Assesment of Fuel Economy Improvement Potential for a Hydraulic Hybrid Transit Bus

Predrag Mrdja[1], Nenad Miljic[1], Slobodan J. Popovic[1], Marko Kitanovic[1], Vladimir Petrovic[1]
[1]Internal Combustion Engines Department, Faculty of Mechanical Engineering, University of Belgrade, Serbia

Abstract
Hybridization, in particular Hydraulic Hybrid Technology (HHT), is offering significant powertrain efficiency breakthroughs in near and mid-term. A data acquisition on a transit bus has been performed to assess the potentials for fuel consumption reduction based on deceleration energy calculations. Initial study suggests fuel economy improvements of 20 % are possible. Additional investigation was carried out to quantify fuel savings that would be achieved by implementing a start-stop system. Significant fuel consumption occurs during bus idling periods at bus stops and traffic lights. Analysis shows that more than 15 % fuel reduction is possible solely by turning off the engine.

Keywords:
IC Engine, Hydraulic Hybrid, regenerative braking, start-stop system, emissions

1 INTRODUCTION

Rising fuel prices and increasing awareness of environmental issues place greater importance on the quest for solutions that improve vehicle fuel economy and reduce harmful emissions. One of the many possible directions in that regard, but perhaps the most promising, is the hybridization of the powertrain. Hybrid drives combine at least two energy converters and two energy storage systems for powering the vehicle. Internal combustion engines, hydraulic or electric motors are most commonly used as energy converters in hybrid systems. Fuel tanks, electrochemical batteries and hydraulic accumulators are examples of energy storage devices. What all hybrid concepts have in common is the advantage of possessing additional energy sources which are characterized by different optimal operating conditions.

Achieving improved fuel economy, lower emissions and relatively low price without sacrificing performance, safety, reliability, and other vehicle-related aspects represents a great challenge for the automotive industry. Being an important segment of the hybrid technology, Hydraulic Hybrid vehicles have been increasingly drawing attention from researches and automotive manufacturers all over the world.

Hydraulic accumulators are characterized by higher power density and the ability to sustain high rates and high frequencies of charging and discharging, both of which are not yet achievable by electrochemical storing devices. By providing extremely high power density, the hydraulic hybrid concept is very well suited to all types of vehicles undergoing frequent stopping and starting phases, such as buses circulating in urban traffic conditions. Such driving conditions significantly affect the fuel economy and pollutants emission. Energy stored in the hydraulic accumulator can be used during vehicle acceleration, or to assist or replace the combustion engine at unfavourable operating points.

The Hydraulic Hybrid system has 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 employ hydrostatic transmission instead of commonly used mechanical transmission, eliminating the mechanical connection between the engine and the driving wheels [1, 2], thus increasing the control possibilities.

In this paper, an introduction regarding the hydraulic hybrid technology concept is presented, along with the most important aspects of its operation. Expected and measured fuel economy improvements obtained from research efforts around the world are further introduced. Then, results of the initial study of data acquired in real-world driving conditions of a transit bus circulating in Belgrade's transportation system in different traffic and occupancy conditions are laid out. This analysis permits assessing the potential fuel economy benefits that could be achieved by implementing a hydraulic hybrid powertrain.

2 HYDRAULIC HYBRID TECHNOLOGY CONCEPT

The single, most significant mechanism responsible for energy efficiency increase in a hydraulic hybrid system is based on regenerative braking (RB) technology, whose task is to convert the vehicle's kinetic energy and store it in hydraulic form. This energy would normally be wasted as a heat emitted to the environment from the braking system. 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.

The basic architecture of a hydraulic regenerative braking system is similar to that of 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 Hybrids result in different potentials for fuel consumption improvement. These differences primarily arise from capabilities of energy storage devices used in electric (EH) and Hydraulic Hybrids (HH).

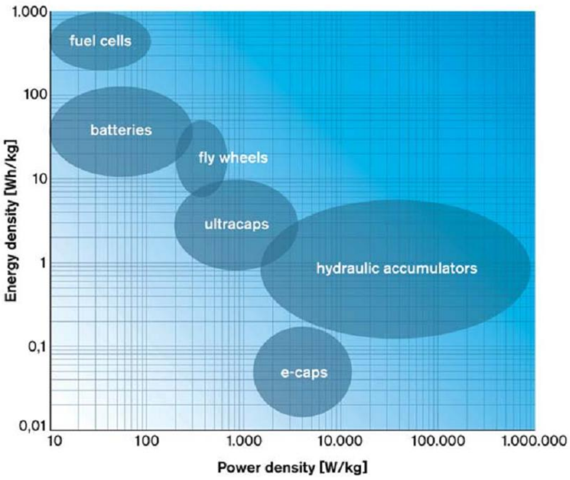


Figure 1: The Ragone plot ranks various energy storage devices by their energy and power density [3].

