Optimizing Drive Force Allocation in Hydraulic Hybrid Motor-Assisted Systems Using Machine Learning

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Abstract

Hydraulic hybrid powertrains offer a feasible solution for urban mobility in light of the increasing need for energy-efficient and eco-friendly automobiles. This research presents an innovative hydraulic hybrid vehicle including wheel motors, aimed at improving power output and fuel efficiency. A predictive simulation model of the proposed vehicle is created, with system characteristics customized to fulfill particular power performance criteria. A diminutive engine, with its maximum power diminished by 11.96%, is chosen to enhance efficiency. The simulation model is calibrated and confirmed via experimental testing on a bespoke test bench. Simulation outcomes demonstrate substantial enhancements in vehicle performance. The acceleration time from 0 to 100 km/h is diminished by 36.3%, decreasing from 19.63 seconds to 12.5 seconds, in contrast to a normal car. The vehicle's top speed attains 140 km/h, and the maximum gradeability is 29%. Furthermore, utilizing the engine in economy mode results in a 35.59% reduction in fuel consumption, reducing from 15 liters to 9.66 liters per 100 km on the Urban Dynamometer Driving Schedule (UDDS) cycle. These findings highlight the potential of hydraulic hybrid motor-assisted systems, augmented by machine learning, to improve driving force distribution, attain enhanced fuel efficiency, and provide strong performance in urban transportation contexts.

Keywords: Hydraulic Hybrid Motor**,** ML, Optimized drive, Motor Assisted model.

1. Introduction

The increasing emphasis on energy conservation and environmental protection has driven the development of energy-efficient and eco-friendly vehicles. Among the primary solutions are new energy vehicles and hybrid powertrain systems. While new energy vehicles offer potential, challenges such as safety, stability, and high costs have hindered their widespread adoption. As a result, hybrid powertrain vehicles have emerged as a practical and effective alternative for reducing energy consumption and emissions, gaining significant global attention as a short- to mid-term solution. Hybrid vehicles are defined as vehicles equipped with two or more energy storage systems, both capable of providing propulsion power either independently or in combination. Most hybrid systems rely on internal combustion engines (ICE) as the primary power source, supplemented by auxiliary energy devices. Common types of hybrid vehicles include electric hybrids, mechanical hybrids, and hydraulic hybrids. Hydraulic hybrids, in particular, have garnered attention due to their high-power density, making them highly efficient in urban environments with frequent start-stop conditions. One of the standout advantages of hydraulic hybrid systems is their ability to enhance vehicle fuel economy through effective regenerative braking. Hydraulic components also provide significant benefits in terms of size and weight, offering improved spatial layout flexibility and contributing to vehicle lightweighting. This research focuses on optimizing drive force allocation in hydraulic hybrid motor-assisted systems using machine learning techniques. By leveraging machine learning, the system dynamically adjusts force allocation to enhance efficiency, improve fuel economy, and maximize the performance of hydraulic hybrid systems, particularly in urban driving conditions. This approach not only addresses the limitations of traditional control strategies but also demonstrates the potential for intelligent and adaptive solutions in the field of hybrid vehicle technologies. Hybrid powertrain architectures play a crucial role in improving energy efficiency and reducing emissions. Among them, series, parallel, and series-parallel hybrids each offer unique advantages and challenges.

In a **series hybrid system**, the engine is decoupled from the driving conditions, eliminating the need for mechanical transmission components found in traditional vehicles. This decoupling allows the engine to operate at optimal performance conditions, significantly improving fuel economy and reducing emissions. Additionally, series hybrids make it easier to implement continuously variable transmission (CVT) and achieve integrated drive/brake control.

On the other hand, **parallel hybrid systems** are widely adopted due to their simpler retrofitting processes and high transmission efficiency. However, the engine in a parallel hybrid system cannot fully decouple from driving conditions as in series hybrids, limiting optimization opportunities and resulting in lower energy-saving efficiency. Furthermore, parallel hybrids do not benefit from the inherent advantages of CVT.

