# Energy Efficient Hydraulic Hybrid Drives

Karl-Erik Rydberg
Department of Management and Engineering, Linköping University, Linköping, Sweden,
Karl-Erik.Rydberg@liu.se

**Abstract**

Energy efficiency of propulsion systems for cars, trucks and construction machineries has become one of the most important topics in today's mobile system design, mainly because of increased fuel costs and new regulations about engine emissions, which is needed to save the environment. To meet the increased requirements on higher efficiency and better functionality, components and systems have been developed over the years. For the last ten years the development of hybrid systems can be divided into two major technologies, electric hybrids and hydraulic hybrids. Today, there is a hard competition between these two branches. Therefore, it is interesting to compare these two technologies to figure out their individual capabilities.

This paper will discover the advantages of hydraulic hybrid systems over electric hybrids and how to succeed with the hybrid system design. One obvious advantage with hydraulic hybrid systems is that they create a unique opportunity to optimize the engine loading at all speeds. About the power density, hydraulic machines have around 5 times higher density than electric machines. This gives the opportunity to use direct hydraulic drive and remove mechanical gearings needed in an electric hybrid system. This fact has a large impact on the system overall efficiency.

By using hydraulic accumulators, a part of the potential load energy can be reused, which make it possible to design a system with improved endurance compared with a similar one without such devices. This kind of regenerative capabilities increase the power supply capability. The additional power can be used to improve the performance of the system, without increasing the primary engine power. Another advantage of using a hydraulic accumulator is that its round-trip efficiency is higher than for an electric battery, especially at frequent acceleration and braking.

**Keywords**: Hybrid system, Hydraulic hybrids, Electric hybrids, Energy storage.

## 1 Introduction to hybrid technology

The history of modern hybrid technology for vehicle applications covers about three decades. One of the first parallel hydraulic hybrid system launched for the market was the "Cumulo Brake Drive", from Parker Hannifin. A prototype system was developed 1982 and 1991 comes the first series hybrid "Cumulo Hydrostatic Drive".

These two systems are shown in ***Fig. 1***.

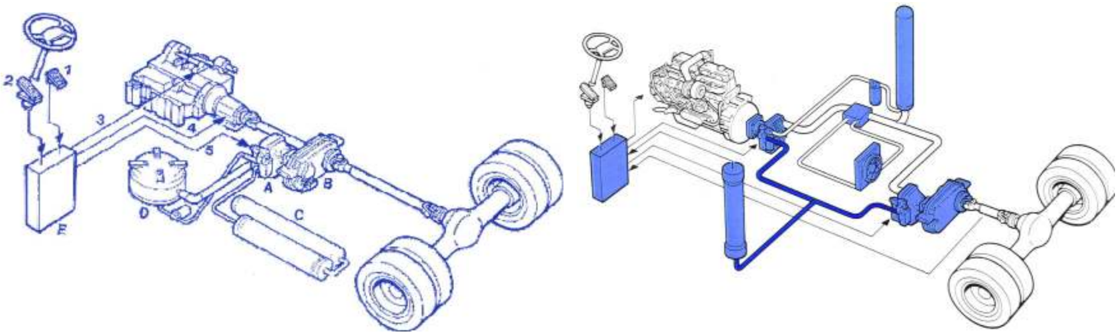


***Fig. 1:*** *Cumulo CBED and CHD hydraulic hybrid systems for city buses, Parker Hannifin, [1]*

The two systems in Fig. 1 have hydraulic accumulators for energy storage, which make it possible to recover and reuse energy. For the parallel hybrid the fuel saving potential was in the range of 10-25% and for the series hybrid 20-40%. Compared to the requirements today on drive-lines, these figures are too low.

Looking at the developments on hydraulic hybrids over the years, it can be recognized that new systems from Parker, Eaton, Artemis etc are still using the same concepts as in the former Cumulo transmissions. This fact will raise the question: Why did not any supplier succeeded 20 years ago? The answer is probably that the technology was not developed, as it is today and the market was not ready for the new concepts.

### 1.1 Requirements on hybrid systems

The target of using hybrid technology in vehicles is to improve the overall system efficiency and that way reduce fuel consumption and emissions. The requirements can be stated as follows:

- Efficient use of the primary power source.
- Efficient transformation of energy for motion.
- Efficient recovering and reuse of energy.

Besides energy efficiency other important requirements are controllability, robustness, reliability and life cycle cost.

### 1.2 Electric hybrids versus hydraulic hybrids

Today the development of hybrid systems has a strong focus on electric solutions. This is based on ideas that electric machines have higher efficiency than hydraulic machines and that electric power is clean and easy to control compared to hydraulic power. ***Fig. 2*** and ***3*** shows common concepts of electric and hydraulic hybrids respectively.

