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DRIVING-DATA BASED STUDY ON THE RECUPERATIVE POTENTIAL OF HYBRID VEHICLES

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ABSTRACT – To correctly dimension a hybrid propulsion system, good statistical data for the driving condition are necessary. The paper presents some possibilities to acquire road records and to process this data aiming the assessment of mean and extreme values for the vehicle dynamic parameters.
The recuperative braking process is considered a good possibility to reduce the fuel consumption and the CO_2 emissions. The study presents estimations on the possible improvements in this field.
Finally, suggestions on the dimensioning of hybrid propulsion system components are presented.

INTRODUCTION

The paper presents a method to process acquired data obtained in road traffic in order to assess valuable peak and statistical values about the vehicles' dynamic parameters.

Combining the driving records with some estimated or supplementary experimental data it is possible to obtain numerous indices about the propulsion system load and about the way the fuel energy is consumed during travel.

ROAD TEST CONDITIONS

The tests presented here were performed with two cars in normal driving. One (B segment) car was driven in mountain road traffic, while the other (C segment) car was driven in a big city, in ordinary rush hour conditions.

The chosen routes were selected so that to be statistically representative for mountain and city traffic. The mountain route was travelled forth and back and is showed as a blue track in a Google Earth map, **figure 1**. The route of 25.2 km started and ended at 798 m altitude, having its highest point at 1263 m (465 m height difference) and a maximal slope of 12%. The altitude and slope profile of the route is presented in **figure 2**.

The city route is showed as a yellow track in a map obtained with the software Garmin MapSource and has a length of 9.8 km. The route has one end at 620 m altitude and the other at 610 m altitude, having its lowest point at 580 m and very small slops (under 1%). The route was travelled 3 times forth and 2 times back.

