

# Electric power steering systems: Electronic control strategies for enhanced performance and efficiency

Somashekarappa M <sup>1,\*</sup> and Rajesh S R <sup>2</sup>

<sup>1</sup> Department of Automobile Engineering, DACG Government Polytechnic, Chikmagalur, Karnataka, India.

<sup>2</sup> Department of Electronics and Communication Engineering, DACG Government Polytechnic, Chikmagalur, Karnataka, India.

World Journal of Advanced Research and Reviews, 2021, 12(02), 668–679

Publication history: Received on 20 September 2021; revised on 15 November 2021; accepted on 28 November 2021

Article DOI: <https://doi.org/10.30574/wjarr.2021.12.2.0492>

## Abstract

This research paper explores advancements in electric power steering (EPS) systems, focusing on electronic control strategies that enhance vehicle performance and energy efficiency. EPS has become a crucial technology in modern vehicles, offering significant benefits over traditional hydraulic systems, including reduced energy consumption and greater integration potential with advanced driver assistance systems (ADAS). This study examines the evolution of steering systems, highlighting the transition from manual to hydraulic and eventually to EPS, as well as the key components and architecture of modern EPS systems. The paper further delves into innovative control algorithms, such as model-based, adaptive, and robust control strategies, which contribute to precise steering control and improved driving experience. In addition, it discusses performance enhancement techniques, including variable steering ratio and disturbance rejection, alongside energy-efficient motor control techniques and power-on-demand strategies that optimize system efficiency. Finally, this paper addresses the integration of EPS with ADAS and autonomous driving technologies, reliability and fault-tolerance measures, and the challenges and future trends shaping the next generation of steering systems. Through an analysis of current research and industry developments, this study provides a comprehensive overview of EPS technology and its future prospects.

**Keywords:** Electric Power Steering (EPS); Steering Systems; Electronic Control Strategies; Energy Efficiency; Advanced Driver Assistance Systems (ADAS)

## 1. Introduction

Electric Power Steering (EPS) systems have emerged as a transformative technology in the automotive industry, gradually replacing traditional hydraulic power steering systems. The key distinction between EPS and hydraulic systems lies in the elimination of the hydraulic pump, which continuously drains power from the engine in traditional systems. EPS, on the other hand, operates only when steering input is detected, resulting in significant improvements in fuel economy and energy efficiency, particularly in electric and hybrid vehicles where energy management is crucial.

The evolution of EPS technology has opened new possibilities in vehicle design and performance. One of the key advantages of EPS is its packaging flexibility. Without the need for bulky hydraulic components, EPS systems can be more easily integrated into compact and lightweight vehicle architectures. This has allowed automotive manufacturers to optimize space and reduce overall vehicle weight, contributing further to fuel efficiency and lower emissions.

Moreover, EPS systems are better suited for integration with advanced electronic systems compared to their hydraulic predecessors. In particular, the rise of advanced driver assistance systems (ADAS) has pushed the need for precise and

\*Corresponding author: Somashekarappa M

responsive steering control, which EPS is uniquely equipped to handle. Features such as lane-keeping assist, automated parking, and stability control rely heavily on the precision offered by electronically controlled steering [1].

At the heart of modern EPS systems is the sophisticated electronic control unit (ECU), which processes inputs from various sensors, including torque sensors and vehicle dynamics data, to deliver optimal steering assistance. These control strategies range from basic feedback loops to advanced model-based, adaptive, and robust control algorithms that tailor the steering response to various driving conditions. This adaptability ensures better handling, improved safety, and a more comfortable driving experience.

In addition to enhancing vehicle dynamics, EPS technology has paved the way for significant advancements in steering feel and feedback, which are critical for driver satisfaction. Modern EPS systems incorporate performance enhancement techniques such as variable steering ratios and active return-to-center functionality, which dynamically adjust steering responsiveness based on vehicle speed and road conditions. This ensures that drivers experience precise control at high speeds and ease of maneuverability at low speeds.

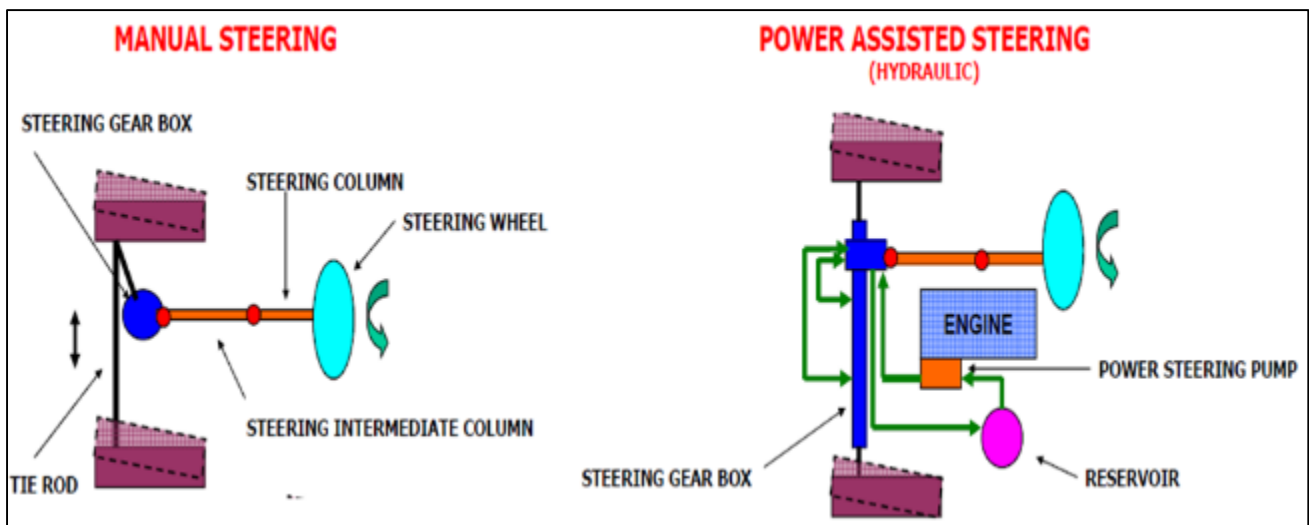
This paper investigates the latest technological advancements in EPS, focusing on how electronic control strategies are pushing the boundaries of both steering performance and energy efficiency. By analyzing the evolution of steering systems, innovations in control algorithms, and future trends in integration with ADAS and autonomous driving systems, this study aims to provide a comprehensive overview of the current state and future prospects of EPS technology in the automotive sector.