Batteries used in electric hybrids are distinguished by their ability to store considerable amounts of energy at a relatively slow rate. The disadvantage being that, for reasonably sized batteries, they are unable to accept significant braking power due to their low power density and high internal resistance. Because of this, electrochemical devices are presently unsuited 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 increased 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 are able to efficiently store braking energy, but continuous storage of excess IC Engine power is limited. The Ragone plot in Figure 1 illustrates the power vs. energy relationship of different energy storage devices. The underlying differences in characteristics of hydraulic and electric types of energy storage devices are responsible for radically different optimal control strategies.

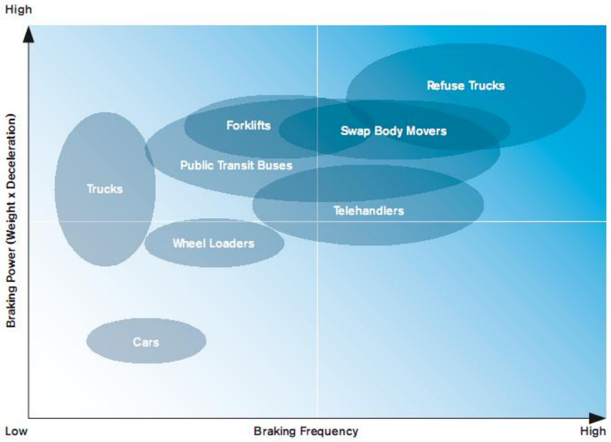


Figure 2: Influence of vehicle mass and driving cycle characteristics on RB potential [4].

Vehicles with high starting and stopping torques, i.e., high braking and acceleration forces, such as city buses can take the full advantage that the hydraulic hybrid 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. The Hydraulic Hybrid excels in quite different circumstances: the power from the braking process is reused in the following acceleration phase. Since the hydraulic hybrid regenerative braking system (HRBS) stores the vehicle's kinetic energy, benefits are amplified with increased vehicle mass and deceleration (braking power) and with increased braking frequency (Figure 2).

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 more than 60 % of energy harnessed during deceleration can be returned into the next acceleration phase (Figure 3). The lower individual machines' efficiencies, and in particular the inability of the battery to store energy at high rates, are responsible for the significantly lower RB efficiencies attained with the EH concept (less than 20 %, Figure 4).

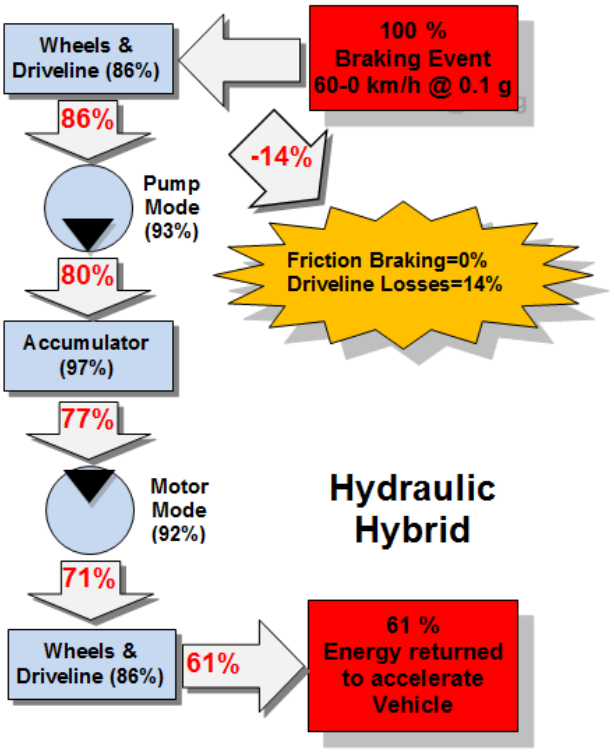


Figure 3: Overall regenerative braking energy efficiency of a hydraulic hybrid concept [5].

With regard to considerations relating to the exact configuration of the hydraulic hybrid system elements in a vehicle's drivetrain, two basic arrangements are possible: parallel and series hybrid.

