

REDUCING ENERGY CONSUMPTION BY PASSENGER CAR WITH USING OF NON-ELECTRICAL HYBRID DRIVE TECHNOLOGY

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ABSTRACT

Not only electrical hybrid technology is used for drivetrain of passenger cars. Also other systems using non-electrical principles (hydraulic or air pressure, mechanical energy storage) can be found in modern vehicles. There is a quantification of the spared energy by using a hybrid vehicle in the paper. Driving cycle ECE 15 was chosen as a platform for simulation of driving resistances.

Keywords: non-electrical hybrid technology, transport energy intensity, driving resistances, energy storage.

INTRODUCTION

Energy intensity of transport is a current topic around the world. All sites of transport service are trying to improve vehicle fuel consumption, which is the biggest part of the energy consumption in transport. Hybrid vehicles are the last direction in this area. Hybrid vehicles are vehicles equipped mostly with petrol-electric engines, which are used for recuperation of the vehicle kinetic energy during breaking phases of driving. But not only electric hybrid vehicles are used. This paper deals with the calculation of energy savings using non-electric hybrid drive technology in cars.

HYBRID AIR

The system is presented in two concepts, Citroën C3 and Peugeot 2008. Hybrid Air system of drive module combines air, hydraulics and fuel.

It uses compressed air (actually pure nitrogen) and a hydraulic motor instead of electricity, supporting the combustion engine. It theoretically gives the same benefits for fuel consumption as it is at a conventional hybrid.

OPERATION PRINCIPLE OF THE HYBRID AIR SYSTEM

Hybrid Air system combines two energy to achieve maximum performance depending on various situations. Compressed air helps gasoline engine or supplies it. Together they contribute to the most efficient operations in transient phases - during the acceleration and starting.

Three-cylinder spark-ignition engine delivers more power through a planetary gearbox that controls the distribution of both of the used energy sources. In this case the noise and vibration are problems but, on the other hand, they can be used in condition monitoring [14, 15]. Engine weight is up to 21 kg lower, compared to the current three-cylinder engine. Planetary gearbox supplies mechanical gearbox and it offers better automation in the gearshift. The pump and hydraulic motor powered by compressed air take the role of the electric motor.

The charging of the high-pressure tank proceeds in two ways. The deceleration is not done by using of brake pads pressure on the disc during the deceleration (braking or releasing the accelerator pedal) but by the resistance to compression

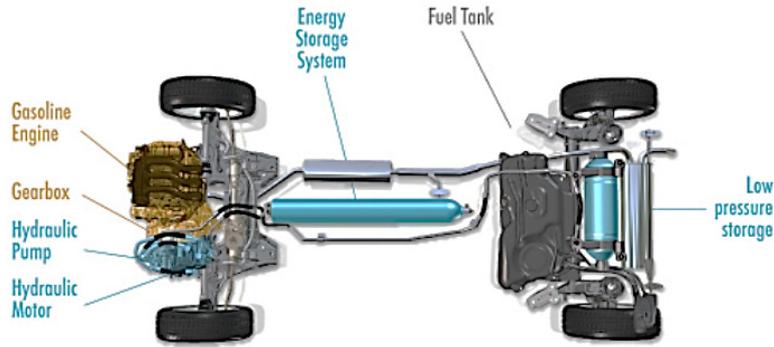


Fig. 1. Diagram and description of Hybrid Air system components [2]

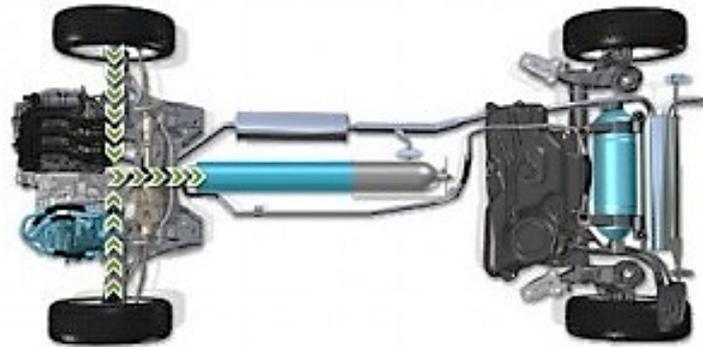


Fig. 2. The air compression into the high-pressure tank [2]

of air in this tank. The second alternative is to re-charge it by the starting of the gasoline engine. The part of the energy obtained from the gasoline engine is used to compress air in this situation. In both alternatives, maximum energy capacity of the high-pressure tank is very quickly achieved, i.e. within ten seconds. This energy is re-used during the starting or overtaking.

