HYDRAULIC HYBRID TECHNOLOGY REVIEW – PERSPECTIVES AND BENEFITS OF ITS IMPLEMENTATION ON PUBLIC TRANSPORTATION VEHICLES

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Abstract: IC engines amount to 25% in global energy consumption, which is mostly due to their massive share in road transport of approximately 99%. The motivation for development of fuel efficient vehicle propulsion systems arises from strong dependence of the transportation sector on fossil fuels and the need for a rapid response to the global warming challenge. Hybridization has, globally, proven its capabilities in enhancing the powertrain efficiency and is the only technology offering significant breakthroughs in near and mid-term. While there are a number of approaches, Hydraulic Hybrid Technology (HHT) has been lately utilized as an alternative power source for vehicles. HHT gives unique advantages for easy and cost-effective implementation in current production vehicles as well as an aftermarket solution. It seems to be the replacement for expensive, bulky and environmentally hazardous battery technology. Hydraulic energy conversion and storage provide exceptional power density and efficiency making them ideally suited for regenerative powertrain design. It is particularly efficient in city traffic conditions, characterized by frequent stops, coasting and long idling periods. Additionally, emissions are reduced, particularly at idling and low speeds, compared to conventionally powered vehicles. While HHT is still in the prototype and simulation stage, this paper reviews current state-of-the-art.

Key words: IC Engine, Hydraulic Hybrid, regenerative powertrain, fuel consumption, emission

1. INTRODUCTION

Ever rising energy prices and increasing awareness on environmental issues place greater importance on the quest for solutions that improve vehicle fuel economy and reduce emissions, particularly CO_2. One of promising solutions is the hybridization of the drivetrain. Hybrid drives, generally, combine at least two energy converters and two energy storage systems built into the vehicle for powering it. Energy converters may be internal combustion engines, hydraulic or electric motors. As energy storage, the fuel tank, the battery or the hydraulic accumulator may be used. What all hybrid concepts have in common is the advantage of possessing additional energy sources which can be exploited under differing operating conditions.

The search for improved fuel economy, better emissions, and yet affordable vehicles, without sacrificing performance, safety, reliability, and other conventional vehicle attributes, has made the hybrid technology one of the challenges for the automotive industry. Being an important branch of hybrid technology, Hydraulic Hybrid vehicles have been increasingly drawing attention of the researches and automotive manufacturers all over the world.

The advantages of hydraulic accumulators are higher power density and the ability to accept high rates and high frequencies of charging and discharging, both of which are not favorable for batteries. Providing extremely high power density, the concept of Hydraulic Hybrid is almost perfectly suited to all those types of vehicles characterized by frequent stopping and starting phases, buses circulating in urban traffic conditions being a very good example. Such driving conditions significantly affect the fuel economy and pollutants emission. Energy stored in the hydraulic accumulators can be used during vehicle acceleration, or later to assist or replace the combustion engine at unfavorable operating points.

The Hydraulic Hybrid system, using a combination of an engine and a hydraulic pump/motor, have the potential for improving fuel economy by operating the engine in the optimum efficiency range and by harnessing the vehicle's deceleration energy. Hydraulic Hybrid vehicles may also employ hydrostatic transmission instead of commonly used mechanical transmission, eliminating the mechanical connection between the engine and the driving wheels [1, 2].

2. THE CONCEPT OF HYDRAULIC HYBRID TECHNOLOGY

2.1. Principles of Hydraulic Regenerative Braking

The basic idea of the Regenerative Braking (RB), within the scope of Hydraulic Hybrid Technology (HHT), is to convert the vehicle's kinetic energy and store it into hydraulic form, rather than waste it as a heat emitted to the environment. During vehicle acceleration, the stored energy is fed into the traction drive to relieve the IC Engine, as a prime mover, or to significantly improve its torque characteristics. Moreover, the acceleration response, improved by means of regenerative braking, increases drive comfort due to the uninterrupted driving power flow during gear shifting (25 % 0-50 km/h acceleration time improvement [3]). Utilizing Hydraulic Hybrid technology only for regenerative braking purposes can lead to fuel savings of up to 25 % [4-6]. Corresponding reduction in CO_2 emissions is an additional benefit.

