

# Advanced Analysis and Modelling of Hydraulic Hybrid Vehicles

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**Abstract** - A hybrid vehicle is a vehicle that uses two or more distinct types of power. The basic principle in hybrid vehicles is that different engines work better at different speeds; An electric motor is more efficient at producing torque, or rotational power, and a combustion engine is better at maintaining a high speed than a typical electric motor. Switching from one to the other in time while accelerating yields gains for both parties in terms of energy efficiency, which translates into greater fuel efficiency.

It also includes other means of storing the energy of pressurized fluids in hydraulic hybrids. Hydraulic power conversion and storage provide exceptional energy density and efficiency, making it ideally suited to renewable powertrain design. It is especially effective in city traffic conditions, is characterized by frequent stops, coasting and long idle periods. In addition, emissions are reduced, particularly at idling and at lower speeds, compared to conventional powered vehicles. This paper reviews the latest developments in this field.

**Key Words:** hydraulic hybrid vehicle, Parallel hydraulic hybrid, accumulator, reservoir and pump/motor unit.

## 1. INTRODUCTION

Because of the volatility in the price of crude oil, the price of gasoline has risen. As a result, Hybridization is used as a technique to improve the overall fuel efficiency of a vehicle. A hybrid vehicle is one that uses a combination of propulsion sources to create motive power. Normally, the vehicle is powered by an internal combustion engine (ICE) that burns fossil fuels. The power is transferred to the wheels through the transmission system by way of a mechanical drivetrain. When a second power source is added to the existing one, it's known as a "hybrid" vehicle. Electrical, chemical, or other sources of additional power can be used. Power storage and production can be hydraulic, flywheel operated, or any other method.

Hybridization occurs for a variety of reasons. The major causes of this have recently been environmental pollution and gasoline savings. The exhausts of traditional automobiles contaminate the air in large cities, necessitating an alternative source while the other serves as a working medium or energy reservoir, allowing the system to be more flexible. Hydro-mechanical and power assist systems the term "architectural" is also used to describe these structures. Systems in series, parallel, and power-split configurations [1].

## 1.1 Hydraulic Hybrid Vehicle

The Hydraulic Vehicle has several advantages such as Improving Vehicle performance, hydraulic fluid power is simple to use, Improved fuel economy, hydraulic hybrids may achieve efficiencies of up to 70% when compared to conventional hybrids, which have an efficiency of less than 40% Reducing pollutant emissions, hydraulic hybrids offer more than 40% reduction in carbon dioxide emissions because of the lesser need to operate the engine [3]. A hybrid vehicle is able to reduce vehicle losses in four ways, make sure the engine is running smoothly, downsizing the engine, using regenerative energy to brake and shutting engine off when not needed [3-7].

## 2 Studies on Hydraulic Hybrid Transmissions

### 2.1 Series Hydraulic Hybrid Systems

In the series hydraulic hybrid vehicle design, the typical gearbox and driving shaft are eliminated, as shown in Figure. The hydraulic pump, which is mechanically attached to the engine, converts the engine's mechanical power into hydraulic power. The accumulator is then charged or immediately charged by the high-pressure hydraulic fluid. The fluid is sent to the wheel-end pump/motor, which moves the vehicle forward. It is feasible to use this setup to the vehicle's ground speed and engine speed are separated. As a result, it is possible to at its torque-speed map, the engine should be managed at its most efficient efficiency regime. Furthermore, When the brakes are engaged or the vehicle comes to a complete stop, the engine may be switched off. The power was turned off [4]. The structure of SHH is shown in Figure1. The main component is the accumulator, Pump /motor unit and tank (low pressure accumulator). Accumulator is energy storage unit. Pump /motor is connected to the ICE to refill the accumulator. Pump/motor 2 is connected to the drive shaft to propel or slow the vehicle. Since Due to the separation of the internal combustion engine from the drive shaft, higher efficiency can be achieved through operation The motor only has the torque and speed required for maximum efficiency [5].