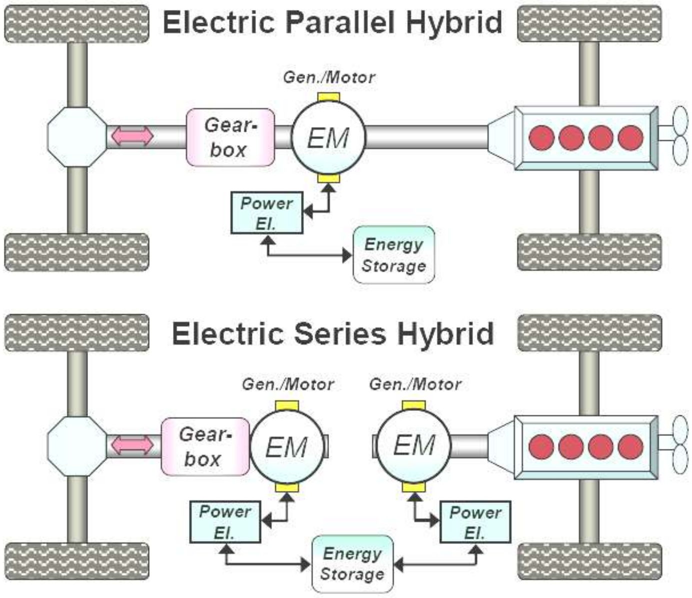



***Fig. 2:*** *Electric parallel and series hybrids*

Electric hybrids are mainly parallel because current electric system cannot handle full power, with exception of light vehicles. Today's hydraulic machines can handle much more power per kg than electric machines, which means a favour for series hydraulic hybrids. The two basic concepts of hydraulic hybrids are shown in Fig. 3.

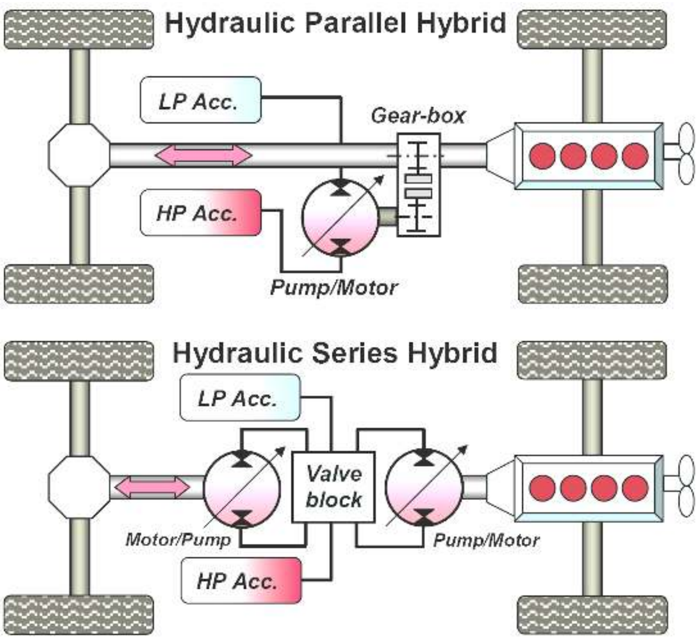



***Fig. 3:*** *Hydraulic parallel and series hybrids*

An interesting difference between the electric and the hydraulic system is that in the hydraulic system there is no need for a gear-box between the hydraulic motor and the driving wheel. Therefore, the mechanical losses will be lower in hydraulic hybrids than in electric ones.

When it comes to energy recovering, low mechanical losses is extremely important, because the energy has to be transferred through the mechanical path two times, both during driving and then during braking.

## 1.3 Energy recovering potential

The energy consumption for a vehicle drive system depends on the number of series connected components in the drive line and the efficiency of each component. ***Fig. 4*** shows an electrical and a hydraulic parallel hybrid system.

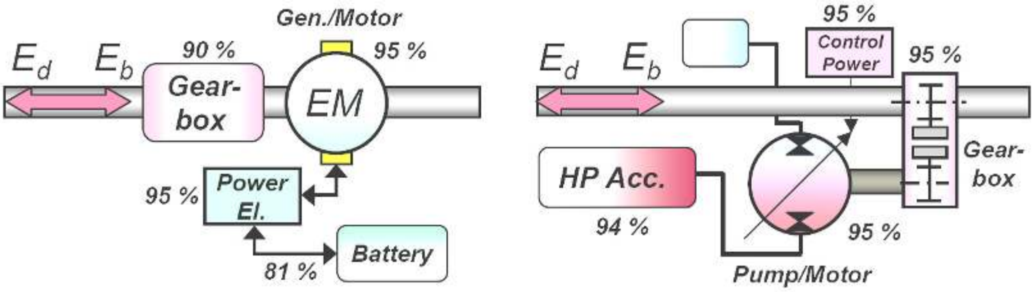



***Fig. 4:*** *Electric and hydraulic parallel hybrid system*

In Fig. 4 the efficiency for each component in series connection is given. Assume a cycle starting with driving, where the load energy is $E_d$ and than the cycle continues with braking, where the braking energy is $E_b$ (= $E_d$).