## 2. Evolution of Steering Systems

Steering technology in automobiles has undergone significant changes over the past century, driven by the need to improve driver comfort, safety, and vehicle performance. The evolution from manual steering to hydraulic and then electric power steering reflects the continuous advancements in automotive engineering aimed at providing better control and efficiency.

### 2.1. From Manual to Hydraulic Power Steering

The earliest vehicles used manual steering systems, which relied entirely on the driver's physical effort to turn the wheels. While functional, these systems were challenging to use, especially in larger or heavier vehicles, where steering at low speeds required significant force. To address this, hydraulic power steering (HPS) was introduced in the mid-20th century, using a hydraulic pump powered by the engine to assist with steering effort. HPS greatly improved ease of use, particularly in urban driving and parking situations, reducing the physical strain on drivers. However, it also had limitations, such as continuous energy consumption, even when steering input was not required [2].



**Figure 1** Evolution from Manual to Hydraulic Power Steering

## 2.2. Transition to Electric Power Steering

The development of Electric Power Steering (EPS) in the late 20th century marked a major milestone in steering technology. Unlike hydraulic systems, EPS uses an electric motor to assist steering, operating only when needed. This results in significant energy savings, especially in modern vehicles where fuel efficiency and environmental impact are critical. The transition from hydraulic to electric steering was driven by the need to reduce parasitic energy losses in vehicles, particularly with the growing focus on sustainability. EPS systems also offered new opportunities for integrating advanced electronics, enabling greater precision and adaptability in steering control.

