- Transmission losses: Since the motor and the pump are coupled by a shaft and a coupling, there are minor mechanical losses that are being overlooked.

(ii) Flowrate obtained: 3.27 litres/ min.

- As stated (5.5.2.2.1), the flowrate of a gear pump is invariable of the pump efficiency.
- The theoretical flowrate calculated was 3.21 litres/min, whereas the obtained flowrate was 3.27 litres/min, which are approximately equal.
- The minor error involved is due to human error involved while measuring the flowrate of the system.

9. FUTURE WORK:

The advent of EPHS system has led to the creation of a new branch of technology, involving the marriage of hydraulics and modern electronics design. Despite the rapid pace of development, EPHS systems are still in their infancy in India, especially for the larger vehicles, and much still has to be learned. Progress has been encouraging more recently with less expensive and more efficient power units.

The system is yet to be tested for the amount of steering assistance provided by the system. The steering assistance can be distinguishingly felt when the MPRU is ON as compared to when the MPRU is OFF. Therefore a measure of torque difference in both the cases is yet to be calculated and validated.

Recognizing the potential of this system, the future work will be the development of a stand-alone system as an after-market product.

In order to achieve this feat, the main objective of the company should be to establish contacts with gear pump and BLDC motor manufacturers/suppliers based on the designed system.

Furthermore, the most important part includes the hydraulic mapping of the system, i.e. the motor control design based on the amount of fluid to be supplied as per the data collected from the CAN bus.

10. CONCLUSION

Electrically Powered Hydraulic Steering (EPHS) Systems is a pioneer technology that contributes in reducing the overall emissions from automobiles. Moreover the system is an ideal replacement for the existing hydraulic steering system with almost no disadvantages in comparison. This potential of the system has to be recognised and adopted for a greener alternative.

Heavy vehicles where power steering is a necessity, currently hydraulic steering systems are being used. Since heavy vehicles are a major contributor to pollution due to emissions, EPHS is the best solution available at this point of time.

The objectives of the project were met satisfactorily. In conclusion the required values were calculated theoretically and practically. They were validated agreeably.

Finally, we believe this project provided a real world experience to the design of a physical entity and provided the necessary challenges which we worked to overcome.

11. APPENDIX

1) The graph below shows the advantage of an EPHS system over conventional hydraulic power steering system. It shows the comparison between the power consumptions of the two systems under various driving conditions.