During the deceleration, the wheels energy actuates the hydraulic pump that pushes hydraulic fluid into the high pressure tank and compresses the air inside the tank (Figure 2). If the vehicle needs to speed up, the system works in

reverse. Compressed air pushes the hydraulic fluid that actuates the hydraulic motor connected to the planetary gearbox.

CALCULATION OF THE VEHICLE KINETIC ENERGY

The vehicles Citroen C3 and Citroen C3 Hybrid Air were used in calculations. The calculations refers to the urban driving cycle ECE 15. The most often used tire size for vehicle Citroën C3 is 175/65 R14.

Table 1. Parameters required to the calculation of the vehicle Citroën C3 kinetic energy

Vehicle curb weight	1140 kg	Rotating masses coefficient (δ)	1,1 [1]
Vehicle actual weight by (m)	1340 kg [1]	Overall transmission efficiency estimating ¹	0,93
Aerodynamic drag coefficient (c_x)	0,307	Rolling resist. coefficient (f)	0,011 [1]
Frontal area (S)	2,11 m ²	Vehicle acceleration (a)	1,043 m.s ⁻²
Gravity acceleration (g)	9,81 ms ⁻²		0,741 m.s ⁻²
Air density (ρ)	1,29 kg.m ⁻³		0,534 m.s ⁻²
Vehicle speed (v)	4,17 m.s ⁻¹	Vehicle deceleration (b, -a)	0,834 m.s ⁻²
	8,89 m.s ⁻¹		0,808 m.s ⁻²
	13,89 m.s ⁻¹		0,521 m.s ⁻²
	9,73 m.s ⁻¹		0,811 m.s ⁻²

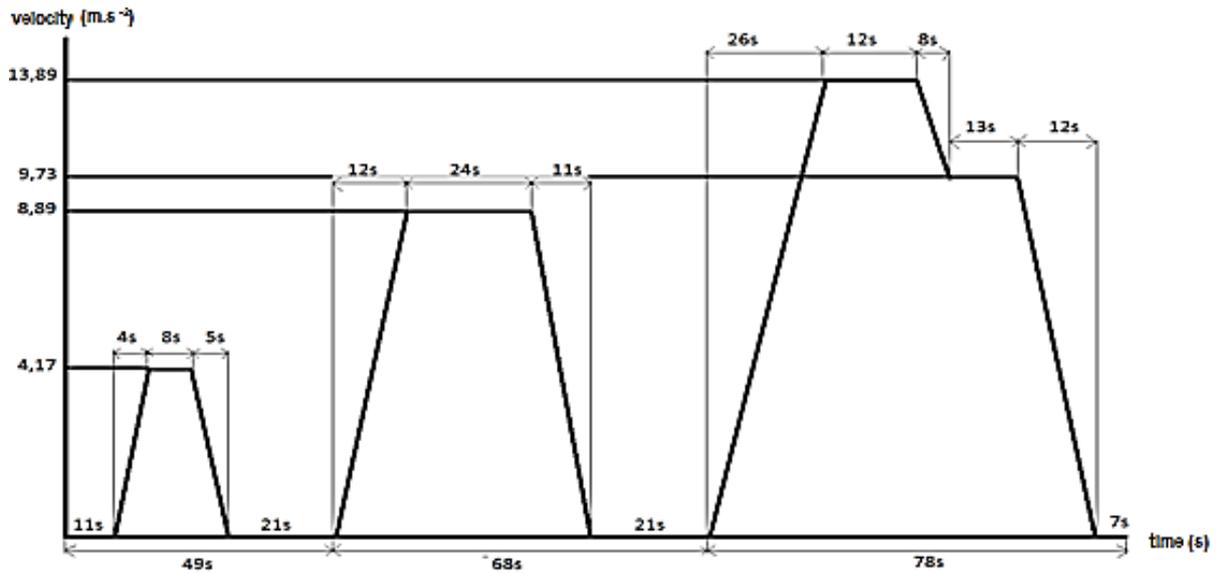


Fig. 3. Driving cycle ECE 15 divided into partial periods and 3 phases

The parameters needed to calculate the kinetic energy of Citroën C3 Hybrid Air vehicle are the same. The only difference is in the weight and size of the tire. In the calculation the same values of parameters except of the weight and rolling resistance coefficient were considered. The weight of the Hybrid Air system is about 100 kg higher than the common Citroën C3 and tires size is 165/50 R 18. They have a smaller value of the rolling resistance coefficient, with an estimation of about 0,008 [3, 4, 7, 9].