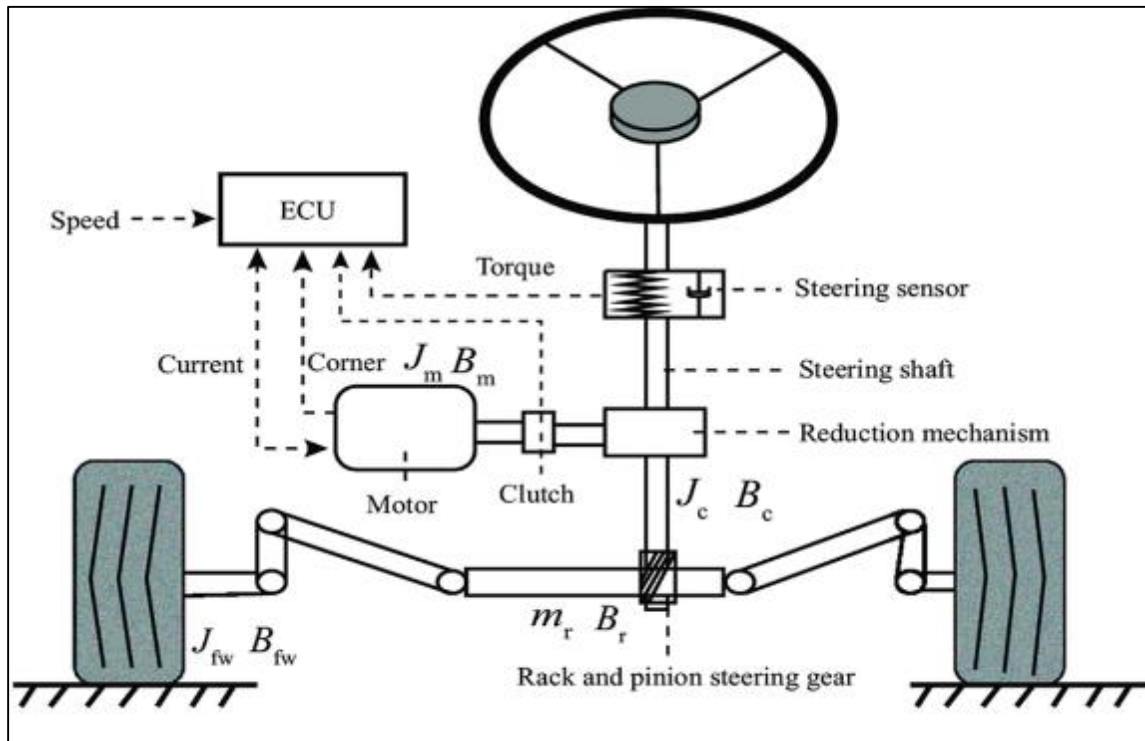


Figure 2 Transition to Electric Power Steering

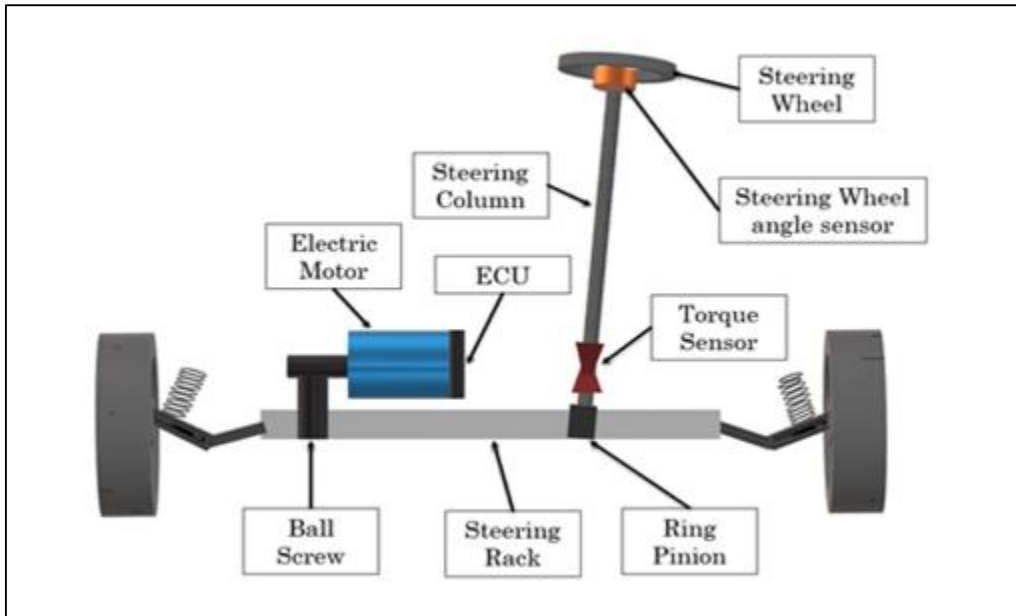
## 2.3. Advantages and Challenges of EPS

EPS provides numerous advantages over hydraulic systems, including improved energy efficiency, enhanced vehicle dynamics, and easier integration with modern electronic systems like ADAS. The removal of hydraulic fluid and pumps simplifies maintenance and reduces environmental impact. EPS systems are also lighter, contributing to overall vehicle weight reduction, which further enhances fuel efficiency. Moreover, the precision of electronic control allows for adaptive features like variable steering ratios and customizable steering feel, making EPS more versatile for different driving conditions.

However, EPS also presents challenges. The reliance on electronic components makes the system more complex and potentially vulnerable to faults, such as sensor or motor failures. This necessitates robust fault-tolerant designs to ensure safe operation under all conditions. Additionally, achieving the same level of road feedback and steering feel as hydraulic systems remains a challenge, as EPS systems tend to filter out some of the tactile feedback drivers expect.

## 3. Architecture of Modern EPS Systems

The architecture of Electric Power Steering (EPS) systems is a sophisticated combination of mechanical and electronic components working together to provide precise steering assistance. By replacing the traditional hydraulic systems with electric motors and control electronics, EPS systems improve both the efficiency and responsiveness of vehicle steering. This section explores the key components of EPS, the differences between column-type and rack-type configurations, and the role of advanced sensor technologies[3,4].



**Figure 3** Schematic diagram of a typical EPS system

### 3.1. Components of an EPS System

Modern EPS systems consist of several core components that work in unison to control the steering effort based on the driver's input:

- **Electric Motor:** The electric motor is responsible for generating the torque needed to assist with steering. Depending on the system's configuration, it is either mounted on the steering column or integrated with the steering rack. The motor is controlled by the Electronic Control Unit (ECU), which adjusts its output to match the required steering assistance.
- **Torque Sensor:** The torque sensor measures the amount of force the driver applies to the steering wheel. This data is crucial for the ECU to determine the appropriate level of assistance. The sensor also detects the direction of the steering input, allowing the system to provide steering assistance in the correct direction.
- **Electronic Control Unit (ECU):** The ECU is the brain of the EPS system. It processes input from the torque sensor and other sensors to determine how much assistance the electric motor should provide. The ECU runs sophisticated algorithms, including model-based and adaptive control strategies, to ensure the optimal steering feel and response for various driving conditions.
- **Reduction Gear:** The reduction gear connects the electric motor to the steering column or rack. It reduces the motor's speed while increasing the torque, ensuring that the steering assistance is both smooth and powerful enough to help the driver turn the wheels with minimal effort.

### 3.2. Column-Type vs. Rack-Type EPS

EPS systems can be classified into two main types based on the location of the electric motor:

- **Column-Type EPS:** In this configuration, the electric motor and reduction gear are mounted on the steering column. This design is more compact and easier to install, making it a popular choice for small to mid-sized vehicles. However, because the assistance is applied directly to the steering column, column-type EPS may offer slightly less precision compared to rack-type systems, especially in high-performance driving situations.
- **Rack-Type EPS:** In rack-type EPS, the electric motor is mounted directly on the steering rack, which provides more direct assistance to the wheels. This setup is often used in larger vehicles or those requiring higher performance, as it offers better steering precision and feedback. Rack-type EPS systems are more complex and typically more expensive, but they are preferred for vehicles where steering performance is critical.