The energy recovering efficiency for this cycle can be calculated as the energy stored during braking over the energy used for driving. This quote is expressed as,

$$\frac{E_{\mathrm{s,b}}}{E_{\mathrm{u,d}}} = \eta_{es} \cdot \eta_{pc}^2 \cdot \eta_{p/m}^2 \cdot \eta_{mg}^2 \tag{1}$$

where the component efficiencies are:

$\eta_{es}$ = round-trip efficiency for energy storage device, [-]
$\eta_{pc}$ = power control efficiency, [-]
$\eta_{p/m}$ = machine (pump/motor] efficiency, [-]
$\eta_{mg}$ = mechanical gearing efficiency, [-]

Calculating the energy recovering efficiency, according to the efficiency values given in Fig. 4, the figures for the electric system is $(E_{s,b}/E_{u,d})_{el}$ = 0,53 and for the hydraulic system, $(E_{s,b}/E_{u,d})_{hyd}$ = 0,69.

The higher energy recovering efficiency, for the hydraulic system than for the electric ones, belongs to higher round-trip efficiency for the energy storage device and lower mechanical losses, because of lower gear ratio in the gear box.

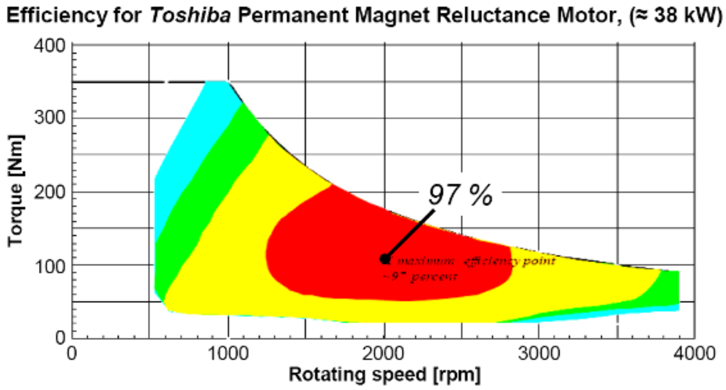
The round-trip efficiency for a hydraulic accumulator is given as 94 % (see Fig. 4), which has been proven by Parker Hannifin in their Cumulo systems. In the electric system the round-trip efficiency for the battery is about 81 % (90x90%), which is a normal value for Li-ion battery, [4].

## 1.4 Electric machines versus hydraulic machines

Today, Toshiba, [3] and UQM, [4] are the world leaders in electric machines for hybrid vehicles. The motors are developed for vehicle applications in sizes up to 150 kW.

One of the new permanent magnet reluctance motor from Toshiba has a nominal power of 38 kW. The motor is very compact and the shaft torque is high, 350 Nm for speeds up to 1000 rpm. As illustrated in Fig. 5 the max efficiency is very high, 97 %.

In comparison with the Artemis digital hydraulic motor (see ***Fig. 5***) the range of max efficiency for the electric motor is smaller. Especially at low speeds, the hydraulic motor has higher efficiency than the electric motor. This is an important advantage in a vehicle application. Here it is worth to be mentioned that the Artemis digital displacement machine has a special design to meet the requirements on high overall efficiency even at partial loading.



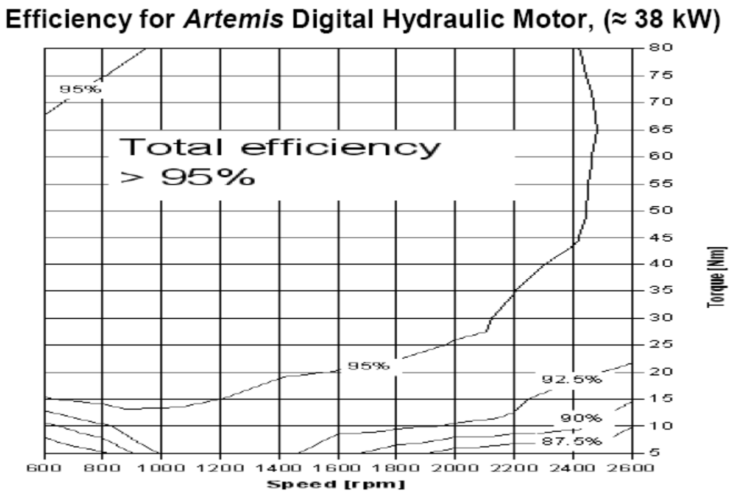




***Fig. 5:*** *Overall efficiency for electric and hydraulic motors, [2], [3]*

UQM has developed an electric motor, PowerPhase for use in series electric hybrids. Today they offer two sizes of large motors, PowerPhase 100 and 150 with nominal power of 100 and 150 kW respectively. A performance comparison of an UQM PowerPhase motor and the Artemis digital hydraulic motor is shown in **Table 1**.