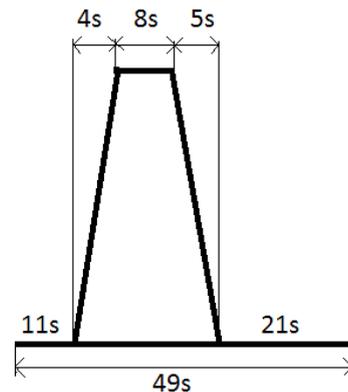


Fig. 4. First phase of driving cycle ECE 15

CALCULATION OF THE DRIVING RESISTANCE AND ENERGY

To calculate the total energy, first it is necessary to calculate the forces needed to overcome the driving resistances that act on the vehicle and the energy required for acceleration of the vehicle, steady vehicle driving and braking of the vehicle [12, 13].

Phase 1 has duration 49s, where acceleration time is equal 4s and has value 1,043 m.s⁻², stage of constant speed continues 8s with value 4,17 m.s⁻¹ and deceleration stage is equal 5s with value 0,834 m.s⁻².

Equations of the vehicle driving resistances have been used for calculation all resistances with inputs from the Table 1.

- Air resistance

$$O_v = \frac{1}{2} \cdot \rho \cdot S \cdot c_x \cdot v^2 \quad (1)$$

- Rolling resistance

$$O_f = f \cdot G \cdot \cos \alpha = f \cdot m \cdot g \cdot \cos \alpha \quad (2)$$

- Inertia resistance

$$O_a = a \cdot m \cdot \delta \quad (3)$$

- Vehicle acceleration

Distance necessary for the vehicle acceleration:

$$s = \frac{t^2 \cdot a}{2} = \frac{v^2}{2 \cdot a} = \frac{4,17^2}{2 \cdot 1,043} = 8,34 \text{ m} \quad (4)$$

Energy calculation was done as multiple of the driven distance and driving resistance, for example: energy to overcome rolling resistance:

$$E_f = s \cdot O_f \quad (5)$$

The total energy E_T in acceleration process is summary of energy consumption in all modes:

$$E_T = E_f + E_v \pm E_a = 1205,96 + 15,18 + 12821,77 = 14\,132,91 \text{ J} \tag{6}$$

Constant speed of the vehicle

Distance with a constant speed of the vehicle:

$$s = v \cdot t = 4,17,8 = 33,36 \text{ m} \tag{7}$$

Energy needed for the constant speed:

$$E_{CV} = (O_v + O_f) \cdot s \tag{8}$$

Deceleration of the vehicle

Distance needed for the vehicle deceleration:

$$s = \frac{t^2 \cdot b}{2} = \frac{v^2}{2 \cdot b} = \frac{4,17^2}{2 \cdot 0,834} = 10,43 \text{ m} \tag{9}$$

Total energy during the deceleration:

$$E_T = E_f + E_v \pm E_a = 1508,18 + 18,98 - 12815,62 = -11\,288,46 \text{ J} \tag{10}$$

All calculated results for Citroën C3 are presented in the Table 3. At this phase acceleration of the vehicle requires energy of ca 14 kJ to overcome air resistance, rolling and inertia resistance. At a constant speed a vehicle needs to consume the energy of 5 kJ to overcome air and rolling resistance and in deceleration to consume energy of 1.5 kJ to overcome only air and rolling resistance (Table 2).

The calculations of the 2nd and 3rd phases for Citroën C3 and for all three phases for Citroën C3 Hybrid Air were done in the same way. The results for Citroën C3 Hybrid Air are in the table 2.

The differences in the calculation of the required power and rolling and inertia resistance can be seen in Table 2. It is caused by changing vehicle weight and the coefficient of rolling resistance. Air resistance takes the same values.

In all three phases, the vehicle power is needed to overcome air, rolling and inertia resistance (Table 2) fixed on the path to achieve the desired speed to the urban driving cycle ECE 15.

