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Mechatronic Systems for Kinetic Energy Recovery at the Braking of Motor Vehicles

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1. Introduction

Vehicle manufacturers are continually concerned with reducing fuel consumption and lowering polluting emissions. (Gauchia & Sanz, 2010). Besides the vehicles which use liquefied gas, methanol, electricity or fuel cells, also, there have been designed and manufactured diferent *hybrid propulsion motor vehicles*. (Toyota, 2008; Permo Drive, 2009; Eaton, 2011).

It is known that during a work cycle of a motor vehicle, which consists of a period of acceleration, another one of running at constant speed and a period of deceleration, the power required during acceleration is much greater than that required while running at constant speed and, in principle, it is this power what determines the size of engine installed on the motor vehicle. Upon vehicle braking, kinetic energy acquired by acceleration of the motor vehicle is converted into heat energy, which is located in the braking system and gets lost, irreversibly, into space, with negative effects on *global warming*. So, rightfully, there has been formulated the technical problem that, during the motor vehicle braking stage, the kinetic energy gained by it to be recovered and stored in power batteries and then used during start-up and acceleration stages. Therefore, vehicle manufacturers consider that one of radical solutions in order to achieve the above mentioned goals is a deep change of motor vehicle propulsion method, promoting *hybrid propulsion systems*, which are considered to be solutions for the near future, for a substantial decrease of fuel consumption and polluting emissions. Propulsion systems that are composed of, besides a conventional propulsion system with an internal combustion engine, at least another one based on another type of energy, capable of providing torque/traction moment at the motor vehicle wheels, form a hybrid propulsion system. If they, along with propulsion, can recover, during braking stage, part of the kinetic energy accumulated in the acceleration stages, and then they are called hybrid regenerative systems. A feature of *regenerative hybrid vehicles* is that they include components that capture and *store kinetic energy* of the vehicle during braking process, for it to be used later, or when accelerating or at constant speed movement. Systems for capturing and storing kinetic energy perform its converting and storing under different forms of energy, namely: as mechanical/ kinetic energy of a flywheel, as potential energy of a working fluid (liquid or gas), as electrochemical energy (Gauchia & Sanz, 2010)), or as electrostatic energy. To restore the recovered and stored energy, drive/propulsion systems are, also, of several types, namely: hydro-mechanical systems (hydrostatic or hydrodynamic), electromechanical systems (direct current or alternating current) and mechanical systems (mechanical or mechanic-inertial). Worldwide, various solutions have been designed for developing hybrid systems, but most common are hybrid systems with thermo-electric drive and hybrid systems with thermo-hydraulic drive. A special competition is under development between the *thermo-electric hybrid system*, (Toyota, 2011; Eaton, 2011), which, in addition to the heat engine, also has an electric propulsion system, and the *thermo-hydraulic hybrid system*, (Permo-Drive, 2011; Eaton, 2011a; Bosch Rexroth, 2011), which, in addition to the driving heat engine, has a hydraulic propulsion system. Compared with electric vehicles, characterized by a reduced autonomy of movement, *hybrid vehicles have many advantages*, Usually, the kinetic energy of the motor vehicle, accumulated in the accelerating phase, in the braking phase is converted in the thermal energy which is, normally and irremediable, wasted in atmosphere. Therefore, the main objectives of the *hybrid systems* are the *recovering kinetic energy* of the road motor vehicles and reducing the *fuel consumption* and *the environment pollution* (Parker Hannefin, 2010).

From the above presented issues, it is clear that hybrid propulsion systems are very complex systems, multidisciplinary and interdisciplinary. Also, they develop dynamic/transient operation modes, with rapid succession of events over time, difficult to drive and control with conventional means. Therefore, for such complex systems, the only technology able to manage, optimize and control in conditions of total safety, is *mechatronics technology*, for which reason *hybrid propulsion systems* represents *a new field of application of mechatronics* (Ardeleanu & al.; Cristescu et al., 2008b; 2007; Maties, 1998).

2. The mechatronic system for kinetic energy recovery at the braking of motor vehicles

Basic solution, adopted to achieve the kinetic energy recovery system for the braking stage, was that of kinetic energy recovery *by hydraulic means*, based on the use of a *hydraulic machine* which can operate both as a pump, during braking, and as an motor, during acceleration/start-up. In the braking stages, the mechanical/kinetic energy of the motor vehicle is *converted* by the hydraulic machine, which is working as a pump, into hydraulic/hydrostatic energy and *stored* at high pressure, in hydro-pneumatic accumulators. In the acceleration/start-up stages, hydrostatic energy, *stored* in hydro-pneumatic accumulators, is *converted back* into mechanical energy by the hydraulic machine, which is working now as a motor and generating acceleration of the motor vehicle, (Cristescu, 2008a).

The *aim* of the designed hydraulic system is the recovery of kinetic energy, in the braking stage of a motor vehicle.

The *technical problem*, which is solved by the energy recovery hydraulic system, is the capturing and storing of the lost energy in the braking stages at medium and heavy motor vehicles.

The *method* consists in using one mechanic and hydraulic module, which is able to capture and convert the kinetic energy into hydrostatic energy and, also, storage and reuse it for acceleration and start-up of the road motor vehicles.

The implementation of a hydraulic system for recovery of kinetic energy, on a motor vehicle, transforms it into a *hybrid motor vehicle* and leads to decreasing of the fuel consumption and, also, to reducing of the environmental pollution.

The *main objectives* of the *hybrid propulsion systems* are *the recovery of kinetic energy* of the road motor vehicles, in order to reduce the fuel consumption and to increase the energy efficiency of the propulsion systems of the motor vehicles.

2.1 Conceptual model and mechatronic configuration of the kinetic energy recovery system

2.1.1 Constructive configuration and implementation of the energy recovery system on motor vehicles

Constructive and functional concept of developing and implementing a system for braking energy recovery is shown, in schematically, in Figure 1, which presents a conceptual model of construction and installation/implementation of the kinetic energy recovery system on a motor vehicle. The energy recovery system consists, in essence, of a hydro-mechanical module which includes a variable displacement hydraulic machine, that can operate both in pump mode, during braking, and in motor regime, during start-up/acceleration of the motor vehicle. The hydraulic machine is driven by a mechanical transmission and is controlled by an electric and electronic control subsystem, which performs, also, the interfacing with the braking and acceleration systems of the basic motor vehicle, operation being controlled through a processor, which provides the information support, specific to mechatronic systems.

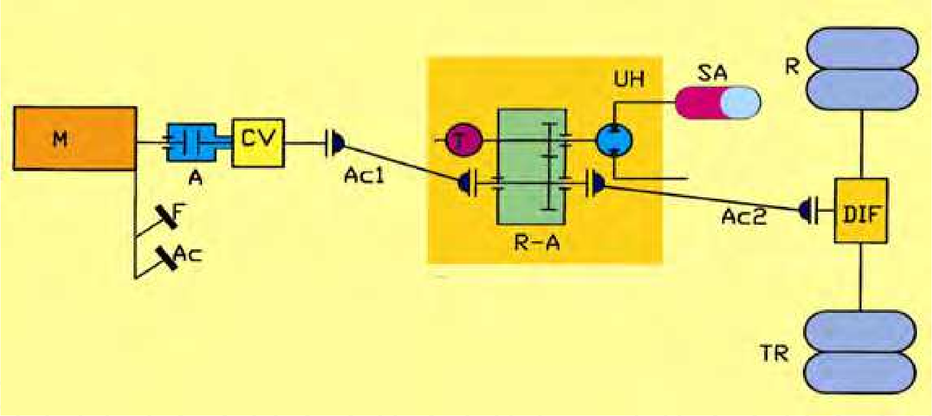


Fig. 1. A conceptual model of construction and installation/implementation of the recovery system on motor vehicles.

Implementation/installation of the energy recovery system can be done on motor vehicles that have a long cardan axle between the gearbox CV and the differential mechanism DIF, by replacing it with two shorter axles. Mechanical connection between the cardan axles Ac1 and Ac2 and the recovery system R-A is permanent and is achieved through a mechanical transmission, which adapts the rotational speed of the cardan axle to the operating rotational speed of the hydraulic machine/unit UH in the system. Depending on the specific conditions provided by the motor vehicle on which the recovery system is installed, the coupling outlet and mechanical transmission can be placed at the end of the cardan axle Ac1 close to the gearbox, at the end of the cardan axle close to the rear drivetrain TR, or between the gearbox CV and the drivetrain TR, by splitting the cardan axle.

Hydraulic unit is a hydraulic machine with variable displacement/geometric volume, which can vary between 0 and a maximum value (V_g=max). Axial piston hydraulic unit can be removed from the zero displacement position, only when the vehicle goes forward. When it goes into reverse, the displacement of the unit remains zero (Vg = 0).

Basic schematic diagram of the automatic adjustment system of the motor vehicle hybrid propulsion system, that includes an energy recovery system, is shown in Figure 2. The adjustment system achieves proportionality between the the stroke of the brake pedal, respectively, the stroke of the acceleration pedal, on slowing down, respectively, on starting-up the motor vehicle.

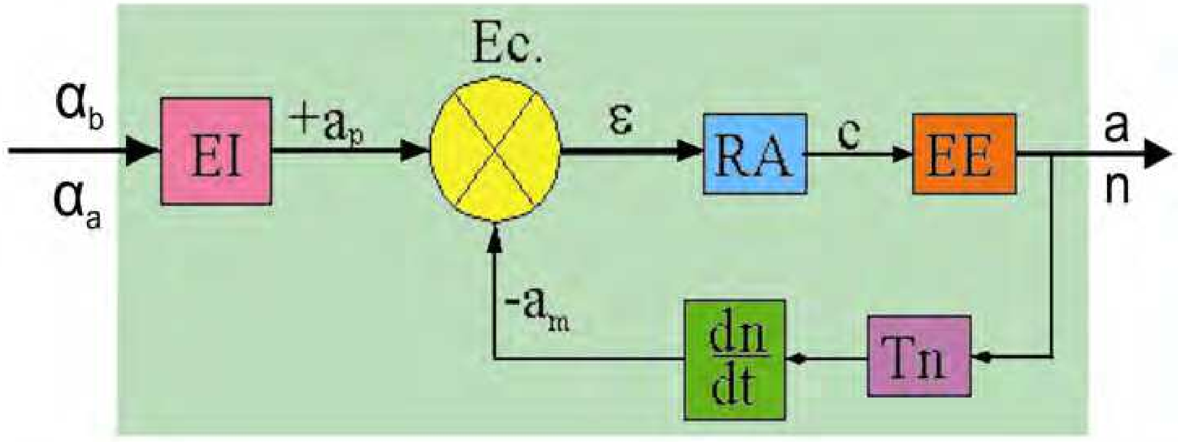


Fig. 2. Automatic adjustment schematic diagram of the hybrid propulsion system of motor vehicles.

According to the adjustment schematic diagram in Figure 2, component elements of the system are the next ones:

EI - the input element, which converts the input parameter of the system, that is the angular stroke of brake pedal α_f , respectively angular stroke of acceleration pedal α_a , into the preset parameter a_p , that is the deceleration, respectively, acceleration, according to the operation stage, braking or acceleration;

EC - the comparison element, which compares the preset parameter a_p with the measured acceleration a_m and transmits to the automatic regulator RA the discrepancy $\in$ between the two parameters, in order to operate correction;

RA - the automatic regulator, which determines, depending on the error $\in$, the value of the drive parameter c,, that will work to equalize the preset acceleration a_p with the actual acceleration value a ;

EE - execution element, represented by the axial piston hydraulic unit, which determines the value of vehicle acceleration proportional to the received command; this item plays a double part: information and power circulation.

Recovery system also comprises the hydraulic devices to achieve hydraulic circuits, as well as the transducers required for monitoring and automatization of braking and start-up/acceleration processes.

According to the theory of automatic systems, the global systemic model is shown in Figure 3.

Fig. 3. Global systemic model of a motor vehicle equipped with a kinetic energy recovery system.

During the braking stage, the recovery system ERS captures, from the drivetrain VDR, the vehicle's kinetic energy (with mechanical parameters: torque/moment *M* and rotational speed *n*), converts it into hydrostatic energy (with hydraulic parameters: pressure *p* and flow *Q*) and stores it inside the storage subsystem ESS. During the start-up stage, the hydrostatic energy (with hydraulic parameters: pressure *p* and flow *Q*) is transmitted to the recovery system ERS which converts it into mechanical energy (with mechanical parameters: torque *M* and rotational speed *n*), and uses it to add torque/moment to the propulsion and drivetrain of the vehicle, for acceleration or start-up, as appropriate. The general systemic model of interfacing and interconditioning of the energy recovery system with the systems, that command and control motor vehicle movement (braking and acceleration systems), is shown roughly in Figure 4.

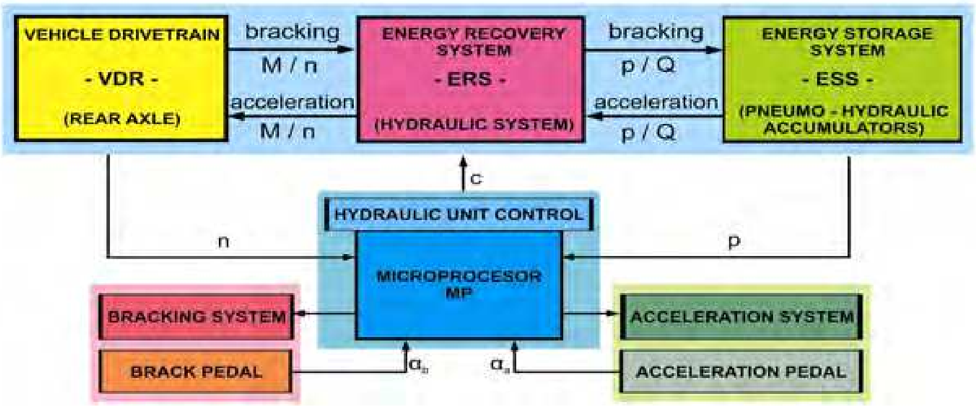


Fig. 4. General systemic model of the command and control system.

As it is shown in Figure 4, the microprocessor MP manages all data of the whole hybrid vehicle, making its operation optimal during the two stages, braking and acceleration. The microprocessor receives information on the braking or acceleration command, rotational speed of drivetrain, pressure inside the storage system, and manages the entire process through commands sent to the energy recovery system and to the conventional braking or acceleration systems.

2.1.2 Mechatronics structure of the kinetic energy recovery system

As one can see in Figure 5, mechatronic model of kinetic energy recovery system in motor vehicle braking has a typical mechatronics structure, see (Maties, 1998; Cristescu et al., 2008b), consisting of the next four main subsystems:

- *mechanical-hydraulic subsystem*, which consists of hydro-mechanical module, hydraulic station, battery of hydro pneumatic accumulators and hydraulic commands pump, installed on a special transmission of the heat engine;

- *electronic drive and control subsystem*, which consists of all electric, electronic and automation elements and components which ensure system operation, including the drive and control panel;
- *subsystem of sensors-transducers*, which consists of all necessary sensors and transducers that provide capturing of evolution over time, of process parameters and conversion into electric parameters, easily processable by the system;
- *computer subsystem* for process control, consisting of user licensed purchased software or software specifically designed and dedicated to the proper functioning and performance of the system, and also the related processor or computer.

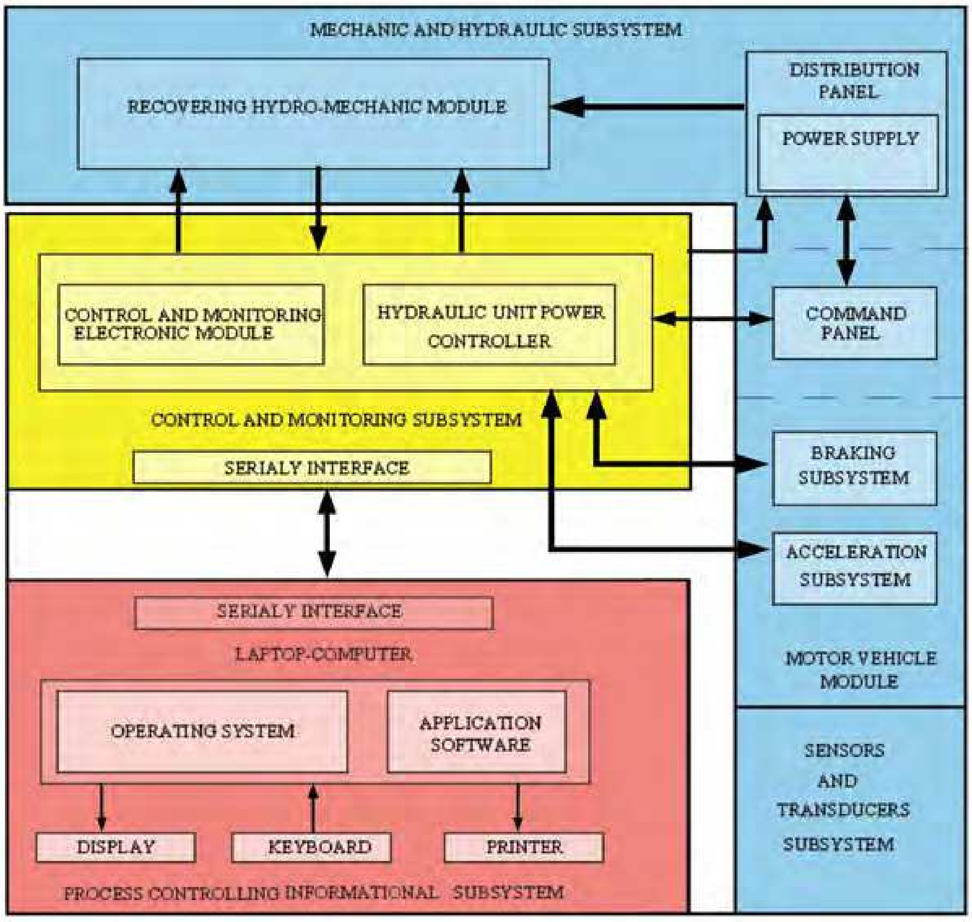


Fig. 5. Mechatronics model of energy recovery system at the braking of motor vehicles.