Fig. 1: The mountain route presented in Google Earth

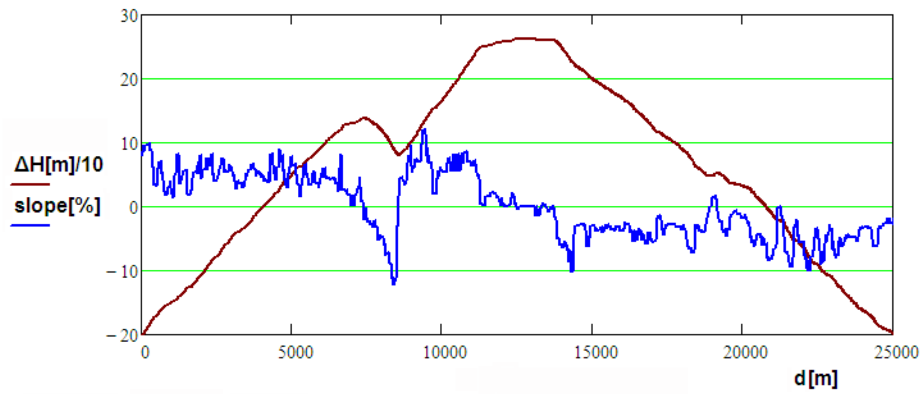

Fig. 2: Altitude and slope profile of the mountain route

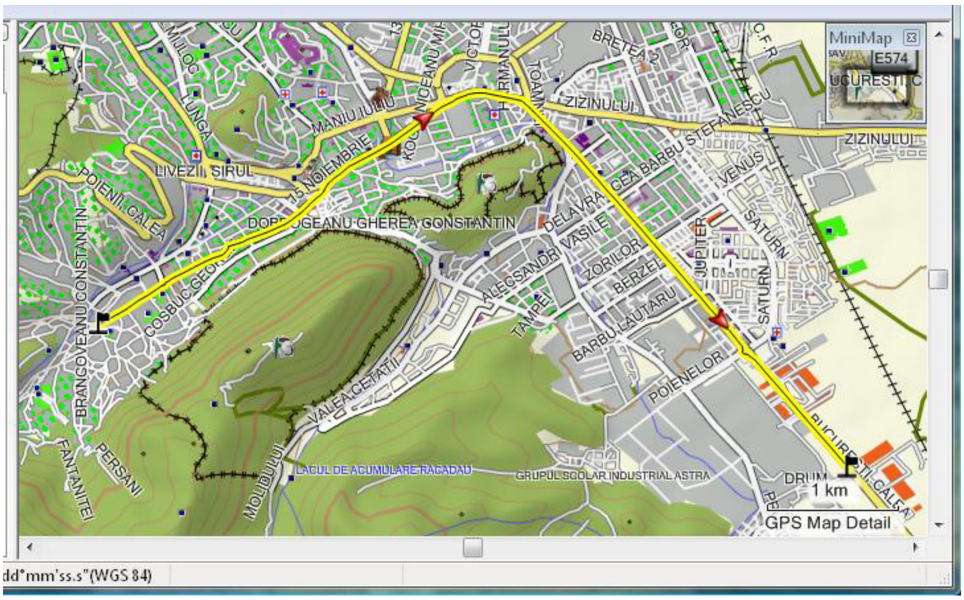

Fig. 3: The city route presented in Garmin MapSource

The rolling-, aerodynamic- and drive train drag was estimated for each vehicle using a coast-down based experimental method (4). For that, before each road test, the tyres inflation pressure was adjusted to the prescribed values and the vehicle's total weight was measured. Also, the atmospheric pressure and temperature were noted.

For the data acquisition were used two different methods (1), (2), (5): one based on the GPS technology (applied on the mountain route) and the other based on the reading, through a corresponding interface, of the information available on the vehicle's CAN bus (applied on the city route).

The acquired GPS data used for the study consisted in records of time, latitude, longitude, altitude and vehicle speed. The records were provided with an exact frequency of 1 Hz (one record per second).

The data from the CAN bus (provided by the vehicle's sensors and primarily processed by the on-board computer) was read at an approximate rate of 2.5 Hz (one record at 0.4 second). The recorded information was: time, vehicle speed, engine speed, hourly fuel consumption, position of accelerator pedal, coolant temperature, status of the control pedals (accelerator, brake and clutch – actuated or not) and few others.

PROCESSING ALGORITHM

The recorded data was post-processed using algorithms largely presented in (1), (3), (5). The authors realised computer programs able to import the data from the GPS device and from the CAN bus using files in standard or proprietary formats. The conceived programs were run in PTC Mathcad and in Autodesk AutoCAD environments, taking benefits from their computation power (in the firs case) and graphical and list processing features (in the second). Both software environments permit to process data with different structures, allowing also adding, removing or extracting easily some wonted sets of data.

From the speed information, the vehicle's travelled distance d and the longitudinal acceleration a_x can be obtained, respectively, by integration and differentiation:

$$d = \int v \, dt \qquad \text{(Eq. 1)}$$

$$a_x = dv/dt \qquad \text{(Eq. 2)}$$

Because in the case of the GPS data the vehicle's position is known, the distance can be found also processing the longitude, latitude and altitude (1), (3). Approximating in a certain point the vehicle's trajectory with a circular arc and constructing this arc, the turning radius R of the road can be ascertained. Then, the lateral component of the acceleration a_y and the total acceleration a can be computed.

$$a_y = v^2 / R \qquad \text{(Eq. 3)}$$

$$a = (a_x^2 + a_y^2)^{1/2} \qquad \text{(Eq. 4)}$$

The same position data can be used to calculate the road slope. If assumes small inclination, that is the case of main roads, results:

$$\sin\alpha = \tan\alpha = h/100 = \mathrm{d}H/\mathrm{d}d \quad \text{(Eq. 5)}$$

In this equation, α represents the road inclination angle, h the road slope expressed in percents and H the altitude. Because the altitude information is not so accurate as the longitude and latitude, the slope values were numerically filtered.

Now the vehicle's resistance forces can be estimated (1), (4) – the aerodynamic drag R_a, the rolling drag R_r, and the grade force R_g:

$$R_a = \rho\, c_x\, A\, v^2 / 2 \quad \text{(Eq. 6)}$$

$$R_r = W f_0\, (1 + f_1) \quad \text{(Eq. 7)}$$

$$R_g = W \sin\alpha \quad \text{(Eq. 8)}$$

where ρ is the air density (computed based on the atmospheric pressure and temperature); c_x – the aerodynamic drag coefficient; A – the vehicle's frontal area; W – the vehicle's weight; f_0 and f_1 – coefficients of the rolling resistance. The values of these magnitudes are determined after the coast-down test (4).

Because the longitudinal acceleration is already computed, the available force F_d (able to accelerate or to brake the vehicle) and the force at the driving wheels F_w can be estimated:

$$F_d = m\, \delta\, a_x \quad \text{(Eq. 9)}$$

$$F_w = R_a + R_r + R_g + F_d \quad \text{(Eq. 10)}$$

where m is the vehicle's mass and δ a coefficient depending on the rotary inertia of the propulsion system (which has a value bigger than 1 and can be estimated).

