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HYDRAULIC-PNEUMATIC REGENERATIVE BRAKING SYSTEM FOR HYBRIDIZATION OF COMMERCIAL URBAN VEHICLES

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Abstract: *This article presents a new concept of hybrid powertrain for commercial vehicles. The proposed system is comprised of a hydraulic system integrated to a pneumatic system, which enables the conversion of braking energy into potential energy. Unlike the current hybrid-hydraulic systems, the hybrid vehicle concept presented herein adds a pneumatic system for the production of compressed air. Compressed air can be used to supply the pneumatic auxiliary devices of the vehicle such as brakes, chassis suspension, doors opening and closing, among other applications. In addition, the proposed design has greater energy storage capacity compared to the volumetric capacity of hydraulic accumulators, usually characterized by their low energy density. In this context, the dynamic simulation responses of a hybrid bus are shown in similar conditions to that found in urban driving cycle. During the deceleration, the hydraulic-pneumatic system is used as a regenerative braking system and, during the increase of speed the hybrid system assists the engine in the acceleration work. The results show that the proposed hybridization generates fuel economy for the vehicle above 10 % and that regenerative braking is able to provide compressed air network autonomy.*

Keywords: *Hybrid Commercial Vehicles. Hybrid-Hydraulic Systems. Hybrid-Pneumatic Systems. Hybrid-Hydropneumatic Systems.*

NOTATION

Hydraulic system model

ε_p	pump/motor displacement ratio	
ε_m	motor displacement ratio	
ω_m	hydraulic motor angular speed	[rad/s]
τ_m	hydraulic motor torque	[N m]
$\tau_{p/m}$	pump/motor torque	[N m]
qv_m	motor flow rate	[m³/s]
qv_{ac}	flow rate into and of the accumulators	[m³/s]
qv_{RV}	flow rate relieved through the relief valve	[m³/s]
qv_{PV}	flow rate discharged through the proportional valve (1V1)	[m³/s]

Pneumatic and Vehicle model

τ_{cardan}	torque generated at the cardan shaft	[N m]
ω_{cardan}	angular speed generated at the cardan shaft	[rad/s]
$\alpha_{throttle}$	acceleration signal	
α_{brake}	braking signal	
α_{slope}	road inclination	
v_{vehi}	vehicle speed	[m/s]
i_T	vehicle transmission ratio	
i_H	hybrid system gearbox transmission ratio	
i_D	differential transmission ratio	

qv_p	pump/motor flow rate	[m³/s]	H_{clutch}	hybrid system clutch signal	
$qv_{suction}$	suction flowrate at pump/motor inlet	[m³/s]	Z_{b1}	braking intensity	
qv_{return}	flowrate of return line	[m³/s]			
p_H	Hydraulic circuit pressure	[m³/s]	τ_c	compressor torque	[N m]
p_{cc}	accumulators pressure	[Pa]	p_{air}	air pressure	[Pa]
U_{1V1}	electric input signal used to command the valve (1V1)	[V]	N_c	number of stages of the compressor	
U_{1V3}	electric input signal used to command the valve (1V3)	[V]	E_{air}	air reservoir energy	[J]

1. INTRODUCTION

Hybrid vehicles are defined as those that have more than one propulsion power source (REDING, 2007). The integration of different technologies used for power generation and energy recovery is particularly interesting for hybrid commercial vehicles, since weight and space restrictions are not as stringent as those found in small passenger vehicles. Hybrid vehicles have the potential to reduce both petroleum usage and greenhouse gas emissions. The fuel consumption improvement can be attained by hybridization in several ways. These ways are related to the regenerative braking, engine downsizing, stop-start system (which shuts down and restarts the internal combustion engine automatically), change in the engine operating region in times of low power demand, and so on (GUZZELLA *et al.*, 2010; GUZZELLA e SCIARRETTA, 2007).

Regenerative braking refers to a process in which a portion of the kinetic energy of the hybrid vehicle is stored by a short-term storage system. Energy normally dissipated in the brakes is directed by a power transmission system to the energy storage system during deceleration. That energy is held until required again by the vehicle, whereby it is converted back into mechanical energy and used to accelerate the vehicle or assist the auxiliary devices. The magnitude of the portion available for energy storage varies according to the type of storage, drive train efficiency, drive cycle and inertia weight (DROZDZ, 2005; GUZZELLA e SCIARRETTA, 2007).