This structure defines and substantiates the *mechatronic conception* of developing the recovery system. Mechatronic system for recovery of braking energy at motor vehicles operates based on dedicated software, which monitors the system and enables registration of the output parameters and control of the main parameters of the system.

In addition to the specific subsystems of a energy recovery system, mentioned above, mechatronic system monitors and controls, through special interface components, some other subsystems of the basic motor vehicle, on which implementation has been performed, namely: subsystem for interfacing with the classic acceleration subsystem of the motor vehicle and subsystem for interfacing with the classic braking subsystem of the motor vehicle. The energy recovery system is conducted by a computer with specialized software.

2.2 Presentation of the thermo-hydraulic propulsion system

Further on, there is presented a Romanian technical solution for a hybrid propulsion system that has been obtained by implementation of an energy recovery hydraulic system on a medium motor vehicle, which has, already, an existing thermo-mechanical propulsion system. In this maner, the mounting of the hydraulic recovery system, on the motor vehicle with thermo-mechanical propulsion system, leads to transformation of the vehicle into a thermo-hydraulic hybrid vehicle. Entire hybrid propulsion system has been conceived as a mechatronic system, see (Cristescu, 2008a).

2.2.1 The conceptual model of the thermo-hydraulic hybrid vehicle

In Figure 6 is presented the conceptual model of the Romanian technical solution for a hybrid propulsion vehicle, which consists in a energy recovery hydraulic system that has been implemented on a medium motor vehicle.

The *conceptual model* illustrates a thermo-hydraulic parallel hybrid motor vehicle, as the energy recovery hydraulic system implemented does not interrupt the thermo-mechanical direct driveline to the motor vehicle wheels.

This hybrid vehicle has resulted after the implementation of kinetic energy recovery system with hydraulic drive on the vehicle type *ARO-243*, with thermo-mechanical propulsion. Basic motor vehicle allows discontinuity of the thermo-mechanical driveline of the rear bridge, by removing the appropriate cardan axle, thermo-mechanical drive remaining only on the fore bridge, which is exactly the *thermo-mechanical* propulsion subsystem of the vehicle. By mounting *the energy recovery hydraulic system* on the rear bridge of the vehicle, there is created a second drive subsystem namely the *mechanical-hydraulic subsystem* that drives the rear bridge; thus there is made a *parallel hybrid thermo-hydraulic propulsion system* of the motor vehicle, these subsystems being able to propel either separately or together, (Cristescu, 2008a).

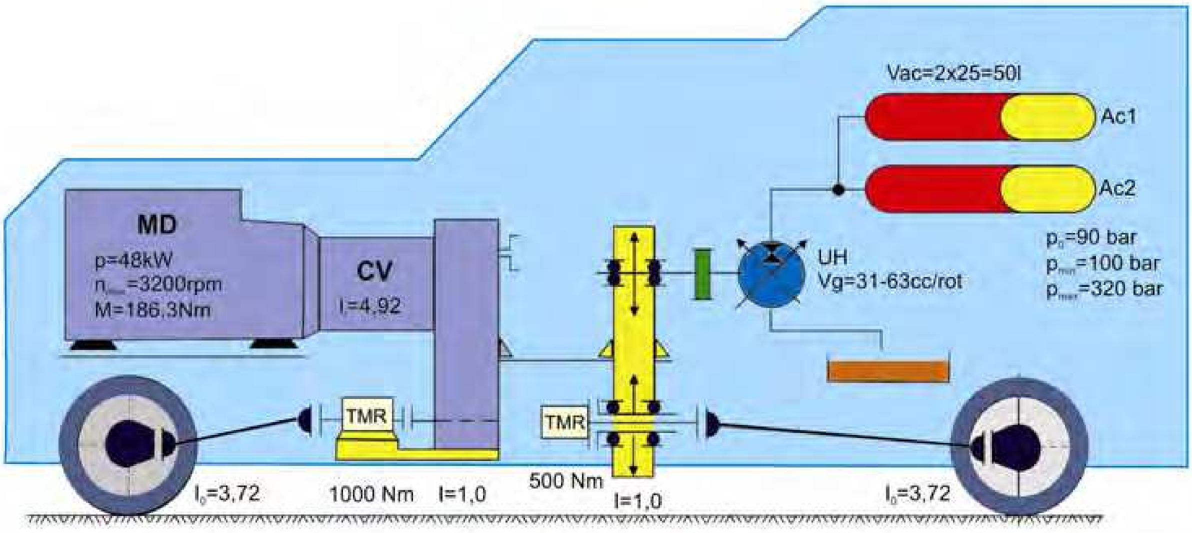


Fig. 6. The conceptual model of the thermo-hydraulic hybrid vehicle with energy recovery hydraulic system.

The recovery hydraulic system of kinetic energy has been designed to be implemented on a Romanian automotive, well-known as *ARO 243* type, which has a *4x4 driving* system. In the conceptual model of the hybrid propulsion vehicle, presented in Figure 6, can be distinguished the Diesel engine MD, the gearbox CV and the gear transmission to the front wheels, through one torque transducer (TMR) and one cardan axle. There can be seen the mechanical transmission to the hydraulic machine/unit UH, the tank for low pressure LT and the storing system for height pressure, which consists of the two hydraulic and pneumatic accumulators AC1 and AC2. The hydraulic power is transmitted, to the breech wheels, through the torque and rotation transducer (TMR) and a cardan axle. The hydraulic machine can be connected, in parallel, anywhere in the driveline, but, generally, it is mounted between the gearbox and differential mechanism. The main part of the recovery system is the hydraulic machine with variable geometrical volume, that can work both as a pump, in the braking process, and, also, as a hydraulic motor, in the start-up process of the motor vehicle.

The hydraulic machine is driven through a gearbox transmission, being assisted by an electro-hydraulic system, which is interfaced with the subsystems for braking and acceleration of the vehicle, all controlled by a processor. Operation of the recovery system has a lot of sensors and transducers, for monitoring and controlling the evolution of parameters.

The hybrid propulsion system, which contains the energy recovery hydraulic system, has been developed in a *mechatronic conception (*Maties, 1998). The system contains: mechanical and hydraulic subsystem, drive and control electronic subsystem and the data management informatic subsystem. The interface of the first two subsystems is the subsystem of sensors and transducers, which provides information on the evolution of the main parameters of the kinetic energy recovery mechatronic system. The sensors and transducers subsystem allows data acquisition from the torque, temperature, flow and pressure transducers (Calinoiu, 2009). The mechatronic system is working on basis of dedicated software, which allows monitoring and recording the evolution of output and control parameters of the system. This component defines the mechatronics basis for the system design and development.

2.2.2 The main physical modules of the energy recovery hydraulic system

In essence, by mounting of the kinetic energy recovery system, Figure 7, on the motor vehicle *ARO-243*, presented in Figure 7(a) and Figure 7(b), transforms it in a *hybrid motor vehicle*, which have now, besides of the existing thermo-mechanic propulsion subsystem, an supplementary propulsion system, named hydro-mechanic propulsion subsystem.

The main parts/subassemblies of the kinetic energy recovery mechatronic system are:

- *hydro-mechanical module*, Figure 7(c) , is composed of a chain transmission, equipped with a torque and rotation transducer TMR, and a hydraulic unit/machine UH, *serving* as a pump, during braking, and as an motor, during start-up. The hydraulic machine is a variable-displacement one, manufactured by the company *Bosch Rexroth Group* (Bosch Rexroth Group, 2010), where flow control is performed electronically, through an automatic control closed loop;
- *hydraulic station* SH itself, Figure 7(d), represents the subassembly connecting the hydro-mechanical transmission and the hydro pneumatic accumulators battery, where hydrostatic energy is stored. Hydraulic station consists of oil tank with its specific elements, and of hydraulic blocks with equipment necessary to perform the functions;

(a) The motor vehicle ARO-243(lateral view) (b) The motor vehicle ARO-243(behind view)

(c) The hydro-mechanical module (d) The hydraulic station

(e) The accumulators battery (f) Installation of the pump command

(g) Electronic drive and control subsystem (h) Informatics subsystem

Fig. 7. The main parts/subassemblies of the kinetic energy recovery mechatronic system.

- *hydro pneumatic accumulators battery, Figure 7(e), is a unit consisting of two hydro* pneumatic accumulators, enabling hydrostatic energy storage, during braking stage, and supply of hydraulic motor with potential hydrostatic energy, during start-up or acceleration of the motor vehicle;
- *pump command*, Figure 7(f), is mounted to the power outlet of the heat engine and serves to hydraulically drive the hydraulic machine and unlockable valves for hydrostatic power supply of hydraulic machine.

In addition to the presented subsystems, the system has, also, an electronic drive and control subsystem, Figure 7 (e), and an *informatics management subsystem*, Figure 7 f), all designed and developed in a unitary mechatronic conception.

2.3 Some theoretical results obtained by mathematical modeling and numerical simulation

Motor vehicle dynamic behavior is determined by the size, direction and way of forces acting on it. They are classified into two broad categories: active forces or *traction forces*, which cause motor vehicle movement, and *resistance forces*, which oppose its movement. *Resistant forces* are given by the resistance to running on the road, the resistance of air to movement, additional resistance opposed to running on a ramp, as well as inertial forces that appear on accelerating or stoping a motor vehicle. To overcome these resistance forces, energy consumed to propel the motor vehicle fall into:

- *irreversible consumed energy*, for overcoming all resistance to forward (rolling, aerodynamics, losses in transmission) and which are due, first, to internal and external friction of the motor vehicle;
- *recoverable energy*, used for accelerating or climbing a ramp, in this case the kinetic energy and potential energy, which can be recovered. This recoverable energy can be partially accumulated, instead of being dissipated through braking system, if the motor vehicle is equipped with energy recovery, storage and reuse system.

Therefore, as a first step, preliminary theoretical research has been conducted, based on mathematical modeling and numerical simulation, in order to know the dynamic behavior of motor vehicle *ARO 243*, intended to be equipped with a hydraulic system for kinetic energy recovery at braking. For mathematical modeling and computer simulation of dynamic behavior of experimental motor vehicle there have been used mathematical relations in the specialized literature and *MATLAB with Simulink* software package, (The Math Works Inc., 2007), which is dedicated to numerical calculation and graphics in science and engineering. Some theoretical results obtained are presented below.

2.3.1 Dynamic behavior of the motor vehicle with thermo-mechanic propulsion system

To model the start-up of the motor vehicle *ARO 243* with thermo-mechanical propulsion system, when propulsion is provided exclusively by a 48 kW Diesel heat engine, there has been conducted, first, mathematical modeling and developed a sub-software for simulation of the external feature of heat engine, i.e. of variation diagram of moment/torque Me and engine power Pe, depending on engine rotational speed n_{mot}. This simulation sub-software will be included, as a subroutine, in the general software for simulation of starting the heat propulsion motor vehicle. After numerical simulation, using the data about the engine, we obtained the diagram in Figure 8.

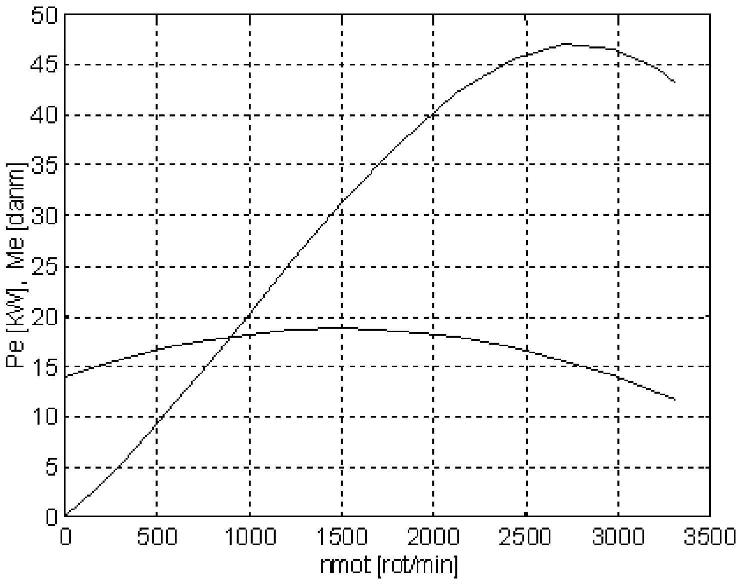


Fig. 8. External feature of a 48 kW Diesel engine.

Mathematical modeling of motor vehicle start-up stage is performed on the basis of relations known in specialized literature, which are based on the principle of *D'Alembert,* according to which equation of movement is written as:

$$\delta \frac{G_a}{g} \frac{dv_a}{dt} = \left(F_R - \sum F \right), \tag{1}$$

where: v_a is the motor vehicle velocity; G_a is the motor vehicle total weight; g is gravitational acceleration; F_R is the traction force at drive wheels, and $\sum F$ is the sum of resistances to advance that do not depend on acceleration. Coefficient δ is the inertial coefficient of rotating masses, which takes into consideration their influence on motor vehicle movement, with values in the range 1.2 ÷ 1.4, for speed step I, see (Untaru et al., 1974).
It can be written that the sum of resistance forces is given by the next relation:

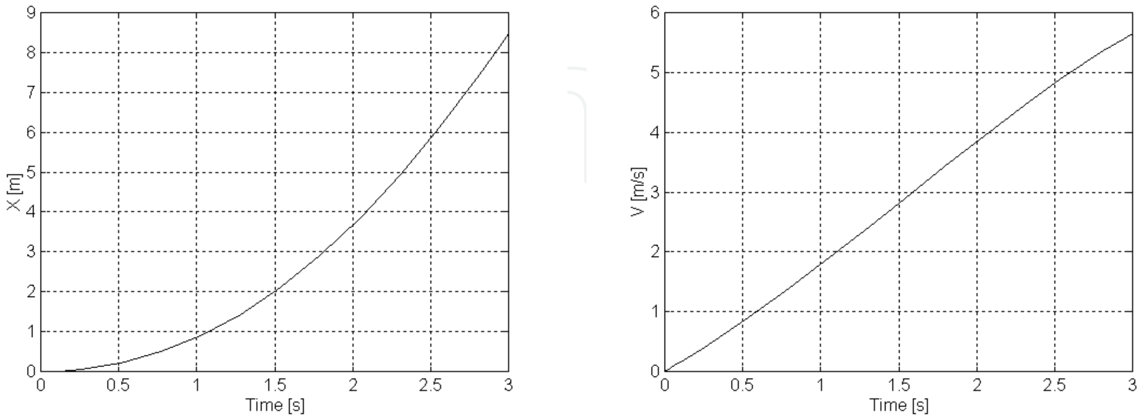
$$\sum F = G_a \left(f \cdot \cos\alpha + \sin\alpha \right) + K \cdot S \cdot v_a^2 \tag{2}$$

where: f is the coefficient of resistence to running; a is the ramp angle; K is the aerodynamics resistance coefficient; and S is the frontal surface of motor vehicle. With this notations, the equation becomes:

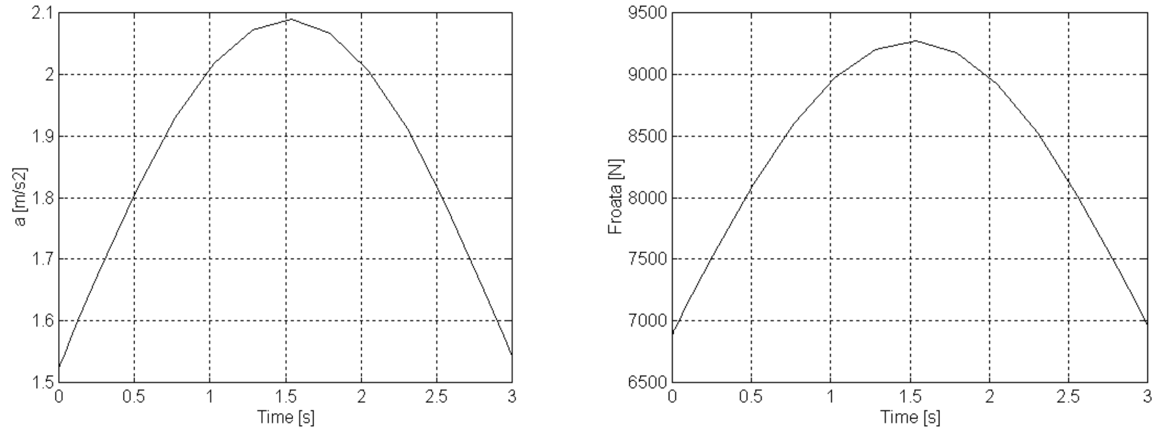
$$\frac{dv_a}{dt} = \frac{g}{\delta \cdot G_a} \cdot \left(F_R - G_a \ \ \mathrm{f} \cdot \cos\alpha \text{-} \mathrm{G_a} \cdot \sin\alpha \text{ - } \mathrm{K} \cdot \ \mathrm{S} \ \cdot \mathrm{v_a^2} \right) \tag{3}$$

If it is considered that the movement is done in a horizontal plane, and starting of the motor vehicle is done at low velocity, equation can be simplified more. Based on the relationship known in classical literature, there has been developed a complete mathematical model for the starting-up stage and, based on this one, there has been developed a numerical simulation software, which allowed, based on structural and functional features of the vehicle, to obtain some theoretical results of interest in the dynamic evolution of the motor vehicle. Some of these preliminary theoretical results are shown in the figures below. Thus,

Figure 9 shows the variation of kinematics parameters and traction force at the wheels of the investigated motor vehicle. The variation of stroke on start-up is shown in Figure 9(a) and the variation of velocity on start-up in Figure 9(b). The variation of acceleration on start-up it can see in Figure 9(c) and the variation of traction force at the wheel is done in Figure 9(d).