The corresponding powers ones obtain multiplying each force with the vehicle's speed. The positive values of the power at the driving wheels $P_w = F_w\, v$ represent the traction power and one obtains subtracting from the engine's effective power P_e the power lost by friction into the drive train P_f:

$$P_w = P_e - P_f = P_e\, \eta \quad \text{(Eq. 11)}$$

where η is the efficiency of the drive train. The negative values of the power at the driving wheels P_w represent the braking power (consumed into the wheel brakes, engine or driveline retarder). That braking power may be recovered, contributing to the increase of the vehicle's overall efficiency.

The integrals of the described powers vs. time represent the corresponding energies and were calculated here in order to mark out where the energy is consumed and what amount of the vehicle kinetic or potential energy may be recovered.

OBTAINED RESULTS

Further, some results obtained by the data processing will be presented. These were obtained from the second record on the mountain route and from the first record on the city route.

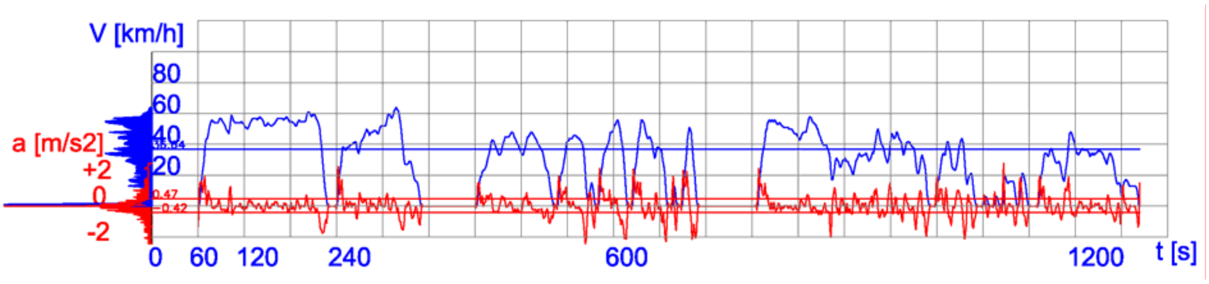

Fig. 4: City route record: vehicle's speed and longitudinal acceleration vs. time (right); probability density for the speed and acceleration apparition (left)

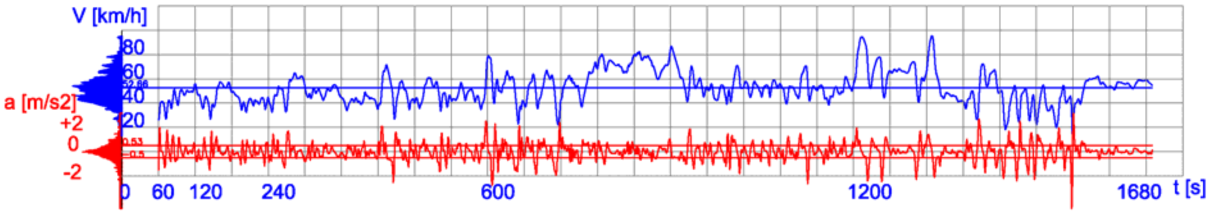

Fig. 5: Mountain route record: vehicle's speed and longitudinal acceleration vs. time (right); probability density for the speed and acceleration apparition (left)

Table 1. Statistical values of the routes' kinematic parameters

	Mountain km/h	City km/h
Max. veh. sp.	95.3	57
Mean veh. sp.	52.7	36.6
Max. acceleration	3.2	2.9
Mean acc.	0.53	0.47
Min. acceleration	-4.7	-2.5
Mean acc.	-0.5	-0.42