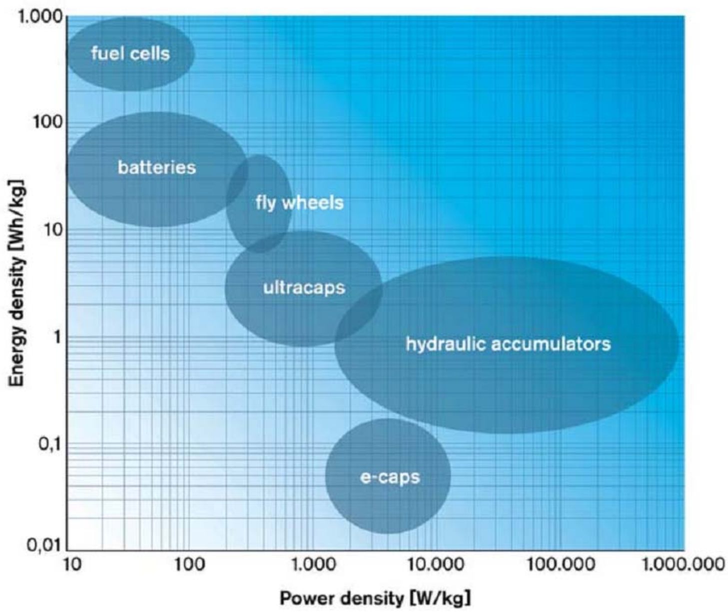

Figure 1: The Ragone plot ranks various energy storage devices by their energy and power density [4]

The basic architecture of a hydraulic regenerative braking system is similar to an electric hybrid, connecting the additional energy storage device and converter to the existing drivetrain with the IC Engine. However, different characteristics of the individual components used in electric and Hydraulic Hybrid give different potentials for fuel consumption reduction. These differences especially arise from capabilities of energy storage devices used in electric (EH) and Hydraulic Hybrids (HH).

Batteries used in the electric hybrids are characterized by the ability to slowly and continuously store considerable amounts of energy. The disadvantage being that, for reasonably sized batteries, they cannot accept significant braking power due to their comparatively low power density and high internal resistance. This also makes them inappropriate for delivering the amount of power needed for accelerating heavy-duty vehicles.

On the other hand, hydro-pneumatic accumulators used in Hydraulic Hybrid powertrains offer a significantly greater power density. The generated braking energy can be accumulated completely even on large mobile machines and commercial vehicles and under strong braking conditions. Hydraulic accumulators, however, suffer from a relatively low energy density. Reasonably sized hydraulic storage devices allow the braking energy of a vehicle to be stored efficiently, but continuous storage of unused IC Engine power is fairly limited. Therefore, HHT concept is more suitable to mild than full hybrids. The Ragone plot in Fig. 1 illustrates the power vs. energy relationship of different energy storage devices. This means that vehicles with electric and Hydraulic Hybrid drives require different operating strategies, and that these concepts are best applied to different vehicle categories.

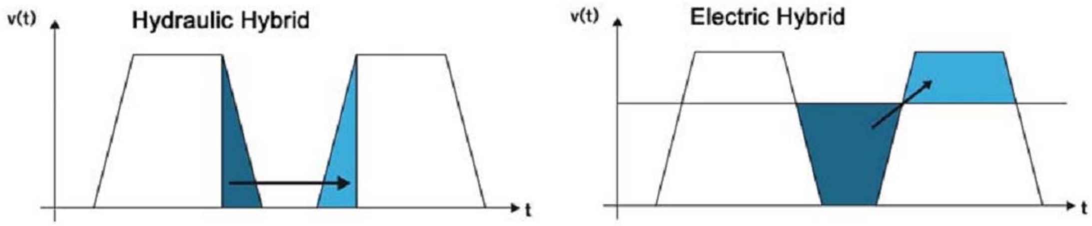

Figure 2: Comparison of hydraulic and electric hybrid drive [7]

Hydraulic Hybrids are well suited for the task of braking energy recuperation. Vehicles with high starting and stopping torques, i.e., high braking and acceleration forces, such as city buses can take the full advantage that this concept brings. Electric Hybrids' focus, on the other hand, is on raising the load point of the IC Engine and to store the continuously generated energy for use in a purely electric traction drive or for covering peak power needs. The EH concept thus has limited suitability for driving conditions involving frequent and cyclical starting and stopping phases, since they involve large amounts of braking and acceleration forces. It is mainly suited for passenger car applications in moderate partial load conditions, especially those vehicles equipped with high displacement engines.