(a) Variation of stroke on start-up (b) Variation of velocity on start-up



(c) Variation of acceleration on start-up (d) Variation of traction force at the wheel

Fig. 9. Variation of kinematics parameters and traction force at wheels on thermal starting of the motor vehicle.

2.3.2 Dynamic behavior of the motor vehicle with hydro-mechanic propulsion system

As mentioned above, through implementation, on the motor vehicle ARO 243, of the hydraulic system for the recovery of kinetic energy during braking, it became a *parallel thermal-hydraulic hybrid motor vehicle,* which can be powered exclusively by the heat engine, analyzed in section 2.3.1, exclusively by hydraulic means, which will be studied in this subchapter, or combined, using both sources of power, being a *hybrid propulsion system*. To concretize the way of transmission of energy flow and to highlight the main subsystems participating in the starting process, there has been developed a conceptual model of the hydro-mechanic system, shown in Figure 10. At this stage, it was envisaged that the flow of hydrostatic energy comes from the hydro pneumatic accumulators, where it is stored for reuse, through the hydraulic station of the system, reaching the hydraulic machine which, operating as a hydro motor, converts the hydrostatic energy into mechanical energy and directs it, by means of the cardan axle and differential mechanism, towards the rear axle to drive wheels of the motor vehicle.

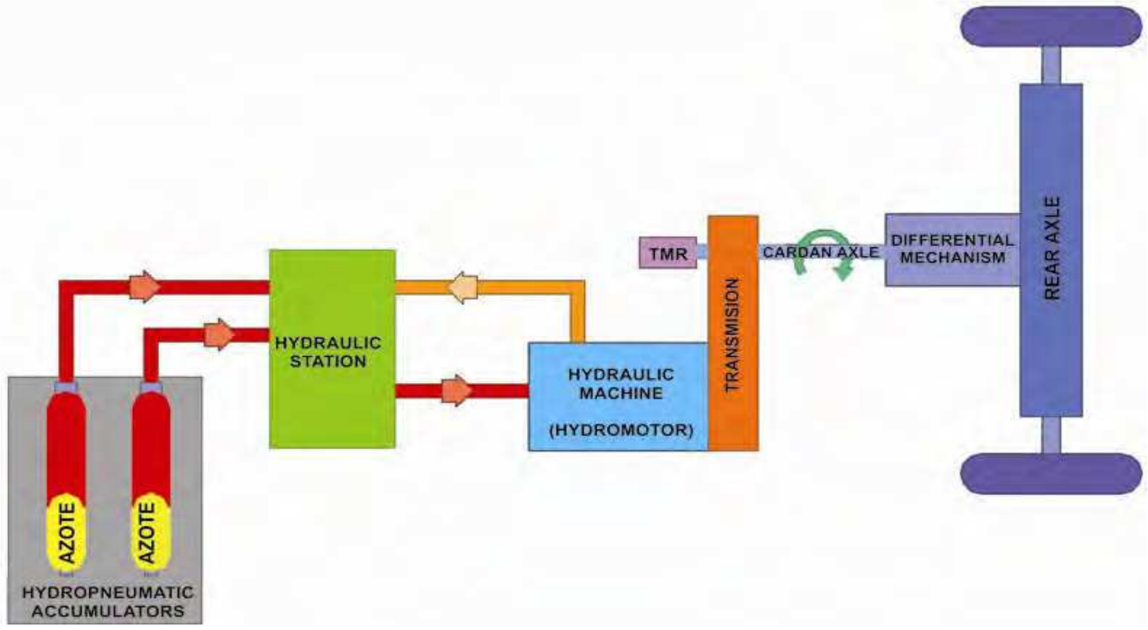


Fig. 10. A conceptual model of the hydro-mechanic starting system of the motor vehicle.

The sstudy upon the dynamic behavior of the motor vehicle equipped with hydraulic system for energy recovery, during starting, propelled, exclusively, by a hydraulic system, also, has been achieved through mathematical modeling and numerical simulation, and it has enabled knowledge of evolution of the main kinematic and dynamic parameters of the motor vehicle. Mathematical modeling of the motor vehicle powered exclusively by hydrostatic energy, supplied by hydro pneumatic accumulators, started from the known equation of motion of the motor vehicle, but, first, there was necessary mathematical modeling of the *polytrope decompression* process of azote inside the accumulators, Figure 11, to assess/evaluate the variation of pressure of the oil that actuates the hydraulic motor, see (Cristescu, 2008).

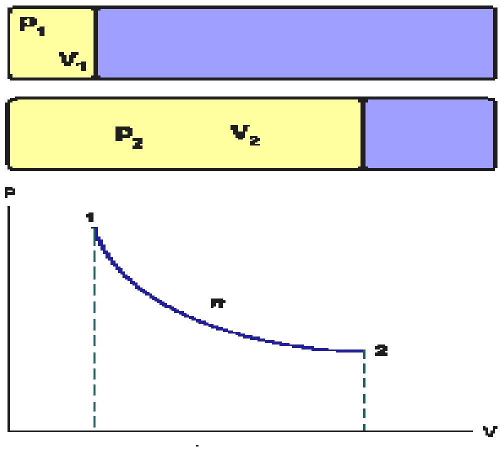
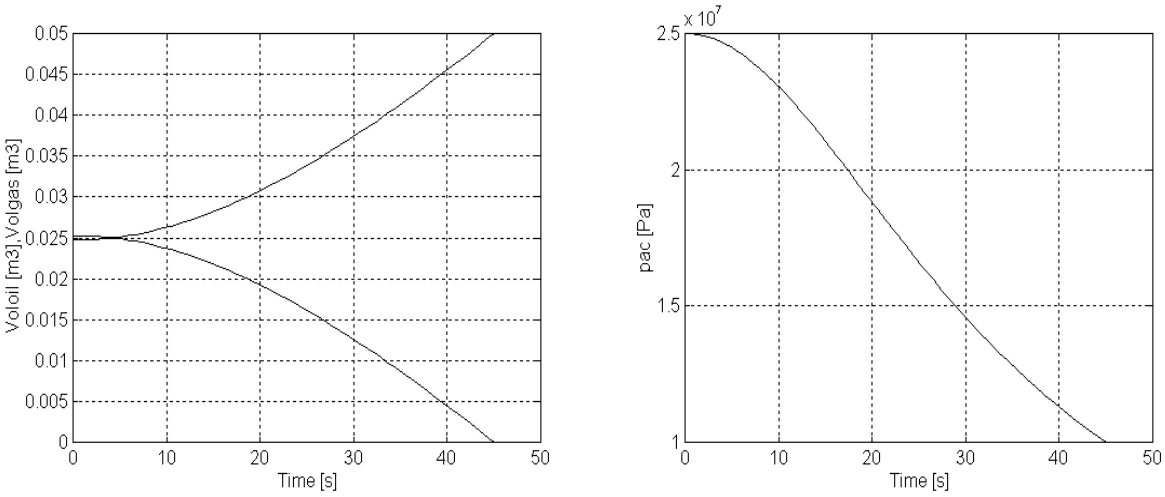
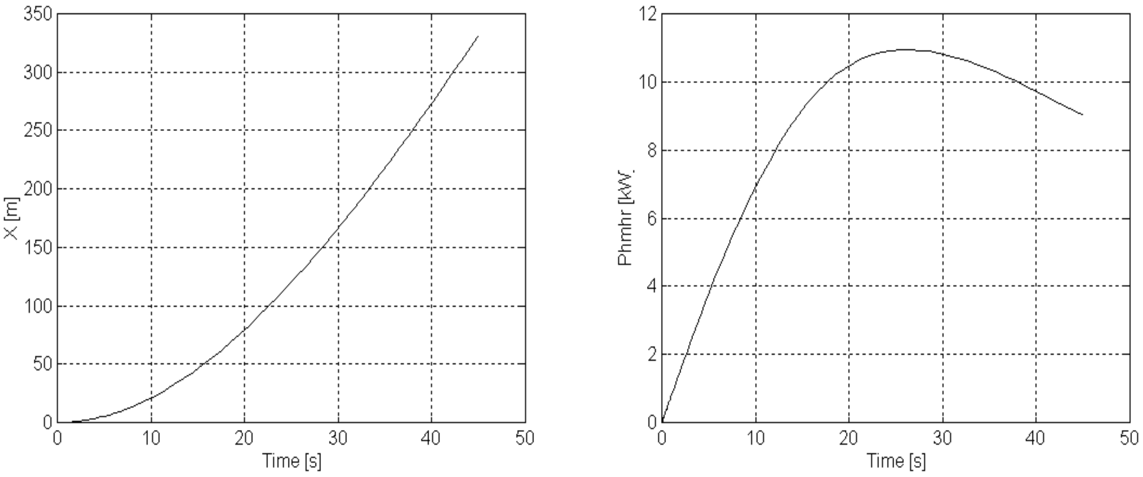


Fig. 11. Polytrope transformation of azote between the initial state 1 and final state 2 during the starting process.

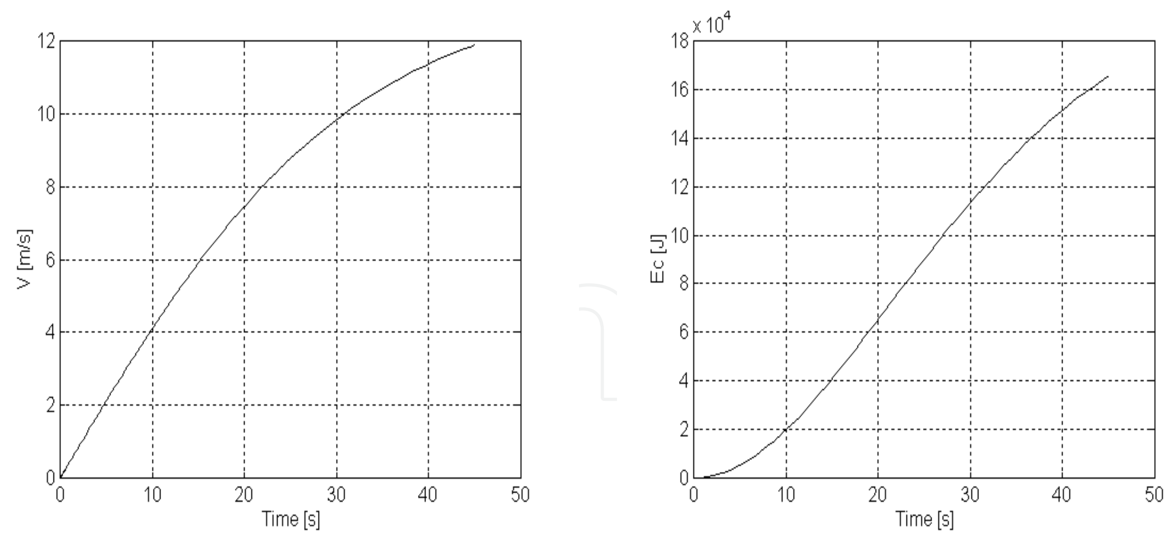
In the assumption that there is no loss of fluid along the hydraulic circuits and the liquid is incompressible, and if it is marked with θ_{MH} rotation angle of the hydraulic motor shaft and with ω_{MH} its angular velocity of rotation, then it is obtained the pressure variation law for the oil inside the accumulators, according to the relation (4). With the relations known in classical literature (Untaru et al., 1974), there has been developed a mathematical model for the hydraulic starting-up stage and, after mathematical modeling and numerical simulation, have been obtained the variations of main parameters of dynamic behavior of the motor vehicle with hydraulic propulsion, presented in Figure 12.



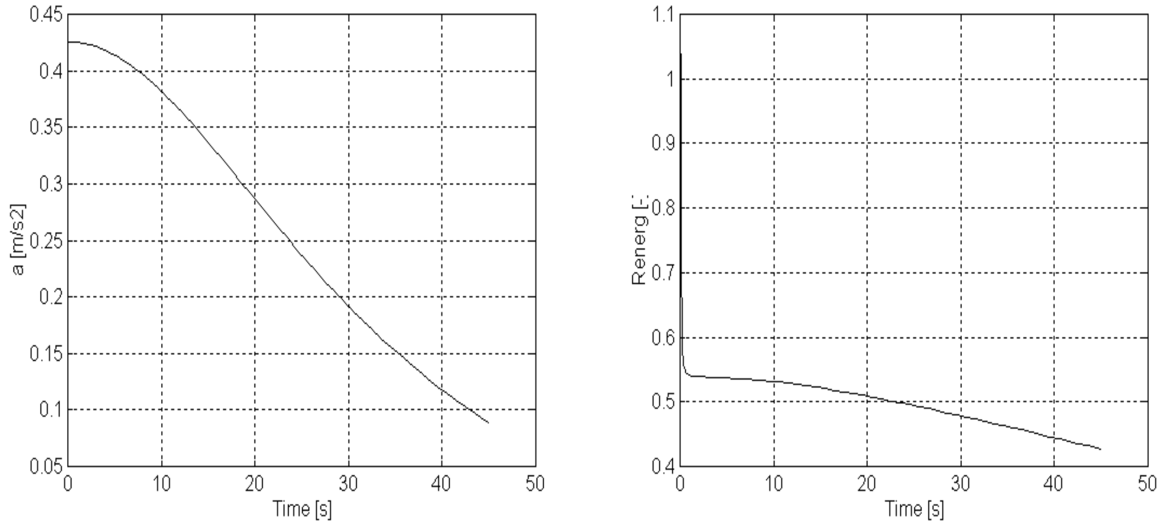
(a) Variation of oil and gas volumes (b) Variation of pressure inside the accumulators



(c) Variation of start-up stroke (d) Variation of power of HM



(e) Variation of start-up velocity (f) Variation of kinetic energy of the motor vehicle



(g) Variation of acceleration on start-up (h) Variation of energy efficiency

Fig. 12. Variation of the main parameters of hydraulic starting process of a motor vehicle.

In the Figures 12, there are presented some theoretical results of interest regarding the dynamic behavior of the motor vehicle at its hydraulic start-up. Thus, the variation of oil and gas volumes are shown in Figure 12(a), where it can see that the oil volume is in decreasing and the gas volume is in continuous increasing. The pressure in the accumulators is in continuous decreasing, as see in Figure 12(b). The variation of start-up stroke is shown in Figure 12(c). The Figure 12(d) highlights the existing of a maximum value of the power at e hydraulic motor (HM). The variation of start-up velocity is done in Figure 12(e) and this corresponds with the variation of kinetic energy of the motor vehicle, which is shown in Figure 12(f). The variation of acceleration on start-up of the vehicle is presented in Figure 12(g). The variation of energy efficiency of hydraulic propulsion is shown in Figure 12(h) and is around of 60%. The pressure variation in accumulators is done by the next relation (4):

$$p_{ac} = \frac{p_0}{\left(\left(\frac{p_0}{p_1}\right)^{\frac{1}{n}} + \frac{V_g}{V_0}\cdot\frac{\theta_{MH}}{2\pi}\right)^x} = \frac{p_0}{\left(\left(\frac{p_0}{p_1}\right)^{\frac{1}{n}} + \frac{V_g}{V_0}\cdot\frac{\omega_{MH}}{2\pi}\cdot t\right)} = p \tag{4}$$

In the above relation, *state 0* is the state of preloading the battery with azotes, characterized by azotes loading pressure p_0 and their maximum volume V_0. State 1 is the *initial state* of the decompression process, characterized by the maximum pressure p_1 and minimum volume of gas $V_{1,}$, and *state 2* is the *final state* of the start-up process, when the minimum allowable pressure p_2 is reached and, also, the minimum volume of gas V_2. Based on this relation and on those known from the technical literature (Calinoiu et al., 1998)) there has been developed a mathematical model and a numerical simulation software in *MATLAB with Simulink* graphical environment, (The Math Works Inc., 2007), which allowed to obtain graphs of variations of the main parameters of interest, describing the dynamic behavior of the motor vehicle propelled exclusively by a hydraulic system.