**Table 1:** *Electric and hydraulic motor performance.*

| **Performance (max power: 100 kW)** | *El-motor UQM PowerPhase* | *Hyd-motor Artemis DD* |
|---|---|---|
| *Power density* | 0.5 kW/kg | >4 kW/kg |
| *Efficiency at 20% load* | 90 % | 93 % |
| *Cost* | 1 / kW | 0.3 / kW |

Table 1 makes clear that the hydraulic motor has advantages in most of the criteria, which can be lied on a unit for hybrid systems in vehicles.

In order to compete with electric hybrids the hydraulic machines must be more efficient, smaller, and lighter than most of the common machines are today. The commonly used axial piston machines with variable displacement are easy to control but their efficiency at low displacement setting is not impressive. The efficiency problem is addressed in ***Fig. 6***. This figure shows the overall efficiency versus speed for conventional axial piston motors with constant supply pressure (35 MPa). In the diagram the displacement setting varies from max 1.0 to 0.25.

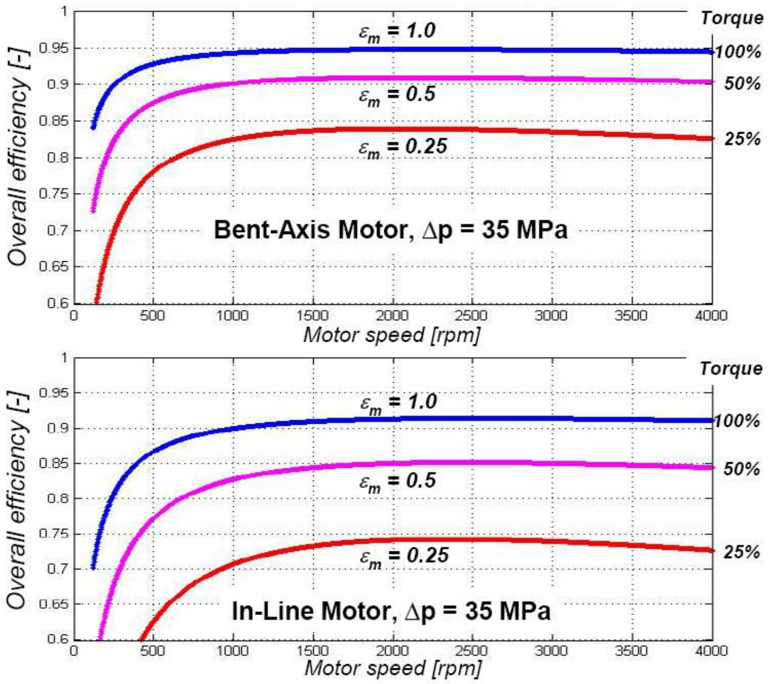



***Fig. 6:*** *Overall efficiency versus speed for variable bent-axis and in-line hydraulic motors, [5]*

The figure shows that the efficiency is drastically reduced at low torque/displacement. Especially for the In-Line motor the efficiency drops from 90% to 73% at a constant power of about 90 kW. This behavior makes it difficult to create an energy efficient hybrid system.

During the latest 5 years new hydraulic machine concepts have been developed. Two of the most promising concepts are the earlier mentioned Digital Displacement pump/motor from Artemis, [2] and the Floating Cup machine from Innas, [6]. These machines are depicted ***Fig.*** *7*.