Fig. 2 illustrates differences between energy storage capabilities of these two concepts. An electric hybrid stores excess power from the ICE in the battery and then reuses it on demand. The Hydraulic Hybrid excels in quite different circumstances: the power from the braking process is reused in the following acceleration phase. The high power density of the hydraulic accumulator means that large braking power levels can be harnessed by the system. The Hydraulic Regenerative Braking System (HRBS) is therefore especially suited for heavy vehicles whose driving cycles involve frequent starting and stopping periods encountered in urban conditions. Since HRBS stores the vehicle's kinetic energy, benefits are amplified with increased vehicle mass and deceleration (braking power) and with increased braking frequency (Fig. 3).

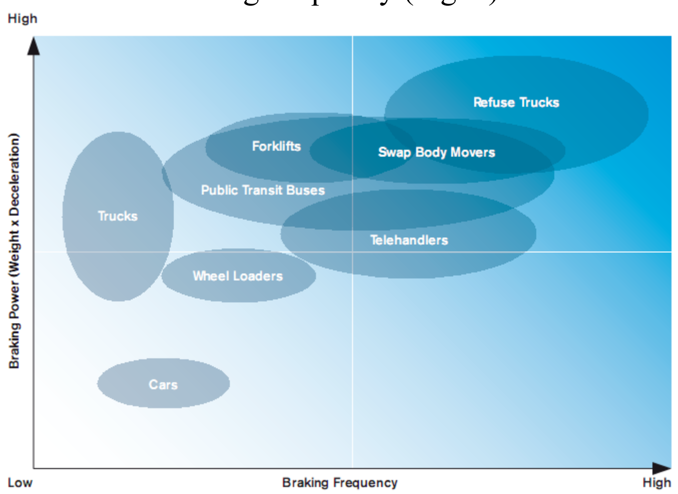

Figure 3: Influence of vehicle mass and driving cycle characteristics on RB potential [7]

Comparing the overall regenerative braking efficiencies attained with the implementation of these two hybridization concepts, it can be clearly said that the advantage is on Hydraulic Hybrid's side with figures showing that up to 70 % of energy harnessed during the deceleration can be returned into the next acceleration phase (Fig. 4). The lower individual machines' efficiencies, and in particular the incapacity of the battery to store energy at high rates, are responsible for the significantly lower RB efficiencies attained with the EH concept (up to 20 %).