2.3.3 Dynamic behavior of the motor vehicle at braking with kinetic energy recovery

To know the dynamic behavior of the hybrid motor vehicle, during braking with recovery of the kinetic energy available/accumulated at the beginning/before of the braking, there is made the *assumption* that, in this stage, the heat engine is operating at ralanty rotational speed and is disconnected from the transmission, being precluded the use of engine braking. Assuming the above, all available *kinetic energy* is taken by the running system and sent to the mechanical hydro pneumatic system of energy recovery at a motor vehicle through the rear axle, where it is mechanically coupled, by means of the differential mechanism and cardan axle. The *kinetic energy* taken from the drivetrain is then *converted* by the hydraulic machine, which operates in *pump mode* during this stage, into *hydrostatic energy* that is *stored* in the battery of accumulators. To concretize the way of transmission of energy flow and to highlight the main subsystems participating in the braking process with kinetic energy recovery, there has been developed a conceptual model of hydraulic braking process with kinetic energy recovery, shown in Figure 13.

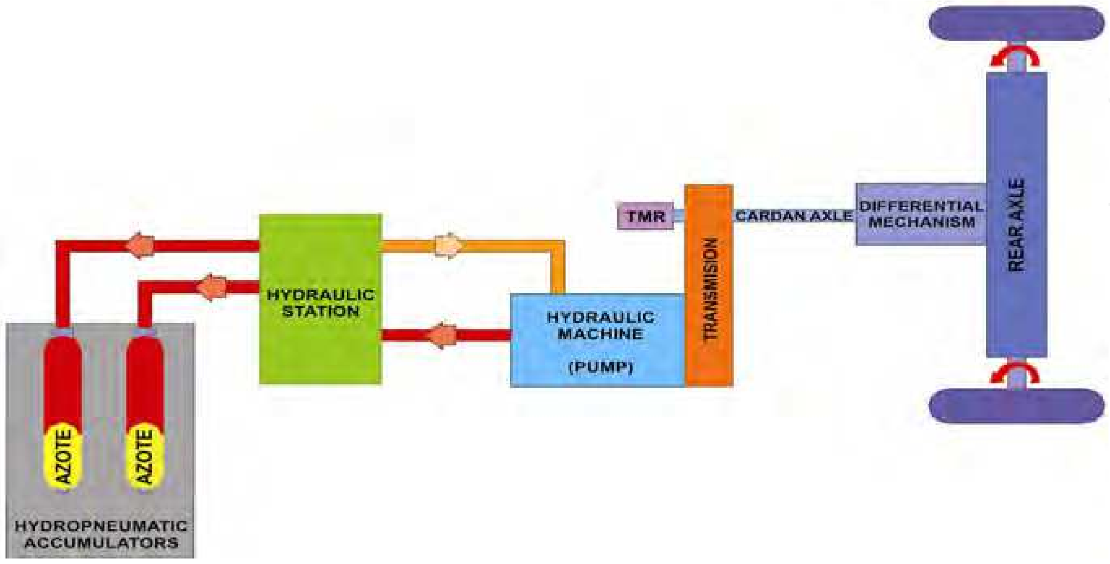


Fig. 13. A conceptual model of the hydraulic braking process with kinetic energy recovery.

At this stage, it was envisaged that the flow of mechanical/kinetic energy comes from the rear axle and drive wheels of the motor vehicle, by means of the differential mechanism and cardan axle, reaching the hydraulic machine which, operating as a pump, converts it into hydrostatic energy and directs it, through the hydraulic station of the system, towards the hydro pneumatic accumulators, where it is stored for reuse. Based on this conceptual model, there has been developed the *physical model* of braking system with energy recovery in, which lies at the basis of mathematical modeling. In Figure 14 is presented the *physical model* of the brake process with recovery of kinetic energy.

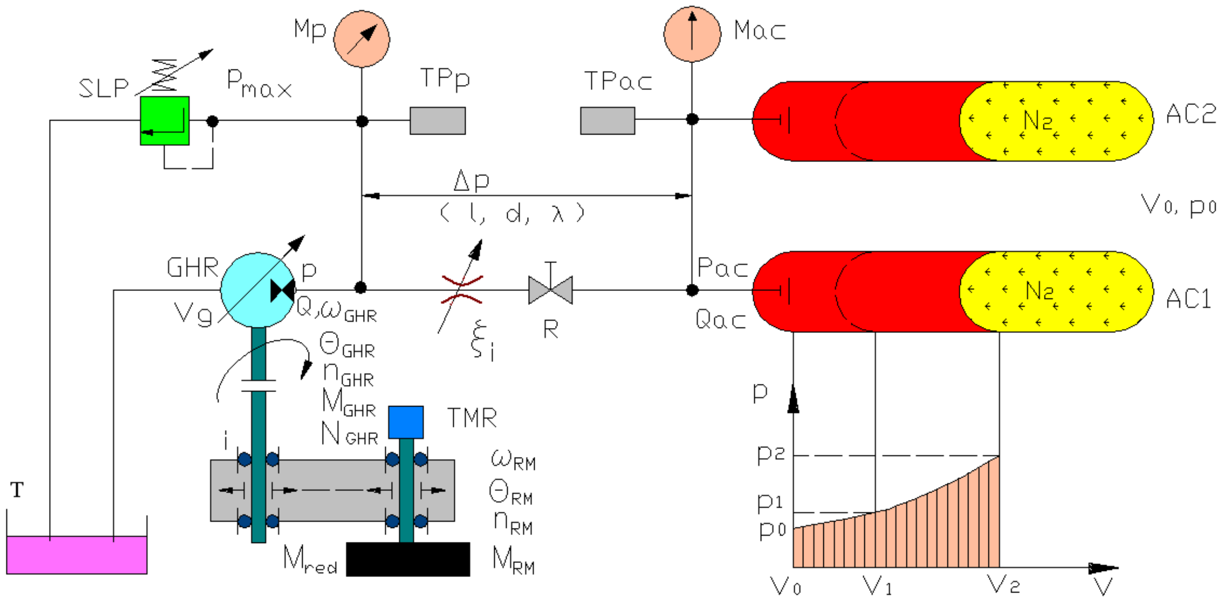


Fig. 14. The physical model of hydraulic braking system with kinetic energy recovery.

The kinetic energy *Ec,* accumulated by the motor vehicle before beginning of braking, impresses on the reduced masses M_{red} a translational motion, respectively a rotational motion, with reduced kinematic parameters at the axis of drive wheels, as indicated in the figure 7: $\theta_{RM}\ \omega_{RM}\ , n_{RM}$, respectively angular stroke, angular velocity and rotational speed at drive wheels, and, also, $\theta_{GHR}\ , n_{GHR}$ şi ω_{GHR} , representing angular stroke, rotational speed and angular velocity at the axis of hydraulic rotary generator (pump) GHR with displacement V_g and flow *Q*. Reduced torque at drive wheels M_{RM} , actuates the hydraulic machine (pump) GHR with torque M_{GHR}. The pump discharges the fluid flow *Q,* through a pipe with diameter *d*, length *l*, with local ζ and linear λ resistance, producing, on the route, a pressure drop Δp, before it can be compressed from a pressure p_1 or p_0, , to the pressure p_2, inside the accumulators AC1 and AC2. In the meantime, oil volume increases from V_0 or V_1 to V_2. The pump limit discharge pressure is read from a manometer M_P, controlled by the pressure limiting valve SLP and taken over electronically from the pressure transducer TP_p. The pressure inside the hydropneumatic accumulators p_{ac}, is read from the gauge M_{ac} and taken over electronically from the pressure transducer. Given the length of the braking process, which is a few tens of seconds, it is considered that the *compression process of azote* inside the accumulators is *polytrope*, with heat exchange with the environment, and must be properly modeled mathematically. Mathematical model of the hybrid motor vehicles, during braking with recovery of the kinetic energy, can, also, be obtained based on the principle of *d'Alembert,* with the equation of motion,\ of the following form:

$$M_{red}\frac{dv}{dt} = F_{act} - F_{rul} - F_{rezh} - F_{reza} \tag{5}$$

In the above equation, we have made the following notations:

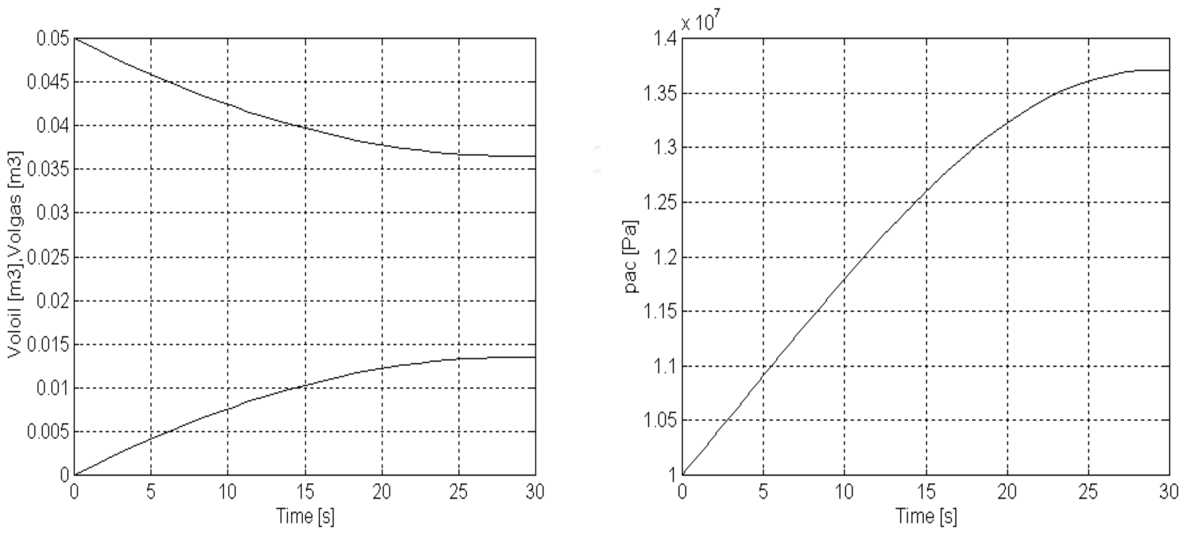
- F_{act} is the sum of active forces that generate or sustain motion,
- F_{rul} is the *resistance force at running on a ramp of angle* α ,
- F_{raer} is the *aerodynamics resistance force,*
- F_{rezh} is braking hydraulic resistance force, reduced at drive wheels

Resistant hydraulic brake torque, produced by the hydraulic generator of displacement V_g, reduced at driving wheels, M_{RM}, generates a *resistance hydraulic brake force* at driving wheels, which is determined by the relation:

$$F_{rezh} = F_{roata} = \frac{1{,}59Vg \cdot \left(p_{ac} + \Delta p\right) \cdot i_o \cdot i_t}{\eta_{mh} \cdot R}\ , \tag{6}$$

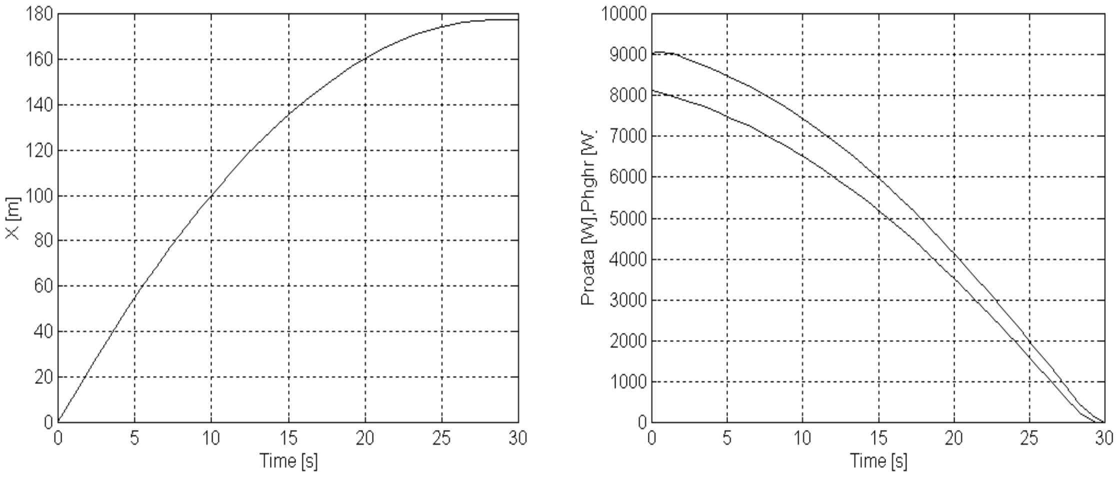
where: $p = p_{ac} + \Delta p$ is pressure of the fluid discharged by pump, and Δp pressure drop along the hydraulic circuit; i_0 is the transmission ratio of the differential mechanism; i_t – the transmission ratio of the mechanical transmission from hydraulic generator to cardan axle; η_{mh} - mechano-hydraulic efficiency, and R is the running radius of drive wheels.

Given the above, as well as other parameters known from the previous section, the equation of motion of the hybrid motor vehicle, during the braking stage with recovery of the accumulated *kinetic energy,* becomes like in (7). In Figure 15 is shown variation of the main parameters of *dynamic behavior* of the motor vehicle with energy recovery system in the braking process with kinetic energy recovery, obtained after mathematical modeling and numerical simulation.

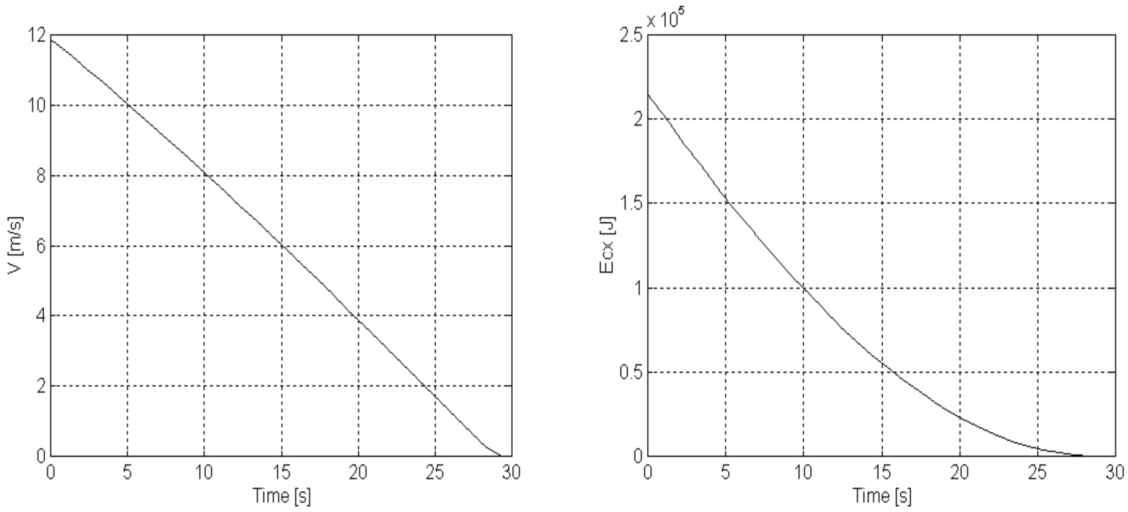


(a) Variation of volumes of oil and azotes inside the accumulators

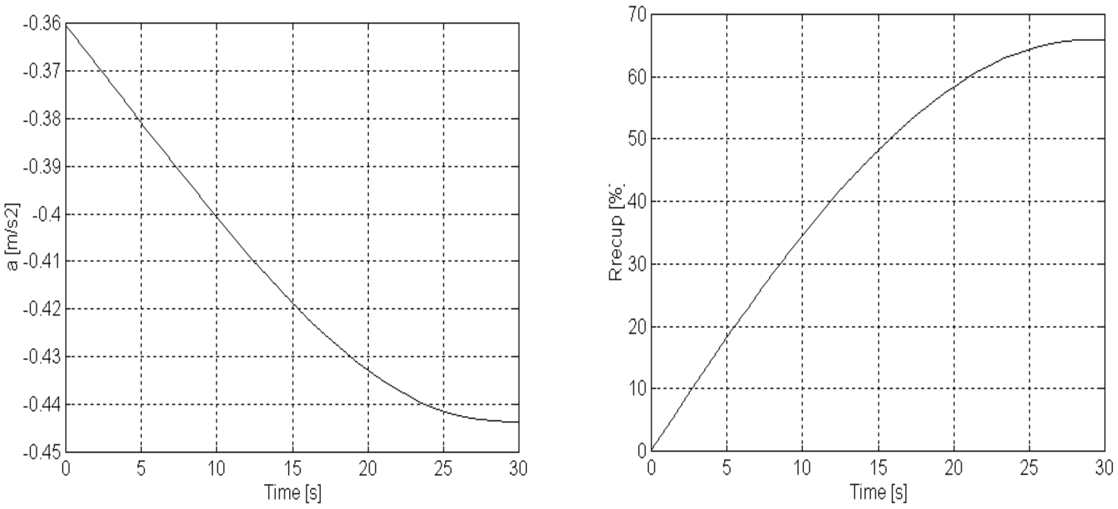
(b) Variation of pressure inside the accumulators