In a parallel Hydraulic Hybrid (Figure 7), 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 stored in the high pressure accumulator. During acceleration, the entire process is reversed: the pressurized fluid in the accumulator is allowed to be discharged 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 % [5]. For that reason, parallel hybrids are commonly known as “mild hybrids”.

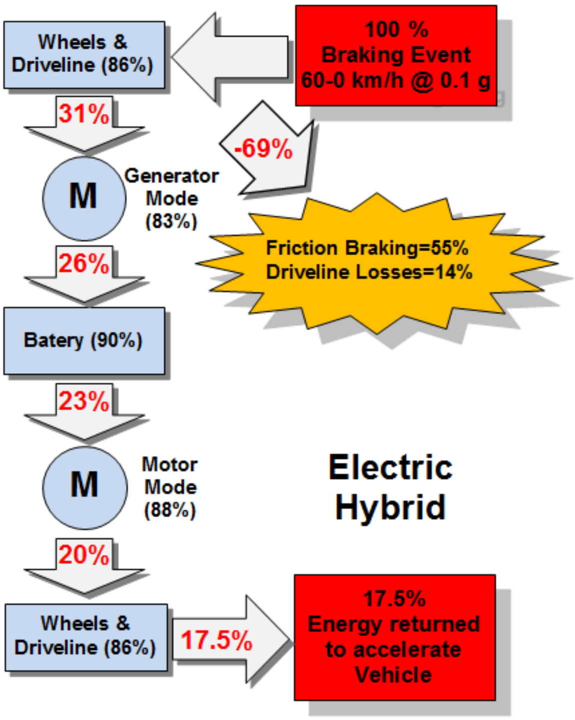


Figure 4: Overall regenerative braking energy efficiency of an electric hybrid concept [5].

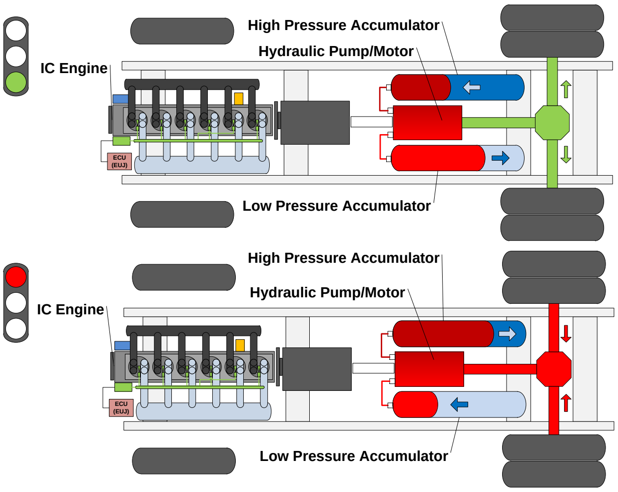


Figure 5: Hydraulic Hybrid Regenerative Braking phases.

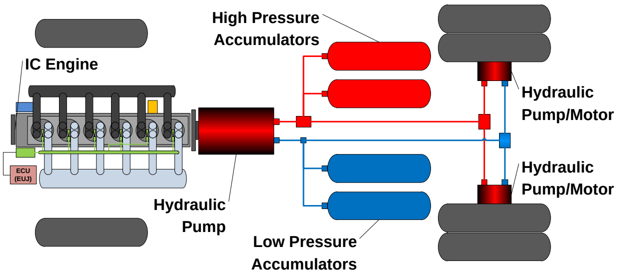


Figure 6: Series Hydraulic Hybrid configuration.

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 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 allows the IC Engine to operate with higher efficiency by moving the operating points toward higher brake mean effective pressures. The vehicle recovers and stores energy in practically the same way as Parallel Hydraulic Hybrid vehicles do. Even though hydraulic components create more losses compared to the conventional mechanical transmission elements, these losses are offset by the energy that is recuperated during braking phases. Powertrain control possibilities are maximized.

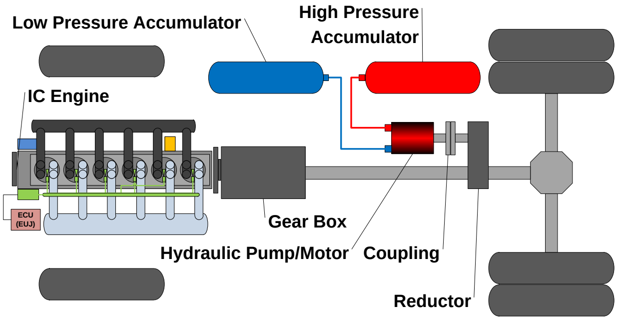


Figure 7: Parallel Hydraulic Hybrid configuration.