Series-parallel hybrid systems combine the benefits of both series and parallel architectures. They enable the hybrid powertrain to operate at peak performance under various driving conditions, offering the potential for substantial fuel economy improvements. However, the complexity of their structure demands highly reliable components and advanced control systems to ensure smooth transitions between driving modes.

Hydraulic hybrid technology, a promising alternative, has traditionally been applied to medium, heavy, and engineering vehicles. However, advancements in hydraulic components have expanded its application to light vehicles, urban transport vehicles, and SUVs. This technology is gaining traction due to its high-power density, regenerative braking capabilities, and compact, lightweight components.

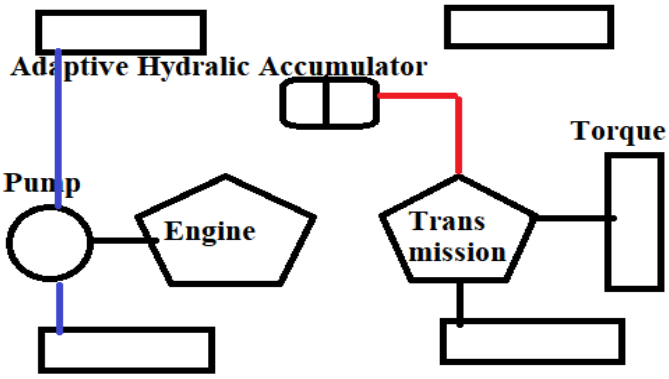

Figure :1 The structure principle of typical hydraulic hybrid vehicles

The United States Environmental Protection Agency (EPA) has been at the forefront of hydraulic hybrid technology research. Over the years, the focus has shifted from auxiliary drive applications in heavy vehicles to full hydraulic drive solutions for light vehicles.

In this context, machine learning offers a powerful tool to optimize drive force allocation in hydraulic hybrid motor-assisted systems. By leveraging real-time data, machine learning algorithms can dynamically adjust power distribution, maximize fuel efficiency, and enhance system performance across a range of driving conditions. This approach addresses the limitations of traditional control methods, paving the way for smarter, more efficient hydraulic hybrid systems.

2. Literature survey

The increasing focus on energy saving and environmental sustainability has prompted significant research into energy-efficient and eco-friendly vehicle systems. New energy cars and hybrid powertrain systems have garnered considerable interest among the foremost solutions. Although new energy vehicles exhibit potential, issues about safety, stability, and elevated costs have impeded their extensive deployment. As a result, hybrid powertrain vehicles have arisen as viable alternatives, offering an efficient mid-term answer for diminishing energy usage and emissions. Hybrid cars, with several energy storage devices that may deliver motor power either independently or in conjunction, provide adaptability and efficiency. Common varieties encompass electric hybrids, mechanical hybrids, and hydraulic hybrids, each with unique benefits and uses.

Hydraulic hybrid vehicles have gained popularity because to their high-power density and efficient regenerative braking characteristics, particularly in metropolitan settings characterised by frequent start-stop scenarios. Hydraulic components are more small, lightweight, and provide flexible spatial configurations than conventional hybrid systems, rendering them suitable for urban transit and light vehicles. The United States Environmental Protection Agency (EPA) has been conducting research on hydraulic hybrid technology, expanding its uses from auxiliary drives in heavy vehicles to complete hydraulic drives in light vehicles. This development highlights the capability of hydraulic hybrid systems to enhance fuel efficiency and diminish emissions across several vehicle categories.

Hybrid powertrain topologies can be classified into series, parallel, and series-parallel systems, each possessing distinct properties. Series hybrid systems separate the engine from driving circumstances, hence removing conventional mechanical gearbox elements. This decoupling enables the engine to function under optimal circumstances, markedly enhancing fuel efficiency and decreasing pollutants. Moreover, series hybrids enable the adoption of continuously variable gearbox (CVT) and integrated drive/brake control, rendering them a favoured option for energy-efficient vehicle designs.

