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IMPROVEMENT OF AUTOMOTIVE HYDRAULIC SYSTEMS THROUGH ELECTRO-HYDRAULIC CONTROL, ENERGY MANAGEMENT AND CONDITION MONITORING

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Abstract: Automotive hydraulic systems remain essential in braking, steering, suspension, transmission actuation and several auxiliary functions because they provide high force density, compact actuators and reliable transmission of mechanical power. Nevertheless, conventional hydraulic arrangements often operate with continuous pump delivery, throttling losses, delayed pressure response, temperature-dependent fluid properties and limited diagnostic capability. These characteristics increase energy consumption and can reduce control accuracy, particularly in electric, hybrid and highly automated vehicles. The purpose of this study is to develop an integrated engineering framework for improving automotive hydraulic systems through on-demand electro-hydraulic actuation, closed-loop pressure control, energy storage, condition monitoring and fault-tolerant architecture. The research combines a structured review of published studies with analytical modelling of fluid flow, actuator force, leakage and energy consumption. A representative electro-hydraulic brake subsystem is used to demonstrate the proposed approach, while steering and active suspension applications are considered to evaluate the wider relevance of the method. Illustrative simulations show that closed-loop pressure control can shorten the time required to reach the commanded wheel-cylinder pressure and substantially reduce overshoot compared with a conventional open-loop hydraulic arrangement. A normalized duty-cycle analysis also indicates that replacing a continuously driven pump with an intelligent on-demand motor-pump unit can reduce the relative hydraulic energy demand. The study further shows that pressure, temperature, moisture and contamination sensing can support predictive maintenance and improve functional safety. The proposed improvement strategy does not eliminate hydraulic technology. Instead, it transforms conventional hydraulics into a sensor-rich, electronically controlled and energy-aware mechatronic system. Such integration is especially important for electric vehicles, brake-by-wire functions, automated driving and advanced chassis control.

Keywords: Automotive hydraulics, electro-hydraulic control, brake-by-wire, power steering, active suspension, energy efficiency, condition monitoring, hydraulic pressure control, predictive maintenance, vehicle safety.

Introduction

Hydraulic power transmission has been used in automobiles for many decades because a pressurized incompressible fluid can transfer large forces through compact pipes and actuators. The most familiar examples are the service brake, hydraulic power steering, clutch actuation, automatic transmission control and hydraulic or hydropneumatic suspension. In each case, the fluid transmits force from a source to an actuator while valves regulate direction, flow and pressure. The technology is mechanically robust, well understood and capable of producing smooth motion. At the same time, modern requirements have exposed limitations in conventional layouts. Continuous pump operation wastes energy, long pipelines and compliant hoses delay pressure development, fluid temperature changes viscosity, contamination accelerates wear, and purely mechanical control provides little information for diagnostics.

The electrification of the vehicle powertrain has made these limitations more visible. A conventional engine-driven vacuum booster or belt-driven hydraulic steering pump depends on the operation of the internal combustion engine. Battery electric vehicles do not naturally

provide these sources, while hybrid vehicles operate the engine intermittently. Hydraulic functions must therefore be supplied independently and only when demanded. Electric motor-driven pumps, accumulators, pressure sensors and electronically controlled valves provide a practical transition from traditional hydraulics to electro-hydraulic systems. This transition retains the force density and fail-safe potential of hydraulic actuation while adding digital control, energy management and communication with the vehicle controller.

Early work on electro-hydraulic braking established the concept of separating pedal input from wheel-cylinder pressure generation. Jonner and coauthors described an electro-hydraulic brake architecture in which a high-pressure accumulator supplies pressure for normal braking and electronic commands regulate wheel pressure [1]. The arrangement was an important step toward brake-by-wire because it allowed active braking intervention and compatibility with stability control. Pan and coauthors later proposed a compact electro-hydraulic brake with a pedal simulator, motor-pump unit, accumulator and solenoid valves, and used modelling and test-bench data to evaluate pressure regulation [2]. These studies demonstrated that the brake pedal can be treated as a demand sensor while hydraulic pressure is generated and controlled independently.

The current development of integrated one-box electro-hydraulic braking systems is reviewed by Zhao and coauthors [3]. Their analysis shows that modern systems combine pressure generation, pedal simulation, valve control, electronic control and fallback functions in a compact module. Integration reduces pipe length and installation complexity, but it also raises demanding requirements for motor control, sealing, thermal management, redundancy and fault diagnosis. The review further emphasizes that autonomous braking and high-level driving automation require a braking system capable of generating pressure without driver input and maintaining acceptable performance after a single fault.