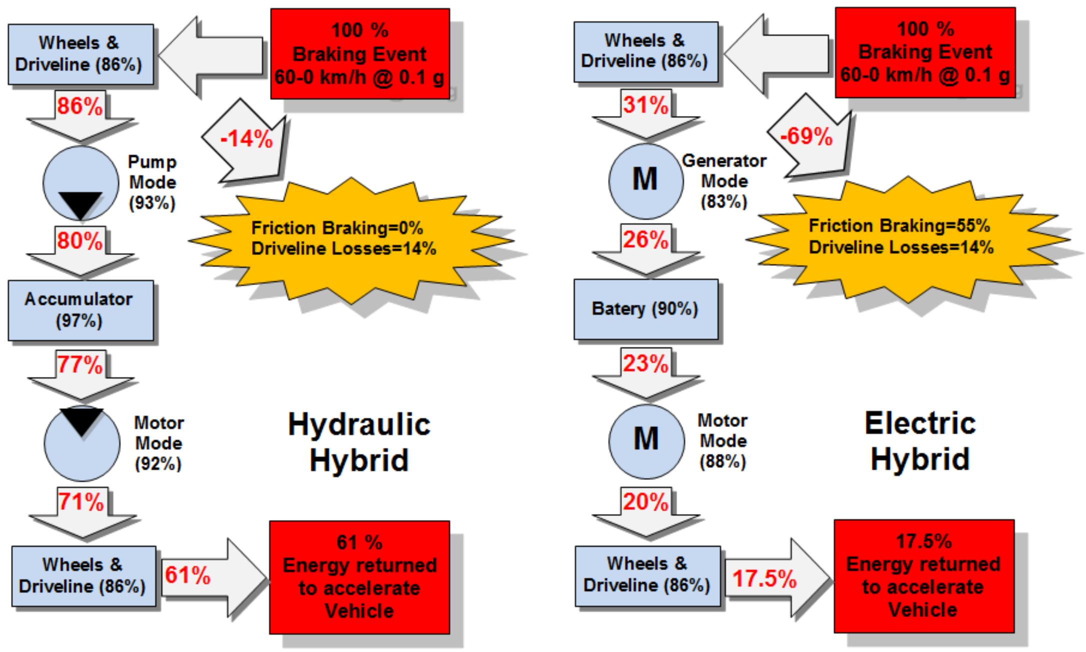

Figure 4: Overall regenerative braking energy efficiency comparison between HH and EH concepts [8]

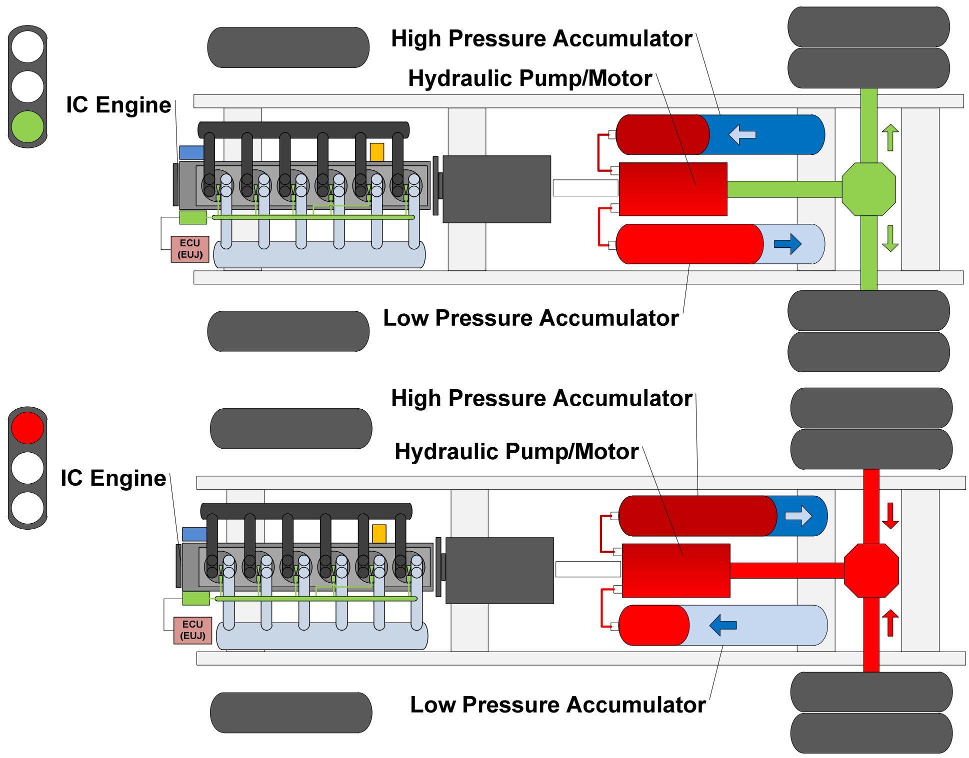

Figure 5: Hydraulic Hybrid Regenerative Braking phases

2.2. Series versus Parallel Hydraulic Hybrid

In a parallel Hydraulic Hybrid, the conventional vehicle driveline is supplemented by the hybrid system. It is designed for vehicles having a conventional mechanical drivetrain and an IC Engine as the primary drive. When braking, a gearbox connects the hydraulic pump to the mechanical drivetrain to convert kinetic into hydraulic energy. The hydraulic pump converts the released braking energy into hydraulic energy by charging the high-pressure accumulator. During acceleration, the entire process is reversed: the fluid pressurized in the accumulator is discharged in a controlled manner and flows back through the hydraulic pump, which now acts as a motor transferring its energy to the mechanical drivetrain. Modular construction means that the parallel Hydraulic Hybrid system gives unique advantages of easy and cost-effective implementation in current production vehicles. It also represents a convenient aftermarket solution for vehicles already in service. Parallel hybrids represent a compromise where the potential for maximum efficiency is sacrificed for cost effectiveness and ease of implementation, achieving fuel savings of approximately 20-40 % [8]. For that reason, parallel hybrids are commonly known as "mild hybrids".