Parallel hybrid systems are often utilised because of their straightforward retrofitting procedures and superior gearbox efficiency. Nevertheless, the engine in parallel hybrids does not completely disengage from driving conditions, constraining optimisation possibilities and diminishing energy-saving potential relative to series hybrids. Moreover, parallel systems do not intrinsically accommodate CVT capability, hence limiting their efficiency in specific applications.

The series-parallel hybrid system integrates the benefits of both series and parallel configurations, facilitating maximum performance across various driving circumstances. This hybrid setup optimises fuel efficiency and overall vehicle performance. Nonetheless, its intricate architecture necessitates dependable components and sophisticated control systems to guarantee seamless mode transitions and resilient performance. Notwithstanding these problems, the series-parallel hybrid system continues to be a viable alternative for hybrid powertrain applications.

Machine learning has become an effective instrument for optimising drive force distribution in hydraulic hybrid systems. Conventional control strategies frequently depend on predetermined algorithms that may not entirely optimise the system's efficiency in diverse conditions. Utilising historical data and real-time operating metrics, machine learning algorithms may adaptively modify force distribution to enhance fuel efficiency and performance. Neural networks and reinforcement learning facilitate adaptive and intelligent control, overcoming the constraints of traditional methods and revealing new opportunities for hydraulic hybrid systems.

The incorporation of machine learning into hydraulic hybrid motor-assisted systems could transform hybrid vehicle technology. Machine learning algorithms can optimise power distribution in real-time, improving energy efficiency, minimising emissions, and maximising performance. This method enhances the operating efficiency of hybrid systems while offering a scalable and adaptable answer for the future of urban transportation.

In conclusion, the advancement of hybrid powertrain systems, especially hydraulic hybrids, presents a viable avenue for attaining energy-efficient and environmentally sustainable automobiles. Integrating machine learning into drive force allocation control enables researchers to fully realise the capabilities of hydraulic hybrid systems, facilitating the development of more intelligent, efficient, and environmentally sustainable transportation solutions.

3. Materials and methods

Driving Mode

In a hydraulic hybrid motor-assisted system, the electronic control unit (ECU) is pivotal in regulating drive force distribution through constant monitoring and optimisation of the system's performance. Upon vehicle initiation or acceleration, the ECU monitors the pressure level within the high-pressure accumulator. Should the pressure decrease beneath a specified lower threshold, the engine engages to operate the variable displacement pump, delivering high-pressure oil to the hydraulic system. If the pressure surpasses the upper threshold, the accumulator autonomously delivers high-pressure oil to activate the variable displacement wheel motors, enabling the engine to idle or cease operation. In rapid acceleration circumstances, the engine and accumulator collaborate to provide supplementary power, hence diminishing the peak power need on the engine. This control method reduces inefficiencies and emissions commonly linked to engine operation during the beginning and acceleration phases.

When the vehicle functions at a steady velocity, the ECU utilises a dual-condition technique contingent upon the accumulator pressure. When the pressure falls below the lower threshold, the engine functions within its optimal fuel efficiency range while concurrently replenishing the accumulator with surplus high-pressure oil. Should the pressure surpass the upper threshold, the accumulator releases energy to energise the system, enabling the engine to idle or cease operation. This intermittent engine operation guarantees that the engine consistently functions within its optimal performance range. During reverse driving, the ECU identifies the reverse gear signal and modifies the rotational direction of the variable displacement wheel motors. The energy transfer system resembles the forward driving mode, guaranteeing smooth operation in all directions.

Deceleration Mode

In braking situations, the ECU identifies brake pedal signals and promptly idles or deactivates the engine. The variable displacement pump stops delivering high-pressure oil to the hydraulic system, prompting the ECU to modify the displacement of the wheel motors to a negative number. In this mode, the wheel motors operate as pumps, transforming the vehicle's kinetic energy into hydraulic energy, subsequently stored in the high-pressure accumulator. When the accumulator attains its maximum capacity, surplus high-pressure oil is diverted to the low-pressure reservoir via a relief valve. This technique is highly effective yet results in a swift increase in oil temperature. Upon this occurrence, the conventional braking system automatically activates to maintain safety and avert overheating.