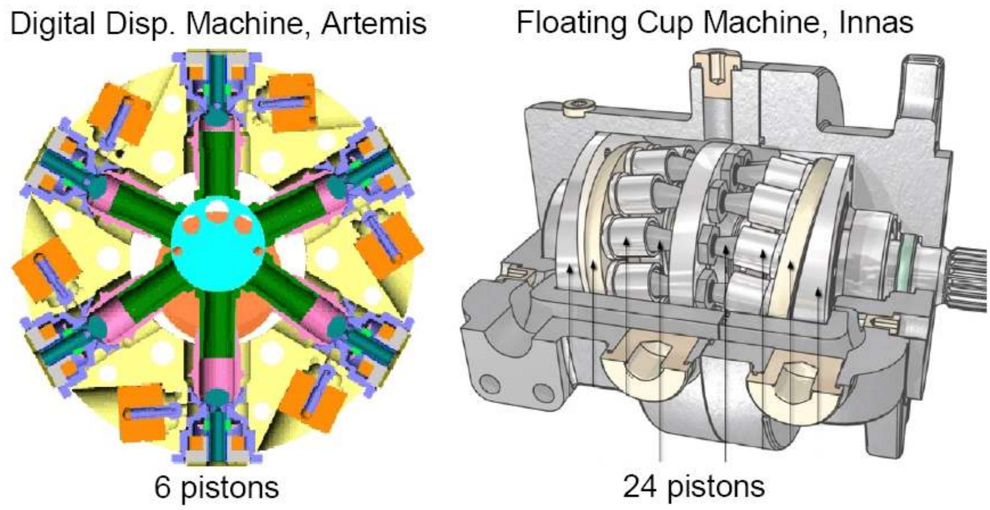



**Fig. 7:** *Artemis DD machine and Innas Floating Cup machine, [2], [6]*

The Digital Displacement machine has a kinematically perfect mechanism with best arrangement of loaded bearings, which gives lowest possible losses for the active cylinders. The second graph in Fig.5 shows measurements of the total machine efficiency (delivered fluid power/input shaft power). The efficiency is > 95% in a large loading range.

The floating cup machine has been tested as a pump and shows high efficiency in a wide range of operating conditions, with a maximum efficiency of 97%. The hydro-mechanical losses are very low at the operating condition of low speeds in combination with high loads.

When it comes to efficiency requirements these two machines are well adapted for hydraulic hybrid applications. Also the idling losses are small compared to common axial piston machines.

### 1.5 Engine characteristics

In order to minimize the fuel consumption for a hybrid system the engine and the hydrostatic system have to be controlled simultaneously. The engine speed has to be adjusted according to the loading torque to follow the optimal loading characteristics, see ***Fig. 8***.

Using hydrostatic machines with variable displacement it is possible to control the hydraulic system and the engine speed for optimal utilization of the power source and that way maximize the system overall efficiency.

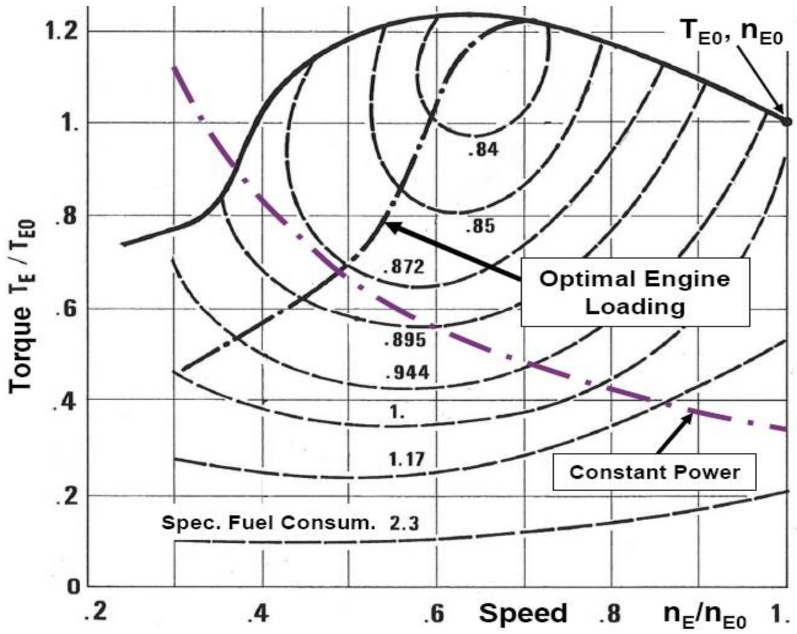



***Fig. 8:*** *Schematic characteristic for a combustion engine, [5]*

Looking at the constant power curve in Fig. 8 it is obvious that "over speed" of the engine can drastically reduce its efficiency. In a series hybrid system over-speed of the engine also means over-speed of the hydraulic pump. This will reduce the overall efficiency for the hydraulic system too.

## 2 New developments of hydraulic hybrids

A newly developed system is the series hydraulic hybrid for cars from Artemis, [2]. The system is built as a direct drive hybrid, as shown in ***Fig. 9***. In this system the hydraulic motors are directly connected to the driving wheel axis without any gear-box. This direct drive means that the mechanical losses are minimized. Therefore, the energy recovering system also will be very efficient.