Since regenerative braking results in an increase in energy output for a given energy input, the efficiency is improved. The amount of work done by the engine of the vehicle is reduced, in turn, reducing the amount of prime energy required to propel the vehicle. In order for a regenerative braking system to be cost effective, the prime energy saved over a specified lifetime must offset the initial cost, size and weight penalties of the system. The energy storage unit must be compact, durable and capable of handling high power levels efficiently, and any auxiliary energy transfer or energy conversion equipment must be efficient, compact and of reasonable cost (DE OLIVEIRA *et al.*, 2014; GUZZELLA e SCIARRETTA, 2007).

Heavy commercial vehicles, with a high stop & go frequency, like refuse trucks or parcel delivery vehicles, produce in a short time a huge amount of energy. This energy is converted into wasted heat and given off, unused into the environment, when the vehicle brakes again. This, in comparison to other commercial vehicles, leads to an above-average higher fuel consumption, as well as wear on the brakes (LINDZUS, 2010). In heavy vehicles, significantly more power is needed to accelerate the vehicles, which in turn means there is considerably more power during deceleration as well. This fact gives a distinct advantage for using hydraulic hybrid technologies for heavy vehicle applications. Studies have shown that hydraulic-hybrid vehicles can use up to 30% less fuel than their conventional counterparts for start-stop duty cycles and reduce brake wear by up to 50 percent (LINDZUS, 2010; MIDGLEY e CEBON, 2011; RYDBERG, 2009). Previous work by Midgley and Cebon (MIDGLEY e CEBON, 2012) concluded that hydraulic systems would be 20% lighter and 33% smaller than electrical or mechanical (flywheel) hybrid powertrains. Based on this and analysis of criteria such as the cost, durability and packaging, hydraulic systems were found to be well suited to urban hybrid vehicles applications (MIDGLEY; CATHCART; CEBON, 2013; ZENG, 2009).

One marketed by Parker Hydraulics, which claims fuel usage reductions of between 30% and 50%, and one built by Eaton Hydraulics. The refuse vehicle by Eaton Hydraulics is a parallel hybrid, whereas that by Parker Hydraulics is a power-split architecture hybrid (ECHTER, 2012; MIDGLEY *et al.*, 2013).

In the electric-hybrid systems for heavy commercial vehicles, the batteries must be replaced after 3-4 years, which calls for extra work and extra costs. This replacement is not needed with a hydraulic system. All main components are designed to the lifespan of the vehicle. The components require only little maintenance effort, which can be handled by a vehicle workshop with experience with hydraulic implements (LINDZUS, 2010).

Hydraulic accumulators offer a good range of sizes, fast response to pressure variation, and provides high power output, whose characteristics are essential to supply energy to the hybrid powertrain in heavy vehicles, in which significantly more power is needed to accelerate and decelerate the vehicle (LINDZUS, 2010; LINSINGEN, 2011). Conversely, gas accumulators have low energy density, which severely limits the quantity of energy recovered, which is the main constraint of this type of technology (HUI; LIFU; JUNQING, 2010).

In this way, this article presents a new concept of a hybrid system, which integrates a pneumatic unit to the current hybrids-hydraulic system already used in heavy vehicles, such as buses and refuse trucks. This architecture is characterized by the possibility of increasing the energy density of the system and still supply the compressed air demands for the auxiliary devices of the vehicle. In order to determine the energy recovery capacity and its potential to provide fuel economy, a mathematical model of the system is developed by which the vehicle is tested under conditions similar to those found in urban traffic. Two ratios of the transmission system, which connect the hydraulic-pneumatic circuit to the vehicle shaft are evaluated in order to compare the results obtained from the hydraulic and pneumatic storage systems independently.

The article can be divided into the following parts: Section 2 describes the operation of the hydraulic-pneumatic system. Section 3 presents the procedures followed to obtain the results and the specifications of the main components of the system. Section 4 discusses the simulation responses and Section 5 presents the conclusions of the work.

2. DESCRIPTION

The hydraulic-pneumatic system components are based on serial production components, which has been producing since years. This ensures good availability, reproducible quality and a system lifetime on vehicle level. The diagram in Figure 1 shows the circuit of the parallel hydraulic-pneumatic regenerative system.