3 ANALYSIS OF HYDRAULIC HYBRIDS’ POTENTIAL BENEFITS

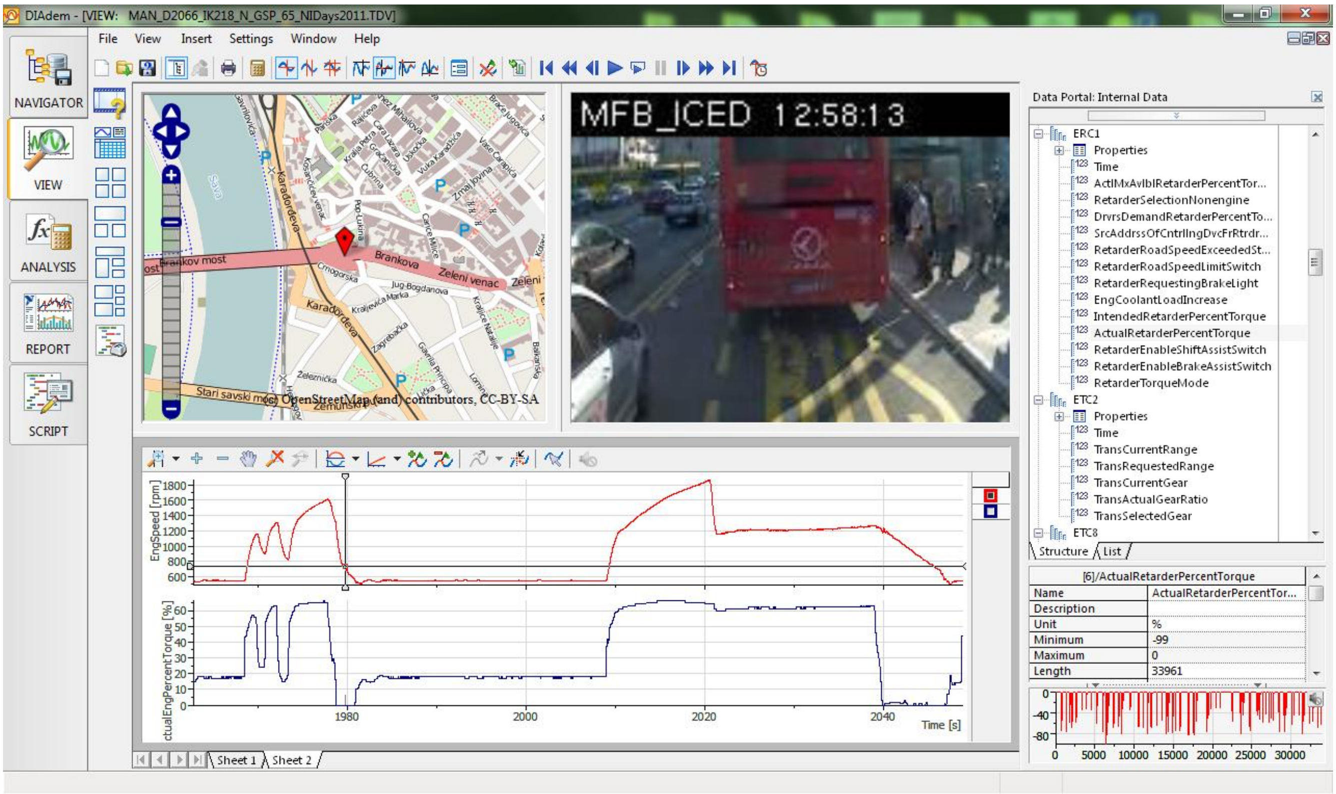
Utilizing Hydraulic Hybrid technology only for regenerative braking purposes can lead to fuel savings of up to 25 % [3, 6, and 7]. Corresponding reduction in CO_2 emissions is an additional benefit. The acceleration response, allowed by hydraulic power assist, can be improved by as much as 25 % (0-50 km/h [8]).

In a Series Hybrid Hydraulic System, the demonstrated fuel economy improvement is significant (fuel savings of approximately 60-80% [5, 6] are achieved).

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%

Table 1: Improvements in fuel economy with different HHT concepts and control strategies [7].

