

ADVANCES IN AUTOMOTIVE HYDRAULIC HYBRID DRIVES

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ABSTRACT

The consumption of fossil fuels is one of the largest problems facing humankind. One of the heaviest users of our non-renewable resources is the automotive industry, in particular, the heavy road transport sector. Tightening worldwide legislation aims to place restrictions on the heavy transport industry to reduce its use of fossil fuels and reduce the levels of pollution being released to the atmosphere. Although several different alternatives to the conventional Internal Combustion Engine (ICE) have been investigated, none have as yet become a competitive source of energy. Alternative research into development of hybrid-drive vehicles was specifically concerned with electric hybrids especially for passenger vehicles. Currently there is a resurgence of interest in the Hydraulic-type Hybrid Vehicle (HHV) in application to commercial and to a lesser degree to large passenger vehicles. This paper gives an overview of hydraulic hybrid technology.

KEYWORDS

Hydraulic hybrid, pumps, motor, hydrostatic drive

INTRODUCTION

Hybrid vehicles are not a new concept; Justus B. Entz built the first petrol-electric hybrid vehicle in 1897 [1]. At the time of its development the electric system was mainly included to assist the acceleration of the internal combustion engine (ICE). Shortly after this prototype was built the capabilities of subsequent ICE's improved and removed the necessity to include the electric motor. Interest in hybrid vehicles resurged in the 1970's following the oil crisis and was driven by perceived advantages of hybrid drives [2]. Several different types of hybrid have been considered in the past and are still undergoing extensive research. The development of Electric Hybrids Vehicles (HEV's) which use a motor/generator and battery packs, resulted in commercial availability of such vehicles [3]. Mechanical

Hybrid Vehicles (MHV's), which use flywheels to store energy were less successful in commercialization, although a number of such vehicles were tried [4]. Hydraulic Hybrid Vehicles (HHVs), which use hydro-pneumatic accumulators to store kinetic energy captured during braking and return energy to driveline during vehicle acceleration, reemerged only over the last few years as viable technology, especially in applications to larger vehicles. The development of Hydraulic Hybrid Vehicle (HHV) is the main topic of this paper.

HYDRAULIC HYBRID CONFIGURATIONS

A generic model of a power flow in a powertrain has three internal power paths, Figure 1. In general, there is a power flow between three basic components: the engine ICE (the primary source of power), the wheel W

(transfer of motive power to the wheels) and the storage ESU (a generic device able to store and release energy). The energy storing capability the ESU block can be implemented in several ways, the most common being electrical, mechanical, and hydraulic. Using combinations of different paths we may derive three basic powertrain schemes.

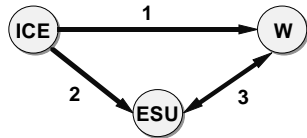


Figure 1 Generic power flow model

In Scheme 1, there is no ESU and the first possible energy converter between ICE and W (path 1) is the standard closed circuit hydrostatic transmission with a variable pump connected to a fixed or variable motor (with proper additional subsystems for boosting, limiting pressure and fluid replacement) and possibly complemented by a mechanical gearbox, Figure 2. In principle, a similar solution is offered by the so called hydromechanical units where the power follows two paths, one through shafts and gears, and the other through a hydrostatic transmission.

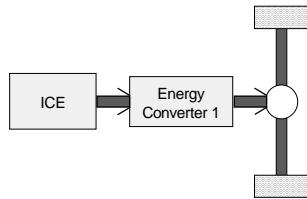


Figure 2 Conventional driveline layout (Scheme 1)

In Scheme 2 (serial - paths 2 and 3) the energy converter is a closed circuit hydrostatic transmission with a variable pump connected to a reversible motor (i.e. motor displacement can go from zero to maximum in both directions) and an accumulator in a high pressure line. The transmission, which is also known as secondary controlled transmission, has the usual additional subsystems and can be complemented by a mechanical gearbox. The primary feature of the transmission is its ability to recover a certain percentage of the braking energy of the vehicle. This scheme offers a looser link between the speed of engine and wheels thus making possible to have more efficient engine operation. In principle, a similar solution could be implemented using a hydromechanical unit. Figure 3 shows the driveline layout for the series hybrid vehicle. Energy converter 1 represents a pump in a hydraulic circuit whereas energy converter 2 represents a hydraulic motor. With the series hybrid, the ICE is effectively uncoupled from the road, i.e., the operation of the engine is independent of the vehicle operation. The vehicle is capable of regenerative

braking to recharge the storage device, or by using the ICE, either during driving or when the vehicle is stationary.