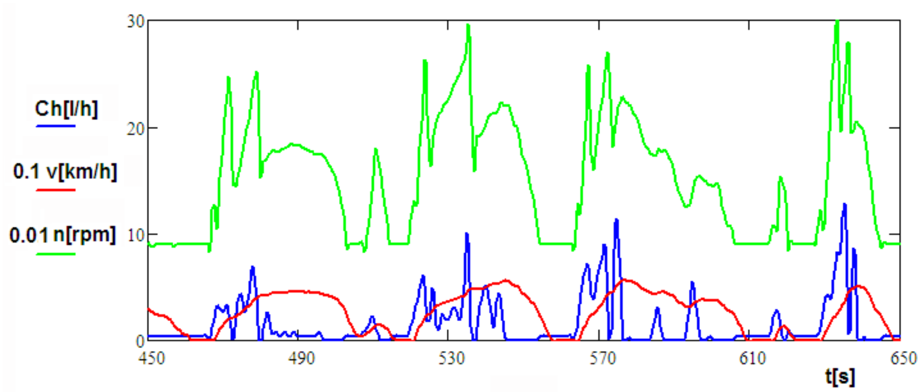

Fig. 6: Plot of vehicle's speed, engine's speed and hourly fuel consumption vs. time, recorded on the city route

The evolutions in time of the speed and acceleration can be observed from the **figure 4** and **figure 5**. Some statistical values of the routes' kinetic parameters are presented in the **Table 1**. This data and the histograms with the probability density for speed and acceleration apparition, presented in the left side of the **figures 4** and **5**, indicate that the mountain route is most dynamic as the one in city.

In **figure 6** are plotted vs. time the vehicle's speed, the engine's speed and the hourly fuel consumption (only a fragment it is presented). From the figure one observes that the diesel engine of the car is able to totally interrupt the fuel injection, reducing the consumption and the pollution and increasing the engine breaking effect.

In city traffic the engine speed remains low, never exceeding three quarters of the engine's rated speed. Based on the hourly fuel consumption and the total route length, it was computed the mean fuel consumption (1.4 litres per hour or 4.9 litre per 100 km). Also, the maximal hourly fuel consumption of 12.6 litres per hour was recorded at a speed of 35 km/h that means 36.1 litres per 100 km. The idling fuel consumption was of 0.4 litres per hour.

Using the equations presented in the previous chapter, the instantaneous powers and the values of the energy consumed from the record start to a current moment were also calculated. Some results for the mountain route are showed in the **figure 7**, while in the **figure 8** can be seen results for the city route. Each figure contains two sets of plots: in the upper side are presented the vehicle's speed, the road's difference of altitude and the recoverable power (the power that is consumed in the different brakes of the vehicle); in the lower side of the figure one can see how the mechanical energy delivered by the engine it is consumed.

The maximal braking power was 35.6 kW in the city and 78.5 kW on the mountain, while the tractive power at the wheel recorded in the city a maximum of 45.2 kW (49.7 kW delivered by the engine; 77 kW rated power) and 69.7 kW at the wheel (76.6 kW delivered by the engine; 85 kW rated power) on the mountain road. Here, a drive train efficiency of 0.91 was assumed. In the mentioned condition of city route, the 9.8 km of travel needed 0.483 litres of diesel fuel. Considering for the fuel the heating power of 44.8 MJ/kg and the density of 0.86 kg/l, that means the engine consumed 18.61 MJ and delivered 5.33 MJ (a mean indicated efficiency of 0.29).

The curves plotted in the lower side of the figures 7 and 8 separate the area in 6 domains. In the abscissa it is indicated the travelled distance. For a certain point on the route, the vertical distances between the curves represent a mean percentage of the energy use, from the starting point to the current point.

The lower domain corresponds to the losses in the drive train (from the engine to the driving wheels). The 9% losses correspond to the assumed constant efficiency of 0.91. The third and the fourth domains correspond to the rolling and aerodynamic drag. At the route end (figure 7), 35.5% of the engine energy was consumed to overcome the rolling resistance and 15.5% for the aerodynamic resistance.

Because the route starts with an ascending part of 7 km, the second domain shows that a lot of the engine's energy is consumed to overcome the grade resistance, i.e. to raise the vehicle's potential energy due to the increase of the altitude (approx. 60% at the beginning, but reducing continuously when the vehicle descend the mountain).