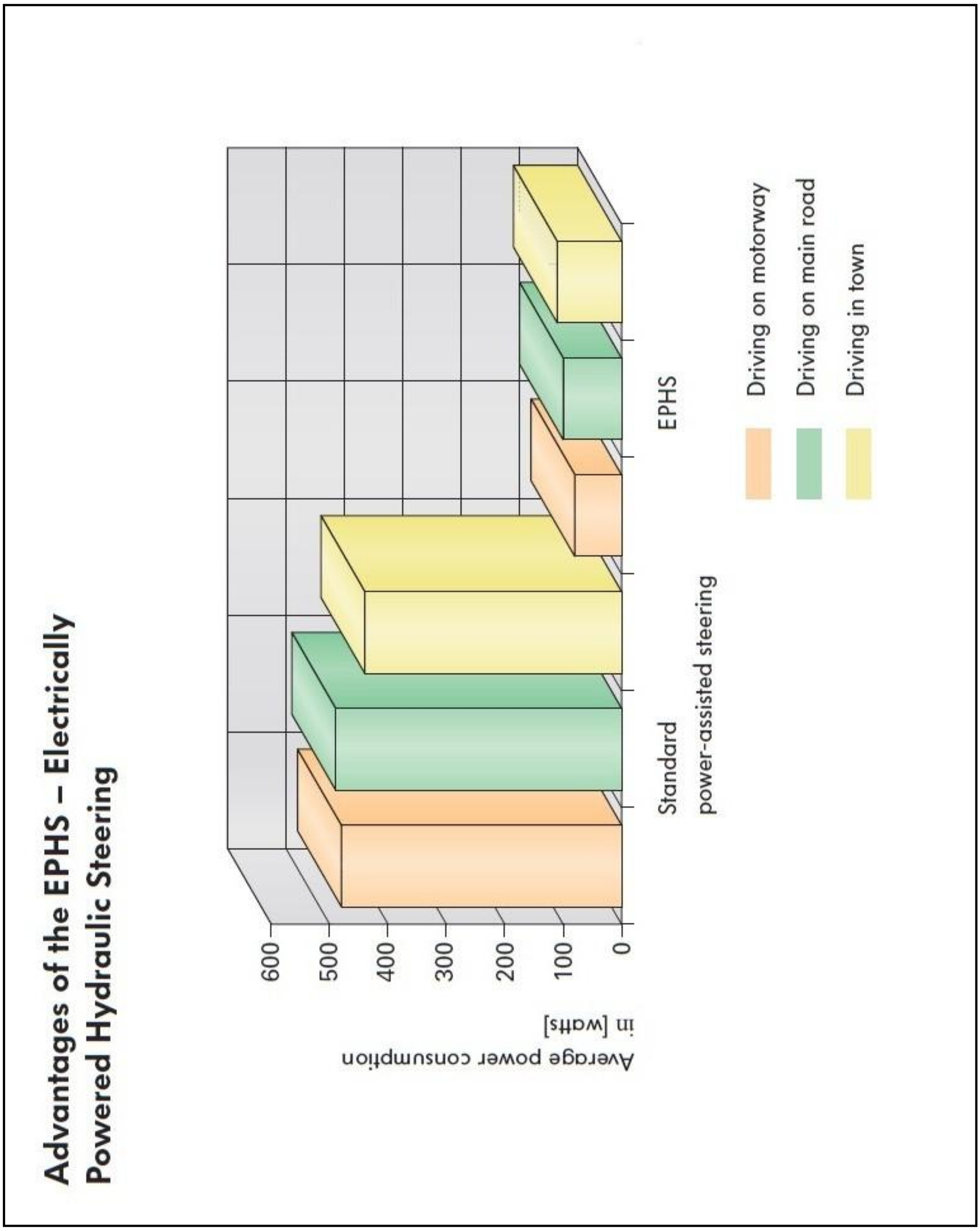