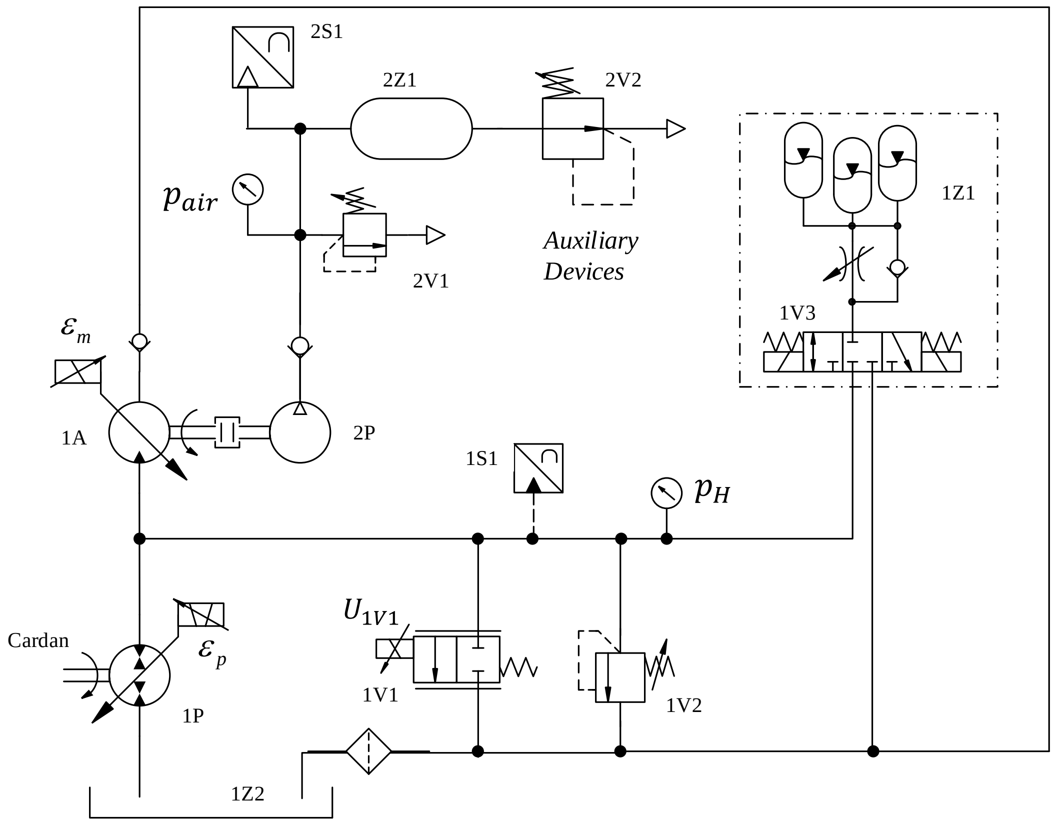

Figure 1. Hydraulic-pneumatic regenerative braking system diagram. Adapted from (BRAVO, 2017).

Hydraulic regenerative braking uses the differential pressure of hydropneumatic accumulators (1Z1) to drive a variable axial piston unit (1P), as shown in Figure 1. During deceleration the fluid is pumped from a low-pressure reservoir (1Z2) into a high-pressure accumulators (1Z1) or to the hydraulic motor (1A), providing braking torque at the vehicle wheels and driving torque to the air compressor (2P), respectively. A gearbox connects the pump/motor (1P) to the mechanical drive train (cardan shaft) to convert kinetic energy into potential energy when braking. In order to prioritize the accumulators charging, the motor speed (1A) is maintained at low speed, of 1500 rev/ min. The speed adjust is made by the motor volumetric displacement ε_m control. The proportional directional valve (1V1) is used to restrain the maximum speed of the air compressor (2P), aiming to avoid that this value is higher than the manufacturer indication. The pneumatic energy absorbed in the air reservoir (2Z1) can be used in the auxiliary devices of the vehicle, as brakes and chassis suspension.

During acceleration the process is reversed: the high-pressure fluid is used to drive the pump/motor and provide a positive torque to the wheels and the return fluid flows back into the low-pressure reservoir (1Z2). The variable piston unit (1P) is driven by the hydraulic pressure and acting as a motor, transferring its energy to the mechanical drive train and relieving the existing combustion engine. In this situation, the motor (1A) volumetric displacement ε_m is kept at minimum displacement, i.e., $\varepsilon_m \cong 0$. Any fluid deviated from the circuit by valves or drains is re-circulated to the system reservoir (1Z2). An electronic controller along with a hydraulic valves manifold controls all this process.

3. METHODOLOGY

A mathematical model was developed to represent the mechanical, hydraulic and pneumatic subsystems of the hybrid vehicle. With the purpose of validate the model an experimental unit was built in a scale of 1:20. Experimental results and responses comparison are detailed in (BRAVO, 2017).

In order to evaluate the real vehicle performance under city traffic conditions, a 19-ton bus, 420 hp is analyzed (VOLVO, 2012). Simulation results were obtained with the validated model. The data of the bus model were obtained through catalogs, technical literature and scientific publications. The block diagram presented in Figure 2 provides a fast overview of the developed model. The MATLAB/ SIMULINK software was used as a modeling and simulation tool.