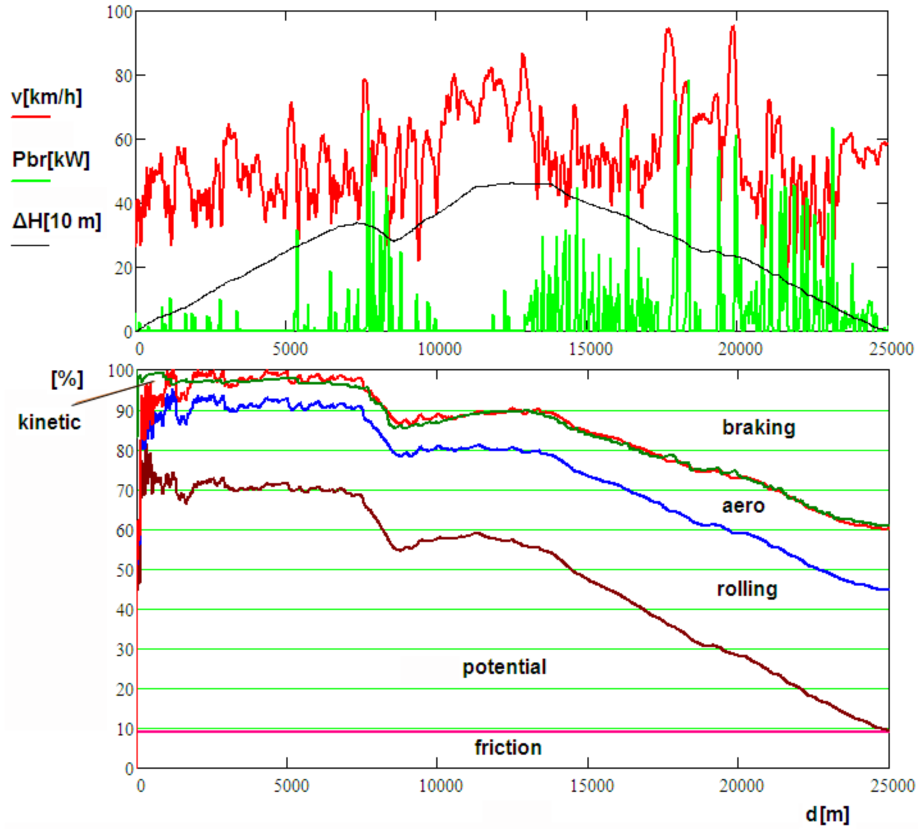

Fig. 7: Mean use of the mechanical energy produced by the engine between the record start and the current moment – mountain route

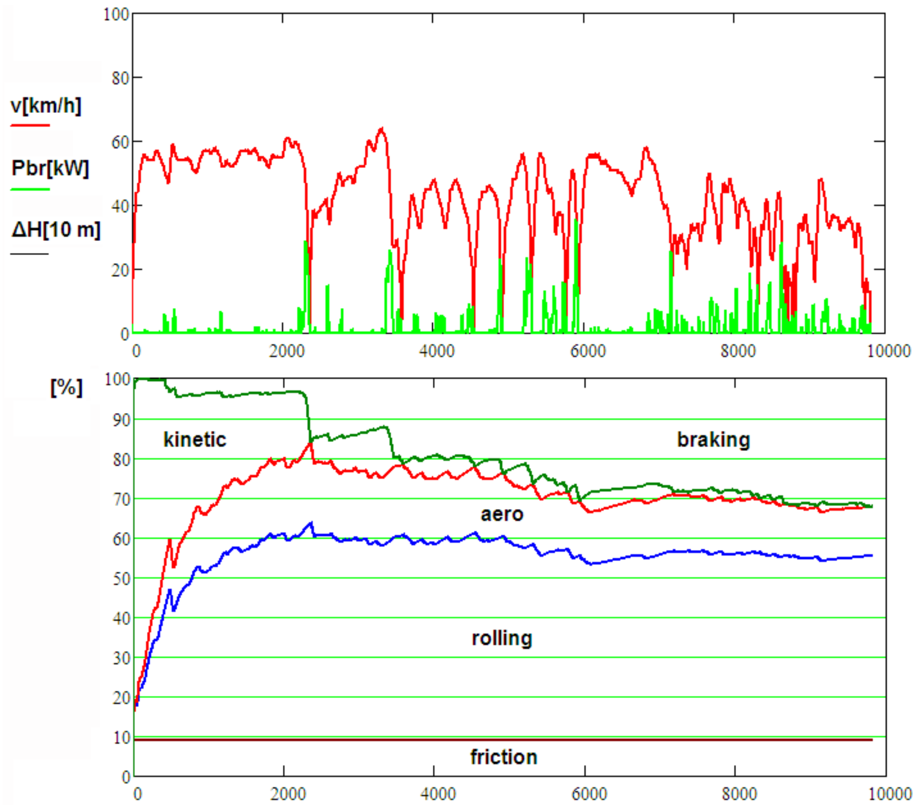

Fig. 8: Mean use of the mechanical energy produced by the engine between the record start and the current moment – city route

When the vehicle attains finally the same altitude as on the starting point, all the consumed energy for climbing was recovered and the percentage become zero.