Since the 1970s, a series of HHTs have been investigated for decades. The development of this system was the main focus of the study on the series HHT in the early investigations. A mechanical bypass in parallel with a series hybrid has been investigated, with fuel improving from 17% to 22% when compared to a traditional series hydraulic hybrid [8]. Simulating a series of HHV for passenger cars revealed

significant fuel savings and the potential to be applied to real-world design [9].

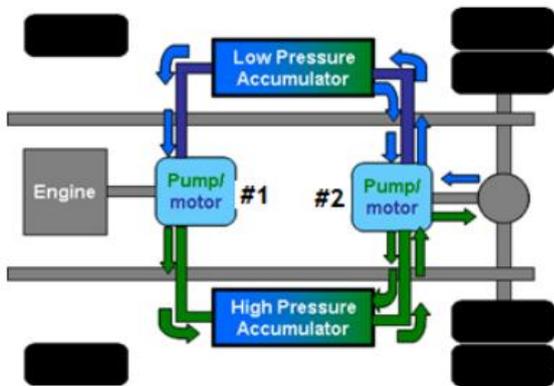


Figure 1-1: A series hydraulic hybrid configuration [6].

Volvo introduced prototype work on series hydraulic hybrids with Cumulo Hydrostatic Drive in the early 1990s. For dynamometer testing, a bus was employed with a trapezoidal driving cycle. Estimated a 48% decrease in fuel consumption [10]. EPA, Eaton, and UPS, together with other industry partners, fitted a UPS delivery truck with series HHT in 2006, and during field testing, fuel savings of 60% to 70% were achieved [11].

In recent studies, FTA, Altair, and Parker partnered each other to develop a series HHT for city buses with a more efficient engine and reduced vehicle mass. The hybrid bus showed fuel improvement of 29% over the most efficient electric hybrids, 47% over the identical nonhybrid bus, and 109% over the conventional city bus [12]. Several simulation studies on the series HHT have been conducted in order to assess performance and fuel savings. With the Federal Urban Driving Schedule (FUDS) cycle, a series hybrid in a passenger car was simulated and a fuel economy of 60 mpg was reached [13].

Power bond graph approach has been applied to predicting the dynamic response characteristics of a series HHT [14]. Fuel economy of the medium truck with a series HHT showed improvement of the fuel economy by 72% and reduction of the particulate emission by 74% compared to the conventional baseline, which was studied by simulation and the engine-in-the loop (EIL) techniques [15]. The performance of a rule-based, SDP, and MPC energy management strategy has been studied for a series of HHTs using different driving cycles and model parameters [16].

Based on the simulation, a topological study of a series of hydraulic hybrid refuse-collecting vehicles was performed, revealing fuel savings of up to 14% [17].

There are several studies for the control of the series HHT; For the FUDS driving cycle, Johri and Filipi provided optimized supervisory control for a series of HHTs with a

fuel economy of 93 mpg with engine idling and 110 mpg with engine shut-downs [18]. Simulation work has been done on the engine power management based on the condition of the charge control, which is part of the series hydraulic hybrid for a light truck, and fuel economy projections for the optimized system suggest fuel savings of more than 50% when driving through city traffic [19].

A model predictive controller was studied for a series HHV to improve a fuel economy [20]. A neural network power management was investigated for series HHTs to reduce average fuel consumption, and it showed a 12% reduction. When compared to a baseline constant control strategy, there was a 26% reduction [22]. In addition, Strategies for managing series energy an open-circuit setup was used to research HHTs [24]. The pros and cons of open and closed circuits of series HHTs have been studied in terms of the weight of hydraulic components [25]. An A series hybrid drive train is modelled and compared to a hydro-mechanical hybrid drive train in operation. The U.S. Environmental Protection Agency's Urban Dynamometer Driving Schedule the excellent fuel efficiency is demonstrated by the hydro-mechanical system. Despite the economy's potential, development work in the field is required Pump/motors with great efficiency at low speeds [26].

A simulation model based on lumped parameter thermodynamic analysis was used to investigate the transmission of a series of HHV. A thermal model was developed in order to capture the very transient thermal phenomena. The unstable system comes in a variety of forms. The model was put to the test. Measurement data from an HIL test rig was used to validate the model. The FTP-72 driving cycle is being tracked. The simulation findings suggest that there is a They show a high connection with measured data and suggest that the approach given here provides useful information on the temperature environment. Hydraulic hybrid system behavior the thermal model is a useful tool used to determine the system's thermal stability and packaging optimization prior to vehicle production, of components and cooling system design [27].