Of course, vehicle needs more energy for acceleration, driving and deceleration. Some energy is lost in the transmission system. The total efficiency of transmission system of the vehicle with front-wheel drive is approximately 93% (Table 3 and 4).

Based on the previous calculations for the vehicle Citroën C3, part of the kinetic energy during the deceleration of the vehicle is consumed to overcome air resistance and rolling. The rest of the available energy is converting into the heat in braking. Hybrid vehicle Citroën C3 with Hybrid Air system can store usable energy with efficiency $\eta = 70\%$. This energy is re-used during acceleration of the vehicle thereby reduce the energy

Table 2. The resulting values of driving resistance and energy for Citroën C3 Hybrid Air

Cycle	Mode	Dist. [m]	O_v [N]	O_f [N]	O_a [N]	E_v [J]	E_f [J]	E_a [J]	E_T [J]
1. phase	acceleration	8,34	1,82	113,01	1651,32	15,18	942,50	13772,01	14729,69
	const. speed	33,36	7,27	113,01	0,00	242,53	3770,01	0,00	4012,54
	deceleration	10,43	1,82	113,01	1321,06	18,98	1178,69	13778,61	-12580,94
2. phase	acceleration	53,34	8,26	113,01	1173,48	440,59	6027,95	62593,42	69061,97
	const. speed	213,36	33,02	113,01	0,00	7045,15	24111,81	0,00	31156,96
	deceleration	48,9	8,26	113,01	1280,16	403,91	5526,19	62599,82	-56669,72
3. phase	acceleration	180,57	20,15	113,01	846,22	3638,49	20406,22	152802,22	176846,92
	const. speed	166,68	81,61	113,01	0,00	13436,07	18836,51	0,00	32429,36
	deceleration	90,81	20,15	113,01	825,66	1829,82	10262,44	74978,18	-62885,93
	const. speed	126,49	39,56	113,01	0,00	5003,94	14294,63	0,00	19298,58
	deceleration	58,38	9,89	113,01	1284,36	577,38	6597,52	74980,94	-67806,03

Table 3. Energy required for acceleration, deceleration at the desired speed for Citroën C3

Cycle phase ECE 15	1. phase	2. phase	3. phase	
Desired speed [km.h ⁻¹]	15	32	50	35
Energy needed to acceleration [J]	14132,91	66413,31	171878,45	-
Energy needed to acceleration based on the total efficiency of transmission system (93%) [J]	15122,21	71062,90	183909,94	-
Energy for constant speed [J]	5066,38	37897,00	37704,38	23294,40
Energy for constant speed based on the total efficiency of transmission system (93%) [J]	5421,03	40549,79	40343,68	24925,00
Energy needed for deceleration [J]	1527,16	7474,85	14960,95	8999,13
Usable energy [J]	0	0	0	0

Table 4. Energy required for acceleration, deceleration at the desired speed for Citroën C3 Hybrid Air

Cycle phase ECE 15	1. phase	2. phase	3. phase	
Desired speed [km.h ⁻¹]	15	32	50	35
Energy required to acceleration [J]	14729,69	69061,97	176846,92	-
Energy required to acceleration based on the total efficiency of transmission system (93%) [J]	15760,77	73896,30	189226,20	-
Energy for constant speed [J]	4012,54	31156,96	32429,36	19298,58
Energy for constant speed based on the total efficiency of transmission system (93%) [J]	4293,42	33337,95	34669,42	20649,82
Energy required for deceleration [J]	1197,67	5930,10	12092,26	7174,90
Usable energy [J]	12580,94	56669,72	62885,93	67806,03

required to accelerate the vehicle to the desired speed [5, 6, 8, 9].

USABLE ENERGY OF VEHICLE CITROËN C3 HYBRID AIR BY THE CYCLE ECE 15

During the braking it is not possible to recover complete kinetic energy to the tank because part of the energy is consumed to overcome air resistance and rolling, some of the energy is consumed in transmission system. This feature is known as transmission losses. They are represented by value of the transmission system. Equations used for energy storage are under the Table 4.

Equation 11 has been used for the calculation of the recuperated energy amount E_{UX} in the phase 1. The same equation can be used for other phases of the driving cycle.

$$E_{UX} = E_{TX} \cdot \eta \tag{11}$$

$$E_{U1} = E_{T1} \cdot \eta = 12580,94 \cdot 0,7 = 8806,66J$$

Total usable energy:

$$E_S, E_P = \sum E_{U1,2,3} \tag{12}$$

where: E_p – energy used for driving cycle by conventional Citroën C3,

E_s – energy used for driving cycle by Citroën C3 Hybrid Air.