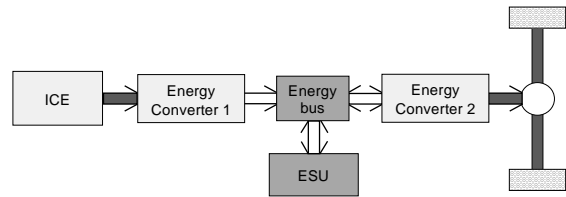


Figure 3 Serial driveline layout (Scheme 2)

In Scheme 3 (parallel – path 1 and path 3) a conventional mechanical transmission is inserted between the engine and the wheel block (path 1), while a hydrostatic reversible unit is inserted between the wheels and the storage block ESU, i.e. the accumulator (path 3). The driveline layout for the parallel hybrid (power assist, launch assist or add-on) is shown in fig. 4. Both the ICE and regenerative system are able to add torque to the driveline at the same time, however the ICE speed is determined by the vehicle speed and the selected transmission ratio. The storage unit is recharged via regenerative braking, and depending on the position of the regenerative system and the clutch, can be recharged by the ICE whilst vehicle is stationary. The operating condition for this scheme is generally the same as in Scheme 2, but it is clear that unlike the series hybrid, parallel hybrid vehicles can still be driven following the failure of the regenerative sub-system.

Schemes 2 and 3 can be combined in a form of power split hybrid drive which uses a planetary gear set (CVT) to combine both the parallel and series configurations. This driveline configuration has the advantage of being able to operate the ICE at speeds independent of the vehicle, or even turn it off during periods of low demand. There is no gear shifting in this configuration, and the regenerative system is able to add or take power from the driveline depending on the demand.

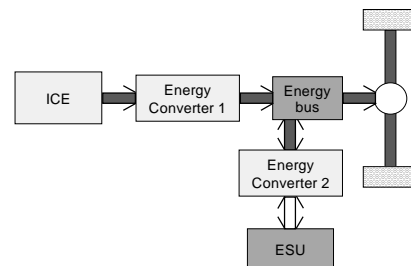


Figure 4 Parallel driveline layout (Scheme 3)

HYDRAULIC HYBRID VEHICLES (HHV)

This section of the paper briefly discusses past and current work in the field of HHVs.

Laboratory simulations

One of the earliest investigations into the hydraulic hybrid system for energy recovery was performed by Searl Dunn and Wojciechowski [5, 6]. From this initial research, using flywheel-accumulator apparatus, they concluded that well over 50% of the normally wasted kinetic energy during braking could be captured by the hydraulic system. Similar experiments were performed by Pourmovahed *et al* [7, 8] and by Maeda [9]. Although experimental results of these experiments differed, the above experiments provided some indicators regarding energy recovery of hydraulic systems.

Computer simulations

Simulation software packages for vehicle powertrain modeling are usually *forward facing* in which simulations begin with a driver model, which determines the vehicle input (accelerator and brake pedal displacements) through feedback control of the current vehicle speed. A *backward-facing* automotive simulation, e.g. the ADVISOR (ADvanced VehIcle SimulatOR) developed by the National Renewable Energy Laboratory (NREL) in the United States, begins the tire/road interface [10]. Calculation is made to find vehicle acceleration required to meet the given duty cycle over the time step. This acceleration is then used to calculate a wheel force and speed requirement, which works its way *backward* up the driveline towards the engine. All simulation models discussed below are *forward facing* unless stated otherwise.

A methodology for modeling of vehicles was proposed by Rubin *et al* [11], with further elaboration and discussions by Munns [12]. Elder and Otis [13] developed a computer model of the series type hydraulic hybrid vehicle. Their work covered several vehicle types, such as buses and delivery vans, but focused primarily on the urban passenger car. The study shows that the hydraulic hybrid powertrain is a feasible concept and that considerable gains are to be made in fuel economy and emissions reduction.

In a study by Wu *et al.* [14], a small passenger car was the subject of a computer-based investigation aimed to find the optimum operating parameters for a series hybrid driveline with fixed component sizes. Since in series hybrids the ICE can be operated at speeds independent of the vehicle speed, it was the goal of the researchers to find the optimum engine speed for a list of different control parameter combinations. It was concluded that for the 3000 lb passenger car a fuel economy of 60 mpg was attainable with a serial hydraulic hybrid system.

Tollefson [15] evaluated the parallel hydraulic hybrid vehicle system. Model of the system was based on the baseline vehicle used by Wu *et al.* [14] and used the same control concept. The difference between the two studies was in the driveline layout, and selection of driving cycles used for the study. This investigation

looked at the effectiveness of the hybrid system in two urban cycles (FUDDS and NYCC) and one highway cycle (FHC). It was concluded that fuel economy of 65 mpg was attainable for urban driving situations, but little benefit was obtained for the open highway driving due to the lack of opportunity for regenerative braking.