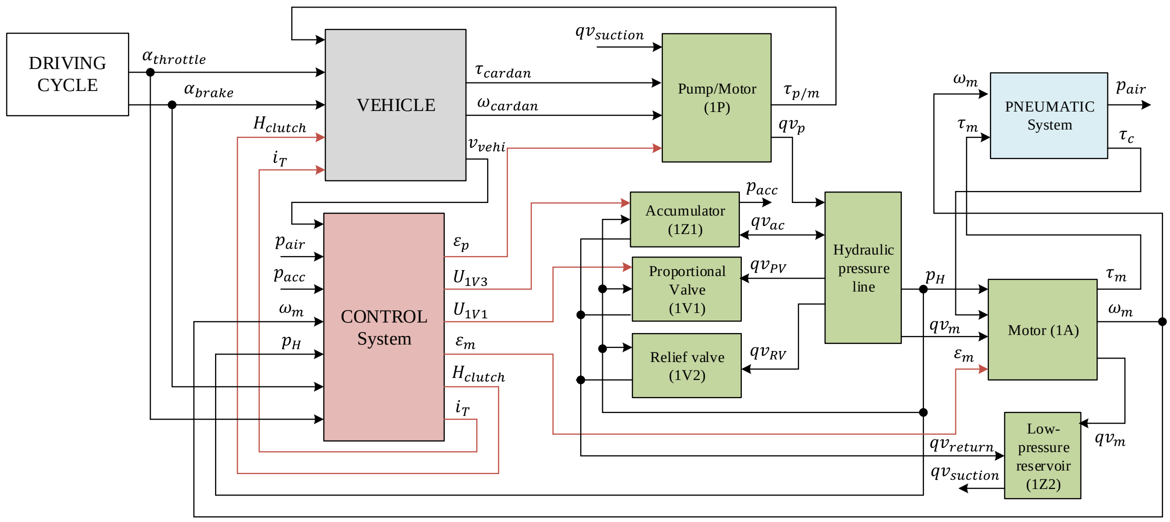

Figure 2. Simplified model of the system. Adapted from (BRAVO, 2017).

To control the hybrid system in the simulation platform, five operating modes were developed with the following goals (BRAVO; DE NEGRI; DE OLIVEIRA JUNIOR, 2016):

- to recover energy through regenerative braking;
- to use the recovered energy for compressed air production and
- to assist the engine during the start-stop episodes.

General structure of the hybrid control system is shown in Figure 3 according to (BRAVO *et al.*, 2016).

Two operating modes are used in *regenerative braking* on slopes or in short braking, respectively, assigned *REGENERATIVE BRAKING MODES 1 and 2* (RG_{M1} and RG_{M2}). Two other modes, called *CHARGING MODE 1 and 2* (CH_{M1} and CH_{M2}), are activated when the compressed air state of charge is low, i.e. when the working air pressure of the vehicle reaches a minimum value required by the auxiliary devices. In this situation, the power supply for air production comes from the engine or from the potential energy stored in the accumulators, respectively.

The fifth mode, named *POWER ASSIST MODE* (PA_M), applies the energy stored in the accumulators for mechanical power generation, which is used to assist the vehicle driving system during the periods of acceleration. In this article only the modes used in urban traffic, that is, *REGENERATIVE MODE* 2 and *POWER ASSIST MODE* will be discussed.

The tests described are carried out to evaluate the regeneration process and the use of energy recovered during the vehicle motion. The driving cycle conditions were:

- The vehicle is subjected to start-stop successive episodes using the hydraulic system as braking system, and as an auxiliary power unit to the internal combustion engine. After reaching steady-state speed, the vehicle is decelerated by the braking torque produced exclusively by the pump/motor (1P).

- Initial speed of the vehicle, $v_{vehi\_i} = 70$ km/h. At time $t = 0$ s, the vehicle is decelerated until its stop.

- At the time 100, 300 and 500 s the vehicle is accelerated to a speed of 40 km/h; at the time 0, 200, 400 and 600 s, the vehicle is decelerated until its total stop.

- In the deceleration period, the motor (1A) rotational frequency is maintained by the control system in $n_m \cong 1500$ rev/min in order to distribute the pump/motor flow rate in a controlled manner, however, seeking out to prioritize the charging of the accumulators.