The hydraulic hybrid vehicle (HHV) is a novel technology that is being developed to increase road vehicle fuel economy. This technology also has disadvantages, such as poor energy density and no ability to connect to the power grid. The goal of this study is to assess a new approach for upgrading HHV technology.

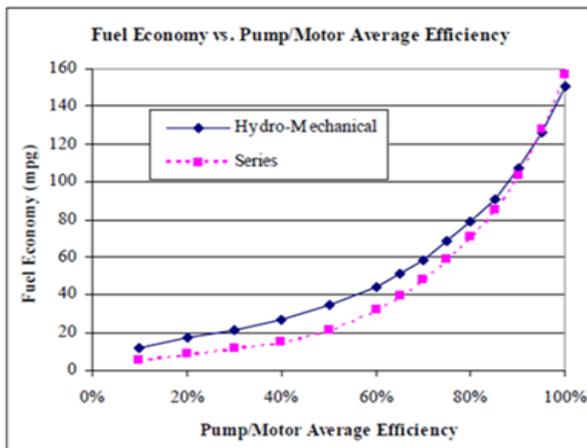


Figure 2: The fuel economy predicted by the simulation for the series and hydro-mechanical

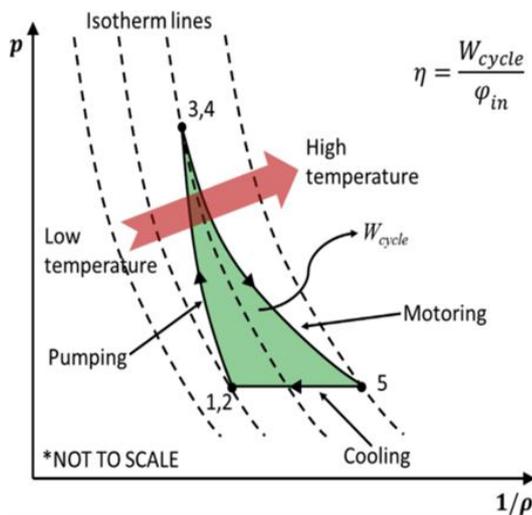


Figure3: Thermodynamic diagram of the transmission of the series HHV [27].

The air system can be charged through grid plug-in or by the internal combustion engine with the addition of an air system to HHV (ICE). The novel system has the potential to considerably increase the energy density of hydraulic hybrid vehicles while also allowing them to plug in. This research develops a parallel hybrid simulation model for the new system based on a symbolic programmed created in MATLAB/Simulink [2].

### 2.2 Power Split Hydraulic Hybrid Systems

The power split powertrain design, as shown in the figure, combines the convenience of a pure hydrostatic powertrain (the ability to run the engine at its most efficient points) with the high overall transmission efficiency of a hydro mechanical powertrain using a planetary gear train arrangement to provide the benefits of both layouts while minimizing their disadvantages. [29, 30,31]. The first

prototype of the power split HHTs was created and patented in 1980 for a passenger car, indicating a 100% fuel savings [32]. By simulating various transmissions of power split HHTs for city buses, they were able to improve fuel economy by 5% for a hydrostatic power split transmission and 14% for a compound power split transmission. And 28% for a HHT with a compound planetary power split. Compared to the baseline bus, the gear train [33].

After the year 2000, Kumar and Ivantysynova [34] suggested an HHT for a passenger car with an output coupled power split application. The dynamic analysis and controller of a power split HHT were studied for a passenger vehicle [35]. Peugeot and Bosch Rexroth developed an output coupled power split HHT for a passenger car and demonstrated fuel savings up to 45% in 2013 (Hybrid Air, an innovative full hybrid gasoline system). Also; On a dynamometer test rig, a power split HHT for medium duty cars showed a fuel efficiency improvement of 19 percent for the Baltimore driving cycle and 52 percent for the New York City Composite cycle [36].