### 3.3. Sensor Technologies in EPS

Advanced sensor technologies are integral to the performance and safety of modern EPS systems. Beyond the basic torque sensor, several other sensors play a key role in ensuring the system operates optimally:

- **Steering Angle Sensor:** This sensor measures the angle of the steering wheel relative to the vehicle's axis. It helps the ECU determine how much assistance is needed and whether the vehicle is following the driver's intended path.
- **Vehicle Speed Sensor:** The vehicle's speed influences the amount of steering assistance required. At higher speeds, less assistance is needed, while at lower speeds, such as during parking, more assistance is necessary. The vehicle speed sensor provides this critical data to the ECU.
- **Yaw Rate Sensor:** This sensor detects the rotation of the vehicle around its vertical axis (yaw). The yaw rate sensor is particularly important for advanced driver assistance systems (ADAS) and stability control, as it helps maintain vehicle stability by providing input for corrective steering measures.

---

## 4. Electronic Control Strategies

The heart of an Electric Power Steering (EPS) system lies in its electronic control strategies, which determine how the system interprets the driver's inputs and manages the electric motor to provide precise steering assistance. Modern EPS systems use a combination of basic control loops and advanced algorithms to ensure that steering performance is optimized for different driving conditions. This section explores the control techniques used to enhance the responsiveness, reliability, and efficiency of EPS systems[5].

### 4.1. Basic Control Loop in EPS

At the most fundamental level, EPS operates using a closed-loop feedback system. The basic control loop involves several key steps:

- **Input Measurement:** The system measures the torque applied by the driver to the steering wheel through the torque sensor. The sensor data is then sent to the Electronic Control Unit (ECU).
- **Control Decision:** The ECU processes the input data and compares it to pre-determined assist curves. These curves define how much assistance the electric motor should provide based on the torque applied by the driver and other variables such as vehicle speed.
- **Motor Actuation:** Once the ECU calculates the required assistance, it sends a command to the electric motor to generate the appropriate amount of torque to assist the driver's steering effort.
- **Feedback and Adjustment:** The system continuously monitors the output, adjusting the motor's torque in real-time to maintain smooth and responsive steering.

### 4.2. Advanced Control Algorithms

While the basic control loop is effective for most driving conditions, more advanced algorithms are necessary to handle complex scenarios such as varying road surfaces, weather conditions, or vehicle dynamics. Some of the most common advanced control algorithms in EPS systems include:

- **Model-Based Control:** This method uses a mathematical model of the vehicle's dynamics to predict its behavior in response to different steering inputs. By incorporating variables such as vehicle speed, yaw rate, and lateral acceleration, model-based control algorithms can improve steering precision and vehicle stability.
- **Adaptive Control:** Adaptive control strategies adjust the system's behavior in real-time based on changing driving conditions or vehicle states. For example, the level of steering assistance may be dynamically adjusted based on the load on the vehicle or the type of road surface. This approach enhances both performance and safety by ensuring the system remains responsive under varying conditions.
- **Robust Control:** Robust control algorithms are designed to maintain system performance even in the presence of uncertainties or disturbances, such as sudden changes in road conditions or mechanical wear in components. These algorithms ensure the EPS system remains reliable and responsive, even when operating in less-than-ideal conditions.

### 4.3. Motor Control Techniques

The electric motor in an EPS system must be precisely controlled to deliver the correct amount of torque at the right moment. Two common motor control techniques used in EPS systems are:

- **Field-Oriented Control (FOC):** FOC is a vector control method used to control the torque and speed of electric motors. It involves controlling the motor's stator current in two orthogonal components: one responsible for producing torque and the other for magnetizing the motor. This separation allows for highly precise control of the motor, leading to smoother steering and better overall performance.

- Direct Torque Control (DTC): DTC is another technique that controls the motor's torque and magnetic flux directly by selecting the appropriate voltage vectors. This method offers fast dynamic response and is less computationally intensive than FOC, making it suitable for applications where high performance and quick adjustments are required, such as during sudden maneuvers or emergency situations.