Function of Machine Learning

Machine learning may substantially improve the optimisation of drive force distribution in hydraulic hybrid systems. Through the analysis of historical and real-time operating data, machine learning models can forecast energy demands and dynamically modify engine and accumulator inputs to optimise efficiency. These models can discern trends in driving situations, allowing the system to adaptively enhance engine performance, accumulator utilisation, and braking energy recuperation. This method promotes fuel efficiency and decreases emissions while also improving the reliability and adaptability of the hydraulic hybrid motor-assisted system, rendering it a formidable alternative for contemporary energy-efficient automobiles.

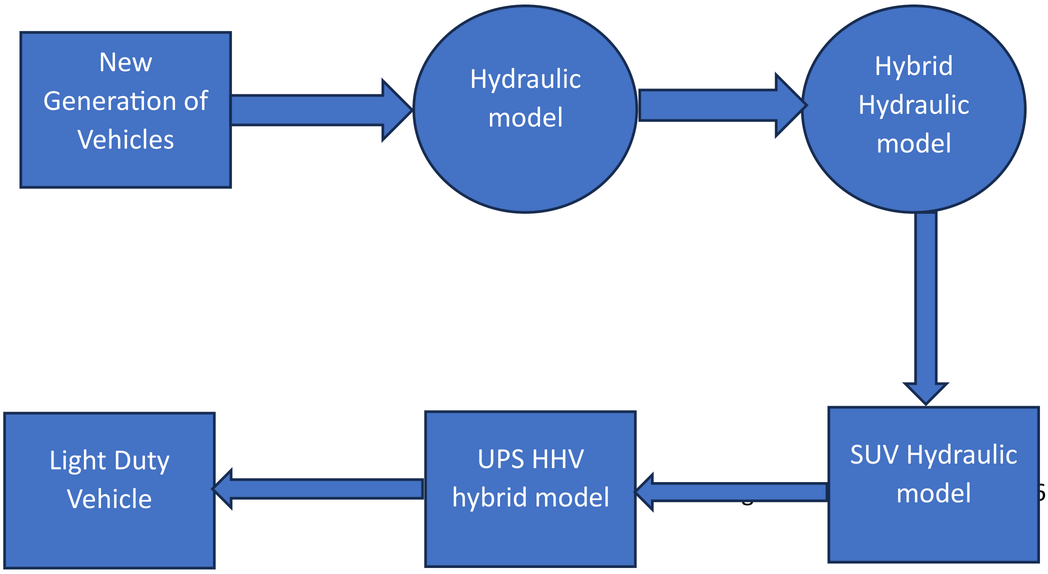

Figure :2 Various Vehicle models over decades

This graphic delineates a framework or development process for hydraulic hybrid vehicle models, illustrating their progression and usage across several vehicle types. Here is an elucidation: Innovative Vehicle Generation This signifies the overarching movement towards sophisticated, energy-efficient, and eco-friendly automobiles. It underscores the initial phase for the advancement and incorporation of hydraulic systems into contemporary vehicle platforms. Hydraulic Model The basic hydraulic model is central to this framework, serving as the basis for the development of diverse hydraulic hybrid systems. This model functions as the foundation for enhancing performance, efficiency, and suitability for various vehicle types. Hybrid Hydraulic Model This innovative system enhances the hydraulic model by incorporating hydraulic technology into hybrid arrangements. The hybrid hydraulic variant integrates enhanced energy-saving and regeneration features designed for hybrid powertrains. Light-Duty Vehicle The hydraulic hybrid model is utilised in light-duty vehicles, including compact trucks, vans, and passenger automobiles. These cars leverage the compact and lightweight characteristics of hydraulic components, enhancing fuel economy and efficiency. UPS HHV Hybrid Model This probably pertains to a particular use, such as the United Parcel Service (UPS) Hydraulic Hybrid Vehicle (HHV) model. This illustrates the application of hydraulic hybrid systems in business fleets, highlighting fuel conservation, regenerative braking, and operational efficacy for delivery vehicles. Hydraulic Model for SUV This signifies the implementation of hydraulic hybrid technology for SUVs (Sport Utility Vehicles). SUVs generally necessitate increased power and torque, rendering hydraulic systems an effective option because of their high-power density and regenerative features shown in above figure 2.