Heggie and Sandri [16] considered the series driveline arrangement with an additional *mechanical-bypass* feature. The results of this work showed, that the fuel economy of the hybrid vehicle could be increased by an additional 17% to 22% by inclusion of driveline de-clutching during periods of constant velocity.

Studies by Buchwald *et al* at the Denmark Technical University [17] were focused on two hybrid parallel buses (one equipped with an automatic transmission and the second bus equipped with a manual transmission) and a small delivery van, which was used as a mini prototype vehicle for model validation. The overall conclusion of this research was that a fuel saving of 25 to 30% is possible with the hybrid hydraulic system. The experimental and simulated results were within 2% of each other.

Kapellen *et. al.* [18] conducted a computer-based research focused on refuse collection trucks and compared four different powertrain configurations, two using accumulator energy storage and two using flywheels. Four different hybrid configurations were run over a simulated garbage truck cycle to measure the potential fuel gains over an estimated baseline fuel use showed that hybrid powertrains could significantly improve fuel economy under urban driving conditions from around 63% to 128%.

A novel hybrid concept, which utilized both hydraulic and electric technologies for a hybrid bus, was investigated by Chicurel and Lara [19]. The main idea behind the system was to reduce peak currents in the battery pack during hard braking by redirecting power to the hydraulic system. An estimate for the round-trip efficiency of the system was made at 60%.

An extensive simulation work on the hybrid military truck was carried out by Stecki and Matheson at Monash University [20, 21, 22]. The work involved development of vehicle models for the purpose of parametric design studies, drive cycle performance analysis, control strategy development and fuel consumption estimates. Models of the system components were developed in the Matlab/Simulink environment, and then implemented the ADVISOR [10]. Additionally *forward facing* models of the vehicle were developed using Vissim [23] and verified against *backward facing* model by Kikker [24].

Control strategy

The control strategy used by Wu *et al.* [14] was based on a *space allocation* concept, that for a given vehicle velocity a certain amount of the accumulator volume must be reserved for regenerative braking, and the remainder must be used for power decoupling.

Buchwald *et al.* [17] considered three different control strategies: an *on-off* strategy, a *best efficiency* strategy, and a *constant ICE torque* strategy, each with their associated advantages and disadvantages.

Kapellen *et al.* [18] in investigation of different hybrid configurations of the garbage truck used an *on-off* control strategy, which enabled the engine to be turned off when the energy stored was at a high enough level.

System controlling Braking Energy Storage and Regeneration System (BER System) developed by Mitsubishi for installation onto Japanese city buses, Nakazawa [25], was realized via a look-up table type arrangement, where the load distribution between the ICE and the hydraulic system was determined by the accelerator pedal stroke. During vehicle cruising, when torque demand is low, the entire load is taken-up by the diesel engine. At stages when the torque demand is high, i.e. during acceleration or passing maneuvers, torque is sourced from both the engine and the hydraulic system. Hugosson [26] dealing with the Cumulo Hydrostatic Drive (CHD), a series type hydraulic hybrid bus developed in the early 1990's, focused on the control strategies employed for the secondary hydraulic unit, a variable displacement pump/motor that delivers torque to the output shaft. The primary unit was run from the ICE and was used to maintain system pressure in the accumulator to varying levels depending on the vehicle speed, in order to keep enough energy for regenerative braking.

Prototype vehicles

A passenger car prototype was developed by Shiber [27]. The vehicle used a powertrain in the power split configuration, combining a CVT with a hydraulic accumulator to store braking energy. This prototype vehicle completed nine ECE driving cycles and doubled the fuel economy in comparison with a vehicle without the hybrid system. One of the earliest hydraulic hybrid projects was undertaken by MAN Maschinenfabrik Augsburg-Nuernberg Ag. in Berlin, Germany [28]. MAN has had vast experience in hybrid bus prototype development, having worked on both flywheel hybrid projects (Gyrobuss I and II) and hydraulic hybrids. A cost-benefit analysis of the MAN prototype hydraulic hybrid buses showed that the most likely payback period for savings on fuel and maintenance versus capital investment costs will be approximately 2.75 years for inner city operation, with a worst case being 4.9 years, and a best case of 1.6 years.

Mitsubishi Motors Japan in 1987 developed the Braking Energy Storage and Regeneration System (BER System), for installation onto Japanese city buses [25]. The BER system, which utilized the power assist (parallel) driveline layout, was installed onto a standard city bus with a downsized engine from 165 kW to 125 kW. The BER and standard buses were tested on a chassis dynamometer according to the M15 Japanese

driving cycle, and a fuel saving of 30% was recorded. It should be noted that Mitsubishi hybrid buses are in production since 1996.