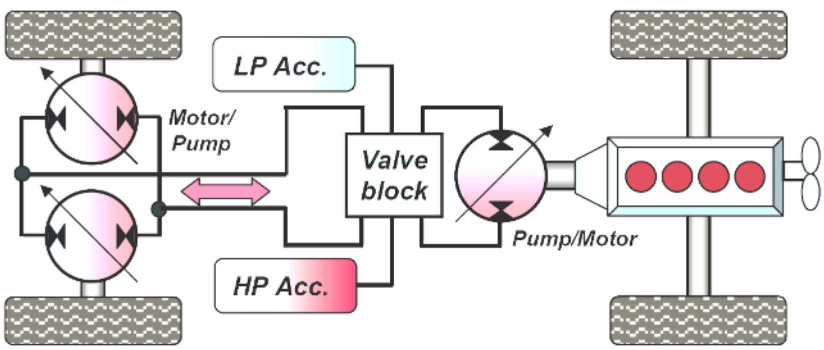



***Fig. 9:*** *Direct drive hydraulic series hybrid*

The hydrostatic machines in the series hybrid are the Artemis Digital Displacement Pump/Motor. Maximum power, which can be transferred by the hydraulic system are about 200 kW. The overall efficiency for the hydraulic system is above 85% in a big part of the operation range. This efficiency is much higher that for a conventional mechanical drive line.

The series hybrid system has been implemented in a standard car, BMW 530i. The car was tested with the original drive line and with the new hydraulic series hybrid system, illustrated in ***Fig. 10***. The driving cycle (European combined, full NEDC) time range is 1160 seconds and includes 13 starts and stops. The speed between the stops varies from 15 to 120 kph.

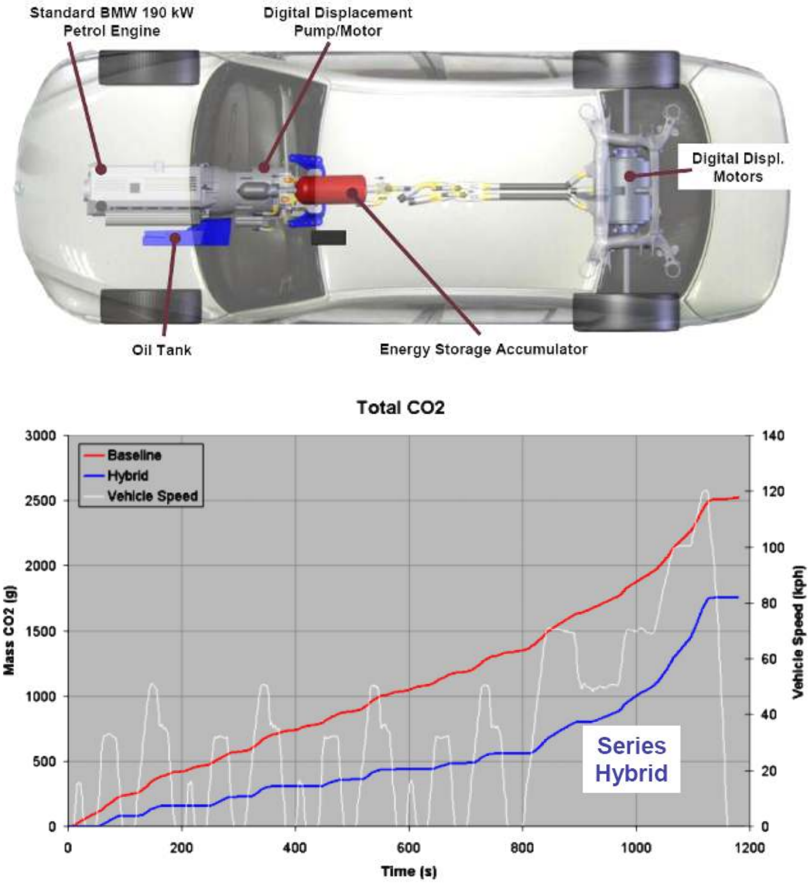



***Fig. 10:*** *Test results for a direct drive hydraulic series hybrid in a BMW 530i, [2]*

The diagram in Fig. 10 shows an overall $CO_2$ reduction of 30%. The reduction of fuel consumption is about 27%. For the European Urban Cycle the test shows a fuel reduction of about 50%. This good result has been reached because of reduced mechanical losses in the propulsion system, regenerative braking and the fact that the combustion engine is working in its best operation point (max efficiency) for all loads.

## 2.1 Eaton parallel hydraulic hybrid system

Another example of a hydraulic hybrid system is the Eaton HLA (Hydraulic Launch Assist) parallel hybrid system, [7]. The first application in which the system will be commercialized is refuse trucks as shown in ***Fig. 11***.


*Fig. 11: Eaton HLA hybrid system and a refuse appl., [7]*

The Eaton HLA system works as a regenerative braking system. In the refuse truck application most of the braking energy is stored in the high pressure accumulator and then the hydraulic energy can be used to improve the acceleration of the truck. Test data for the refuse truck shows a reduction of fuel consumption (gpm) from 17% (Performance Mode) to 28% (Economy Mode). In the "Performance Mode" the HLA system provides 26% higher acceleration than the standard truck, which increases the truck productivity about 11%.