Electro-hydraulic control valves are another central element of system improvement. Xu and coauthors reviewed the development of electro-hydraulic valves and showed that sensors, digital controllers, advanced actuators and communication functions are transforming hydraulic control components into intelligent devices [4]. This trend is directly relevant to automobiles. A valve is no longer only a passive restriction. It can measure its state, receive a digital command, estimate flow and support fault diagnosis. When a valve block is integrated with a controller and pressure sensors, the hydraulic circuit can operate as a closed-loop mechatronic system.

Automotive steering provides a second important example. Conventional hydraulic power steering uses a pump driven continuously by the engine, even when steering assistance is not required. Hur and coauthors developed an electric motor-driven pump unit for electro-hydraulic power steering and optimized motor characteristics and power consumption [5]. Wi and coauthors compared conventional hydraulic, electro-hydraulic and electric steering systems in a vehicle fuel-economy context and reported that electro-hydraulic steering improved fuel economy relative to continuously driven hydraulic steering [6]. These findings support the principle of demand-based hydraulic power generation.

Suspension systems reveal another direction for improvement. A traditional damper converts vibration energy into heat, while a hydraulic active suspension consumes energy to create control forces. Reviews of energy-regenerative suspension show that hydraulic circuits, motors, accumulators and generators can recover part of the energy that would otherwise be dissipated [7]. Wang and coauthors developed and tested a regenerative hydraulic shock absorber that converted oscillatory suspension motion into unidirectional generator rotation [8]. Such systems demonstrate that hydraulic components can be designed not only to consume energy but also to store or regenerate it.

System reliability depends strongly on fluid condition. Brake fluid absorbs moisture over time, reducing its boiling point and increasing the risk of vapor formation under severe thermal

loading. Ibrahim and coauthors developed a fibre-optic sensor for monitoring moisture in brake fluid and proposed integration with automotive electronics [9]. Broader research on multi-sensor hydraulic diagnostics shows that pressure, vibration, temperature and flow signals can be combined with data-driven models to detect faults in real time [10]. These developments indicate that future automotive hydraulic systems should continuously evaluate their own condition rather than depend only on periodic manual inspection.

Research on coordinated regenerative and hydraulic braking also shows that hydraulic pressure control affects energy recovery in hybrid and electric vehicles. Yang and coauthors proposed pressure coordination between regenerative braking and a hydraulic pressure-control subsystem to improve energy recovery while maintaining braking safety [11]. Chu and coauthors investigated pressure-control strategies for a fully decoupled regenerative braking system with normal and redundant operating modes [12]. The common conclusion is that accurate and rapid hydraulic pressure control is necessary both for safety and for smooth blending of friction and regenerative braking.

The reviewed literature confirms the technical potential of electro-hydraulic systems, but many studies focus on a single component or control problem. There remains a practical need for an integrated improvement framework that connects hydraulic architecture, energy demand, pressure dynamics, diagnostics and functional safety. The present study addresses this need by treating braking, steering and suspension as related automotive hydraulic functions. The main objective is to formulate a system-level strategy for improving their efficiency, response and reliability. A representative analytical model is then used to compare conventional and improved pressure-control behaviour and to estimate the relative energy demand of alternative hydraulic assistance architectures.

2. Materials and Methods

The study uses a combined literature-based and analytical method. Published research was examined to identify established electro-hydraulic architectures, control methods, energy-recovery concepts and monitoring technologies. The engineering analysis then considered a representative passenger-vehicle hydraulic system consisting of an electric motor-driven pump, high-pressure accumulator, electronically controlled valve block, pressure sensors, hydraulic lines and wheel-cylinder actuators. The same design principles were extended conceptually to electro-hydraulic steering and active suspension.

The baseline configuration represents a conventional hydraulic arrangement in which pressure is produced by a continuously driven pump or by direct pedal actuation assisted by a booster. The improved configuration uses a demand-controlled electric motor-pump unit, an accumulator for peak flow, proportional or high-speed switching valves, distributed pressure sensors and an electronic controller. A mechanical hydraulic fallback path is retained for essential braking. The controller receives driver or automated-driving requests and calculates the required actuator pressure. Sensor feedback is used to correct valve duty cycle and motor operation.