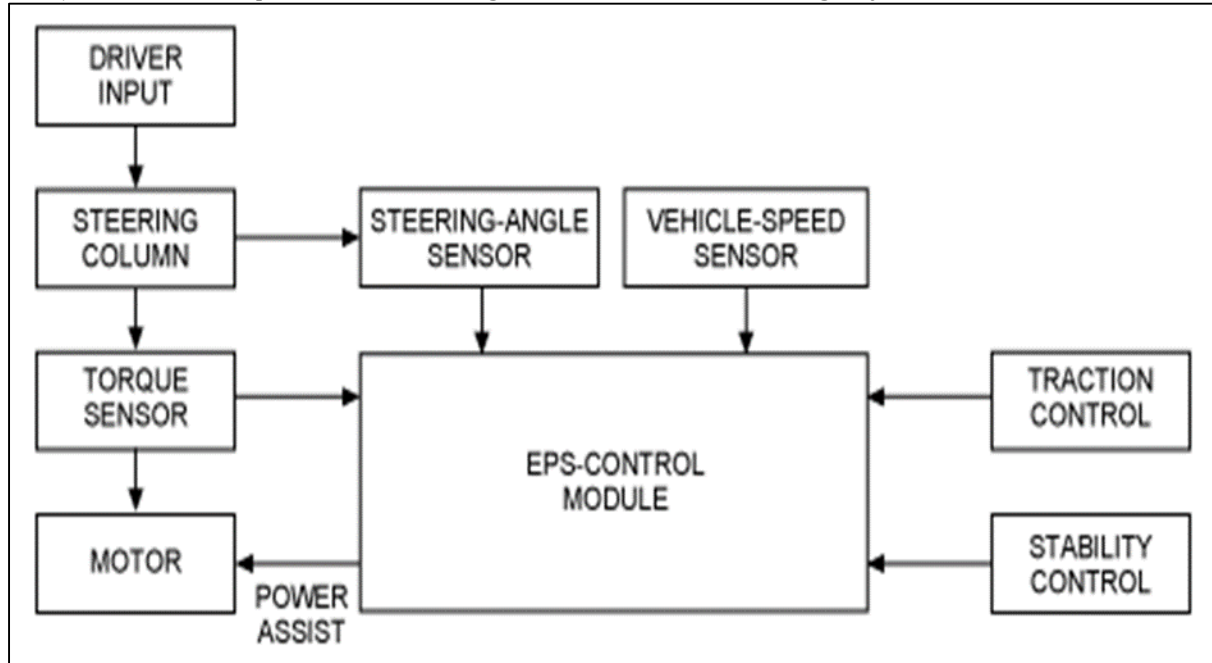


Figure 4 Block diagram of an advanced EPS control system

## 5. Performance Enhancement Techniques

Modern Electric Power Steering (EPS) systems not only provide basic steering assistance but also incorporate advanced performance enhancement techniques to improve the overall driving experience. These techniques enhance steering precision, responsiveness, and driver comfort by adapting the steering response to different driving conditions and minimizing disturbances[6].

### 5.1. Variable Steering Ratio

Variable steering ratio technology allows EPS systems to dynamically adjust the steering ratio based on the vehicle's speed and driving conditions. At low speeds, such as during parking or navigating tight turns, a lower steering ratio provides greater maneuverability, allowing the driver to turn the wheels with fewer rotations of the steering wheel. Conversely, at higher speeds, the steering ratio increases, providing better stability and control by reducing the sensitivity of the steering input. This adaptive approach enhances both the convenience of low-speed driving and the safety of high-speed driving, offering a balanced steering experience.

### 5.2. Active Return-to-Center

The active return-to-center feature in EPS systems automatically returns the steering wheel to its neutral position after a turn, reducing the driver's effort to manually center the wheel. This function is controlled by the electronic control unit (ECU), which uses feedback from the torque and steering angle sensors to determine the optimal moment and force required to return the steering wheel. Active return-to-center not only improves driver comfort but also contributes to vehicle stability, ensuring the car quickly aligns with the intended path after cornering or lane changes.

### 5.3. Disturbance Rejection

Disturbance rejection strategies in EPS systems help mitigate the impact of external forces that can disrupt steering control, such as uneven road surfaces, wind gusts, or sudden vehicle movements. These techniques ensure that drivers experience smooth and predictable steering even in challenging conditions.

- Road Feedback Estimation and Cancellation: EPS systems can estimate the road feedback through sensors that



detect external forces acting on the wheels. By processing this data, the system can filter out unwanted disturbances, such as vibrations from rough terrain, providing the driver with a smoother and more controlled steering feel.

- **Wind Gust Compensation:** Strong crosswinds can cause vehicles to veer off course, requiring corrective steering inputs from the driver. Advanced EPS systems incorporate wind gust compensation algorithms, which detect lateral forces caused by wind and automatically apply counter-steering assistance to keep the vehicle on track. This enhances safety and reduces driver fatigue, especially in high-wind environments.

#### 5.4. Steering Feel Optimization

Optimizing steering feel is one of the key performance objectives in EPS systems. Steering feel refers to the tactile feedback and responsiveness drivers experience when operating the steering wheel. Engineers work to ensure that EPS systems provide a natural and intuitive steering experience, replicating or even improving upon the feedback traditionally associated with hydraulic power steering.

Several techniques are used to optimize steering feel, including adjusting assist curves based on driving conditions, refining motor control algorithms for smoother torque delivery, and fine-tuning the response to road feedback. These adjustments ensure that drivers receive the right amount of feedback for different driving scenarios, such as light steering for parking and firmer steering for highway driving, while maintaining the precise control needed for performance driving.

---

### 6. Efficiency Improvement Strategies

One of the primary advantages of Electric Power Steering (EPS) systems over traditional hydraulic systems is their potential for significant energy savings. With automotive industries increasingly focusing on fuel efficiency and reducing emissions, EPS systems are designed with energy efficiency in mind. This section explores various strategies used to improve the efficiency of EPS systems, further enhancing their appeal in modern vehicles[7,8].

#### 6.1. Energy-Efficient Motor and Drive Designs

At the core of an EPS system's energy efficiency is its electric motor and drive design. Modern EPS systems use brushless DC (BLDC) or permanent magnet synchronous motors (PMSM), which are highly efficient and provide precise torque control. These motors are designed to minimize losses and improve energy conversion efficiency, ensuring that only the required amount of electrical energy is consumed to assist with steering.

The drive system, which controls the motor, is also optimized for efficiency. Advanced power electronics and motor control algorithms, such as Field-Oriented Control (FOC) and Direct Torque Control (DTC), ensure that the motor operates within its most efficient range, minimizing power losses and heat generation. By refining both the motor and drive designs, EPS systems can deliver the necessary performance while consuming minimal energy.