A power split HHT has been simulated and compared to a power split hydrostatic transmission for system optimization [37]. Add to there, Stelson and Ramdan A high level of power Split HHT has been studied for a city bus [38].

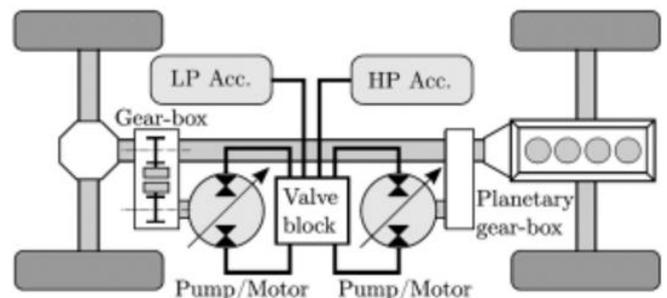
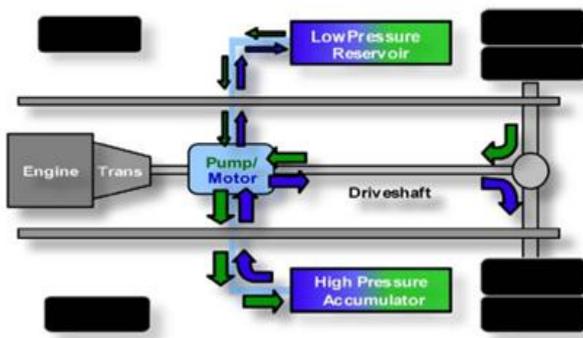


Figure 4: power-split hydraulic hybrid Vehicles [28].

### 2.3 Parallel hydraulic hybrid (hydro-mechanical) system

Figure shows a hydro-mechanical (parallel) powertrain concept that retains the traditional transmission and driveshaft system intact while adding a hydraulic pump/motor unit in parallel to the mechanical path to absorb and/or reduce vibrations. Provide hydraulic power to/from the mechanical system. The architecture does not allow for decoupling. Hence, the engine cannot be started because the engine speed is different from the ground speed. Controlled in the most efficient manner possible. When, on the other hand, the relative sizing is such that the more efficient mechanical transmission transmits a large amount of electricity. The overall fuel efficiency of the hydro-mechanical path is better than the hydrostatic path when compared to the hydrostatic path. For some drive cycles, a parallel powertrain may be preferable to a series powerplant. [ 39, 30,40].



**Figure 5:** parallel hydraulic hybrid Vehicles [5].

The energy management problem in a hydraulic hybrid vehicle is solved using a model predictive control (MPC) approach. To transmit energy between the mechanical and hydraulic domains, MPC employs a variable displacement pump/motor combination, as well as a high-pressure accumulator for energy storage [41]. The round-trip energy storage efficiency of a parallel HHT was tested by utilizing an experimental setup for the construction of the prototype, which exhibited a round trip efficiency of over 50%. and after the study, they achieved the round-trip efficiency of 66% in the improved test rig [42].

In a subsequent study, with the aerodynamic drag of the flywheel taken into account, a round trip efficiency of 75% was reached [43]. In the early 1980s, MAN produced a parallel HHT prototype that showed a 25% reduction in fuel consumption when compared to a conventional bus [44].

Mitsubishi Motors' braking storage system and reduced engine resulted in a 30 percent reduction in fuel consumption [45]. The Canadian National Research Council created a parallel HHT for a bus, which showed a 17 % reduction in fuel usage when compared to the 13 regular buses [46]. In 2000s, Ford, Eaton, and EPA advanced a parallel HHT for SUV, which presented fuel savings of 24% [47]. Eaton developed a refuse truck with a parallel HHT in 2008, resulting in a 30% fuel savings. Experimentation and simulation were used to investigate a hydraulic power system that can be easily installed in regular buses in real-world tests, it demonstrated a 28% reduction in fuel consumption [48]. In Early simulation studies Due to a lack of computational capabilities, the precision of the results is limited. A parallel HHT for a bus was explored and confirmed in a simulation exercise with a small delivery van, indicating possible fuel savings of 25 to 30% [49].