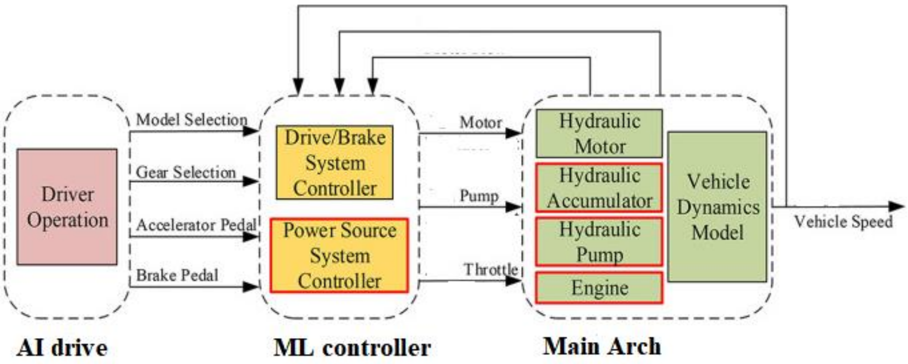

Figure: 3 Proposed model architecture

Artificial Intelligence Drive This section delineates the driver inputs and actions, which constitute the principal source of commands to the system. Driver Functionality: The driver supplies inputs including: Mode Selection: Selection of driving modes (e.g., economy, sport, etc.). Gear Selection: Choosing gears for forward or reverse operation. Accelerator Pedal: Signifies the throttle requirement. Brake Pedal: Indicates intention to decelerate. The ML Controller receives these inputs for processing. Machine Learning Controller This is the fundamental decision-making module that integrates Machine Learning algorithms to enhance the efficacy of the hydraulic hybrid system. Drive/Brake System Controller: This controller analyses driver inputs and system feedback to ascertain the most effective driving or braking strategy. It distributes the driving force between the hydraulic motor and the engine. Modifies brake systems to optimise energy recuperation (regenerative braking). Power Source System Controller: Regulates energy distribution among the engine, hydraulic pump, and accumulator. It guarantees that the engine functions within its ideal performance parameters. Regulates the hydraulic pump to either replenish the accumulator or supply energy to the engine. The ML controller adjusts dynamically according to real-time data (e.g., velocity, load, and pressure), guaranteeing fuel efficiency and best performance. Principal Architecture (Principal Arch) This part includes the essential hardware components of the hydraulic hybrid system and the vehicle dynamics model, which replicates the vehicle's behaviour based on system outputs. Hydraulic Motor: Transforms high-pressure oil from the accumulator into mechanical energy to propel the wheels. Hydraulic Accumulator: Retains high-pressure oil for energy recuperation and reutilization. Hydraulic Pump: Functions in two modes: Charging Mode: Transfers oil into the accumulator while braking or when the engine produces excess energy. Driving Mode: Delivers pressurised oil to the engine. The internal combustion engine (ICE) serves as the principal power source, functioning effectively under the supervision of the ML controller. Vehicle Dynamics Model: Simulates the influence of all components on vehicle velocity and performance, offering feedback to the controllers. Regulation of Sequence Driver inputs, such as throttle or brake, are transmitted to the ML Controller. The Drive/Brake System Controller and Power Source System Controller utilise machine learning methods to ascertain the most effective energy allocation approach. Instructions are transmitted to the components (motor, pump, accumulator, engine). The Vehicle Dynamics Model offers feedback (e.g., vehicle velocity) to enhance subsequent judgements. Essential Insights This technology incorporates AI and ML to improve the efficiency, performance, and energy recovery of hydraulic hybrid systems. The ML Controller guarantees that each component functions at its peak efficiency while adapting responsively to actual driving conditions. The architecture decreases fuel consumption, improves regenerative braking, and facilitates smoother vehicle performance shown in figure 3.