#### 6.2. Power-On-Demand Control

Unlike hydraulic power steering systems, which operate continuously regardless of whether steering assistance is needed, EPS systems feature **power-on-demand** control. This means that the electric motor only operates when steering assistance is required, such as during turning or lane changes. When the vehicle is driving straight or at high speeds, where minimal steering effort is needed, the EPS system consumes little to no power.

This on-demand operation significantly reduces energy consumption compared to hydraulic systems, which are constantly driven by an engine-powered pump. The elimination of continuous power consumption makes EPS systems more efficient, particularly during highway driving where steering input is minimal.

#### 6.3. Regenerative Strategies in EPS

Some advanced EPS systems incorporate **regenerative strategies** to further improve efficiency. In these systems, the electric motor can act as a generator during specific conditions, such as when the driver releases the steering wheel or during return-to-center actions. The motor's kinetic energy is converted back into electrical energy and stored in the vehicle's battery or reused by other systems.

While regenerative strategies in EPS are less common than in braking systems, they represent a promising area for energy recovery, especially in electric vehicles where every watt of energy saved can contribute to extending driving range.

#### 6.4. Optimization of Assist Curves

The **assist curve** in an EPS system defines the relationship between the driver's steering input and the level of assistance provided by the motor. By optimizing these curves, EPS systems can deliver the right amount of assistance at the right time, avoiding unnecessary energy use.

For example, during low-speed maneuvers like parking, higher levels of assistance are required, while at high speeds, minimal assistance is needed. The EPS system dynamically adjusts its assist curve based on real-time input from vehicle sensors, ensuring that the motor is only working as hard as necessary. This helps reduce energy consumption while maintaining smooth and responsive steering.

**Table 1** Comparison of power consumption: Hydraulic vs. Electric Power Steering

Specification	Electric (Standard Screw) Cylinder Roller	Electric Cylinder (Ball Screw)	Hydraulic Cylinder	Pneumatic Cylinder
Motion Profile Control & Flexibility	Easy & Most Capable	Easy & Most Capable	Limited or Complex Servo-Hydraulics	Limited or Complex Servo-Pneumatics
Positional Accuracy & Repeatability	Best Accuracy & Repeatability	Best Accuracy & Repeatability	Limited Complex with Servo-Hydraulics	Limited Complex with Servo-Pneumatics
Max Force	Very High	High	Highest	Medium
Max Speed	High	High	High	Very High
Actuator Life / L10	Very High / Calculated	Medium / Calculated	Medium / N/A	Medium / N/A
Maintenance	Minimal	Minimal	40% to 55%	10% to 25%
System Efficiency	~75%	~80%	40% to 55%	10% to 25%
Energy Consumption	Low	Lowest	High	High
Shock Loads	Low	Lowest	Very High	Very High
Operational Temperature Tolerance	Very Tolerant & Efficient	Very Tolerant & Efficient	Seal Failure, Sluggish Operation	Seal Failure, Sluggish Operation

## 7. Integration with Advanced Driver Assistance Systems (ADAS)

Electric Power Steering (EPS) systems play a crucial role in the integration of Advanced Driver Assistance Systems (ADAS), enhancing vehicle safety, convenience, and driving experience. By providing precise and responsive steering control, EPS systems enable the implementation of various ADAS features that assist drivers and improve overall road safety. This section explores key ADAS features integrated with EPS systems[9].

### 7.1. Lane Keeping Assist

Lane Keeping Assist (LKA) is a critical ADAS feature that helps prevent unintended lane departures by providing steering corrections when the vehicle drifts out of its lane. EPS systems are integral to LKA as they provide the precise steering control necessary for executing these corrections. The system uses cameras and sensors to monitor lane markings and detect if the vehicle is straying from its lane. When lane drift is detected, the EPS system adjusts the steering angle to guide the vehicle back into its lane. This integration enhances road safety and reduces driver fatigue by assisting with lane management on highways and other multi-lane roads.



## 7.2. Automated Parking

Automated Parking Systems (APS) use a combination of sensors, cameras, and EPS technology to enable vehicles to park themselves with minimal driver intervention. EPS systems are crucial for automated parking as they provide the fine-grained steering control required to maneuver the vehicle into tight parking spaces accurately. The APS uses data from ultrasonic sensors or cameras to detect parking spaces and obstacles. The EPS system then controls the steering, while the vehicle manages acceleration, braking, and gear selection, allowing for automated parallel, perpendicular, or angled parking. This feature enhances convenience and reduces the stress associated with parking in challenging environments.

## 7.3. Stability Control Integration

Stability control systems, such as Electronic Stability Control (ESC), help maintain vehicle stability during challenging driving conditions, such as during sudden turns or on slippery surfaces. EPS systems integrate with stability control by adjusting steering input to assist in counteracting skids and maintaining vehicle trajectory. Sensors monitor vehicle dynamics, such as yaw rate and lateral acceleration, and the stability control system uses this data to determine if steering adjustments are needed. By dynamically adjusting the steering, the EPS system helps correct the vehicle's path and enhances overall safety, particularly in adverse weather conditions or during emergency maneuvers.