An experiment consisting of simultaneous logging of J1939 CAN powertrain parameters and GPS tracking data was conducted on a transit bus in Belgrade. The bus line in question was the number 65, connecting Novi Beograd and Zvezdara municipalities. This has allowed us to obtain the driving cycle of a bus circulating in real traffic and occupancy conditions, permitting us to proceed with fuel consumption calculations involving alternative powertrain configurations, and in particular the hydraulic hybrid system.



[6]/ActualRetarderPercentTorque

Name	ActualRetarderPercentTor...
Description	
Unit	%
Minimum	-99
Maximum	0
Length	33961

Figure 8: Analysis of logged data.

		Driving cycle 1 start: 06:03:15	Driving cycle 2 start: 13:10:35	Driving cycle 3 start: 15:11:09
Effective Engine Work	[MJ]	272.2	263.1	248.4
Deceleration Energy	[MJ]	122.3	123.8	106.9
Total Fuel Consumed	[l]	20.0	20.0	18.7
CO_2 Emissions	[kg]	53.4	53.3	50.0
Trip Time	[s]	5962	6731	6823
Deceleration/Engine Work Ratio	[-]	0.45	0.47	0.43
Energy Savings Potentials	**[%]**	**27.0**	**28.2**	**25.8**
CO_2 Emission Reduction Potentials	**[kg]**	**14.4**	**15.0**	**12.9**

Table 2: Initial energy analysis based on data acquired during the experiment.

		Driving cycle 1 start: 06:03:15	Driving cycle 2 start: 13:10:35	Driving cycle 3 start: 15:11:09
Total fuel consumed	[l]	20.0	20.0	18.7
Fuel consumed during stops	[l]	3.75	3.79	4.17
Percent of fuel consumed during stops	**[%]**	**18.8**	**19.0**	**22.2**
Fuel consumed at bus stops	[l]	1.93	2.22	1.70
Fuel consumed due to traffic stops	[l]	1.83	1.58	2.47

Table 3: Analysis of fuel consumption when bus is stationary.

The experiment was conducted on an Ikarbus IK218N, equipped with a MAN D2066 LOH1, 10.5 l, 6-cylinder, turbocharged diesel engine and a Voith 864.5 transmission. A single driving cycle consists of a complete run from Zvezdara to Novi Beograd and back to the starting point (Zvezdara). Results of the initial analysis of data gathered during the experiment are shown in Table 2.

The effective engine work calculation is based on the actual percent torque and friction percent torque data channels that are accessible on the J1939 bus. Values of up to 272 MJ per complete driving cycle are achieved.

The maximum value corresponds to the shortest trip time, meaning that the higher vehicle speeds achieved due to less congestion are correlated with the effective energy delivered to the drivetrain.

The deceleration energy is calculated under the assumption of constant vehicle mass of 23000 kg and accounts only for decelerating periods with fuel cut-off or braking states on. Values up to 124 MJ are obtained, representing nearly 50 % of energy transferred to the vehicle. The minimum value is encountered during the third run, which is associated with the maximum trip time. Because the vehicle speeds are significantly lower than during other runs, the braking energy is also diminished. However, even during this run, the deceleration/engine work ratio is greater than 40 %, which represents a great energy recovery potential.

The total fuel consumed, along with the CO_2 emission, is calculated by integration of the fuel rate data available on the J1939 bus.

The estimated energy savings parameter is based on the assumption that 60 % of the deceleration energy can be reused to accelerate the vehicle. Values range from 25.8 to over 28 %.

It can be said that, regardless of traffic and occupancy conditions or the driving cycle’s road profile, more than 20 % of fuel can be saved with the implementation of a Hydraulic Hybrid Powertrain. Bearing in mind that 100000 kg of fuel is used by Belgrade’s transportation system on a daily basis, this worst-case scenario fuel reduction figure shows that huge amounts of savings can be achieved: over 30000 € could be preserved each day, effectively containing the payback period of a single vehicle to no more than 5 days. The payback period of a single, HHT-equipped bus is approximately 5 years (for a completely new vehicle, not taking into account predicted savings in brake system maintenance costs). Considering the daily fuel consumption of the transportation system, a significant reduction in CO_2 emission in excess of 60000 kg per day can be achieved.