$$T_{\mathrm{tq}} = f\left(n_e, \theta\right)$$

$$P_e = \frac{T_{\mathrm{tq}} n_e}{9550}$$

$$T_{\mathrm{tq}} - T_p = J_e \beta_e$$

The primary function of a hydraulic accumulator is to store and release hydraulic energy. Among the various types, the bladder hydraulic accumulator is widely utilized due to its quick response, reliable sealing, extended cycle life, and high energy density. In this work, a bladder hydraulic accumulator is employed, and its simulation model is developed based on the Boyle–Mariotte law, expressed as follows:

- p_0: Pre-charge gas pressure (MPa).
- V_0: Volume corresponding to the pre-charge gas pressure (L).
- p_1: Minimum working pressure (MPa).
- V_1: Volume corresponding to the minimum working pressure (L).
- p_2: Maximum working pressure (MPa).
- V_2: Volume corresponding to the maximum working pressure (L).
- n_x: Air polytropic exponent, ranging from 1 to 1.4. Adiabatic conditions are represented by $n_x = 1$, while isothermal conditions are represented by $n_x = 1.4$.

The variation in the accumulator's volume corresponds to its flow rate, governed by the flow continuity equation. This equation represents the conservation of energy principle in fluid mechanics, ensuring an accurate depiction of energy transfer within the hydraulic system.

$$p_0 V_0^{\mathrm{nx}} = p_1 V_1^{\mathrm{nx}} = p_2 V_2^{\mathrm{nx}} = \mathrm{const}$$

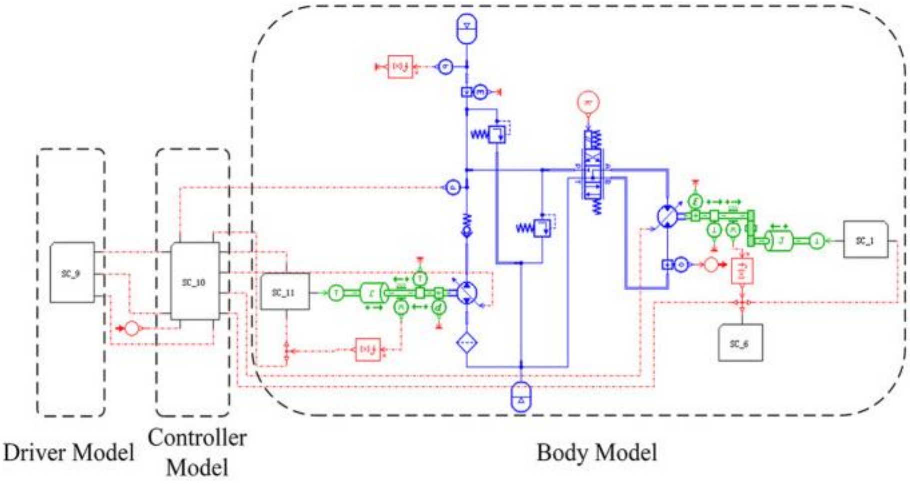

Figure :4 simulation model

Table : Measures on Driver AI

Structural parameters			Technical parameters	
Items	**Value**	**Unit**	**Items**	**Value**
Vehicle mass	2850	kg	Maximum output power of engine	184
Rolling resistance tested coefficient *(f0/f1/f4)*	0.016/0.0028/ 0.004	1	Maximum output torque of engine	350
Air resistance coefficient	0.6	1	0–100 km/h acceleration time	20
Frontal area	3.37	m^2	Maximum gradeability	29
Tyre rolling radius	0.39	m	Maximum vehicle speed	140

A semi-physical simulation test platform plays a crucial role in validating and optimizing system performance. Based on the proposed vehicle structure and its working principles outlined in this study, a hydraulic system test bench has been developed. This platform enables the calibration and verification of the simulation model through experimental testing, ensuring accuracy and reliability in the results.