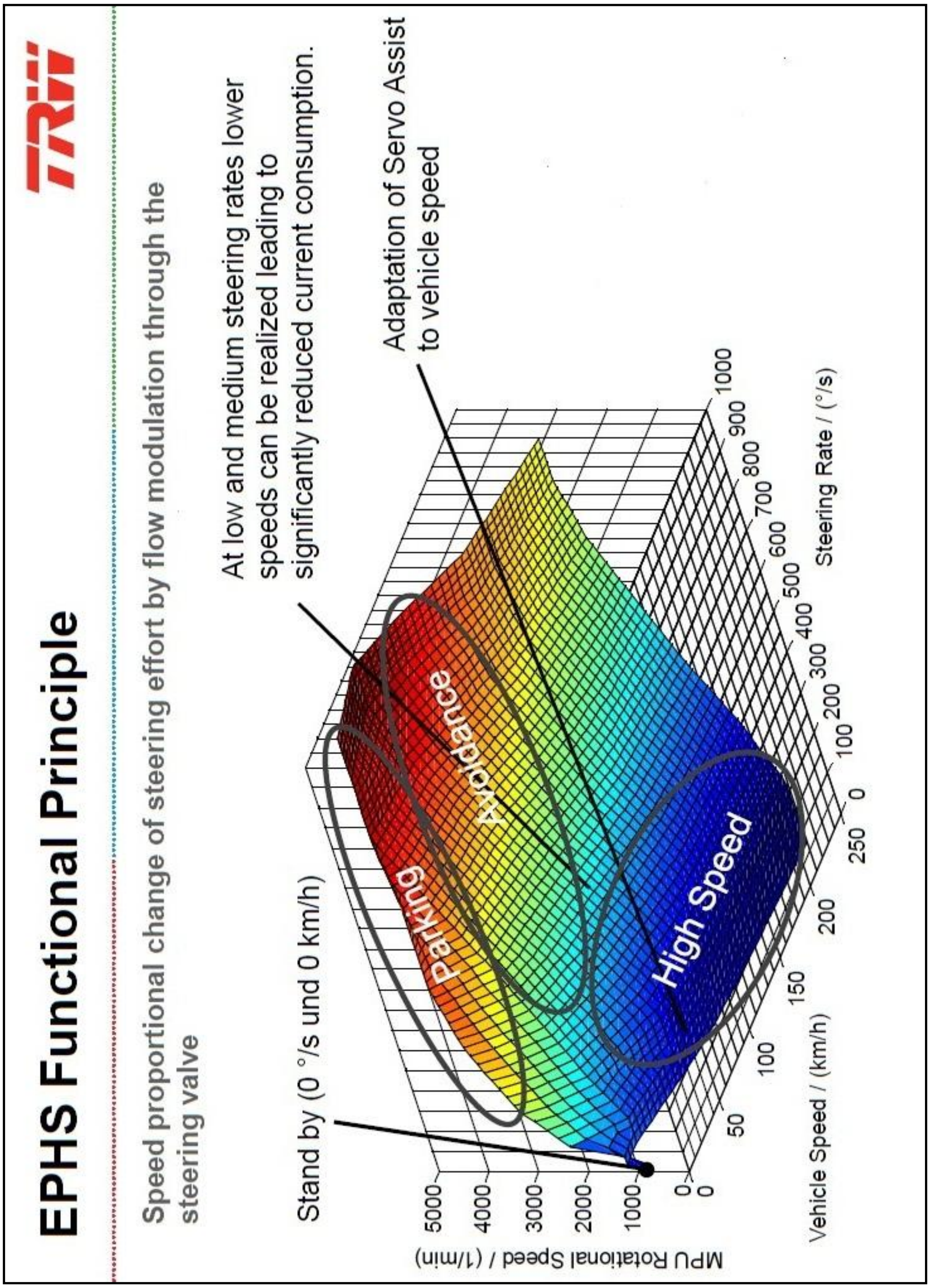