Calculation of percentage difference in the energy required for the cycle ECE 15 based on Table 5:

$$R_p = \frac{E_{HA} \cdot 100}{E_{C3}} = \frac{305,7 \cdot 100}{414,3} = 73,79 \% \tag{13}$$

Based on previous calculations, it can be stated that the vehicle Citroën C3 with Hybrid Air system is capable of maintaining more than one quarter of the energy that would be otherwise converted into heat in braking, as it is in conventional vehicle with internal combustion engine. In the figure 5 and in the table 5 it can be seen the difference of needed energy to overcome driving resistance between the current car and vehicle with Hybrid Air system. The conventional vehicle needs to consume more energy than a vehicle with Hybrid Air system. It is mainly due to lower value of rolling resistance coefficient [10, 11].

CONCLUSION

The energy required to perform the cycle ECE 15 by using the vehicle with the hybrid air system is 26,2% lower than by using conventional vehicles Citroën C3.

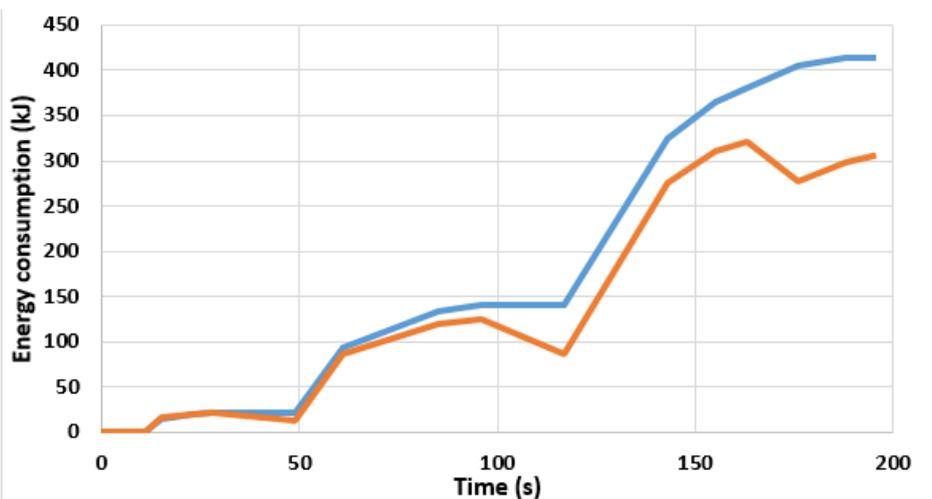


Fig. 5. Comparison of energy consumption of Citroën C3 and Citroën C3 Hybrid Air needed to perform the cycle ECE 15 based on Table 6

Table 5. Energy needed to perform the cycle ECE 15

Time [s]	Citroën C3		Citroën C3 Hybrid Air	
	Consumed overall energy E_{C3} [kJ]	Energy increment [kJ]	Consumed overall energy E_{HA} [kJ]	Energy increment [kJ]
0	0	0	0	0
11	0	0	0	0
15	15,1	15,1	15,8	15,8
23	20,5	5,4	20,1	4,3
28	22,1	1,5	21,2	1,2
49	22,1	0	12,4	-8,8
61	93,1	71	86,3	73,9
85	133,7	40,6	119,6	33,3
96	141,2	7,5	125,6	5,9
117	141,2	0	85,9	-39,7
143	325,1	183,9	275,1	189,2
155	365	40,3	309,8	34,7
163	380,4	15	321,9	12,1
176	405,3	24,9	277,9	-44
188	414,3	9	298,5	20,6
195	414,3	0	305,7	7,2

If we assume that the path of the vehicle drive increases, the number of acceleration and deceleration increases as well and energy savings. The best use of the vehicle with the hybrid air system is in urban traffic at speeds up to $50 \text{ km}\cdot\text{h}^{-1}$, when the vehicle accelerates and decelerates repeatedly. The saving of energy and its re-use reduces consumption and also the production of harmful substances in the emissions of CO, unburned hydrocarbons and CO₂, which contributes to the greenhouse effect. Re-use of stored energy in the tanks also indirectly extends the life of the inter-

nal combustion engine because during the use of stored energy the internal combustion engine is disconnected.

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