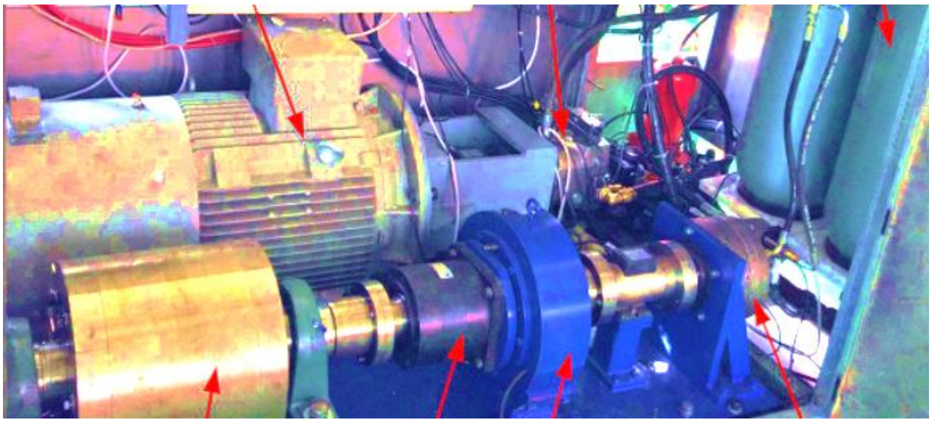

Figure :5 AI hydraulic model

Results and discussion

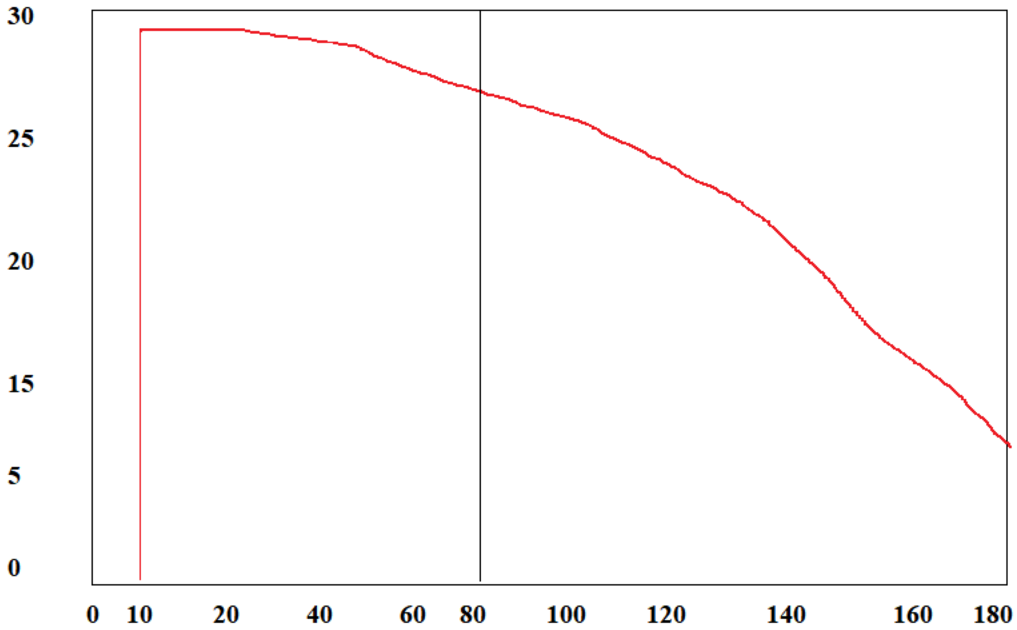

Figure:6 Vehicle speed vs maximum gradeability

The initial pressure of the high-pressure accumulator significantly affects the acceleration time of the vehicle. With higher initial pressure, the acceleration time decreases. During acceleration, the engine operates at its maximum power. At the start, when the power required by the vehicle is lower than the engine's output power, the excess power charges the high-pressure accumulator, causing its pressure to increase. Once the accumulator reaches full capacity, surplus energy is directed back to the low-pressure reservoir via a relief valve.