Hugosson (26) presented a collective report on the status of hydraulic hybrid development at the Cumulo Division of Volvo Flygmotor. The development of Cumulo Brake Energy Drive (CBED), a parallel type hydraulic hybrid, began in 1983 and by 1985 several prototypes were in operation around Stockholm. An average reduction in fuel consumption was recorded at 16% to 25% for normal operation.

The parallel hydraulic hybrid system on a 9700 kg city bus developed in the Mechanical Engineering Division of the Canadian NRC [29] showed during fuel economy trials on 30 mph constant speed cycle, with 5 stops per mile found a 19% improvement from the baseline vehicle. NRC in a three-way project with a Canadian trucking company FIBA Canning Inc. and Volvo Flygmotor installed the CHD system on a city bus and a refuse truck for fuel economy testing [30]. According to FIBA Canning a reduction in energy consumption utilizing BTU measurement of at least 50% and reduction in lubricants use by at least 90%. Similar finding for the hybrid garbage truck were reported.

A Hydraulic Power Assist (HPA) SUV (recreational vehicle), a parallel hybrid, was developed by Ford Motor Company [31] in cooperation with Environmental Protection Agency of USA. Results of dynamometer tests produced a 23.6% saving in fuel consumption over the EPA Federal Test Procedure driving cycle. Environmental Protection Agency (EPA) of USA subsequently produced a comprehensive report on studies of hybrid drives comparing economics of running hybrid and equivalent conventional vehicles and concluded that there are sound economic and environmental reasons for application of hybrid hydraulic technology [32].

The Vehicle Research Institute, Technical University of Lodz, Poland, developed a prototype hybrid drive for a bus. Tests showed that 10-12% saving in fuel and almost 50% lowering of toxicity of exhaust gases is achievable. The system is Scheme 2 hybrid [33, 34].



Figure 5 Hybrid FMTV during fuel trials

Permo-Drive Technologies Ltd, an Australian-based

research and development company, focused its research on the development of a hydraulic parallel hybrid system for use on heavy vehicles, [35, 36]. In the development of hybrid technology, Permo-Drive and DANA Corporation have teamed up with the US military to develop a prototype US Army FMTV HHV tactical vehicle shown in Figure 5.

HYDRAULIC HYBRIDS – THE ISSUES

Some major issues in the development of hybrid technology are:

- Safety – accidents involving hybrid vehicles with high-pressure energy stored in accumulators may present major hazards. Thus further advances in accumulator technology, hydraulic fuses (shutting accumulators when major leakage is developed) and leak proof fittings and valves are required.
- Weight – hydraulic accumulators and components are heavy. This is not a major issue with heavy vehicles but even in heavy vehicles the hydraulic system may be 5-10% of total weight of the vehicle. Development of low weight accumulators using composite material should reduce the weight of systems.
- Optimization of automotive powertrains usually aims to identify the best overall size of driveline components that maximize vehicle fuel economy, performance, and driveability within certain constraints. However it appears that two major factors influencing the fuel economy are the drive cycle and control strategy.
- Control strategy will be of paramount importance to the acceptance of hydraulic hybrids. Decisions related to charging and discharging functions, algorithms relating level of charging with position of swash plate, etc. will have to be considered.
- Driveability of the hydraulic hybrid vehicle. As accumulator charging/recharging is a matter of second rather than minutes, the control system must assure that in the event of exhausting of hydraulic energy the driver must not notice any difference in driveability of the vehicle.
- Availability of pump/motors. Direct hybrid drive, like in Permo-drive system, requires units with a very large speed (equal to shaft speed) and torque capabilities. As such units are not currently commercially available the transfer boxes (like in Cumulo system) and disconnect features allowing disconnect of the pump/motor units are currently used.
- Design of energy storing systems – e.g. utilization of charge bottles. Conventional accumulators are only using approx. 50% of the volume to accommodate fluid between minimum and maximum pressure.

- Defining performance of a particular vehicle, such as fuel economy, acceleration performance and gradeability, over a given drive cycle which can be used as the objective function in the optimization process. Constraints imposed on the optimization are established by the industry, such as the Partnership for the Next Generation of Vehicles (PNGV), a joint effort between the US government and major car manufacturers in the US.
- In the case of hybrid vehicles, it is important to identify the target sizes for the energy conversion and storage devices so that the additional weight penalty is not too great, yet the system has enough capacity to successfully assist vehicle propulsion and capture the maximum energy possible during braking.

CONCLUSION

Current resurgence of interest in the Hydraulic-type Hybrid Vehicle (HHV) resulted in application of this technology to commercial and to lesser degree to large passenger vehicles. This paper provided overview of technology and discussed some design and safety issues, which are important to its success.

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