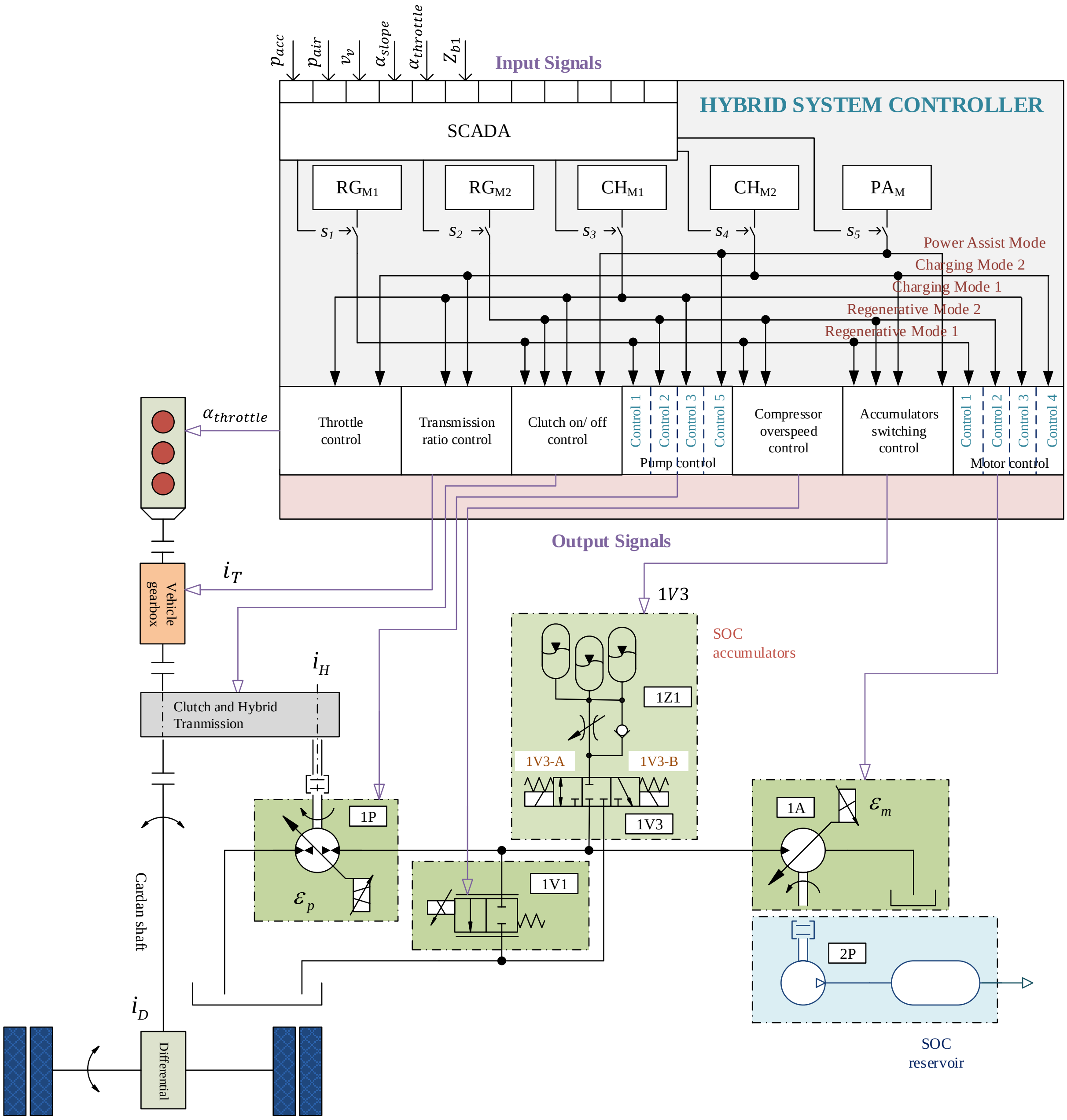

Figure 3. General structure of a hybrid system controller (BRAVO, 2017).

The reference speed choice of the hydraulic motor made by SCADA determines the distribution of energy from the pump/motor to the storage systems. In this way, when the compressed air pressure is low, the speed of the hydraulic motor can be increased with consequent increase of the compressed air production. Conversely, if the air pressure is high, the hydraulic motor speed can be reduced in order to prioritize the charging of the accumulators.

- Three accumulators (1Z1) of 32 L each and an air reservoir (2Z1) of 120 L are used. The selected rated size for pump/motor (1P) is 180 cm³/rev and for compressor (two stages) is 880 cm³/rev. Hydraulic motor (1A) size is 30 cm³/rev, which was sized based on compressor power requirements. In all accumulators up to 0,275 KWh can be stored, accordant to the kinetic energy from braking of 40 km/h down to 0 km/h minus all losses (rolling friction, aerodynamic resistance, etc.).
- Initial pressure in the air reservoir is $p_{air} = 500$ kPa. An initial compressed air pressure is set in the SCADA (Supervisory Control and Data Acquisition) to ensure that the energy absorbed by the accumulators at the initial instants of the test is used to assist the vehicle traction effort, rather than being used to charge the air reservoir[1].
- A ramp function was used as the reference signal to command the acceleration of the vehicle.