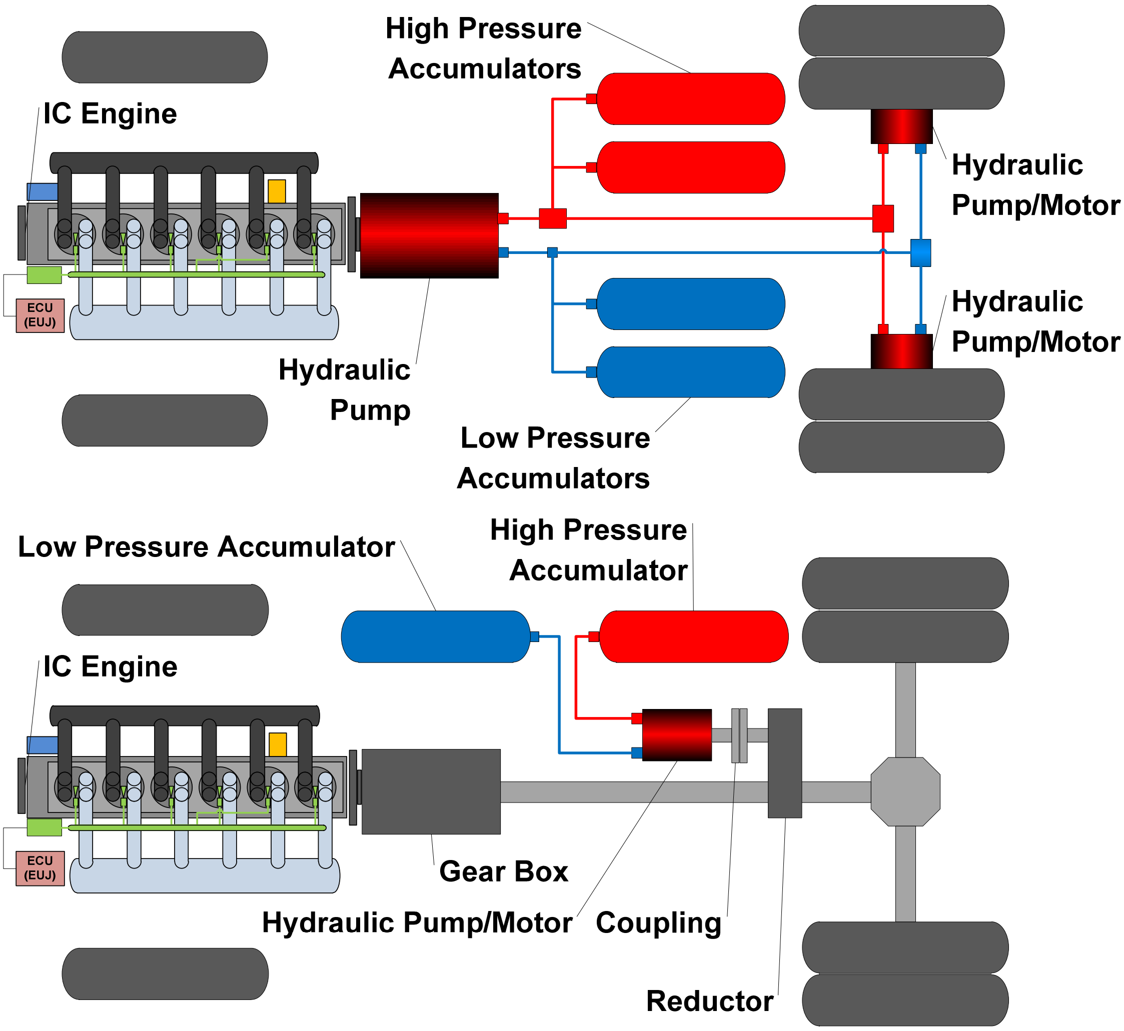

Figure 6: Series (above) vs. parallel (below) Hydraulic Hybrid Regenerative Braking concepts