(c) Variation of brake distance (d) Variation of power at wheel and at pump



(e) Variation of brake velocity (f) Variation of kinetic energy during braking



(g) Variation of brake acceleration (h) Variation of braking energy recovery coefficient

Fig. 15. The variation of the main dynamic parameters of the braking process with energy recovery.

$$M_{red} \cdot \frac{dv}{dt} = F_{act} - G_a\left(f \cdot \cos\alpha + \sin\alpha\right) - \frac{1{,}59V_g \cdot \left(p_{ac} + \Delta p\right) \cdot i_o \cdot i_t}{\eta_{mh} \cdot R} - K \cdot S \cdot v^2 \tag{7}$$

Since research on braking with kinetic energy recovery is conducted on a horizontal track, at speeds below 40km/h, there can be neglected the parameters corresponding to the ramp and air and there can be obtained the simplified form of the equation of motion of a motor vehicle. Reduced mass M_{red} is considering the cumulative effect of the actual mass of the motor vehicle (G_a/g), which is in translation motion and that of the masses in rotating motion. A special problem is modeling the compression of azote inside the accumulators, but based on specific assumptions, (Cristescu, 2008), one gets, in the end, to an expression similar to that in the start-up stage (relation 4). Using the above equation of motion, and the other relations known from literature, there is obtained a complete mathematical model, which, by numerical simulation, allowed obtaining variations of dynamic parameters specific to the braking process with energy recovery. The above figure presents the main parameters of *dynamic behavior* of the motor vehicle with energy recovery system. in the braking process with kinetic energy recovery. Thus, the variation of oil and gas volumes are shown in Figure 15(a), where it can see that the oil volume is in increasing and the gas volume is in continuous decreasing. The pressure in the accumulators is in continuous increasing, as see in Figure 15(b). The variation of braking stroke is shown in Figure 15(c). The Figure 15(d) shows the variation of power at wheel and at pump, in the braking phase. The variation of braking velocity is done in Figure 15(e) and this corresponds with the variation of kinetic energy of the motor vehicle during the braking, which is shown in Figure 15(f). The variation of acceleration on braking of the vehicle is presented in Figure 15(g). The variation of kinetic energy recovered at braking of vehicle and the evolution of coefficient of braking energy recovery is shown in Figure 15(h). His maximum is around of 65%.

2.4 Dynamic behavior of the motor vehicle with hybrid propulsion system

The hybrid system, studied in this section, is a mechatronic system, with the next specifical components: mechanical subsystem, drive and adjustment electrohydraulic subsystem, electronic interfacing component and computer component for "governance" of the process. Mechatronics is an interdisciplinary field of science and technology generally dealing with problems in mechanics, electronics and informatics. However, several areas are included in it, which form the basis of mechatronics, and cover many known disciplines, such as: electro technique, energetic, encryption technology, information micro processing technology, adjustment technique, and others. Among these, a special place is held by the electro hydraulic adjustment systems, which are very complex systems, within them interfering phenomena specific to fluid flow in the field of hydraulic volumetric transmissions and to automatic adjustment processes, (Drumea & al., 2010; Popescu & al.., 2011). Due to the complexity of these phenomena, determining the optimal solutions for their design and implementation is performed iteratively. Meeting the required performances involves the use of mathematical modeling and numerical simulation processes of these systems, together with validation of the achieved results by experimental means. For the system analyzed, was followed the next working procedure: mathematical modeling and numerical simulation of mechatronic system (first, for thermo-mechanic system and then for thermo-hydraulic hibrid system) and, finally, testing the energy recovery system in laboratory conditions.

2.4.1 Simulation of dynamic behavior of the motor vehicle with thermo-mechanic propulsion system

Simulation networks presented in this section have been developed and analyzed by modules using *AMESim* numerical simulation software, (LMS IMAGINE SA 2009). The final model used for simulation of HIL in the stage of tests was made using the models developed during the unfolding of research activity upon the system. The first model developed was the model of the motor vehicle with thermo-mechanic propulsion system, figure 16. Input data into the model are: aerodynamics coefficient of the vehicle and torque at the drive wheels, and output data – rotational speed at its wheels.

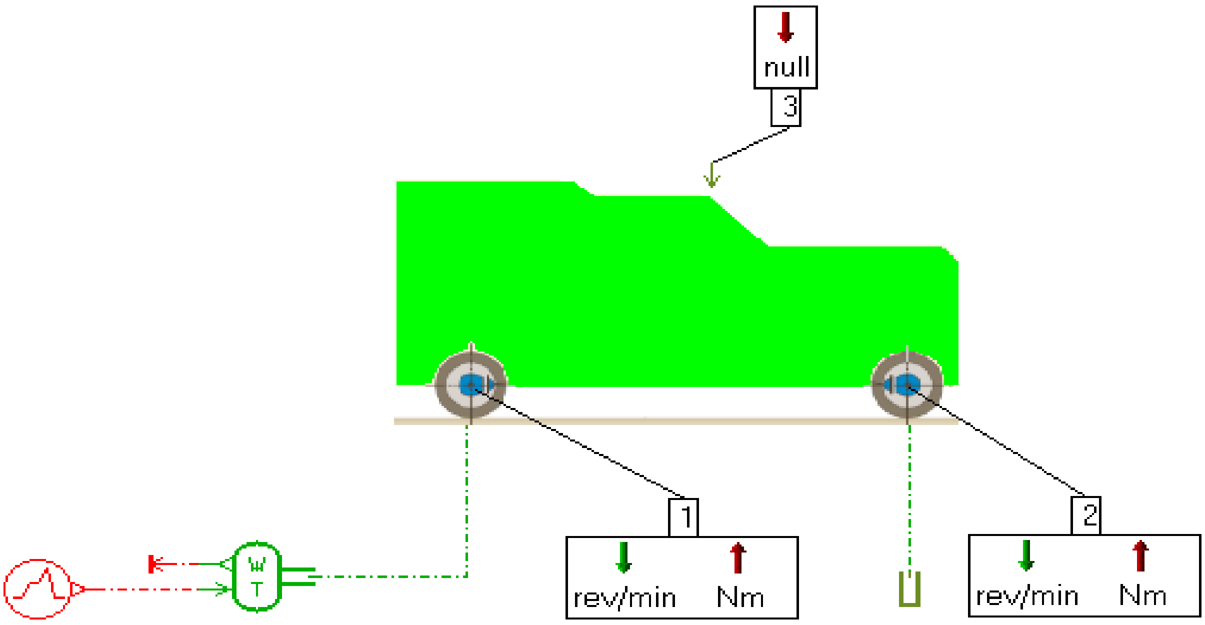


Fig. 16. The model of the motor vehicle with thermo-mechanic propulsion system.

To achieve the simulation network of the motor vehicle with thermo-mechanic propulsion system, the next models have been used: the model of the heat motor vehicle, the models of the elements that convey energy from the vehicle to the ground (drive wheels and free wheels), the model of the differential mechanism, the model of the gearbox, the model of the clutch and the model of heat engine. For the modeling of heat engine, there has been used a simulation network of the external feature of heat engine, using technical data from the table 1. The diagram of relationship between rotational speed and drive torque is presented in Figure 17. This technical feature, from table 1, corresponds to an *Andoria 4CT90 TD* engine, which was part of motor vehicle endowment in some ARO models.

The simulation network of the motor vehicle with thermo-mechanic propulsion system is presented in Figure 18

Rotational speed	[rpm]	1000	1500	2000	2500	3000	3500	4000
Torque	[Nm]	170	183	186	183	178	168	158

Table 1. Table with technical data of heat engine.

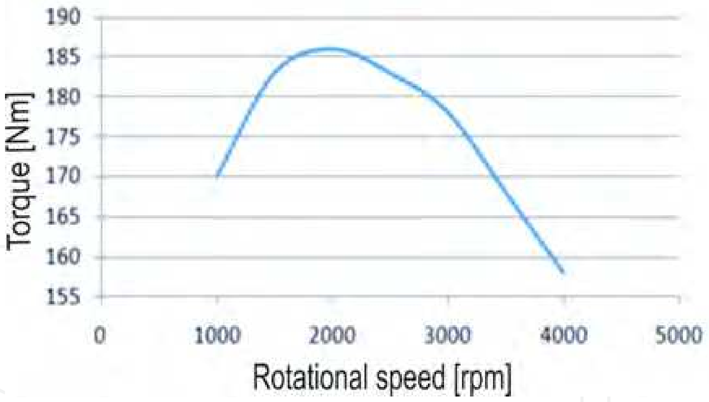


Fig. 17. External feature of the heat engine.

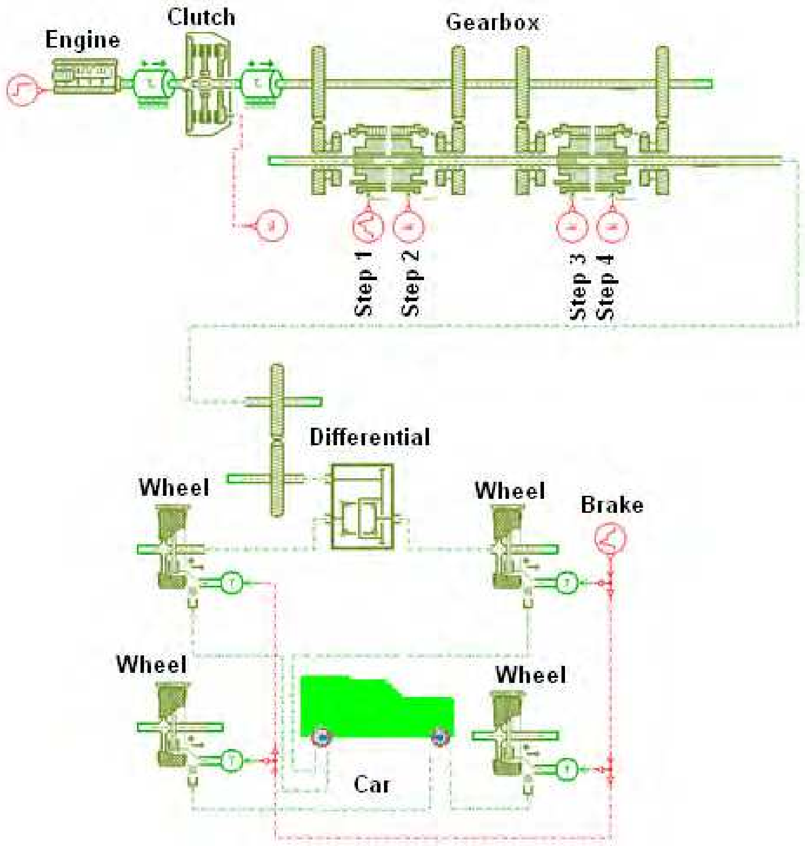
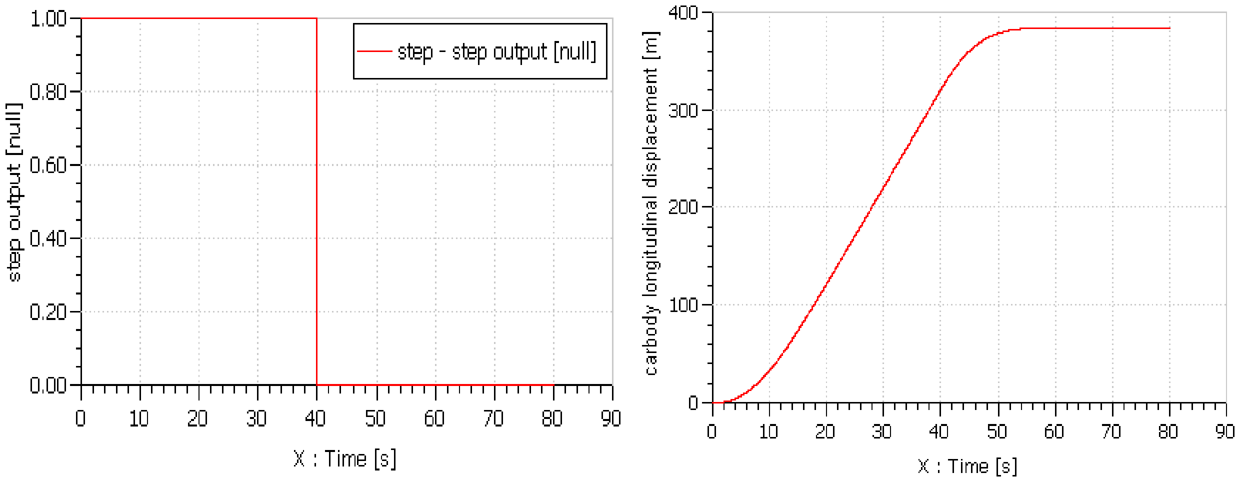


Fig. 18. The simulation network of the motor vehicle with thermo-mechanic propulsion system.

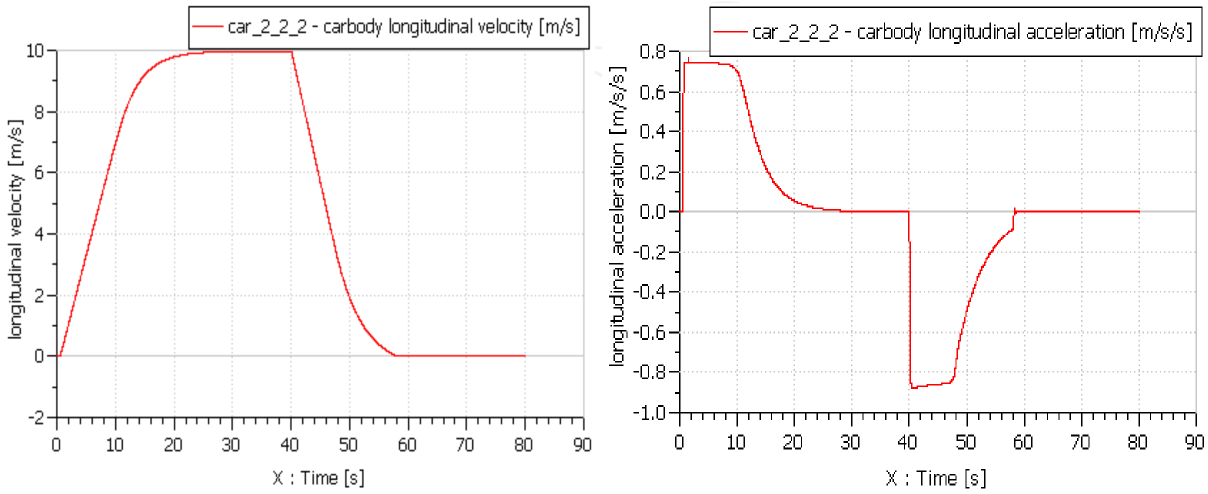
Data about the drive module used to define the models of the simulation network: transmission with 4 speeds (with the next transmission ratios: step I 4.92; step II 2.682; step III 1.654; step IV 1); mechanical switch box with 2 steps; differentials on the front and back bridges, with transmission ratios of 3.72:1; diameter of the wheel D = 736 mm; rolling radius R = 350 mm; cross surface St = 3.57 m^2; motor vehicle weight: own weight 1680 daN; total weight 2500 daN; rolling resistance coefficient f = 0.02; ramp angle α = 0^o; gravitational acceleration g = 9.81 m/s^2; aerodynamics resistance coefficient K = 0.0375 daN/m^2; efficiency of the transmission η = 0.9.

Simulation network was run under the next conditions: at the input of the heat engine has been forced a control signal (acceleration pedal), corresponding to the torque/rotational speed dependence curve in Figure 17. The grafical results ar presented in Figure 19. It was maintained constant (100%) for a period of 40 seconds, as is shown in Figure 19(a). At the moment t = 40 s, full closure was ordered to supply no longer the heat engine. The aim of this simulation was to register the evolution of dynamic parameters of the motor vehicle, in the stage of running on energy received from the heat engine and during movement due to inertia of the system, sees Figure 19, namely: the *variation over time of control signal of heat engine* (0..1 corresponds to 0..100%), see Figure 19(a), the *eevolution over time of displacement of motor vehicle*, see Figure 19(b). Evolution of running velocity of motor vehicle, see Figure 19(c), Evolution over time of acceleration of vehicle, see Figure 19(d), variation of torque at the heat engine shaft, see Figure 19(e), Variation of rotational speed at the heat engine shaft, gearbox and differential mechanism, see Figure 19(f).