[1] When air pressure in either the primary or secondary brakes reservoir falls below the minimum amount required to bring the vehicle to a safe stop, the control system prioritizes the charging of the pneumatic reservoir.

The use of the ramp function allows for controlling of the engine rotational frequency so that the vehicle acceleration is progressive. In other words, the control system can act on the vehicle's transmission ratio during periods of acceleration when the vehicle's driving system is aided by the hydraulic system. The goal is to improve the efficiency of the engine.

The operating modes are enabled by Boolean logic functions. As shown in Figure 3, s_1, s_2, s_3, s_4 and s_5 are the logic switching signals used to select the proper operational mode. Hence, $RG_{M1} = 1$ if $s_1 = 1$, $RG_{M2} = 1$ if $s_2 = 1$, $CH_{M1} = 1$ if $s_3 = 1$, $CH_{M2} = 1$ if $s_4 = 1$ and $PA_M = 1$ if $s_5 = 1$, according to (BRAVO *et al.*, 2016). In the next section the tests results are presented and discussed.

4. RESULTS AND DISCUSSION

In this section, the results obtained under the conditions where the hybrid vehicle is performing the driving cycle described in the previous section are shown.

The Figure 4 shows the speed variation of the vehicle over the test, as well as the evolution of fuel consumption and the compressed air production rate. Considering the compressed air response, it is noted that at the beginning of the test when the vehicle is decelerating, there is a larger compressed air production rate. The high initial value of the amount of air produced per kilometer covered, denominated in the graph of *air specific energy*, is because in the initial instants the vehicle is in the regenerative mode only, whereas later the conversion of mechanical energy into compressed air is accomplished only in part of the path. Hence, for the city traffic conditions, the pneumatic system produces on a quasi-static basis around 110 kJ/ km, which makes the air network self-sustaining. In other words, the hydraulic-pneumatic unit can replace the conventional compressed air network usually installed in commercial vehicles since the hybrid system already fulfills this role. Figure 5 shows the increase of the air pressure as the vehicle slow down. In this case, the air pressure increases around 300 kPa during each episode of regenerative braking.

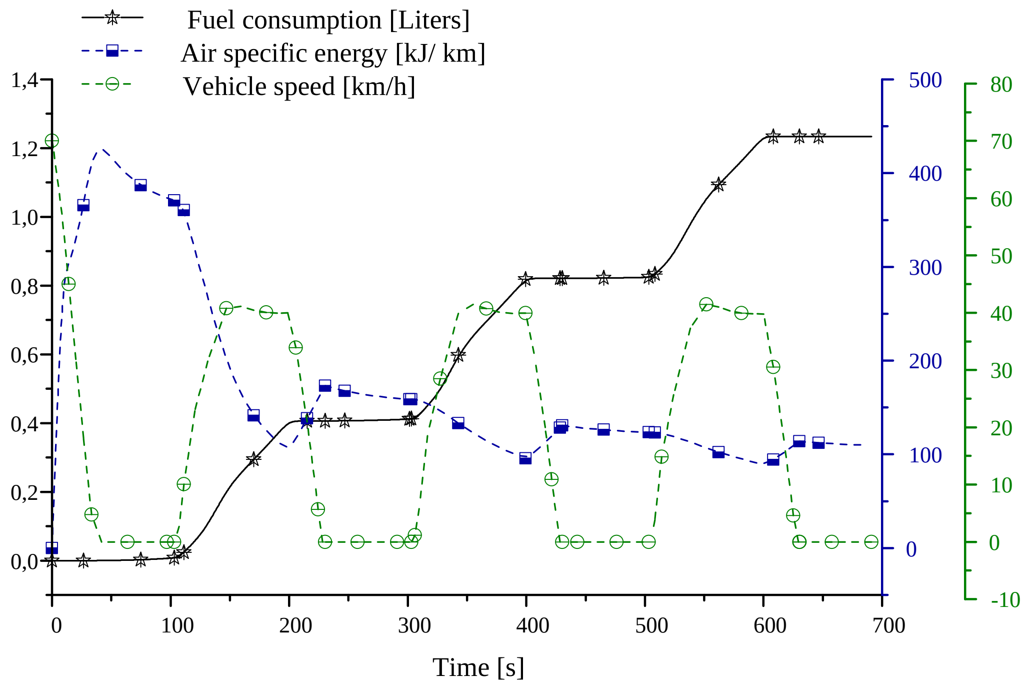

Figure 4. Hybrid vehicle responses.