The full potential of the Hydraulic Hybrid concept can be achieved in a series hybrid configuration. A series Hydraulic Hybrid power system combines an IC Engine and a hydraulic propulsion system to replace the conventional drivetrain and transmission. The entire sum of power to the drive wheels is transferred by means of pressurized fluid. The vehicle uses hydraulic pump/motors and hydraulic storage tanks to recover and store energy. It makes the IC Engine operate at its "sweet spot" of fuel consumption, facilitated by the continuously variable transmission (CVT) functionality of the series hybrid hydraulic system and by regenerative braking. In a Series Hybrid Hydraulic System, the demonstrated fuel economy improvement is significant (fuel savings of approximately 60-80% [5, 8] are achieved). The vehicle recovers and stores energy in practically the same way as Parallel Hydraulic Hybrid vehicles do.

Table 1: Comparison of Parallel and Series Hydraulic Hybrid Configurations

	Parallel Hybrid	Series Hybrid
Advantages	✓ Appears more cost-effective than electric alternatives ✓ Conventional drivetrain still available for backup	✓ The most cost-effective option ✓ Allows optimum engine operation for efficiency and emissions improvements ✓ Approach has been standard in off-road equipment
Drawbacks	✓ Analysis indicates good, but less attractive payback period when compared to series hybrid	✓ Higher risk with new drivetrain components

3. HYDRAULIC HYBRIDS AND POTENTIAL BENEFITS

The efficiency analysis shows that hydraulic components themselves create more losses than the mechanical transmission. But these losses are more than compensated by the energy that is recuperated during the braking phases. Including the recuperated brake energy, the total efficiency of the series Hydraulic Hybrid transmission with Common Pressure Rail (CPR) is in the end somewhat better than the estimated efficiency of an all-wheel drive mechanical transmission.

Fuel savings, discussed above, are derived by implementation of HRB only. Further fuel economy improvement can be achieved and depends on the chosen HHT concept and the IC Engine control strategy. Summary of fuel economy potentials is given in Table 2 [6].

Table 2: Fuel economy improvements with different HHT concepts and control strategies [6]

HHT Concept	Fuel efficiency improvement
Baseline vehicle	–
Hydraulic Hybrid Engine always running	39-44%
Hydraulic Hybrid Engine-off when vehicle not moving	52-59%
Hydraulic Hybrid Engine-off when vehicle decelerating or not moving	70-74%

As part of our government-funded project, dealing with the hydraulic hybrid powertrain implementation aspects, an experiment consisting of the simultaneous logging of a bus' J1939 powertrain parameters and its GPS tracking data was conducted (Fig. 7). This has allowed us to obtain the driving cycle of a bus circulating in real traffic and occupancy conditions, making it possible to proceed with fuel consumption simulations involving alternative powertrain configurations, and in particular the hydraulic hybrid system.

Results of the preliminary, initial analysis of data gathered during the experiment is shown in Table 3. The effective engine work produced during runs in the second direction of the driving cycle is consistently greater than in direction 1, mainly because of the additional power needed to overcome the encountered higher road slope. The braking energy parameter is estimated assuming a conservative, 23000 kg bus mass and by using several logged variables, such as the vehicle's acceleration, retarder and fuel cut-off states. It shows values as high as 66 MJ and represents more than 50 % of energy provided by the IC Engine in all direction 1 runs of the considered driving cycle of 28.3 km in length. A correlation between the traffic congestion state (Trip Time) and the braking/engine work ratio can be spotted, with slightly higher values obtained during shorter runs. This can be explained by the fact that the engine consumes fuel even when the bus is stationary.