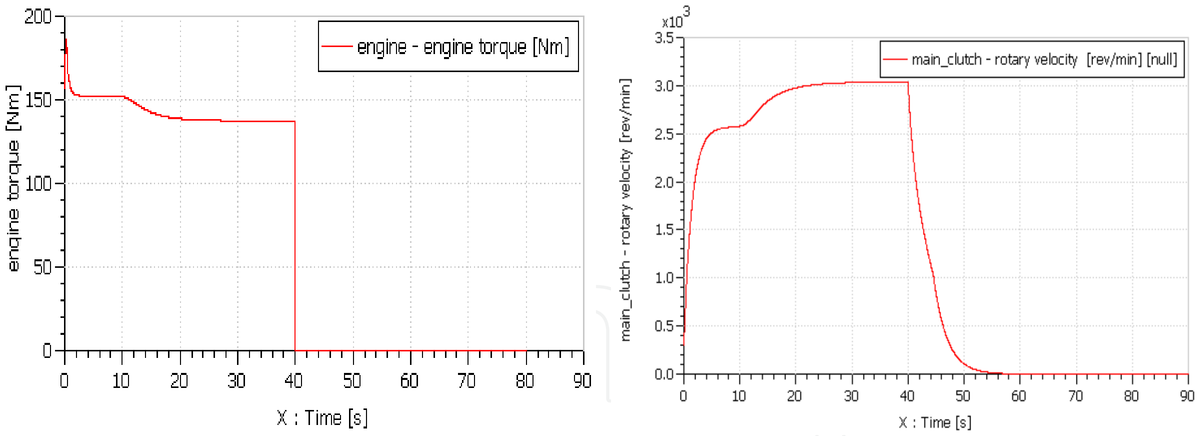
(a) Variation over time of control signal of heat

(b) Evolution over time of displacement of vehicles

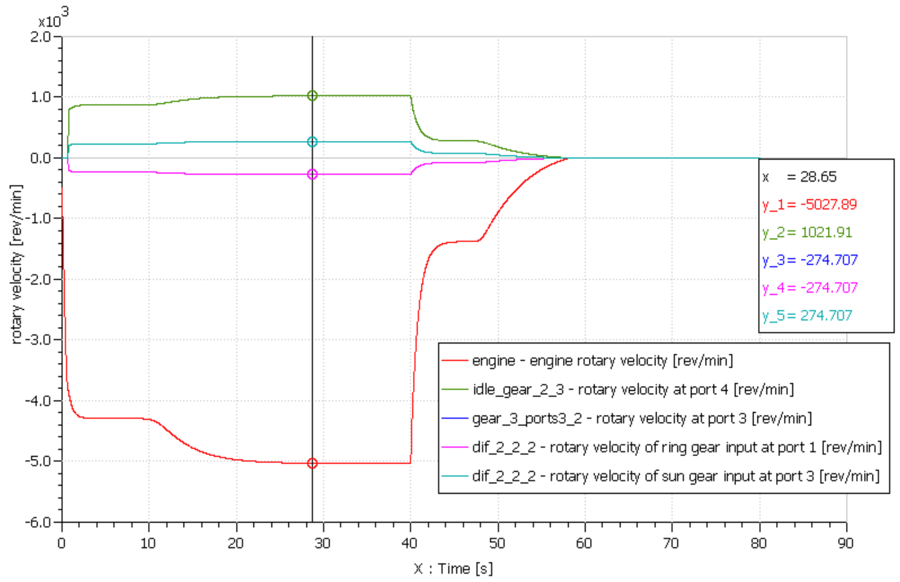


(c) Evolution of running velocity of motor vehicle

(d) Evolution over time of acceleration of vehicles



(e) Variation of torque at the heat engine shaft (f) Cluch rotary velocity



(g) Variation of rotational speed at the heat engine shaft, gearbox and differential

Fig. 19. Variation of the dynamic parameters of the motor vehicle with thermo-mechanic propulsion system.

2.4.2 Simulation of dynamic behavior of the motor vehicle with thermo-hydraulic propulsion hybrid system

The motor vehicle with thermo-mechanic propulsion system has been analyzed with the simulation network shown in Figure 18. The simulation network of dynamic behavior of the motor vehicle with thermo-hydraulic propulsion hybrid system includes the simulation network of thermo-mechanical system, shown in Figure 18, to which was attached the components of energy recovery hydraulic system, to storage and to use of recovery energy achieved at the braking of motor vehicle. Hydrostatic component attached to the thermo-mechanic model is a basic one, greatly simplified for the reason to have an overview of the simulation network. Full schematic diagram includes a series of other elements of hydrostatic instrumentation absolutely necessary for the development of such a system. As it can be seen, in the Figure 20, the most important elements of the hydrostatic system are: bidirectional and reversible hydrostatic unit, battery of oleopneumatic accumulators and mechatronic system for control and adjustment of capacity of the hydrostatic unit.

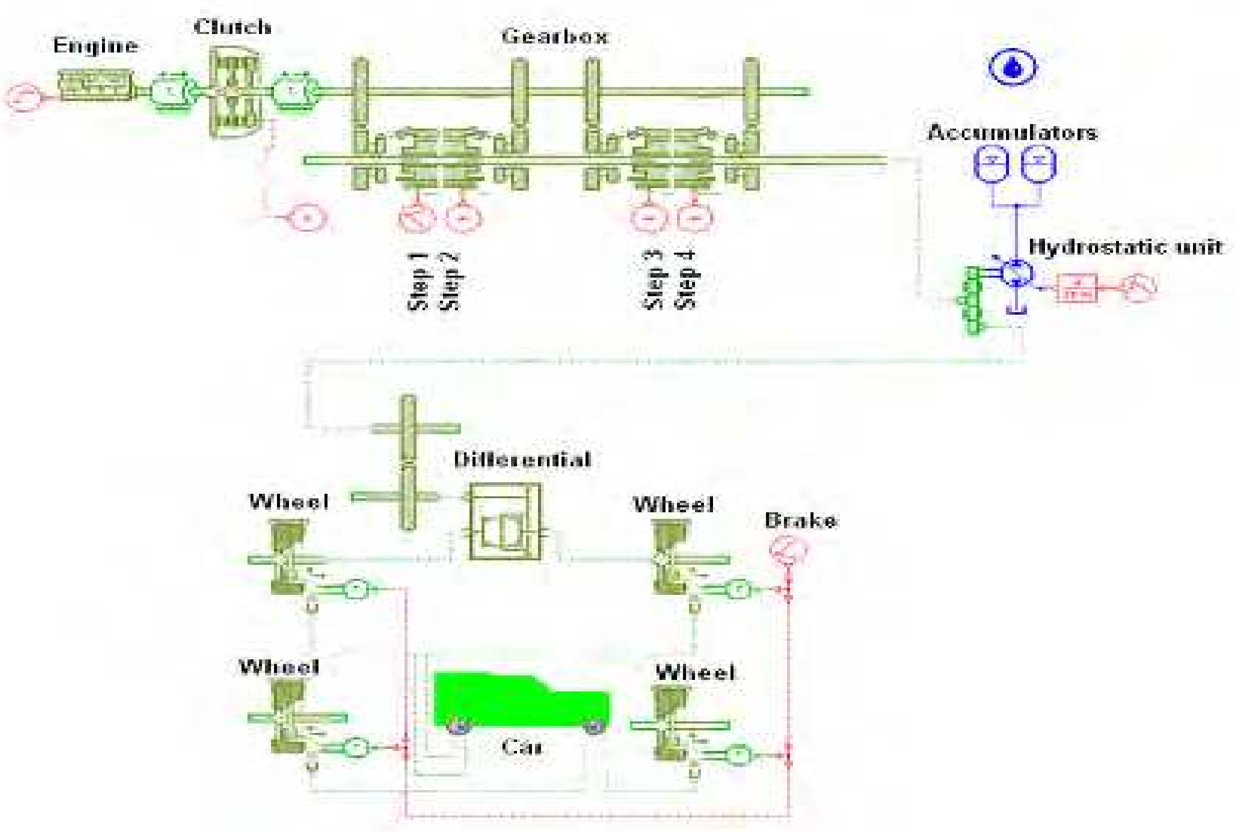
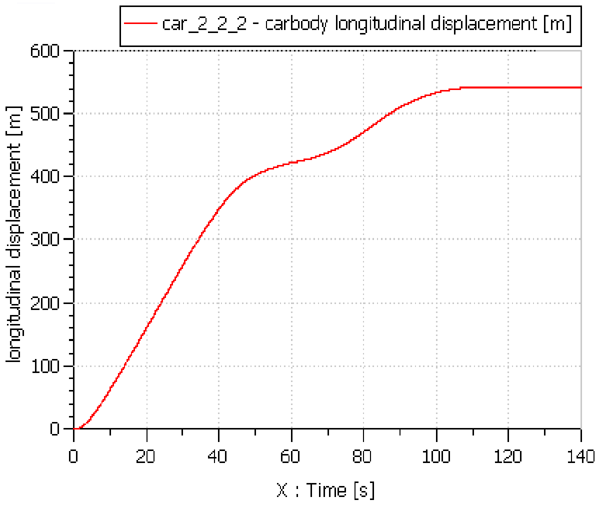


Fig. 20. The simulation network of the dynamic behavior of the motor vehicle with thermo-hydraulic propulsion system.

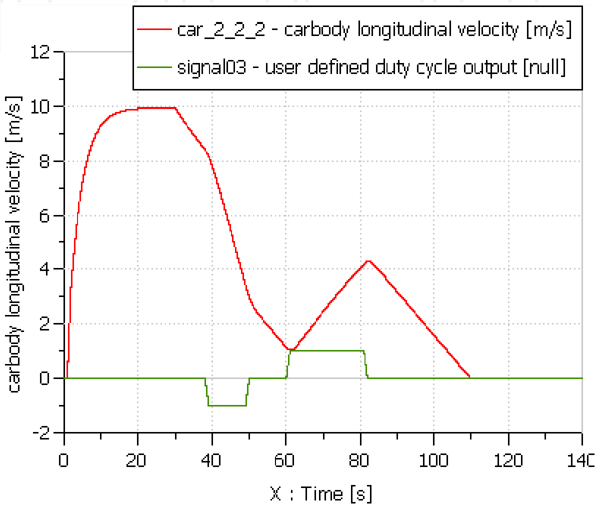
Data about the hydrostatic drive module used to define the simulation network are the next: capacity of the hydrostatic unit: 45 cm^3; volume of the oleopneumatic accumulators: 25 liters; system which conveys mechanical energy between the hydrostatic unit and gearbox with transmission ratio: 1:1; density of working oil 850 kg/m^3; oil elasticity module: 16000 bar; gas pressure inside accumulators: 100 bar. The ssimulation network of the dynamic behavior of the motor vehicle with thermo-hydraulic propulsion hybrid system has been similarly to the previously presented network, to determine the evolution of dynamic parameters of vehicle. The conditions, under which the model has been run, were the next:

- at the input of the heat engine has been forced a control signal (acceleration pedal) corresponding to the torque/rotational speed dependence curve in Figure 17. It was maintained constant (100%) for a period of 40 seconds (Fig. 19a). At moment t = 40 s full closure was ordered to supply no longer the heat engine.
- at moment t = 40 s hydrostatic unit was ordered with a control signal corresponding to its operation in pump mode, with capacity varying after a ramp-step-ramp signal 0 .. 100%, for 10 seconds. During this period the energy recovery function is performed (loading of oleopneumatic accumulators).
- during time span t1 = 40 seconds t2 = 60 seconds the hydrostatic drive has capacity of 0 cm^3, the energy recovery system is "decoupled" from the mechanical system.
- at moment t = 60 s hydrostatic unit was ordered with a control signal corresponding to its operation in motor mode, with capacity varying after a ramp-step-ramp signal 0 .. 100%, for 20 seconds. During this period the use of recovered energy function is performed (discharge of oleopneumatic accumulators).

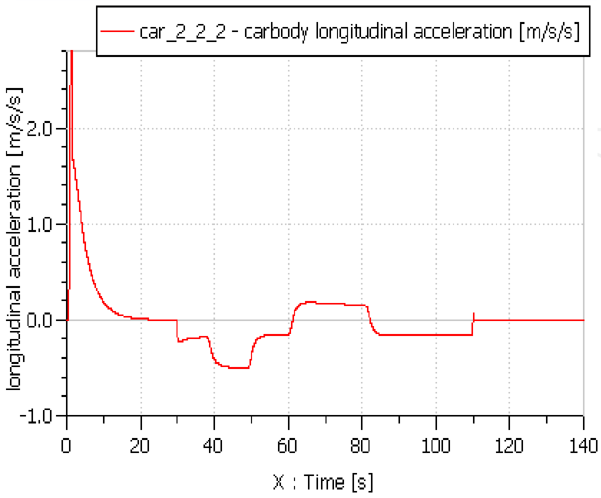
The graphical results, recorded from simulation process, are shown in Figures 21, where it can see: the evolution over time of displacement of motor vehicle, in Figure 21(a), the evolution over time of running velocity of motor vehicle and control signal of hydrostatic unit, in Figure 21(b), the evolution over time of acceleration of vehicle, in Figure 21(c), the variation of torque at the heat engine shaft, in Figure 21(d), the variation of force at the drive wheel, in Figure 21(e), the evolution of pressure inside of accumulators, in Figure 21(f), and, finally, the evolution of the oil flow inside the accumulators depending on control signal of the hydrostatic unit capacity, which can be seen in Figure 21(g),



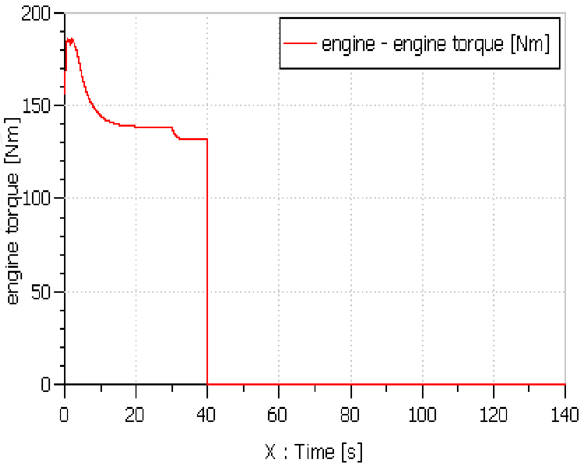
(a) Evolution over time of displacement of motor vehicle



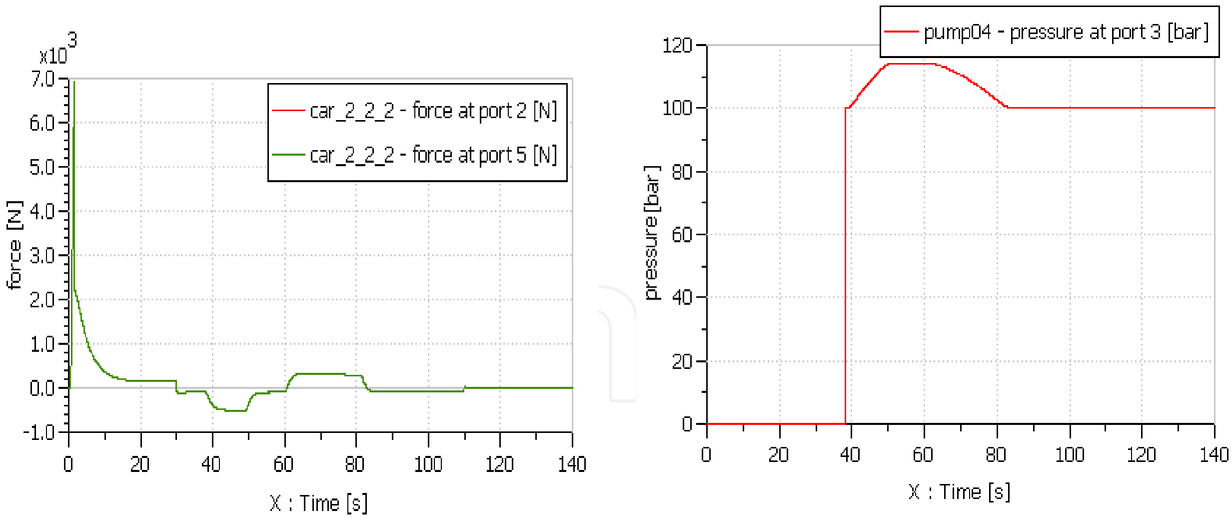
(b) Evolution over time of running velocity of motor vehicle and control signal of hydrostatic unit



(c) Evolution over time of acceleration of vehicle

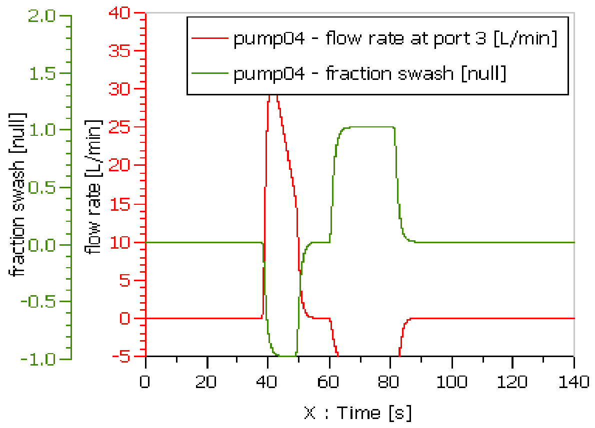


(d) Variation of torque at the heat engine shaft



(e) Variation of force at the drive wheel

(f) Evolution of pressure inside of accumulators



(g) Evolution of oil flow inside the accumulators depending on control signal of the hydrostatic unit capacity

Fig. 21. The variation of the dynamic parameters of the motor vehicle with thermo-hydraulic propulsion system.