The pressure-response graph is an illustrative analytical simulation rather than a report of physical test-bench measurements. The conventional model reaches approximately ninety percent of the target after about 0.42 s and shows an overshoot close to eleven percent. The improved closed-loop model reaches ninety percent of the target after about 0.18 s and limits overshoot to approximately three percent. These values were selected to demonstrate the expected direction and engineering scale of improvement. A real design must be calibrated using measured valve, pump, hose, accumulator and actuator characteristics.

Energy demand was evaluated using a normalized duty-cycle index. The conventional engine-driven hydraulic power-steering architecture was assigned a reference value of 100. A load-sensing hydraulic system was assigned 78 because pump delivery is better matched to demand but throttling and standby losses remain. An electro-hydraulic on-demand architecture was

assigned 62 because the electric pump operates independently of engine speed. An intelligent integrated electro-hydraulic architecture was assigned 48 because it combines on-demand pump operation, accumulator management, coordinated control and diagnostic reduction of leakage losses. The index is comparative and illustrative. It does not represent a universal fuel-consumption percentage.

The proposed improvement framework includes five interacting design layers. The first layer is efficient hydraulic power generation through a variable-speed electric motor-pump unit and appropriately sized accumulator. The second layer is precise actuation through low-leakage valves, short rigid hydraulic lines and closed-loop pressure or position control. The third layer is sensing through pressure, temperature, position, fluid moisture and contamination measurement. The fourth layer is supervisory control that coordinates braking, steering and suspension demands while managing available electrical and hydraulic energy. The fifth layer is functional safety through redundant sensing, electrical monitoring and a hydraulic fallback path for critical braking.

Figure 1 illustrates the proposed integrated architecture. Driver and automated-driving commands enter a vehicle supervisory controller. Sensor fusion provides actual pressure, position, temperature and vehicle-state information. The controller coordinates separate electro-hydraulic subsystems for braking, steering and suspension. A condition-monitoring module evaluates fluid condition, leakage and component degradation. The architecture allows the subsystems to share information while retaining local control and fail-safe functions.

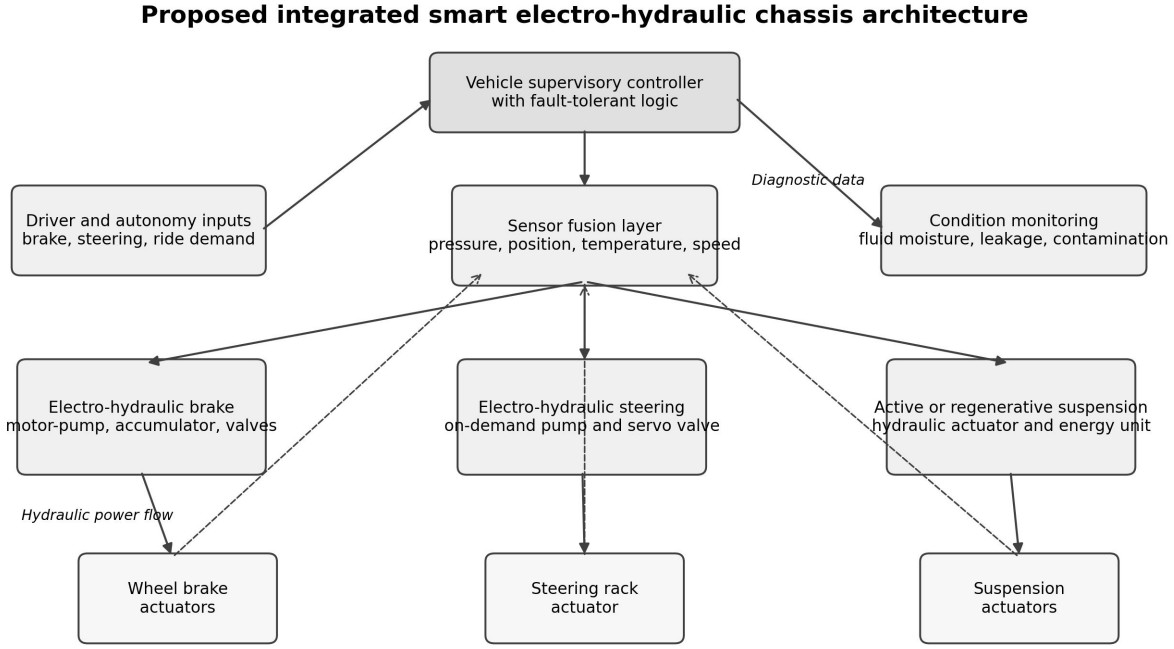


Figure 1. Proposed integrated smart electro-hydraulic architecture for automotive braking, steering and suspension systems.