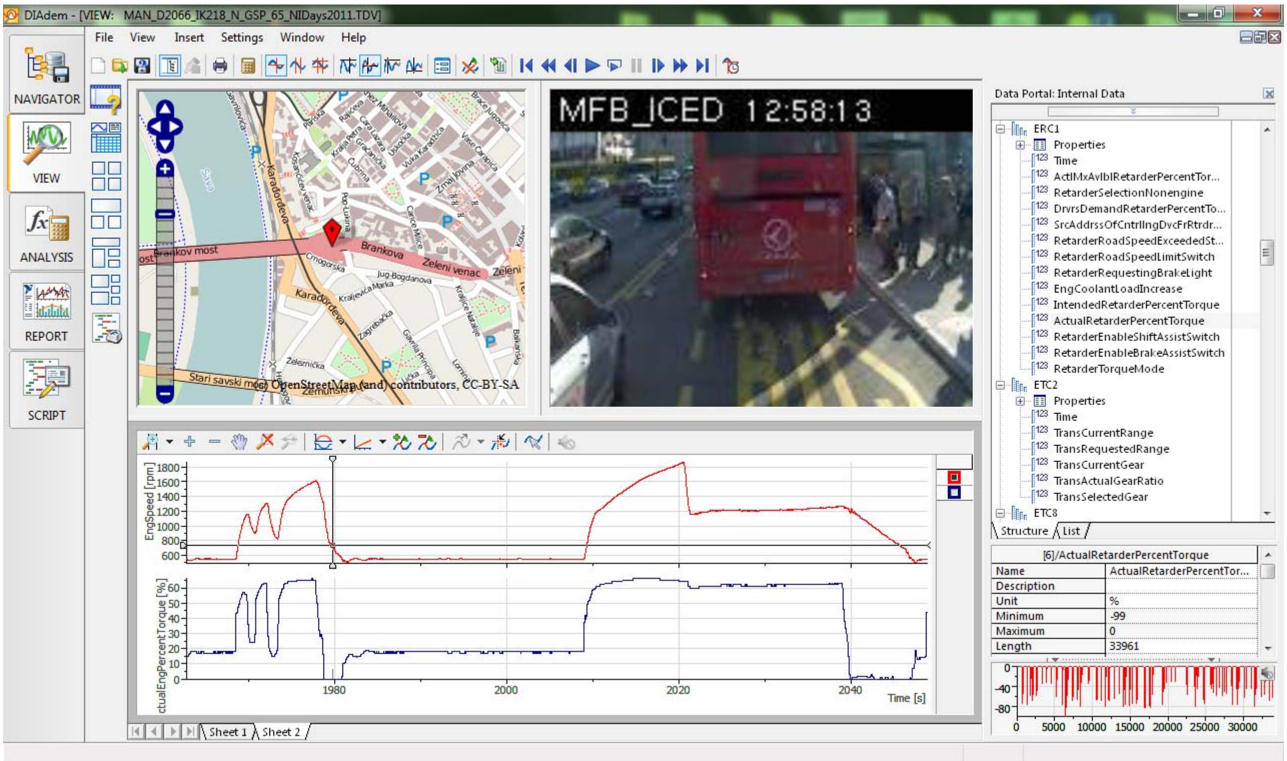

Figure 7: Analysis of acquired bus driving cycle data

Table 3: Initial energy savings analysis based on the data acquired during the experiment

		Driving cycle 1		Driving cycle 2		Driving cycle 3	
		dir. 1	dir. 2	dir. 1	dir. 2	dir. 1	dir. 2
Effective Engine Work	[MJ]	104.669	167.501	116.667	146.457	105.124	143.319
Braking Energy	[MJ]	64.089	58.254	66.883	56.879	60.967	45.883
Total Fuel Consumed	[l]	7.717	12.299	8.846	10.841	7.884	10.858
CO_2 Emissions	[kg]	20.591	32.816	23.603	28.925	21.035	28.971
Trip Time	[s]	2562	3400	3497	3234	2840	3982
Braking/Engine Work Ratio	[-]	0.612	0.348	0.573	0.388	0.580	0.320
Estimated Energy Savings	[%]	36.7	20.9	34.4	23.3	34.8	19.2
Estimated CO_2 Emission Reduction	[kg]	7.6	6.8	8.1	6.7	7.3	5.6

The estimated energy savings parameter, calculated using the assumption that at least 60 % of the energy harnessed during braking phases can be reused to accelerate the vehicle by means of HHT, shows promising values ranging from 19.2 % in worst to 36.7 % in the best case. Even greater fuel efficiency can be achieved by implementing optimized powertrain control algorithms.

It can be said that, regardless of the traffic and occupancy conditions or the driving cycle's road profile, at least 20 % of fuel can be saved with the implementation of a Hydraulic Hybrid Powertrain. Having in mind that 100000 kg of fuel is used by the Belgrade's transportation system on a daily basis, this worst-case scenario fuel reduction figure shows that huge amounts of savings can be achieved: at least 31000 € could be conserved each day, effectively containing the payback period of a single vehicle to no more than 5 days. Concerning the payback period of a single, HHT powertrain-equipped bus, values range from 7 years for the most conservative energy savings figures to 4 years for the most optimistic ones. Considering the daily fuel consumption of the transportation system, a significant reduction of CO_2 emission in the order of 63000 kg per day can be achieved.