3. The mechatronic stand for testing the kinetic energy recovery system

For testing, in laboratory conditions, of the energy recovery mechatronic system, there was necessary to design and physically develop a test stand, able to reproduce the characteristic working modes of a hybrid motor vehicle with the ability to recover kinetic energy during braking. The stand, in itself, is conceived also as one *mechatronic system*.

The goal of stand design and development was to create the possibility of putting the developed mechatronic system for kinetic energy recovery under a series of tests, conducted during all the working modes/stages, before being implemented on a motor vehicle, in order to *understand its dynamic behavior* and the genuine abilities of the system, and, also, to detect early any gaps or shortcomings and new needs, to improve the system on the fly. The stand, also, allows the development of complex experimental research and minimizes the risks borne by a project of this complexity, in case of its direct implementation on the vehicle, without testing in laboratory conditions, (Cristescu, 2008a).

3.1 The technical solution adopted for designing of test stand

The technical solution adopted, in principle, for design and implementation of the test stand of mechatronic system for braking energy recovery, was that of *simulation,* in laboratory conditions, of the *transitional working regimes* for starting and braking the motor vehicles, based on the use of specific equipment only with *electric and hydraulic* drive and control, monitoring the evolution of parameters within the system and managing the processes by computer, using some dedicated software. For *simulating* the operation of the heat engine of the motor vehicle, a combined solution was chosen, based on hydraulic electro-pump, composed of an electric motor and a high pressure hydrostatic pump, which drives a hydraulic motor (or the acceleration module), together simulating the *thermal power*, torque and rotational speed source, parts of the normal equipment of a motor vehicle. The second source of power, *hydraulic power*, characteristic to the energy recovery system, is represented exactly by the *hydro-mechanical module* of the energy recovery system tested on stand, composed of a hydraulic machine and the chain or gear transmission, shown in Figure 25 (a). One load module gathers/integrates, on its input, the two powers, simulating thus the *thermo-hydraulic hybrid propulsion system* of motor vehicles. In this way, *3 propulsion systems* of the motor vehicle can be simulated on stand:

- thermo-mechanical propulsion, based on the heat engine of the motor vehicle;
- mechano-hydraulic propulsion, based on the hydraulic recovery system;
- thermo-hydraulic hybrid propulsion.

Technical solution adopted allows simulation of braking modes with kinetic energy recovery system, namely:

- braking with recovery of kinetic energy impressed by the thermo-mechanical system;
- braking with recovery of kinetic energy impressed by the hydraulic propulsion system

3.2 The general assembly and the structure of the mechatronic test stand

General assembly of mechatronic stand, designed to test the kinetic energy recovery system, is shown in Figure 22, and the physical development of the stand is shown in Figures 23 and Figure 24.

The structure of mechatronic test stand consists of the following modules, which can be seen in Figure 25:

1. *hydro-mechanical module* of the tested mechatronic system for energy recovery, as a source of hydraulic power of the hybrid drive system, consisting of a hydraulic machine and a mechanical chain or gear transmission, fitted with a torque and speed transducer, to monitor the main parameters: torque and speed, shown Figure 25(a);
2. *test module or loading module*, comprising a load device, with a frame containing a torque transducer, having coupled, at its output, a hydraulic unit, and at its input, the hydro-mechanical module of the enrgy recovery system, subjected to testing, shown in Figure 25(b);
3. *module of the electropump,* with variable rotational speed and displacement, which forms together with the acceleration module (hydraulic motor), the subsystem for simulation of the drive engine, shown in Figure 25(c);

4. *acceleration module*, comprising a hydraulic motor, torque and speed transducer, and cardan shaft that connects mechanically the two drive systems simulated, *heat* and *hydraulic*, shown in Figure 25(d);
5. *module for storage of the fluid* under pressure or *battery of accumulators*, comprising a supporting frame on which two hydropneumatic accumulators are mounted, as well as the related security devices, shown in Figure 25(e);
6. *module of the hydraulic station*, with working fluid conditioning subsystem, consisting of an oil tank equipped with temperature control system, drive pump and hydraulic blocks, shown in Figure 25(f);
7. electrical*, electronic and automation subsystem*, with an electrical and electronic subsystem for actuation and control of stand operation and with a *subsystem of sensors and transducers* for monitoring parameters, Figure 25(g);
8. *informatic and control subsystems,* for monitoring and control of stand operation, shown in Figure 25(h);.

The first six modules represent the mechano-hydro-pneumatic subsystem of the test stand, which, toghether with the electronic subsystem and the informatic and control subsystems, create a typical structure of one mechatronic system, (Maties, 1998).

The main modules of the mechatronic test stand were presented in Figure 25.

The stand allows to do testing in the field of hydrostatic transmissions, in order to optimize them functionally and to improve their energy efficiency. The stand is proper for rotary hydrostatic transmissions, with or without energy recovery systems, which are part of fixed (industrial) and mobile (towed vehicles and motor vehicles) equipment, including their subsystems, for functional tests and to establish performance parameters.

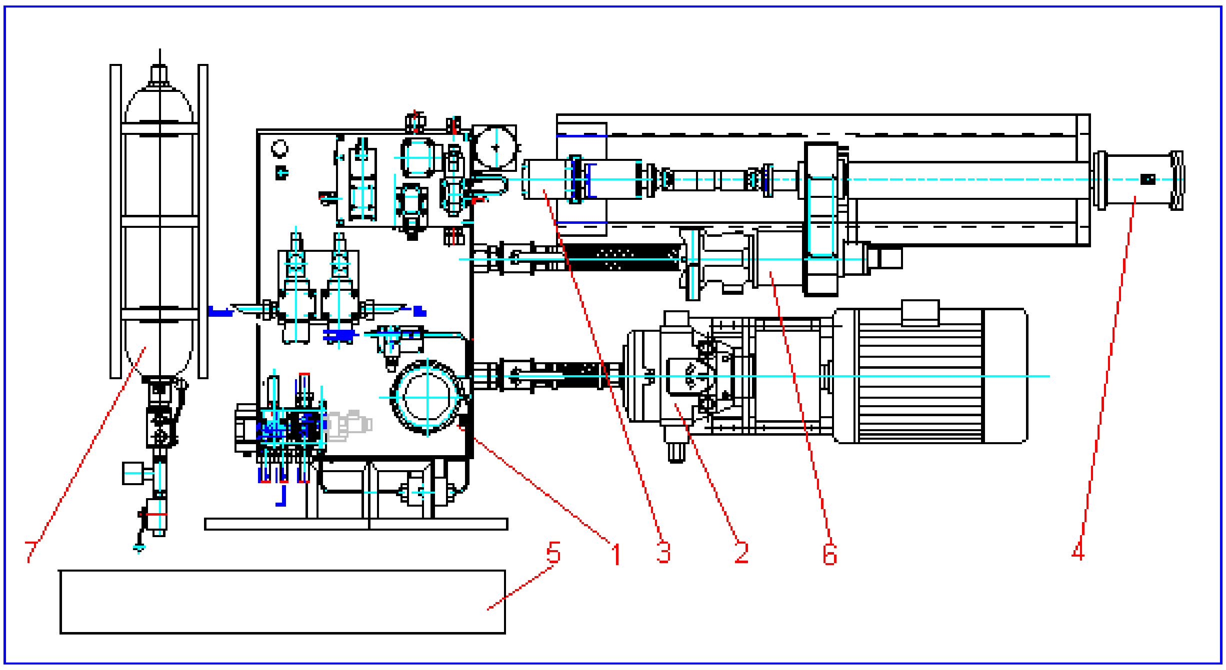


Fig. 22. General assembly of the mechatronic stand for testing of the kinetic energy recovery system.

Fig. 23. Mechatronic stand for testing the kinetic energy recovery system – overview.

Fig. 24. Mechatronic stand for testing the kinetic energy recovery system – frontal view.

a) The hydro-mechanical module of the recovery system

b) The testing module

c) Module of the electropump

d) The acceleration subsystem

e) The accumulating subsystem

f) The hydraulic station

g) The electric and electronic subsystem h) Informatic and control subsystems

Fig. 25. The main modules of the mechatronic test stand.

3.3 Testing of dynamic behavior of the hybrid motor vehicles by using of the real-time simulation network

The analyzed system has been studied both by means offered by conventional methods of mathematical modeling and numerical simulation and, also, by using the hybrid networks of *real-time co-simulation* and simulation (Ion Guta, 2008).

In order to testing of dynamic behavior of the hybrid motor vehicles by using of the *real-time simulation network*, is necessary to do this in two steps. For developing the real-time simulation the first step is the creating of the co-simulation subsystem, which will be presented in the next subchapter. In the second step, it will be used the hybrid simulators, which connect in terms of information the mathematical models and components of physical systems

3.3.1 The creating of the co-simulation subsystem

For achieving the co-simulation networks, there have been used the above presented models, developed by means of *AMESim* software, (LMS IMAGINE SA, 2009). These were coupled to a simulation supervisory application, developed by the authors, of this work by means of *LabVIEW* programming language, (LabVIEW, 1993). This was a first step for developing the real-time simulation application presented in the experimental section of this work. In Figure 26 can be seen the co-simulation subsystem, the process model being coupled to the application developed in *LabVIEW* and loaded on a NI PXI industrial computer, through the communication process implying sharing of memory (shared memory). For communication between the two systems, there can also be used TCP/IP sockets or TCP/IP protocol.

Application developed using *LabVIEW* language, seen in Figure 27(a), has an operator interface that allows governing of the simulation process and visualization of data obtained during simulation, Figure 27(b). The application contains an automation component which controls the hydrostatic equipment within the simulation network, by adjustment of hydrostatic unit capacity, opening and closing of way directional control valves, comprised in the hydrostatic subsystem.

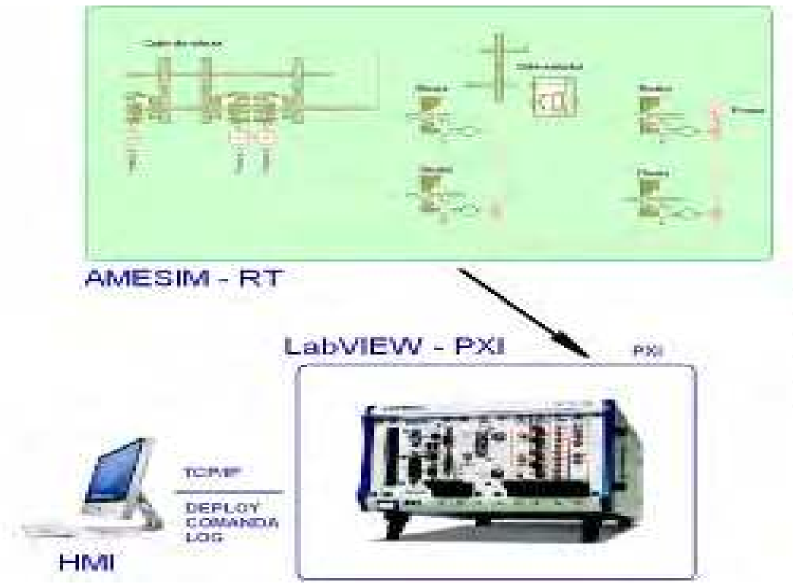
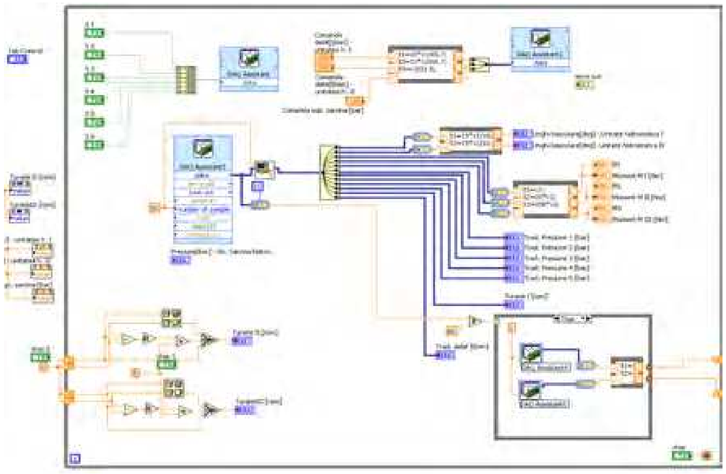
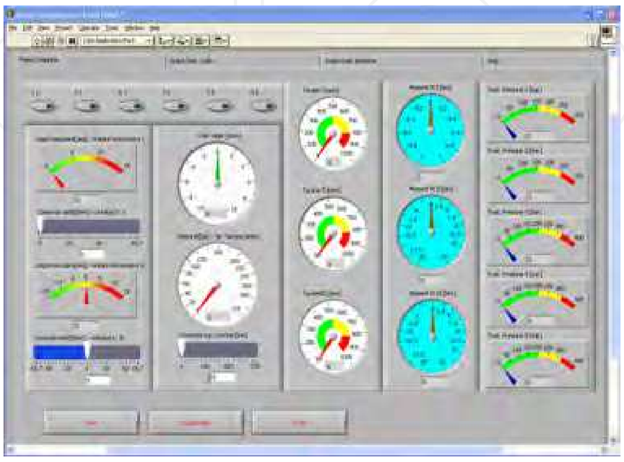


Fig. 26. Co-simulation subsystem.



(a) Block diagram of data acquisition module



(b) Interface VI of stand functioning

Fig. 27. The application developed in LabVIEW language.

3.3.2 Testing energy recovery system by using the hybrid networks of real-time co-simulation and simulation

The solution adopted to achieve the hydrostatic transmission testing system for the energy recovery systems, was that of simulation of operating, braking and start-up modes of motor vehicles, based on electrohydraulic actuation equipment and systems for simulation and numerical modeling specific to the field of hydrostatic drive. The simulations and the experiments have been achieved in the laboratory of hydrostatic transmissions of the institute INOE 2000 – IHP, where. are conducted experimental research in the field of hydrostatic rotary transmissions, in order to optimize them functionally and improve their energy efficiency. To know the dynamic behavior of the energy recovery system, in laboratory conditions, it was used the concept of "*real-time simulation*" of a system, or *„Harwar-in-the loop"* (HIL), involving the simultaneous use of a mathematical model and a *physical part* of the system, see (Gauchia & Sanz, 2010).

The introduction of computers in monitoring and control of industrial process, led to change of technological systems. Great flexibility offered by these systems allows "software" optimization of complex systems. In this scenario it is rational the *use of hybrid simulators*, which connect in terms of information the mathematical models and components of physical systems. This concept has been established in the specialized literature as "*real-time simulation*" or "*numerical simulation with control loop equipment*". (Ion Guta, 2008). Modern methods of experimentation, in the field of hydraulic and pneumatic drive systems, imply the existence of at least one numerical calculation equipment. The necessity of using electro-hydraulic converters, for control and adjustment of various physical parameters such as force, displacement, together with the exponential growth of digital electronics, confirms this. Digital equipment can be found in the structure of sensors and transducers, numerical displays, electronic servo-amplifiers (compensators) or process computers. As part of the endowment of any modern laboratory of electro hydraulic drives there are not lacking *sensors and transducers* with electronic communication interface, adjustment systems (proportional electro hydraulic directional control valves, hydraulic or pneumatic servo pumps/ motors etc.) with analog/digital control ports and electronic adjustment blocks. The ability to "load" the numerical calculation systems, with "virtual models" of systems developed using advanced modeling languages, increases even more their flexibility, as it can be seen in Figure 28.

The system includes a numerical model simulating the dynamic behavior of a motor vehicle with thermo-mechanic propulsion, a process computer of PXI (from *National Instruments*) family, an experimental stand and a system for regular acquisition of data in the analyzed process. The purpose of this analysis is to be excited correspondingly, based on specific input data into the mathematical model, the *power components of the experimental stand* by means of the process computer, in order to be quantified the *amount of energy* that it can recover under simulated operation conditions.