A parallel HHT for a passenger car has been simulated using three distinct driving cycles, with fuel economy up to 64 mpg attainable for urban driving cycles but little gain for highway driving cycles due to the lack of regenerative braking. When compared to city driving [50]. As a design tool, a simulation of HHTs with bond graph has been developed to exploit the system's performance and efficiency [51]. After 2000, Filipi and et al. conducted a comprehensive investigation of a

different suggested parallel hydraulic hybrid powertrain for the Family of Medium Tactical Vehicles (FMTV) [52]. Toulson used modelling and simulation to investigate a parallel HHT for small road vehicles in urban driving conditions [53]. Several authors employed simulation to explore the energy management of parallel HHTs for fuel savings, with refuse vehicles achieving fuel savings of around 20% as compared to conventional automobiles [54,55]. For the control of the system, Wu and coworkers proposed a power management strategy through a dynamic programming for a parallel HHT for a medium-size delivery truck, which yielded the potential fuel savings of 47% [65].

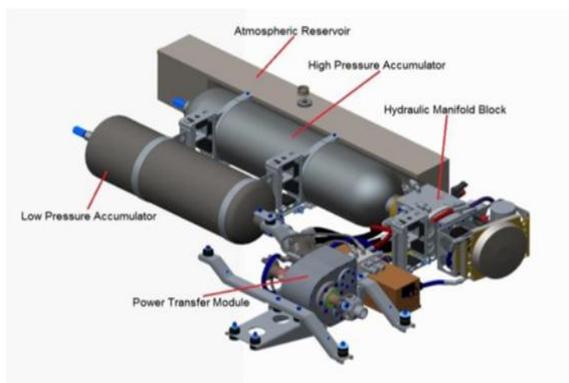
In simulation, a control technique for optimal brake energy recovery was presented for a parallel HHT, and the results showed that 42.7 percent of the brake energy was recovered [57]. For a parallel HHT with an urban driving cycle, the optimal energy distribution with a fuzzy torque control approach was investigated [58, 59,60].

The front-mounted parallel HHT has been analyzed for control strategies and system optimization [61] is a new hydraulic hybrid vehicle with wheel motors that improve vehicle power and efficiency. The vehicle's simulation model is constructed in the future. The settings of the system are set in accordance with the requirements for power performance A smaller engine with a lower peak power output is chosen. by a factor of 11.96% Experiments on the designed model are used to calibrate and verify the simulation model. Bench test Parameterized simulation results show that the acceleration time of the vehicle is 0–100 km/h. When compared to a normal car, the planned vehicle's time is reduced by 36.3 percent, from 19.63 to 12.5 seconds. The top speed of the vehicle is 140 km/h, and the maximum gradeability is 29%. When it comes to the When the engine is set to economy mode, fuel consumption drops by 35.59 percent, from 15 to 9.66 L per hour.100km [62].

The multi-objective optimization function in this article is optimized using the ant colony algorithm. The PHHV system parameters can be resolved using an ant colony approach. Because it has a quick search convergence, it's a good match problem. speed, concurrent computations, and an efficient solution the authenticity and correctness of the simulation findings are demonstrated. The ant-based multi-objective optimization approach an algorithm for colony formation The method of multi-objective optimization is capable of locating the best solution sites in a timely manner If you're looking for one of the major components of a hydraulic hybrid car, go no further. Increase the overall performance of the vehicle [63].

The hydraulic hybrid is a great teaching tool for thermodynamics, fluid mechanics, and vehicle dynamics basics. A MATLAB/Simulink application was built to model the performance of hydraulic hybrid and conventional vehicles. Model information, show student exercises that are organized by level and course, and give an example

evaluation of the simulation tools and associated tasks' effectiveness in improving Student education [64].



**Figure 6:** The hydraulic pump/motor unit with accumulator and reservoir [65].

In MATLAB/Simulink, a feed forward model for the hybrid powertrain was constructed. The model was simulated using a rule-based approach. A tactic for control in comparison to the traditional model shows a minimum 26% reduction in fuel consumption for Hybrid hydraulic technique. Furthermore, the effectiveness of in comparison to regular buses, hybrid buses are acceptable. The parallel hydraulic hybrid model that was created the bus can also be utilized to run additional simulations. Putting in place more complex control strategies [66].