Another possibility for a viable fuel efficiency improvement lies in periods during which vehicles are at bus terminuses, where turning occurs. It has been determined that the mean time a vehicle spends at a terminus is approximately 8 minutes. The minimal idle fuel consumption rate of the bus considered during this experiment is 4.3 l/h, which means that over 0.57 l of fuel is consumed during these events. Bearing in mind that over 20 turning events occur for a bus circulating on line 65, over 11 l of fuel could be preserved per day and per vehicle if a start-stop system is implemented. It should be noted that engines are presently being held turned on because of problems frequently encountered when restarting.

Analysis on data acquired during the experiment to quantify fuel consumption for periods of time during which the bus was stationary has yielded interesting results (Table 3). Indeed, it is concluded that more than 18 % of the total fuel consumed during a driving cycle is spent while the vehicle isn’t moving. This percentage ranges from 18.8 % to 22.2 % while covering driving cycles for which substantially different occupancy and traffic conditions were encountered. This represents a significant potential for fuel consumption reduction. A start-stop system capable of sustaining critical vehicle accessories while the engine is turned off could bring pronounced economy benefits.

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 could be improved by using stored hydraulic energy. Auxiliaries can be downsized and optimized since they can run at given speed, independently of the engine’s speed. They can also be driven by a single, engine-powered hydraulic pump.

According to Eaton [5], capturing 70 % of braking energy via hydraulic fluid can reduce brake wear by more than 50 %. Public transportation vehicles generally require intensive brake system maintenance. Savings accomplished through brake system maintenance reduction only are comparable to 50 % of HH system implementation costs (for low volume production). Besides maintenance costs, reduced brake wear has favorable effect on the environment with reduced emission of fine dust particles from brake pads.

The only clear advantage Electric Hybrids have over Hydraulic Hybrid technology, regarding the implementation on transit buses, is related to noise levels of the corresponding components. Noise generated by hydraulic components is mainly influenced by their number and design aspects (parallel, series concept). However, 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 [9, 10].

Beside the high potentials for fuel economy and exhaust emission improvements, Hydraulic Hybrids offer the lowest incremental costs among all hybrid concepts. The estimated costs for retrofitting a transit 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, is predicted to lead to significant initial costs reduction (up to 75 %).

4 CONCLUSIONS

The characteristics of the components used as part of the Hydraulic Hybrid concept, namely, the high power density of the hydro-pneumatic accumulator and the pump/motors, along with high efficiencies, make it ideally suited for implementation on transit buses. Developed and tested prototypes and demo platforms have demonstrated significant performance improvements in terms of fuel economy (up to 60 %) and pollutants emission reduction. The energy balance analysis of data acquired during an experiment conducted on-board a transit bus circulating in real traffic and occupancy conditions agrees well with figures obtained from other research teams around the world. However, further efforts concerning the integration of hydraulic components in 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.

5 REFERENCES

[1] Hui, S., 2010, Multi-objective optimization for hydraulic hybrid vehicle based on adaptive simulated annealing genetic algorithm, Engineering Applications of Artificial Intelligence, 23, 5, pp. 27-33

[2] Hui, S., Ji-Hai, J. and Xin, W., 2009, Torque control strategy for a parallel hydraulic hybrid vehicle, Journal of Terramechanics, 46, 6, pp. 259-265

[3] Kliffken, M., Beck, M., Ehret, C. and Stawiarski, R., 2009, Put the Brake on Costs and Preserve the Environment with Hydraulic Hybrid Drive, ATZoffhighway 1, 3

[4] Hydraulic Hybrids from Rexroth: Hydrostatic Regenerative Braking System HRB, http://www.boschrexroth.com/country_units/america/united_states/sub_websites/brus_brh_m/en/markets_applications_jg/a_downloads/ra98310_2010-08.pdf

[5] Wendel, G., 2007, Hydraulic Hybrid Technology Review

[6] Gray, C.L., 2006, Hydraulic Hybrids: EPA Hydraulic Truck Initiative, U.S. Environmental Protection Agency, Houston, Texas, USA

[7] Gray, C.L., 2007, Hydraulic Hybrids: Demonstration for Port Yard Hostlers, U.S. Environmental Protection Agency

[8] Kepner, R.P., 2002, Hydraulic Power Assist − A Demonstration of Hydraulic Hybrid Vehicle Regenerative Braking in a Road Vehicle Application, International Truck & Bus Meeting & Exhibition, Detroit, MI, USA, SAE 2002-01-3128

[9] Wendel, G. and Jackson, T., 2006, Balance of Power, Technology Today, 27, p. 32

[10] Innas - Floating Cup, http://www.innas.com/FC.html