Engine auxiliaries such as cooling fan, alternator, A/C, engine oil and coolant pump consume more than 10 % of nominal engine power. Through implementation of hydraulic motors for powering these devices, the overall efficiency can further be improved by using potentials of stored hydraulic energy. Auxiliaries can be downsized and optimized since they can run at demanded speed, independently of the engine's speed. They can also be driven by a single, engine-powered hydraulic pump.

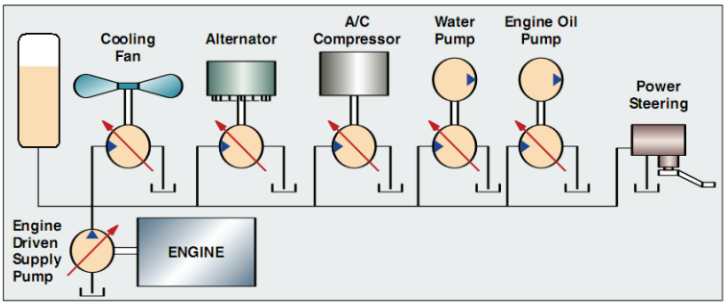

Figure 8: The hydraulic accessory power system for improved drive efficiency [10]

According to Eaton [8], capturing 70 % of the braking energy with the hydraulic fluid can reduce brake wear by more than 50 %. Public transportation vehicles generally require intensive brake system maintenance (as frequent as twice a year). Savings accomplished through brake system maintenance reduction only are comparable to 50 % of HH system implementation costs (low volume production). Besides maintenance costs, reduced brake wear has a positive effect on the environment, reducing emission of fine dust particles from brake pads.

Compared to Electric Hybrids, which have superior performance in overall noise reduction, Hydraulic Hybrids do not offer such a significant improvement. Noise generated by hydraulic components is mainly influenced by their number and design aspects (parallel, series concept). Efforts made by research institutions in the field of hydraulic component development and design have led to new solutions with significantly improved noise and vibration characteristics in recent years [10, 11].

Beside the high potentials for fuel economy and exhaust emission improvements, Hydraulic Hybrids offer the lowest incremental costs among all hybrid concepts. According to Eaton and Bosch-Rexroth, the payback time is between 3-4 years (calculated on the basis of current fuel prices and the average annual operating time for vehicles with prominent stop-and-go phases). The higher the price of fuel is, the greater are the savings and the shorter is the payback time. Payback time calculations are based on the implementation of current, in-series production, widely used hydraulic components. The estimated costs for retrofitting a public transportation bus to full Hydraulic Hybrid specifications range between 30000 and 40000 €. Further development of hydraulic components designed specifically for hybrid drive use, and their massive production and implementation, will lead to significant initial costs reduction (up to 75 %). Additional cost reductions are possible in the case the conventional gearbox is dropped off in an early Hydraulic Hybrid vehicle production phase.

4. CONCLUSION

The advantage that the Hydraulic Hybrid concept has over its Electric Hybrid counterpart is primarily the high power density and the ability to accept the high rates/frequencies of charging and discharging, therefore making it ideally suited for public transportation vehicles characterized by pronounced stop-and-go driving cycles. Developed and tested prototypes and demo platforms have demonstrated significant performance improvements in terms of fuel economy (up to 60 %) and pollutants emission reduction. Using the HRB system to perform a significant portion of the vehicle braking (up to 70 %) can also provide a significant improvement in friction brake component life. Further work to integrate the hydraulic parts with vehicle's powertrain and braking systems will be of crucial importance for bringing this technology beyond the concept demonstration level. In order to achieve this, special attention has to be paid to the following challenges:

- Adapting the industrial pump/motor technology to automotive applications.
- Minimizing the pump/motor noise levels.
- Reducing the cost of composite accumulators.
- Familiarize the end-users with this technology's benefits, reliability and safety aspects.
- Implementing stimulating tax credits for hybrid vehicles in order to encourage their large-scale commercialization.

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