Drive Cycle	Fuel Consumption of Conventional Bus (lit in 100 km)	Fuel Consumption of Hybrid Bus (lit in 100 km)	Reduction of Fuel Consumption (%)	Mean absolute error (km/h)
Tehran	69.5	49.5	28.8	0.9
Nuremberg	70.6	52.2	26.1	0.4

**Table 1:** COMPARISON OF FUEL CONSUMPTION FOR CONVENTIONAL AND PHH BUSES [67].

Configuration	Percentage Improvement (%)
MT vehicle used in this study	— (Baseline)
SHEV	15.4
SHHV	33.8
PHEV	38.2
PHHV	35.9
EV	72.6
HEHV	75.7

**Table 2:** Percentage improvement in economic savings [67].

This study adopted MATLAB Simulink to construct complete HHV and HEV models for backward simulations. New European Driving Cycles were used to determine the changes in fuel economy and, the experimental results revealed that, regardless of whether the UDC or EUDC was used, then HEHV had the best energy-conservation performance (average, NT\$0.631/km). Table 1 shows that, for the MT vehicle used in this study, the HEHV presented a 75.7% improvement in economic savings is presented in Table 2[67].

According to simulation findings from the constructed numerical model for the vehicle braking mode, the pressure in the high-pressure accumulator reached its maximum value during vehicle braking and the accumulator was charged by roughly 85%. According to simulation findings from the generated numerical model for the vehicle starting mode, the hydraulic motor is able to overcome the torque required to start the car, indicating that the stored energy in the high-pressure accumulator is adequate to start the vehicle.

The developed hydraulic hybrid system was shown to be capable of producing, storing, and reusing energy for all driving regimes for the chosen delivery van, resulting in energy savings [68]. In this work A method for developing an energy management plan was presented and applied to a small heat and power unit (SHHV). The model predictive control framework was used to create an online system in this manner. Optimal control is capable of tracking a desired motor speed while in motion. Enforcing efficient powertrain functioning. This research established a rigorous framework for selecting goal functions and optimizing energy use in a hydraulic hybrid vehicle using a receding horizon approach.

The general architecture and tools that have been established the methods laid out here can and will be used to investigate alternative architectures in a controlled environment.

A large number of driving cycles. In particular, architectures that make use of Regenerative braking is an option to explore. The current research found that it is therefore that the accumulator should be considered when optimizing the efficiency of the powertrain. Brakes with a regenerative system. The additional efficiency will be evaluated in future investigations. Improvements that can be made using the proposed energy source [69].

The optimum power management algorithm for a mid-hybrid hydraulic truck is It is formulated and solved using dynamic programming technology to reduce it. The results of forward-looking improvements in DP are used to extract them. Suboptimal rules for power splitting and gear shifting, feasible controllers. The new rules are very different from typical hybrid strategies. Electric vehicles often use hydraulic motors as their only source of power. Process derived from DP. The results enable improved fuel economy

for the hydraulic hybrid truck above. The conventional isotope is between 28% and 47% [70].

The efficiency of the HHV accumulator in charging operating conditions as well as mixed discharge were investigated in the hybrid Parallel-HHV design model. An optimization model is created based on the operating conditions. As the best objective method for energy management, greatest efficiency combination, resulting in optimal mixing. Working circumstances for energy-efficient automobiles, and the best Control laws are in place. Fuel economy is a complicated blend of energy-saving strategies. The conclusions are based on simulations of NEDC settings for vehicles. Implies that, in comparison to standard fuel use, based on 33.12% of models, which indicates that they have better Fuel storage and its implications in hybrid parallel hybrid systems strategy for energy optimization [71].

The goal of this paper is to develop a control strategy for optimal brake energy recovery for a parallel hydraulic hybrid vehicle in which the torque coupler's shifting schedule and braking force distribution are the most important impact factors, based on a thorough examination of braking characteristics. The vehicle simulation models are created using the software Advisor 2002, which has been validated through road tests. According to the simulation results, 42.7 % of the brake energy can be captured in the hydraulic hybrid car, whereas 41.6 percent of the brake energy can be captured in the electric hybrid vehicle. When a typical car brakes, traction energy is squandered. As a result, the optimal energy control approach in a hydraulic hybrid vehicle, brake energy recovery is particularly useful in boosting the efficiency of brake energy recovery [72].