## 7.4. Steer-By-Wire Systems

Steer-By-Wire (SBW) systems represent a significant advancement in steering technology, completely replacing traditional mechanical linkages with electronic controls. In SBW systems, the physical connection between the steering wheel and the wheels is eliminated, with electronic signals used to transmit driver inputs to the steering actuators. EPS systems are fundamental to SBW technology, as they provide the necessary control and feedback mechanisms for this fully electronic steering approach. SBW systems offer greater flexibility in vehicle design, as they do not require a physical steering column, and enable features such as customizable steering feel and remote or autonomous vehicle control. This integration is a step towards more advanced and autonomous driving technologies.

---

## 8. Reliability and Fault Tolerance

Ensuring the reliability and fault tolerance of Electric Power Steering (EPS) systems is essential for maintaining vehicle safety and performance. As EPS systems become increasingly integrated with advanced driver assistance features and autonomous driving technologies, their robustness and ability to handle faults are of paramount importance. This section discusses key strategies employed to enhance the reliability and fault tolerance of EPS systems [10].

### 8.1. Redundancy in Critical Components

Redundancy is a fundamental approach to enhancing the reliability of EPS systems. By incorporating backup components and systems, EPS can continue to function correctly even if one or more components fail. Critical areas where redundancy is implemented include:

- **Power Supply:** Multiple power sources or backup batteries can ensure that the EPS system remains operational if the primary power supply fails.
- **Sensors:** Redundant sensors can be used to cross-check data, such as torque and steering angle, ensuring accurate measurements and reliable system performance even if one sensor fails.
- **Actuators:** In some high-reliability applications, multiple actuators might be used to provide steering assistance, allowing the system to function even if one actuator fails.

This approach ensures that the EPS system can maintain functionality and safety in the event of component failures, contributing to overall system reliability.

### 8.2. Fault Detection and Diagnosis

Fault detection and diagnosis are critical for maintaining the operational integrity of EPS systems. Advanced EPS systems are equipped with various mechanisms to identify and address faults:

- **Self-Diagnostic Algorithms:** The Electronic Control Unit (ECU) continuously monitors the performance of the EPS system components using built-in diagnostic algorithms. These algorithms detect deviations from normal operation and identify potential issues before they lead to system failure.
- **Error Codes and Alerts:** When a fault is detected, the system generates error codes and alerts that can be used

by technicians for troubleshooting. These codes help in quickly diagnosing the issue and performing necessary repairs or replacements.

- **Real-Time Monitoring:** Real-time monitoring of system parameters, such as motor current, voltage, and temperature, allows for the early detection of anomalies. By analyzing these parameters, the system can preemptively address issues that might lead to more severe faults.

### 8.3. Fail-Safe Strategies

Fail-safe strategies are designed to ensure that EPS systems continue to operate safely even in the event of a significant fault. Key fail-safe strategies include:

- **Reduced Functionality Mode:** In the event of a fault, the EPS system may switch to a reduced functionality mode that provides minimal steering assistance while allowing the driver to maintain control. This mode ensures that the vehicle remains drivable until the fault can be addressed.
- **Mechanical Backup:** Some EPS systems are designed with mechanical backup systems that can take over if the electronic components fail. This can include manual steering mechanisms or mechanical linkages that ensure basic steering control.
- **Safe Mode Activation:** If a critical fault is detected, the EPS system can activate a safe mode that disables certain functions or limits steering assistance to prevent unsafe driving conditions. This helps protect the driver and passengers from potential hazards resulting from system malfunctions.

---

## 9. Future Trends and Challenges

As Electric Power Steering (EPS) systems continue to evolve, several future trends and challenges are shaping their development. This section explores key areas where EPS technology is expected to advance and the obstacles that need to be addressed to fully realize these advancements.

### 9.1. EPS for Autonomous Vehicles

The integration of EPS systems with autonomous vehicle technology is one of the most significant trends in automotive engineering. Autonomous vehicles require highly precise and reliable steering control to navigate complex driving environments safely. EPS systems are well-suited for this role due to their ability to provide fine-grained control and real-time adjustments based on input from various sensors and algorithms.

- **Enhanced Precision:** EPS systems in autonomous vehicles must offer exceptional precision and responsiveness to handle complex driving scenarios, such as lane changes, obstacle avoidance, and parking.
- **Adaptive Algorithms:** Advanced control algorithms will be needed to manage the steering dynamics in response to various driving conditions and scenarios encountered by autonomous vehicles.
- **Seamless Integration:** EPS systems will need to integrate seamlessly with other vehicle systems, such as perception and decision-making algorithms, to ensure coordinated and safe operation.

### 9.2. Integration with Electrified Powertrains

The shift towards electrified powertrains, including hybrid and fully electric vehicles, is influencing the design and functionality of EPS systems. Electrified powertrains offer opportunities for synergy with EPS technology:

- **Power Efficiency:** EPS systems in electric vehicles can benefit from the overall power efficiency of the vehicle's electrified systems, reducing energy consumption and improving range.
- **System Integration:** EPS systems must be designed to work harmoniously with electrified powertrains, including managing energy flows and optimizing performance across different driving modes.
- **Reduced Mechanical Complexity:** The absence of a traditional hydraulic pump allows for more compact and efficient EPS designs, which can be advantageous in the packaging of electric powertrains.

### 9.3. Cybersecurity Considerations

As EPS systems become increasingly connected and integrated with other vehicle technologies, cybersecurity becomes a critical concern. Ensuring the protection of EPS systems from cyber threats is essential for maintaining vehicle safety and integrity:

- **Data Security:** EPS systems rely on data from various sensors and communication networks. Ensuring the

security of this data from tampering or unauthorized access is crucial.