The figures for the HLA system are very impressive. However, the common driving cycle for a refuse truck is close to the ideal cycle for a regenerative braking system.

Eaton is running projects for light, medium duty and heavy duty commercial vehicles. Besides refuse trucks, other applications will follow including city transit bus, shuttle bus and package delivery vehicles. Eaton also has made significant improvements of hydraulic machine efficiency, reduction of noise and vibrations and electro-hydraulic control.

## 2.2 Parker advanced series hydraulic hybrid system

The Cumulo system from Parker Hannifin was mentioned in the beginning of this paper. Parker has continued the development of hydraulic hybrids in the project Runwise, [8]. This year Parker will launch their Advanced Series Hydraulic Hybrid system, illustrated in ***Fig. 12***.

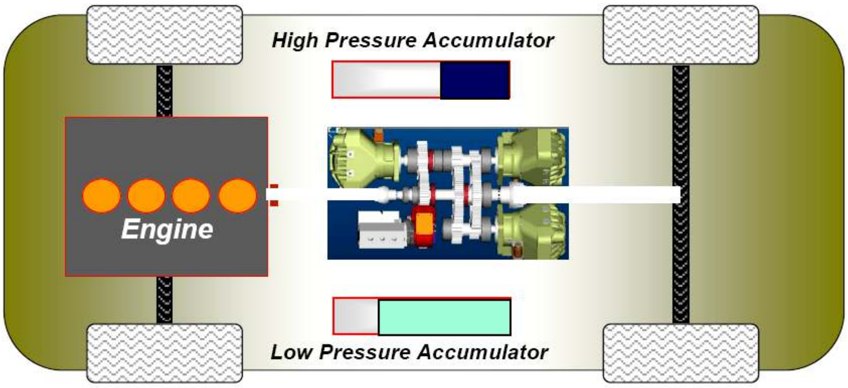



***Fig. 12:*** *Parker advanced series hydraulic hybrid, [8]*

The advanced series hybrid is based on a power split concept with one hydraulic path and one mechanical path in parallel. In the low vehicle speed range (0 - 65 km/h) the power is transferred hydraulically. From 65 to 100 km/h direct mechanical drives is used with disconnected hydraulics. These two gear ratios ensure high efficiency at all speeds. The hydraulic recovering system can handle brake energy from 65 – 0 km/h.

***Fig. 13*** shows the principle of a power split hydraulic series hybrid system.

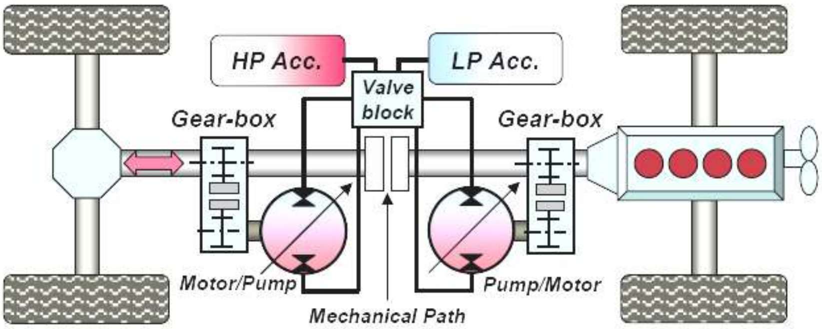



***Fig. 13:*** *Schematic layout of a power split series hybrid*

The motive for disconnecting the hydraulic system from the mechanical ones at high vehicle speed is the fact that the low loading torque gives low efficiency for the hydraulic motor, as pointed out in Fig. 6. Therefore, direct mechanical transmission is the most efficient at high speeds.

### 2.3 Bosch-Rexroth hydraulic hybrid systems

Bosch-Rexroth has developed parallel as well as series Hydrostatic Regenerative Braking system (HRB), [9] for commercial vehicles and mobile equipments. HRB parallel system is a hydraulic hybrid for vehicles not already having a hydrostatic transmission, such as refuse trucks and buses. The HRB series system makes use of the components in the existing hydrostatic transmission. Vehicles can therefore be assembled with the system without great effort or expense.

Bosch-Rexroth claims that their Hydrostatic Regenerative Braking system for heavy commercial vehicles reduces fuel consumption by up to 25%. This figure is not so impressive, but realistic, because the HRB units available today are just add-on systems for existing drive lines.

# 3 Improvements of hydraulic hybrids

High efficient pumps and motors are definitely key components in order to improve the performance of hydraulic hybrids. Another important improvement for hydraulic hybrids is the development of light hydraulic accumulators, as going on at Parker in US.