Figure 2 presents the improved electro-hydraulic braking module in greater detail. The pedal simulator measures driver demand without requiring the pedal to generate normal wheel pressure. An electronic control unit commands the motor-pump unit, high-pressure accumulator and integrated valve block. Pressure sensors create a feedback loop for each wheel circuit. A mechanical hydraulic fallback path provides residual braking if the electronic system or main pressure source fails.

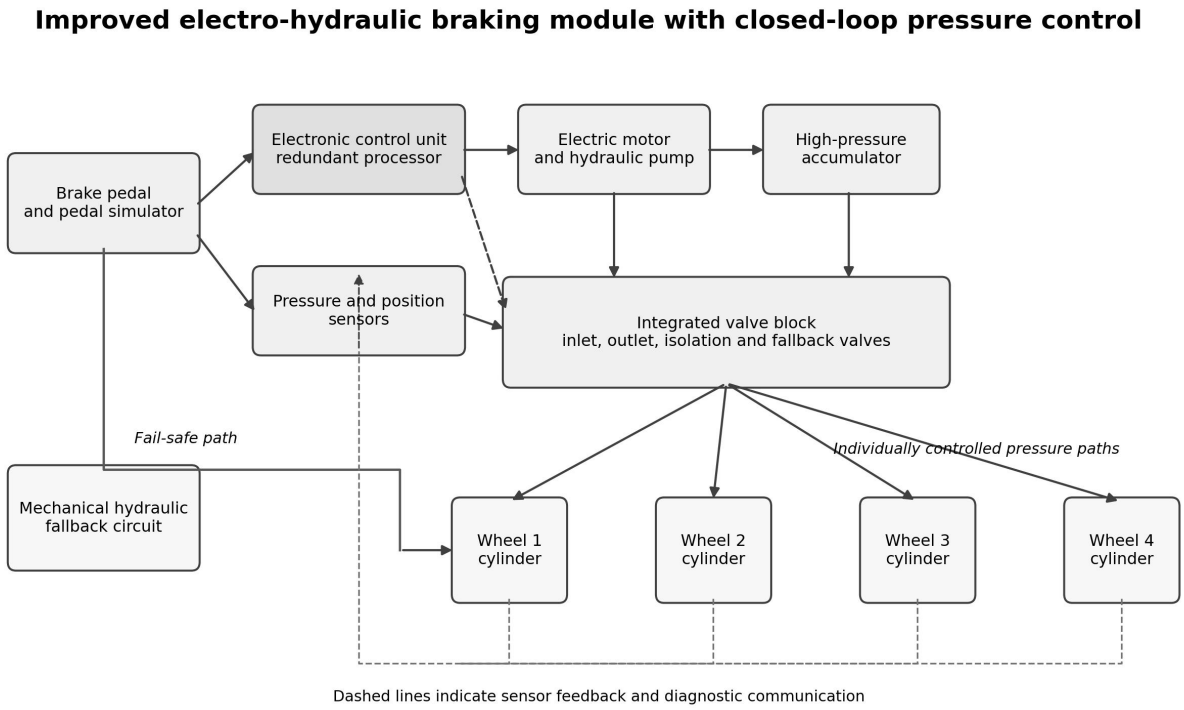


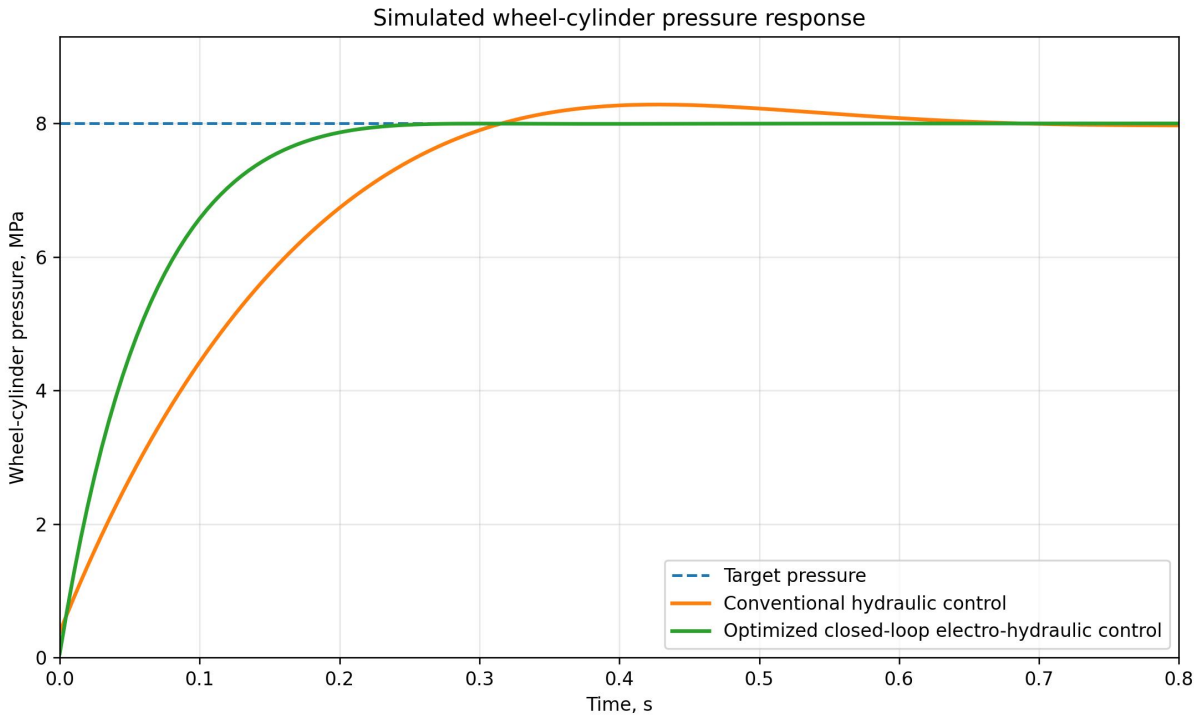
Figure 2. Functional structure of an improved electro-hydraulic braking module with closed-loop pressure control and redundant hydraulic backup.

The method also considers validation requirements. Component-level tests should determine pump flow, valve flow-pressure characteristics, accumulator precharge, actuator displacement, hose compliance and leakage. System-level tests should measure pressure response, braking deceleration, pedal feel, thermal behaviour and fault response. Vehicle tests should include split-friction braking, repeated high-temperature stops, low-voltage operation and transition between regenerative and friction braking. Steering validation should include parking manoeuvres, high-speed returnability and electrical power demand. Suspension validation should compare body acceleration, tire load variation, actuator energy and regenerated power.

3. Results

The analytical results show that the most important improvement is the transition from pressure generation without feedback to pressure generation based on measured actuator demand. In the conventional model, the commanded pressure is reached slowly because the pump, booster, valves, fluid lines and actuator volumes form a compliant dynamic system. When the control action is based only on a predetermined command, valve delay and uncertain fluid properties produce overshoot. In the improved model, pressure sensors detect the actual wheel-cylinder pressure and the controller reduces valve opening as the target is approached.

Graph 1 shows the simulated pressure responses. The target pressure is 8 MPa. The conventional system develops pressure gradually and exceeds the target before settling. The optimized electro-hydraulic system reaches the useful pressure region earlier and remains close to the command. Faster pressure build-up can shorten the delay between a braking request and the development of tire-road braking force. Lower overshoot can improve comfort, reduce unnecessary slip-control intervention and decrease the risk of an abrupt change in deceleration.