- **System Integrity:** Protecting the EPS system from cyber attacks that could compromise its functionality or alter its behavior is essential to prevent potential safety hazards.
- **Regulatory Compliance:** Adhering to cybersecurity standards and regulations, such as those defined by industry bodies and governmental agencies, will be important for maintaining vehicle safety and consumer trust.

#### 9.4. Standardization Efforts

Standardization is a key factor in the widespread adoption and interoperability of EPS systems. Efforts to standardize EPS technology can help address various challenges and promote industry-wide consistency:

- **Technical Standards:** Developing and adopting technical standards for EPS systems, including communication protocols, performance metrics, and safety requirements, can facilitate compatibility and integration across different vehicle models and manufacturers.
- **Regulatory Standards:** Ensuring that EPS systems meet regulatory standards for safety, performance, and reliability is important for market acceptance and consumer confidence.
- **Industry Collaboration:** Collaboration among automotive manufacturers, suppliers, and standardization organizations is essential to drive innovation, reduce costs, and ensure that EPS systems meet evolving industry needs.

---

## 10. Conclusion

Electric Power Steering (EPS) systems represent a significant advancement in automotive steering technology, offering numerous benefits over traditional hydraulic systems. The evolution from manual to hydraulic and then to electric power steering has brought about improvements in energy efficiency, performance, and vehicle integration. Throughout this paper, we explored the architecture and electronic control strategies of modern EPS systems. Key advancements include energy-efficient motor designs, sophisticated control algorithms, and innovative steering enhancement techniques that improve both performance and efficiency. These advancements have enabled EPS systems to deliver precise steering control while minimizing energy consumption, contributing to the overall efficiency of modern vehicles. Integration with Advanced Driver Assistance Systems (ADAS) has expanded the functionality of EPS, allowing for features such as lane-keeping assist, automated parking, and stability control. These integrations highlight the EPS system's role in enhancing vehicle safety and driver convenience. Moreover, the development of Steer-By-Wire systems underscores the potential for EPS technology to support more flexible and advanced vehicle designs. Looking ahead, EPS systems face several challenges and opportunities. The rise of autonomous vehicles necessitates further advancements in EPS technology to provide the precision and reliability required for safe autonomous operation. The integration with electrified powertrains presents opportunities for greater efficiency, while cybersecurity considerations highlight the need for robust protection against potential threats. Additionally, standardization efforts are crucial for ensuring compatibility and safety across the industry. In conclusion, EPS systems are at the forefront of automotive innovation, driving significant improvements in steering performance, vehicle efficiency, and integration with advanced technologies. Continued research and development will be essential to addressing future challenges and leveraging emerging opportunities, ensuring that EPS systems remain a pivotal component of modern and future vehicles.

---

## Compliance with ethical standards

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

---

## References

- [1] Marouf, Alaa, Mohamed Djemai, Chouki Sentouh, and Philippe Pudlo. A new control strategy of an electric-power-assisted steering system. *IEEE Transactions on Vehicular Technology* 61, no. 8 (2012): 3574-3589.
- [2] Dell'Amico, Alessandro, and Petter Krus. Modeling, simulation, and experimental investigation of an electrohydraulic closed-center power steering system. *IEEE/ASME transactions on mechatronics* 20, no. 5 (2015): 2452-2462.

- [3] Saifia, Dounia, Mohammed Chadli, Hamid Reza Karimi, and Salim Labiod. Fuzzy control for electric power steering system with assist motor current input constraints. *Journal of the Franklin Institute* 352, no. 2 (2015): 562-576.
- [4] Chahare, V., I. Mhaisne, and Dnyaneshwar Dongre. An Overview on Future Electric Steering System: A Project Approach. *International Research Journal of Engineering and Technology* 4, no. 7 (2017): 2152-2159.
- [5] Baek, Jaemin, and Changmook Kang. Time-delayed control for automated steering wheel tracking of electric power steering systems. *IEEE Access* 8 (2020): 95457-95464.
- [6] Zhang, Hui, Jinhong Liu, Jing Ren, Yuzhi Zhang, and Yongjun Gao. Research on Electric Power Steering with BLDC drive system. In *2009 IEEE 6th International Power Electronics and Motion Control Conference*, pp. 1065-1069. IEEE, 2009.
- [7] Lin, Faa-Jeng, Ying-Chih Hung, and Kai-Chun Ruan. An intelligent second-order sliding-mode control for an electric power steering system using a wavelet fuzzy neural network. *IEEE Transactions on Fuzzy Systems* 22, no. 6 (2014): 1598-1611.
- [8] Dell'Amico, Alessandro. On electrohydraulic pressure control for power steering applications: Active steering for road vehicles. Vol. 1739. Linköping University Electronic Press, 2016.
- [9] Murilo, André, Rafael Rodrigues, Evandro Leonardo Silva Teixeira, and Max Mauro Dias Santos. Design of a parameterized model predictive control for electric power assisted steering. *Control Engineering Practice* 90 (2019): 331-341.
- [10] Runge, Wolfgang, Alexander Gaedke, Markus Heger, Alexander Vähning, and Hans-Christian Reuss. Electric steering. *ATZ worldwide* 111, no. 10 (2009): 14-20.