For heavy commercial vehicles the energy recovering system might be the most powerful facility for fuel economy improvement. As the technology looks today about development of electric and hydraulic hybrid it is cleat that hydraulic accumulators have an advantage over electric batteries, as explained in Table 2.

**Table 2:** *Hydraulic accumulators versus el batteries*

| **Energy recovering performance** | Hydraulic accumulator | Electric battery, Li-ion |
|---|---|---|
| Power density | 5 kW/kg | 0.5 kW/kg |
| Energy density | 4-11 kJ/kg | 150 kJ/kg |
| Round-trip effic. | 94% | 81% |

The advantage of the hydraulic accumulators belongs to its high power density and high round-trip efficiency. This will gain the energy recovering potential (see paragraph 1.3) compared to electric batteries. The low round-trip efficiency of electric battery depends upon the required charging time. For a typical vehicle cycle the round-trip time is much lower than the optimal round-trip time for the battery. Therefore the round-trip efficiency of a battery in a vehicle application is typically 81%.

The only advantages with electric batteries are their high energy density, which make it possible to develop full electric vehicles. However, full electric drive lines can only be used in very light cars. For a heavy truck it is not useful because of the battery weight, about 20 tons for 1000 km driving, [10].

In order to sum up the development of hydraulic hybrid systems the history of Parker hybrid technology is shown in ***Fig. 14***. The figure ended up with the target for 2010. The figures are typical for commercial vehicles, like refuse trucks.

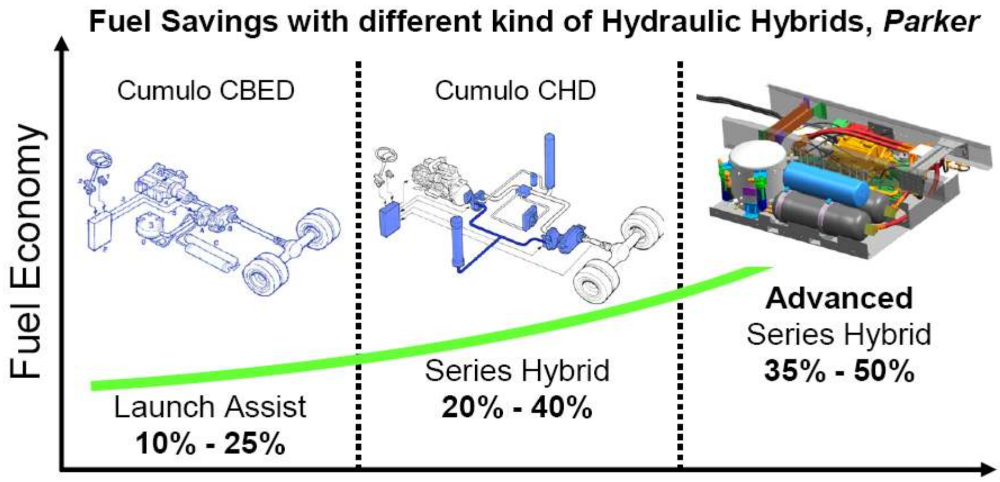



***Fig. 14:*** *History of Parker hybrid system development, [8]*

Hybrid drives are becoming increasingly significant, in passenger cars as well as commercial vehicles and mobile equipments. The advantages of hydraulic hybrid technology are especially obvious in the heavy commercial vehicle segment.

The energy savings potential is most significant in heavy vehicles that have frequent braking cycles. The stronger the braking, the greater is the possible reduction in fuel consumption. In that kind of applications the energy recovering system has the dominant impact on the fuel saving potential. In this paper it has been proved, that hydraulic accumulators are superior to electric batteries, in frequent stop and go driving. Therefore, the electric hybrids of today can not meet the performance of hydraulic hybrids.

## 4 Conclusions

In general the advantages of hybrid technology are most obvious in the commercial vehicle segment. To make benefits of energy recovering facilities in hybrid drives, it requires that the part of stop and go driving is high compared to constant speed driving. Anyhow an optimal hybrid drive system must also have the capability of high efficient energy transfer at constant speed. This idea has been the main target for the development of the “Advanced series hybrid” at Parker Hannifin.

The developments of hydraulic hybrid drives have proceeded quite well the last decade. Most of today’s hybrid systems promise significant fuel saving and emissions reductions. As can be expected, full series hybrids, offers the biggest potential.

Even if hydraulic hybrids have a good position today, there is still a great need for improved component performance and improvement of the control systems. The control of hydraulic hybrids is still much more complex than the control of electric hybrids. It is also important to improve the performance of the mechanical path in the drive train. The mechanical losses in gear-boxes and bearings have to be reduced.

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