In Figure 6 the charging curves of the hydraulic accumulators and the total charging curves of the hybrid system are shown, which include the charging of the compressed air reservoir, where $E_{Total} = E_{acc} + E_{air}$. The responses compare the amounts of energy E recovered, considering two options of the transmission ratio i_H of the hybrid system. The lower ratio of 1.76 is recommended for hybrid road vehicles whose characteristic is to recover energy in braking episodes on long-distance slopes at higher speeds. However, for short-term braking recurring in urban traffic, the use of a higher gear ratio, in this case of 3.2, results in increased braking torque and pump/motor speed with consequent reduction of the distance displaced by the vehicle and the charging time of the accumulators.

It is noted that for the operating condition where the gear ratio is 1.76, the full charge of the accumulators is not achieved, except for the first stop, where the initial speed is 70 km/ h. On the other hand, the accumulators' state of charge reaches the maximum level for the configuration with the transmission ratio of 3.2, in which the best result in fuel economy is obtained. However, due to the smaller distance traveled under braking, the amount of compressed air produced in this condition also becomes smaller, as shown in Figure 5.

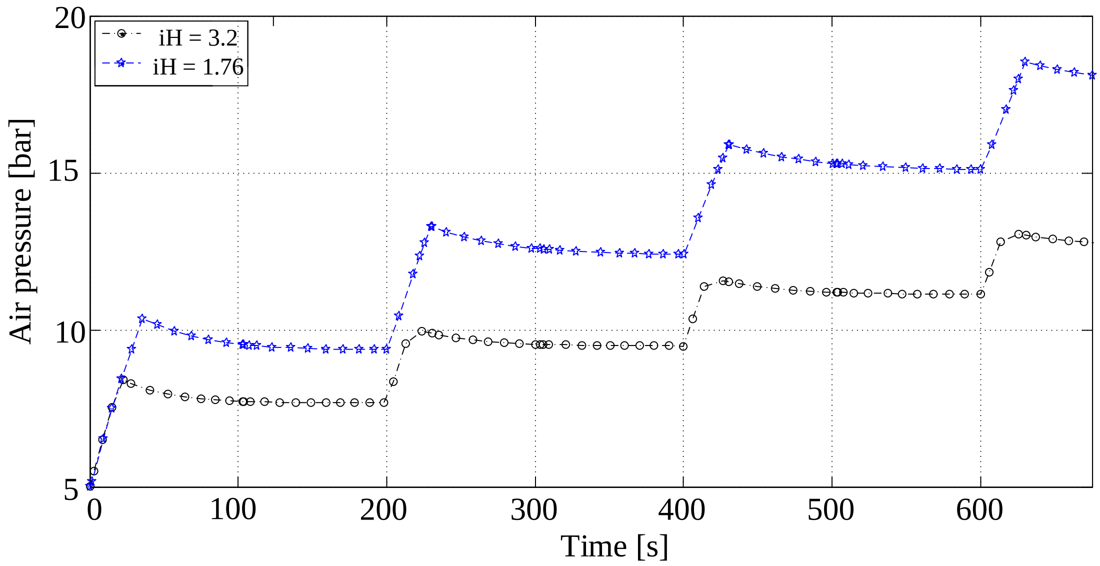

Figure 5. Pneumatic system response.