But the accumulated energy of the vehicle's changes not only when is driven up-hill or down-hill (change of the potential energy), but also when its speed changes.

The kinetic energy percentage can be seen in the fifth region: when the red curve is under the green curve, the kinetic energy increases and will decrease in the opposite case. Because the amount of the engine's energy increases with the travelled distance, the ratio of the kinetic energy reduces continuously.

The upper domain corresponds to the braking energy, which may be recovered. As can be seen in figure 7, the percentage is extremely low in the ascending part of the route, is smaller as 10% in the relatively flat part, but become very important (40%) in the descending part. The energy consumed to overcome the rolling and aerodynamic resistances are respectively 35.5% and 15.5%.

Studying now the figure 8, it observes that the energy consumed to overcome the rolling and aerodynamic resistances are respectively 46.3% and 13.3% in city traffic. That one explains by the reduced vehicle's speed. On the other side, the braking energy percentage is about 30%, having an important potential for recovery even the speeds and braking powers are much lower.

The recovery of the braking energy will be limited by different causes. Neglecting the cost, weight or packaging difficulties, still remain two other importing ones: the abilities to absorb high power and high energy.

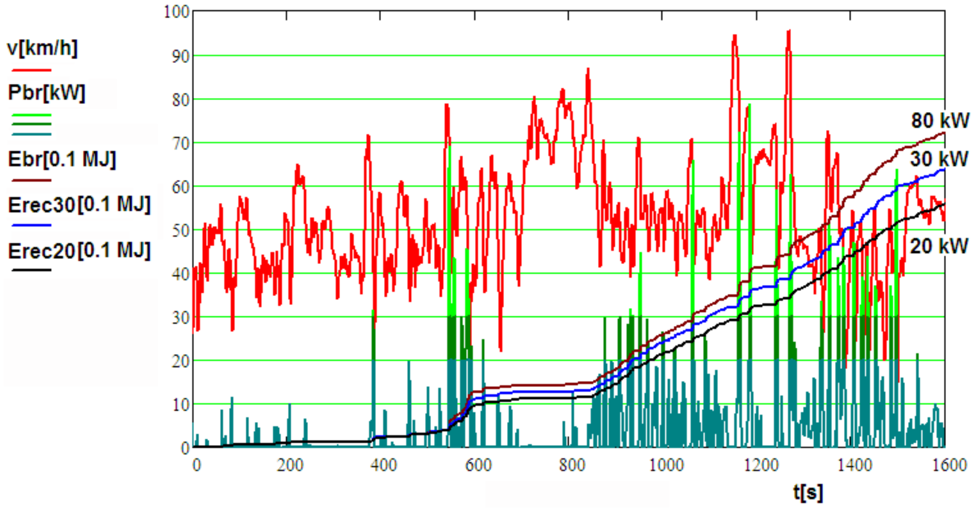

Fig. 9: Mean use of the mechanical energy produced by the engine on mountain route between the record start and the current moment

In **figure 9** are plotted, for the mountain route, the rates of energy recovery if the devices considered for that task will have three different installed powers: 80 kW, 30 kW and 20 kW. As can be seen, if the biggest device is theoretical able to recover all the braking energy, the percentages of the other two are lower: 88.4% and 77.4%. In city traffic, due to the smaller braking powers, the percentages are 99.7% and 96.1% respectively, that means even a low power device can have an important contribution to the recovering process. Off course, each energy transformation (for recovery, adaptation, store and reuse) will affect the overall efficiency of the process, so that the real regeneration percentage will be much smaller as in theory.

The other requirement is the ability of the storing device to absorb the entire energy of the braking energy pulses. In the mountain route, the maximal pulse was of 0.32 MJ in 12 s.

CONCLUSIONS

The paper presented a method to process different vehicle driving data obtained with affordable data acquisition devices. Based on the primary data and measuring or estimating some vehicle's parameters, much other derived information can be ascertained, as forces, powers or energy for moving resistances, traction and braking. The available information processed here is statistically representative for city traffic and for mountain road travelling, permitting to make valuable estimations about the energy recovery, fuel consumption or even chemical pollution. The results of data treatment can be used for the dimensioning, simulation or laboratory tests of the vehicle's hybrid propulsion system. The algorithm used here can be extended for further processing of this type of experimental data: clutch and gearbox use, driver style and others.

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