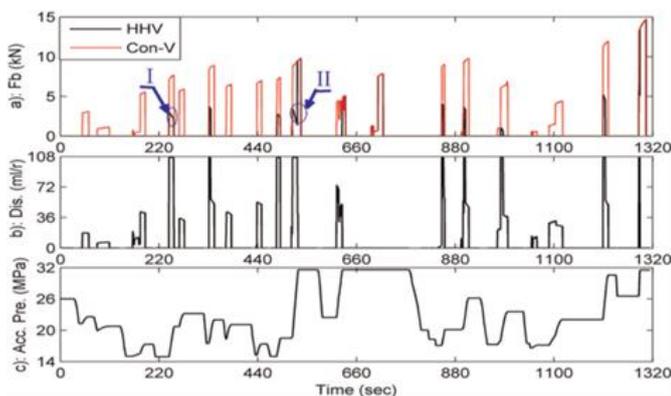


Figure 7: Braking force split trajectories [72].

S. Hui, and et.al. had proved that A new type of configuration is investigated in this study. A PHHV test is presented. A fuzzy-based torque control strategy It is built using the optimization results according to the torque distribution among the engine, hydraulic pump, and transmission The motor and hydraulic pump, and the vehicle load change. We are introduced to the fuzzy torque control strategy for realizing fuel economy to the fullest. The simulation results show That the new configuration of PHHV effectively

improved the potential for braking regenerative power The torque control is fuzzy. The strategy reasonably distributed the propulsion energy. Because of the distance between the power sources, the fuel economy improved .and adaptability to different working conditions, and minimized the disadvantage of the accumulator's lower energy which provided a practical and feasible method for the improving fuel economy of the hydraulic hybrid vehicle [73].

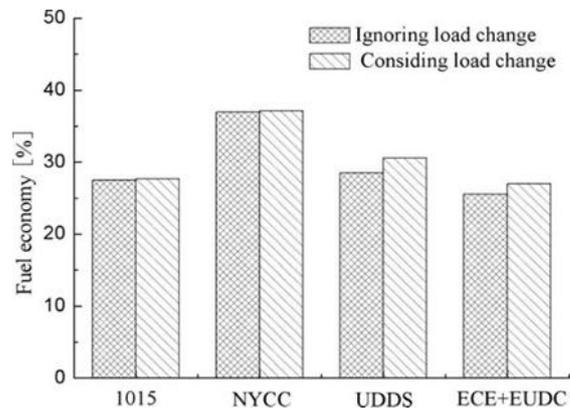


Figure 8: Impacts of load changing on PHHV fuel economy [73].

Filipi and et.al. [74] proved that Fuel economy and emissions were simulated to show comparisons between the PHHB and conventional bus. Simulations of a parallel hydraulic hybrid bus showed 30%improved fuel economy, which was similar to real road-testing results of 28%. It also reduced regulated emissions, shown in Figure 8, at  $p=85\text{bar}$  over one simplified driving cycle. Control strategies were optimized by using an NLPQL algorithm for improving fuel economy and regulated emissions, and performances were improved significantly (FC: 11.5%, CO: 9.2%, HC: 13.2%, NOx: 5.6% and PM:8.1%). Optimum parameters can be selected to meet the fuel economy demand of custom and standard emissions regulations, which are finally transferred to design objectives [74].

### 3. Conclusions

In this paper, a scientific survey on hydraulic hybrid vehicle, due to their importance in reducing fuel consumption and reducing pollutants. Where the following three types parallel hydraulic hybrid System, Series Hydraulic Hybrid Systems and Power Split Hydraulic Hybrid Systems. Focused on parallel hydraulic hybrid System for ease application in practice and theory Where the results mentioned in the scientific survey found to reduce fuel consumption by more than 28%, as well as reducing pollutants.

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