To perform experiments in the simulation model (Figure 20) has been removed simulation of the electro hydraulic subsystem. In place of this component, there has been introduced into the model, information gathered from the testing stand, which contains the physical component of the electro hydraulic subsystem. The next technological parameters on the stand have been introduced into the model: rotational speed at the shaft of hydrostatic unit and torque obtained at the shaft of the unit. From the simulation model, a command has been sent to the physical unit on the stand, by means of which has been emulated the heat engine. The command has been sent so, that rotational speed achieved at the shaft of

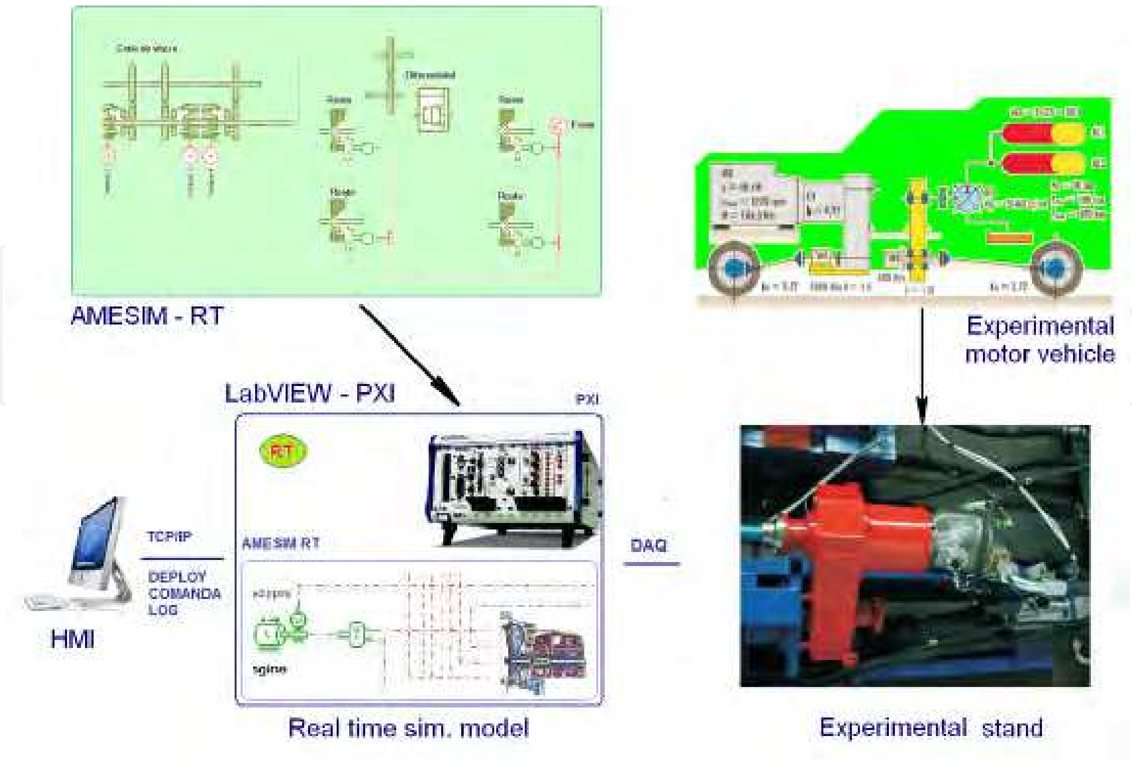


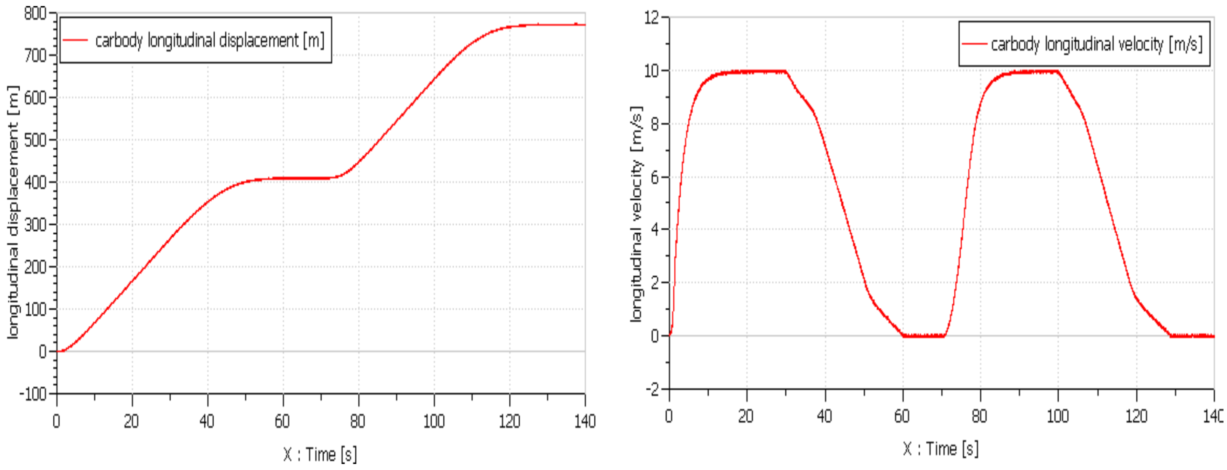
Fig. 28. The hibride network of real-time simulation for testing energy recovery system, in laboratory conditions.

hydraulic motor (which emulates, on the testing stand, the real heat engine) to be dependent on its torque, according to the torque/rotational speed functional curve imposed in the simulation model. Adjustment of rotational speed at the drive shaft has been performed by appropriate variation of the hydrostatic unit capacity. In parallel, computer component of the mechatronic stand, for recovery of braking energy of a motor vehicle, has controlled the devices on the stand so that the simulation model on the PXI industrial computer to record the next cyclogram:

- drive of clutch (coupling of the heat engine to the motor vehicle gearbox) at t = 0 seconds;
- drive of gearbox accordingly to speed step 1 at t = 0 seconds;
- drive of acceleration of the engine till achieving a running velocity of the vehicle of 10 m/s at t = 0 .. 30 seconds;
- drive of clutch (decoupling of the heat engine from the motor vehicle inertial load) at t = 30 .. 70 seconds;
- drive of hydrostatic unit capacity of the energy recovery system, corresponding to its operation in pump mode (working with energy recovery) at t = 32 .. 50 seconds;
- free operation till the motor vehicle stops;
- drive of clutch (coupling of the heat engine to the motor vehicle gearbox) at t = 70 seconds;
- drive of gearbox accordingly to speed step 1 at t = 70 seconds;
- drive of engine acceleration simultaneously with drive of capacity of the system hydrostatic unit corresponding to its operation in motor mode (use of hydrostatic power available in the mechatronic recovery system) till achieving a running velocity of the motor vehicle of 10 m/s at t = 70 seconds;

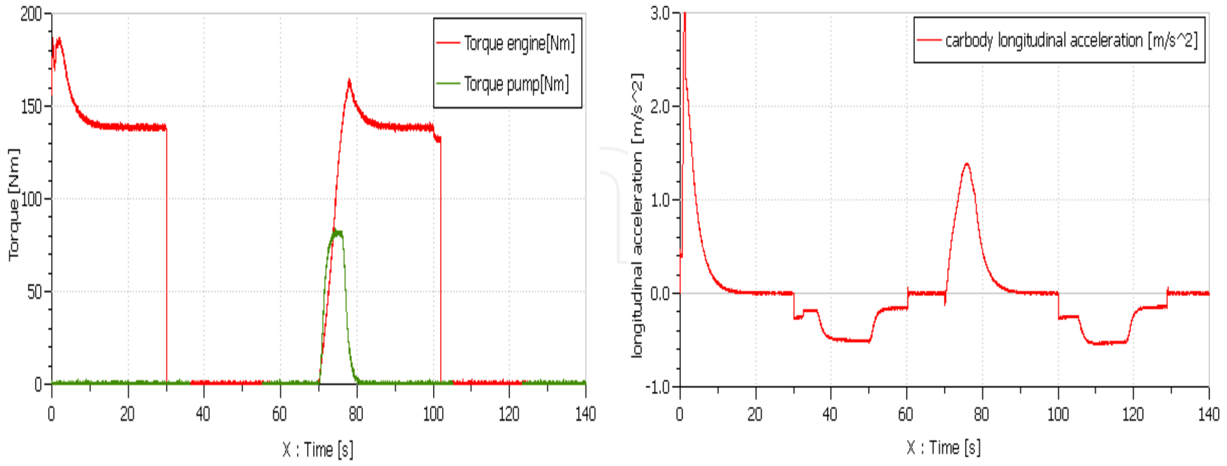
- drive of clutch (decoupling of the heat engine from the motor vehicle inertial load) at t = 100 seconds;
- drive of hydrostatic unit capacity of the energy recovery system corresponding to its operation in pump mode (working with energy recovery) at t = 105..118 seconds;
- free operation till the motor vehicle stops.

Data obtained from experiments of real-time simulation for testing of energy recovery system are shown in Figures 29, where it can see the evolution over time of displacement of motor vehicle, in Figures 29(a), the evolution over time of running velocity of motor vehicle, in Figures 29(b), the vvariation of torque at the shaft of the system equivalent to a heat engine and at the shaft of the hydrostatic unit, in Figures 29(c), the evolution over time of acceleration of motor vehicle, in Figures 29(d). Finally, the comparative study on the evolution of torque at the drive shaft, with and without contribution of mechatronic system for energy recovery in the braking phase ,is presented in Figures 30.



(a) Evolution of displacement of motor vehicle

(b) Evolution of running velocity of motor vehicle



(c) Variation of torque at the shaft of the system equivalent to a heat engine and at the shaft of the hydrostatic unit

(d) Evolution over time of acceleration of motor vehicle

Fig. 29. Data obtained from experiments of real-time simulation for testing of energy recovery system.

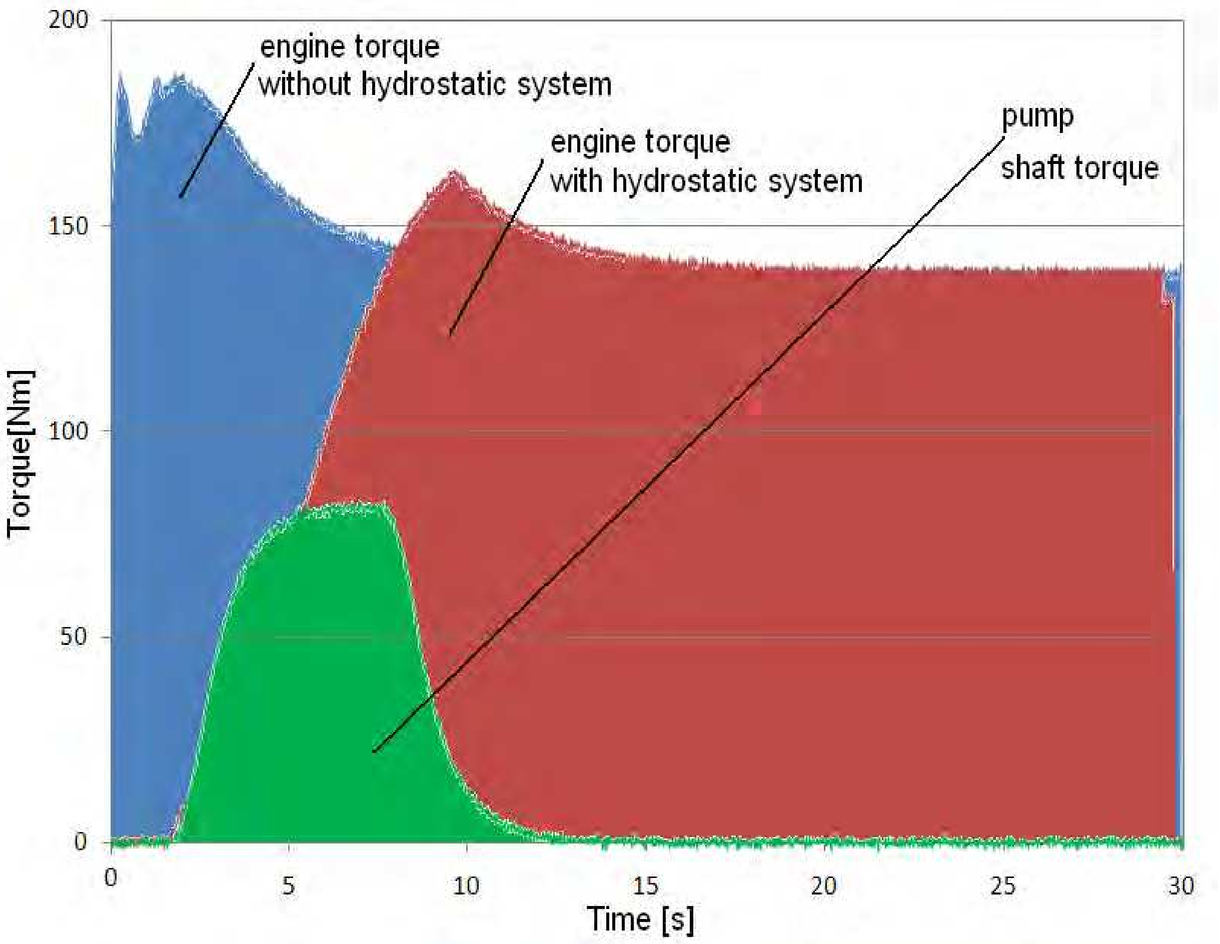


Fig. 30. Comparative study on the evolution of torque at the drive shaft with and without contribution of mechatronic system for recovery of the motor vehicle braking energy.

4. Conclusions

Given the necessity of finding alternative solution to reduce consumption of fossil combustible, being now in exhaustion, and to mitigate the negative impact of emission on the environment, vehicle manufacturers have indicated that an effective solution, could be the development of hybrid propulsion systems, in particular those regenerative propulsion systems, which can recover a portion of the kinetic energy of the vehicle, accumulated before braking.

In this context, the chapter presents some specific problems concerning the complexity of the hybrid propulsion systems of the road vehicles and points out that, indeed, this is a new area suitable for the application of mechatronics, where it is the only technology able to monitor, to manage and to optimize the transient regimes specific for this systems.

By addressing the problem of recovering kinetic energy, when road vehicles are at braking, the authors have reached automatically and at the issue of the hybrid propulsion systems, and they gained o good theoretical and practical experience, which is communicate in this chapter and which can be a point start-up for other researches.

In the first part, the paper presents the general problem of the energy recovery systems and makes a brief presentation for one Romanian mechatronic hydraulic system for energy recovery, which transforms one motor vehicle, where it is implemented, into motor vehicle with hybrid propulsion system, including the main modules of the system.

There are presented some theoretical results obtained by mathematical modeling and numerical simulations, in frame of a preliminary research, which allowed to be chosen some basic components of mechatronic system of energy recovery.

The complexity of issues required by a hybrid propulsion system with energy recovery, have imposed, on the one hand, the choice of mechatronic technology like modality to conceive and to design and, on the other hand, has led to designing and manufacturing of a stand for testing of kinetic energy recovery system, stand which is presented in the second part of the chapter. Also, are presented some graphical results obtained by *real-time simulation*, this new research technology used and by others researchers, which involves the simultaneous use of a mathematical model and a physical part of the studied system. The obtained graphical results confirm, generally, the preliminary theoretical results.

The chapter presents and demonstrates the possibility to design, manufacturing and implementing the energy recovery systems on medium and heavy road motor vehicles, in order to increasing the energy efficiency. The solution allows the extrapolation to different sizes of vehicles and can be mounted on new motor vehicles, as well as on old cars, in the framework of a rehabilitation.The hydraulic and electric necessary components are available on the market

Also, the chapter demonstrates that the only technology which can control and monitories the energy recovery systems, especially the hibrid propulsion systems, is the mechatronics technology.

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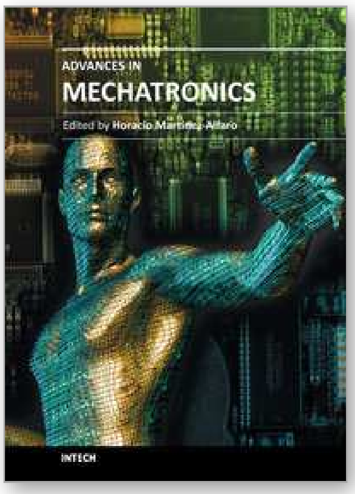

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Numerous books have already been published specializing in one of the well known areas that comprise Mechatronics: mechanical engineering, electronic control and systems. The goal of this book is to collect state-of-the-art contributions that discuss recent developments which show a more coherent synergistic integration between the mentioned areas.Â Â The book is divided in three sections. The first section, divided into five chapters, deals with Automatic Control and Artificial Intelligence. The second section discusses Robotics and Vision with six chapters, and the third section considers Other Applications and Theory with two chapters.

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