As the vehicle speed increases and the power demand exceeds the engine's output, the high-pressure accumulator supplements the engine, co-driving the vehicle. This causes the system pressure to drop as hydraulic energy is released, accelerating the vehicle to its maximum speed. At maximum speed, the vehicle enters a steady-state driving condition, where the engine alone drives the vehicle. The hydraulic system pressure stabilizes, and the variable displacement pump supplies power precisely equal to the vehicle's requirements. In this condition, the engine continuously operates at maximum output power, maintaining a stable maximum speed of 140 km/h.

If the vehicle is driven solely by the high-pressure accumulator, the pressure in the hydraulic system steadily decreases due to the limited hydraulic energy, restricting long-term operation. Hence, the engine takes over to ensure sustained driving. The maximum vehicle speed is determined by the engine and motor power rather than the hydraulic system pressure, as the engine's output power and system parameters remain invariant in the steady state shown in fig 6.

Conclusion and future scope

A novel hydraulic hybrid vehicle with wheel motors has been developed to optimize drive force allocation and enhance both power performance and fuel economy. To evaluate its performance, a forward-looking simulation model has been built, and a test bench designed to validate the simulation through experimental testing.

Simulation results show that the maximum vehicle speed is 140 km/h, the maximum gradeability is 29%, and the 0–100 km/h acceleration time is 12.5 seconds. The power performance of the vehicle meets expectations, with a 36.3% improvement in acceleration. Fuel economy was analyzed under the UDDS cycle, revealing that the engine operates near the minimum brake-specific fuel consumption (BSFC) line in economy mode, leading to a 35.59% improvement in fuel efficiency compared to conventional vehicles.

Future research will focus on developing advanced energy management strategies based on the simulation model and test bench, with an emphasis on optimizing drive force allocation using machine learning techniques. A real-world test vehicle will be designed to validate these strategies.

References

[1] Fu, X., Zhang, Q., Tang, J., & Wang, C. (2019). Parameter matching optimization of a powertrain system of hybrid electric vehicles based on multi-objective optimization. *Electronics*, *8*(8), 875.

[2] Song, D., Li, L., Zeng, X., Li, S., Li, G., Li, G., ... & Li, X. (2018). Hardware-in-the-loop validation of speed synchronization controller for a heavy vehicle with Hydraulics AddiDrive System. *Advances in Mechanical Engineering*, *10*(4), 1687814018767169.

[3] Liga, A. (2018). *Development of microfluidic sample preparation devices for circulating nucleic acids isolation at the point of care* (Doctoral dissertation, Heriot-Watt University).

[4] Perkowski, J. (2012). *Small Modular Reactors: Institutional Assessment* (No. INL/EXT-12-26412). Idaho National Lab.(INL), Idaho Falls, ID (United States).

[5] Yu, H. Analysis of the Simulation and the Match for Range-Extended Electric Vehicle Based on Cruise. Mech. Electr. Eng. Technol. 2010, 39, 28–30.

[6] Song, K.; Zhang, T. Parameter Matching of Electric Motor Drive System for Electric and Series Hybrid Electric Vehicles. Autom. Eng. 2013, 35, 559–564.

[7] Chen, Z.; Hu, H.; Wu, Y.; Xiao, R.; Shen, J.; Liu, Y. Energy Management for a Power-Split Plug-In Hybrid Electric Vehicle Based on Reinforcement Learning. Appl. Sci. 2018, 8, 2494. [CrossRef]

[8] Fu, X.; Wang, H.; Cui, N.; Zhang, C. Energy Management Strategy Based on the Driving Cycle Model for Plugin Hybrid Electric Vehicles. Abstr. Appl. Anal. 2014, 2014, 341096. [CrossRef]

[9] Fang, L.; Qin, S. Parameters Optimization of Hybrid Electric Vehicle Based on Multi-objective Genetic Algorithms. Autom. Eng. 2007, 29, 1036–1040.

[10] Huang, B.; Wang, Z.; Xu, Y. Multi-Objective Genetic Algorithm for Hybrid Electric Vehicle Parameter Optimization. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, China, 9–15 October 2006; pp. 5177–5182