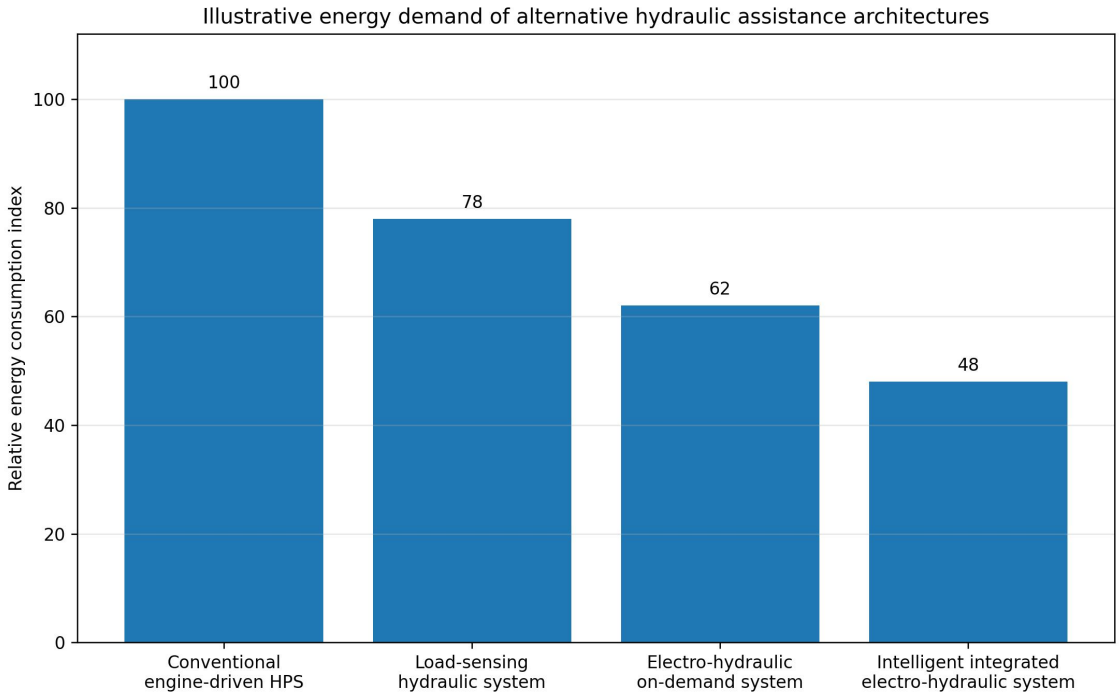


Graph 1. Simulated wheel-cylinder pressure response of conventional and optimized electro-hydraulic brake control systems.

The reduced response time is produced by several coordinated features. The high-pressure accumulator provides immediate flow before the motor-pump unit reaches full speed. The controller uses a feedforward estimate to open the pressure valve rapidly at the start of the command. Sensor feedback then reduces the valve command near the target. Short integrated fluid passages reduce compliance and flow loss. A pressure observer may provide additional estimates when a sensor signal becomes noisy or temporarily unavailable.

The pressure response also supports better integration with regenerative braking. In an electric vehicle, the supervisory controller first requests regenerative torque within motor and battery limits. The hydraulic system supplies the remaining braking force. If hydraulic pressure is slow or inaccurate, the total deceleration can deviate from the driver request when regenerative torque changes. Accurate electro-hydraulic pressure control therefore improves the blending of regenerative and friction braking. It can also reduce friction-brake use and extend pad life when regenerative capability is available.

Energy analysis indicates that continuous pump operation is the main avoidable loss in conventional hydraulic steering and active hydraulic systems. Graph 2 compares the normalized energy-demand index. The conventional engine-driven hydraulic power-steering system has the highest value beca*use* the pump rotates whenever the engine operates. A load-sensing arrangement reduces unnecessary flow, but the pump still has mechanical standby losses. Electro-hydraulic on-demand power steering reduces the index further because the electric pump runs primarily during steering assistance.



Graph 2. Illustrative relative energy consumption of alternative automotive hydraulic assistance architectures.

The lowest illustrative energy index belongs to the intelligent integrated electro-hydraulic architecture. Its improvement is not attributed to one component alone. Variable-speed motor control reduces throttling, an accumulator handles rapid flow demand, low-leakage valves reduce standby replenishment, and supervisory software schedules pump operation according to predicted demand. For example, steering assistance demand can be predicted from steering-wheel speed and vehicle speed, while braking demand can be predicted from pedal movement and automated-driving commands.

The analysis also shows that architecture integration can reduce packaging volume. A compact one-box brake unit shortens the hydraulic path between pressure source, valves and master-cylinder functions. Reduced line length decreases trapped fluid volume and compliance. Similar integration in electro-hydraulic steering places the pump, motor, reservoir and controller in one module. However, compactness increases local heat density. The improvement must therefore include thermal design, electronic derating and fluid-temperature estimation.

Condition monitoring provides a second category of results. Pressure sensors can identify excessive pressure decay after valve closure, which may indicate internal leakage or air in the system. Pump current combined with pressure rise can reveal reduced pump efficiency. Temperature measurement can distinguish a viscosity-related change from a mechanical fault. Moisture sensing in brake fluid can indicate when the boiling margin is no longer acceptable. Contamination monitoring can identify particles that threaten valve or seal performance.

The proposed diagnostic logic uses trends rather than isolated threshold values. A single pressure deviation may be caused by noise, temperature or an unusual manoeuvre. A repeated increase in pump operating time, combined with faster accumulator pressure decay and rising motor current, provides stronger evidence of leakage or wear. Trend-based diagnostics support condition-based maintenance and can reduce unnecessary replacement of healthy components.