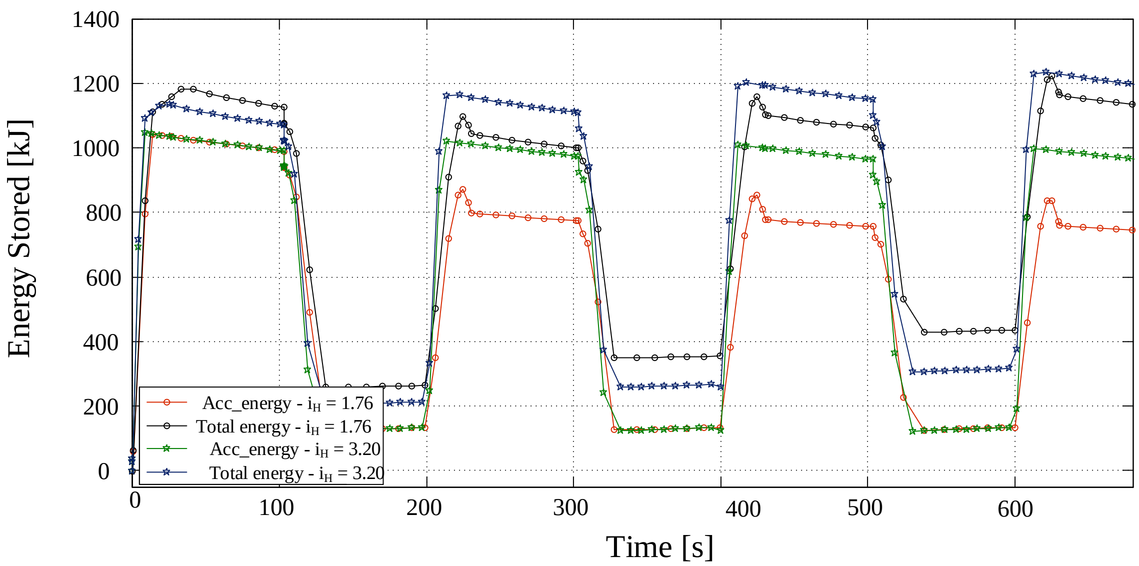

Figure 6. Storage system responses.

Finally, the quantities of energy of the vehicle and hybrid system during the proposed driving cycle are shown in Figure 7, where $i_H = 3.2$. The required mechanical energy from the combustion engine shaft was 17,800 kJ and 19,855 kJ, with and without assist of the hydraulic-pneumatic system, respectively. The energy used to slow down the vehicle generated in the pump/motor was 8286 kJ, while only 2700 kJ of this amount were sent to the accumulators and 230 kJ were stored in the compressed air reservoir. Approximately 2/3 of the accumulators' power was used to aid the vehicle acceleration, i.e., 1800 kJ. The assistance of the hydraulic system to the engine in the PA_M generated a fuel economy of 10.1%, whose value is approximately proportional to the useful energy released by the accumulators.

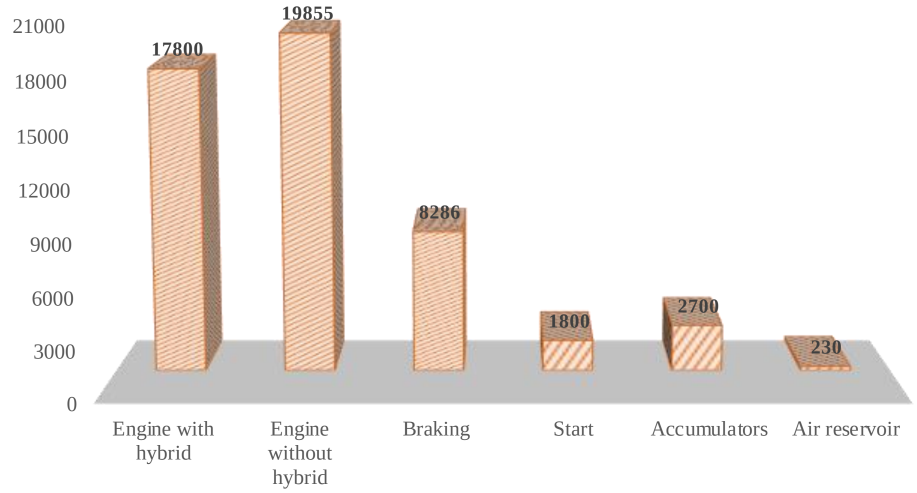

Figure 7. Transferred energy to the hybrid system parts.

5. CONCLUSIONS

The hybrid vehicle results in the urban traffic showed that the energy recovery from the regenerative braking system presented in this article is able to improve the vehicle efficiency above 10%. However, the low energy density of the hydraulic accumulators limits severely the amount of energy recovered, and consequently the amount of energy released during vehicle acceleration. Therefore, the energy storage capacity of the accumulators is directly related to the fuel economy afforded by vehicle hybridization.

Two options of the gear reducer transmission ratio, which connect the hydraulic system to the cardan shaft were evaluated. The comparison indicated that the transmission ratio of 3.2 allows to fully charge the accumulators and reduce the braking distance approximately in the same proportion of increased of the transmission ratio, i.e. 1.82 times. On the other hand, there was less compressed air production due to the diminishing of the braking time.

Other advantage achieved with the presented solution is the simultaneous production of compressed air during the braking, which can provides autonomy for the air system and replaces the conventional compressed air production unit. With the integration of the pneumatic system, the capture capacity has been increased by 5%, that is, in each braking is absorbed on average, at least 50 kJ of extra energy when the transmission ratio of 3.2 is selected.

6. ACKNOWLEDGEMENTS

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