Fig 24: HPS & EPHS comparison

2). The graph below shows the working of EPHS system under various circumstances such as the steering rate, vehicle speed and the motor speed. It shows how the system is kept at standby or run at maximum RPM as per the requirement.



3) The figures below show the EPHS products currently available in the market.

BTS 3001071

OPEL

ASTRA "G"
ZAFIRA

5948001
5948009
04.55.1000

JER 100

BTS 3001072

OPEL
SIGNUM VECTRA
SAAB
5948006
5948074
5948069 SAAB
93180406
93172788
93183575
JER 109

BTS 3001073

OPEL
ASTRA "H"
ZAFIRA

93179568
93190229
5948067
JER 107
M29580442TD
15-0249

BTS 3001074

OPEL

SIGNUM
VECTRA C
93190150
93172789
93183550
5948007
5948073
JER 110

BTS 3001075

OPEL
ASTRA G
ZAFIRA

948000
948089
948091
9156554
21G46123
04.55.0400

BTS 3001077

OPEL ASTRA H

JER 142
13192897
5948070
5948230
5948072
5948229
93190155
93181657

BTS 4002571

OPEL ***KIT*** 93172043
ASTRA "G" 1609126
ZAFIRA 1289042

JRK 100

BTS 4002572

OPEL ***KIT***
SIGNUM VECTRA

JRP 767
JER 109/111

REPL. 5948006

BTS 4002580

VW SEAT SKODA

JRP 289 JR104

BTS 3001080

SEAT
VOLKWAGEN
SKODA

6Q0 423 155AE
6Q0 423 155AB
6Q0 423 156 C
.. E/F/G/M/Q..
JER 104
04.55.0802

BTS 3001060

CITROEN

SAXO

4007 IE
4007 M2
111.849B
183042610H
04.55.0200

BTS 3001061

CITROEN

BERLINGO

183042610Z
4007.Q5
(111849B)
JER 129
4007 9C
04.55.0600

BTS 3001063

CITROEN
Saxo
PEUGEOT
106

4007 S3
JER 128
04.55.0202

BTS 3001064

CITROEN
C 4

9684252580
9684040180
JER 131
ex JER 119

BTS 3001052

RENAULT
CLIO 1
EXPRESS

7700425540
A 5084943
71249363
04.55.0100
109.957
JER 123

BTS 3001053

RENAULT

RENAULT 19

7700829781
04.55.0101
JER 125

BTS 3001054

RENAULT
Kangoo
Dacia 1,5Dci

8200520790
8200718096
J5097227+C

BTS 3001051

RENAULT

CLIO II
KANGOO
183042610Z
7701470783
7700420305A
7700421259
8032191152
J5084975+C

BTS 3001076

OPEL
SAAB

93183575
5948074
R1700056
JER 111
ex JER109
extra pins

BTS 3001090

FIAT
Scudo
PEUGEOT
Partner
CITROEN
Jumpy

1400752580
J5097227+C

BTS 3001010

MERCEDES
A140
A160
A170

A 1684 660301
1681 660101
A 1684 660401
1681 660501

BTS 3001011

MERCEDES

A 221 4600780

BTS 3001030

FORD
Focus II

6M5Y3K514CC
JER 115

BTS 3001032

FORD
Galaxy

6G913K514AL
JER 116

BTS 3001031

FORD
Fiesta II

J5087234+H
YS613K514 BF

BTS 3001041

CITROEN
PEUGEOT

4007SQ
4007VK
04.55.0902

BTS 3001020

MINI ONE

4007 M2

MR 6760060
32416760567
32416769962
32416769963

AM 600055

AM 600055

12V / 600W
ZF 1090415
11 216 071
7625477136
7625377118
S 122258001 C
suitable to :
BTS 3001020

BTS 5001019

BTS 5001019

suitable to
BTS 3001020
AM 600055
11.216.071

AM 813028

AM 813028

suitable to
BTS 3001020
AM 600055

AM 813027

AM 813027

suitable to
BTS 3001010

BTS 5001031

"A" Class repair card

BT 5001031
suitable to
BTS 3001010

AM 600029

AM 600029

12V / 900W
Heavy duty version
suitable to :
BT 3001052
BT 3001053
BT 3001061

AM 813804

AM 813804
07,0 x 12,0 x 18,0

suitable to :
AM 600026
AM 600029

AM 600026

AM 600026

12V/ 800W

AM 813224

AM 813224
80 X 133

suitable to :
AM 600026
112.510

AM 600042

AM 600042

12V / 600W

suitable to :
BT 3001051
BT 3001060
BT 3001063

AM 813223

AM 813223
80 x 125

suitable to :
AM 600042
AM 600142
111.858
111.849

AM 813024

AM 813024
06,0 x 12,5 x 20,0

suitable to :
AM 600042
AM 600142

AM 813030

AM 813030
06,0 x 12,5 x 20,0

suitable to :
BTS 3001031

BTS 813025

AM 813025

suitable to
AM 600042
AM 600142
111.858

BTS 5001071

BTS 5001071

suitable to
AM 813025
AM 813024
AM 600042
111.858

BTS 5001021

BTS 5001021

suitable to
AM 600042
AM 600142
112.858
111.849
112.237
112.242
114.226

BTS 5001018

DISCONTINUOUS

BTS 5001018

suitable to
BTS 3001020
AM 600055

BTS 5001024

BTS 5001024

suitable to
BTS 3001051
7701470783

BTS 5001025

BTS 5001025

suitable to
BTS 3001063
JER 128

BTS 5001023

BTS 5001023

suitable to
BTS 3001060
4007 IE

AM 905008

AM 905008

suitable to
BTS 3001051
BTS 3001052
BTS 3001053
BTS 3001060
BTS 3001061
BTS 3001063
..more..

BTS 600142

NEW

DEVELOPPING

AM 600142

12V / 600W

suitable to :
BT 3001051
BT 3001060
BT 3001063

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