The integrated architecture also improves fault management. If one wheel-pressure sensor fails, pressure may be estimated from motor displacement, valve state and vehicle deceleration for a limited period. If the main electronic control fails, an independent safety controller can activate a reduced braking mode. If electrical power is lost, the mechanical hydraulic fallback

path provides residual braking. Redundancy should be designed according to the safety relevance of each function. Braking requires stronger fallback capability than comfort-oriented active suspension.

For steering, the main result is a reduction of assistance energy at high vehicle speed. Large hydraulic assistance is required during parking, but only limited assistance is desirable at high speed. A variable-speed electro-hydraulic pump can match delivery to steering-wheel speed and vehicle speed. This improves steering feel and reduces unnecessary power consumption. Pressure and motor-current monitoring can also identify increased friction in the steering rack or restricted fluid flow.

For suspension, the proposed improvement combines semi-active or active hydraulic control with energy recovery. A hydraulic actuator can vary damping force according to body acceleration, wheel motion and road input. When suspension motion drives fluid through a hydraulic motor or generator, part of the vibration energy can be recovered. The recovered energy may be modest relative to traction energy, but the system can reduce heat generation and support sensors or low-power vehicle loads. The main design challenge is to recover energy without degrading ride comfort or road holding.

The results show that improving automotive hydraulic systems requires simultaneous consideration of performance, efficiency and safety. Increasing pump pressure alone does not create a better system. High pressure may improve actuator force but increases leakage, structural stress and heat. Faster valves may improve response but require precise control and filtration. Accumulators improve transient flow but introduce precharge, aging and packaging requirements. The integrated method provides a balanced framework in which each improvement is evaluated within the complete vehicle system.

4. Discussion

The analysis supports the continued use of hydraulic actuation in functions where high force density, compact size and mechanical fallback are important. The likely development path is not the immediate replacement of every hydraulic function by a fully electromechanical actuator. Instead, hydraulic power will increasingly be generated, distributed and controlled by electronic means. This hybrid mechatronic approach is especially attractive for braking because hydraulic wheel actuators and friction brakes are mature, while electronic pressure generation enables automated braking and regenerative blending.

The comparison with fully electromechanical alternatives should be made carefully. Electromechanical brakes can eliminate brake fluid and hydraulic lines, but they require powerful actuators at each wheel, reliable power electronics, thermal control and fault-tolerant electrical supply. Electro-hydraulic braking keeps the familiar hydraulic caliper and can provide a mechanical fallback connection. For many vehicle classes, this balance of innovation and continuity remains advantageous.

Pressure-control quality depends on the accuracy of the hydraulic model. Fluid bulk modulus changes with temperature and entrained air. Valve flow coefficients depend on pressure, opening and manufacturing tolerances. Seal friction creates hysteresis. Brake caliper deformation and pad compression change the pressure-volume relationship. A controller designed from nominal parameters alone may perform poorly across the full operating range. Adaptive control, pressure observers and online parameter estimation can reduce this sensitivity.

Integrated pressure estimation is useful but should not be treated as a complete substitute for sensing in safety-critical applications. A model may estimate pressure from motor position and valve state, but the estimate can become inaccurate when leakage, fluid aeration or component wear changes the system. Direct pressure measurement provides independent information. A robust system may combine physical sensors with observers so that each method checks the other.

Energy efficiency depends strongly on operating duty. A continuously driven hydraulic pump is highly inefficient during long periods of low demand. On-demand electro-hydraulic systems provide large benefits in normal passenger-car use because braking and steering assistance are intermittent. In heavy commercial vehicles or special vehicles with continuous hydraulic demand, a different architecture may be preferable. Variable-displacement pumps, load-sensing control and hydraulic energy storage may provide better results than a small electric pump operating continuously at high load.

Accumulator design requires particular attention. A large accumulator supplies rapid flow and reduces motor peak power, but it increases mass, volume and stored energy. A small accumulator is easier to package but may require frequent pump operation. Precharge pressure affects available fluid volume and response. Gas permeation and temperature variation change accumulator behaviour over time. The controller should estimate accumulator state and schedule pump operation before pressure falls below the required safety margin.

Thermal management is another critical issue. Hydraulic losses appear as heat in the fluid, valves, pump and motor. High temperature lowers viscosity and may increase leakage. It also accelerates seal and fluid degradation. Low temperature increases viscosity, causing high pressure drop and slow actuator response. The improved system should use temperature-dependent control maps and should position heat-generating components where cooling is available. In compact integrated modules, thermal simulation is necessary before final packaging.

Fluid selection can support efficiency improvement. Lower-viscosity fluids reduce pumping loss at low temperature, but they must preserve lubrication and sealing at high temperature. Brake-fluid requirements differ from mineral-oil hydraulic systems because brake fluid must tolerate high temperature, absorb limited moisture without phase separation and remain compatible with seals. Mixing fluid types or selecting a fluid only for low viscosity can create safety risks. Improvement must therefore follow applicable material and performance standards.

The condition-monitoring approach proposed in this study can change maintenance practice. Traditional maintenance schedules replace fluid or inspect components after a fixed time or mileage. Condition-based maintenance uses measured degradation. Brake-fluid moisture, pressure decay, pump current and valve-response time can be combined into a health indicator. Maintenance is then scheduled when the indicator reaches a validated limit. This approach can avoid both late intervention and unnecessary early replacement.

Data-driven diagnostics offer new possibilities but require representative training data. A neural network can distinguish fault patterns only if the training set includes the relevant temperatures, pressures, component tolerances and real faults. Laboratory faults created under one condition may not represent field degradation. For safety-critical automotive use, data-driven methods should be combined with physical models and explainable diagnostic rules. The system should provide a reason for a maintenance warning rather than only an unexplained classification.

Cybersecurity also becomes relevant when hydraulic control is connected to vehicle networks. A malicious or corrupted command to a brake or steering controller can create a safety hazard. The improved architecture should authenticate control messages, separate safety-critical communication and monitor command plausibility. A braking command should be checked against pedal input, vehicle motion and supervisory requests. Diagnostic software updates should be protected and traceable.

Manufacturing and serviceability influence practical implementation. Integrated modules reduce assembly connections but can make individual component replacement more difficult. A failed sensor or valve may require replacement of the complete unit. Designers should balance integration with modular service. Replaceable sensor modules, accessible fluid filters and standardized electrical connectors can reduce lifecycle cost.

The two illustrative graphs should not be interpreted as experimental certification. Their purpose is to demonstrate the analytical evaluation method and the expected direction of improvement. A research project based on this article should develop a test bench with a motor-pump unit, accumulator, valve block, pressure sensors and representative wheel cylinder. The experimental program should record pressure response at several temperatures, supply voltages, accumulator precharges and commanded pressure levels. Energy measurements should include motor voltage, current, pump operating time and recovered suspension power where applicable.

5. Conclusion

Automotive hydraulic systems can be substantially improved by combining established hydraulic actuators with electronic power generation, sensor feedback, intelligent control and condition monitoring. The proposed architecture replaces continuous pump operation with an on-demand motor-pump unit, uses an accumulator to satisfy transient flow demand, shortens fluid paths through integration and regulates actuator pressure in a closed loop.

The illustrative pressure-response analysis indicates that optimized electro-hydraulic control can reach the commanded wheel-cylinder pressure faster and with less overshoot than a conventional open-loop arrangement. The normalized energy analysis indicates that on-demand and integrated electro-hydraulic architectures can reduce energy demand relative to continuously driven hydraulic assistance. These values are analytical examples and require experimental calibration for a specific vehicle.

The improvement framework is applicable beyond braking. Electro-hydraulic steering can match assistance to vehicle speed and steering demand. Active or semi-active hydraulic suspension can improve ride and may recover part of the vibration energy. Shared sensor, diagnostic and supervisory-control principles can be applied across all three chassis functions.

Condition monitoring is a necessary part of future hydraulic design. Pressure, temperature, pump current, fluid moisture and contamination data can reveal leakage, aeration, fluid degradation and valve wear before a dangerous loss of performance occurs. Trend-based diagnostics can support predictive maintenance and reduce unnecessary component replacement.

Functional safety must remain the primary requirement. Critical braking functions require redundant sensing, independent monitoring, safe software and a residual hydraulic fallback path. Electronic integration should enhance rather than weaken the inherent reliability of hydraulic actuation. Future work should develop a physical electro-hydraulic test bench and validate pressure response, energy demand, thermal behaviour and fault-detection algorithms across a wide temperature range. The proposed system should also be evaluated during regenerative braking transitions, split-friction braking, low-voltage operation and repeated high-temperature stops. With such validation, the presented framework can support the development of efficient, responsive and reliable hydraulic systems for electric, hybrid and automated vehicles.

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