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Analysis of energy recovery possibilities from motor vehicles

Abstract*. The work presents the characteristics of the currently used motor vehicles and an analysis of fuel consumption by internal combustion engine vehicles in the context of decreasing fuel resources in the EU. It presents the dependencies that describe the resistance forces operating on the vehicle during the drive as well as the methods of determining the power needed to accelerate and to brake. An analysis of energy consumption of a sample vehicle on two routes of different characteristics was made on the basis of the tests performed. Also, an analysis of the possibilities of energy recovery during a car drive was conducted and the problems connected with energy storage limitations were discussed.*

Streszczenie. *W pracy przedstawiono charakterystykę aktualnie wykorzystywanych pojazdów samochodowych oraz analizę zużycia paliwa przez pojazdy spalinowe w kontekście malejących zasobów paliwowych w UE. Zaprezentowano zależności opisujące opory działające na samochód w trakcie jazdy oraz metody wyznaczania mocy niezbędnej do przyspieszania i hamowania. Na podstawie przeprowadzonych badań dokonano analizy energochłonności przykładowego pojazdu pokonującego dwie trasy o różnej charakterystyce. Przeprowadzono również analizę możliwych oszczędności energii podczas jazdy samochodem oraz omówiono problematykę związaną z ograniczeniami zasobników energii. (****Analiza możliwości odzysku energii przez pojazdy samochodowe****).*

Keywords: electric vehicles, energy storages, supercapacitors.
Słowa kluczowe: samochody elektryczne, zasobniki energii, superkondensatory.

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Introduction

The technology development in the automotive industry and the increased mobility of people contributes to considerable growth of the number of cars and to the growing demand for motor fuel. This leads to the fact that more and more attention is put on the ecological and economic aspects of the vehicles manufactured, especially with respect to their use. Analyses of those problems are directed at different aspects and performed both with respect to the improvement of the efficiency of the drive systems designed as well as with respect to the search of new types of energy and new methods of storing it. That is why the present work is dedicated to an analysis of passenger cars, focusing on the energy that can be recovered. Preliminary experiments involving a comparison between the energy demand levels in vehicles without energy recovery capabilities and the energy demand of a vehicle with energy recovery capabilities were performed. The objective of the tests was to analyze the motion resistance forces, the power needed for acceleration and braking, and then – an analysis of the savings that can be obtained during regenerative braking and determination of the limitations connected with the use of different energy storage devices. The last part of the work presents also an analysis of electric energy storage devices that can meet the expectations of the drivers regarding driving that is dynamic and economical at the same time.

Motor fuel demand in the European Union

The development of society is strictly connected with its mobility, both in the commercial space (public transportation, business trips) as well as in the private space (trips, holidays). That is why the number of cars on the roads has grown considerably over the last few years. For example, the number has grown by over 70% in Poland in the last 10 years and currently amounts to about 25 mln – 75% of which are passenger vehicles [4]. In many countries of the European Union, the increase is not so considerable as car saturation – expressed as the number of cars per one thousand inhabitants – is close to the border level and amounts to about 550 [11,12,14], whereas the total number of cars in the European Union approaches 300 million [11].

A topic that is inseparably connected with motor transport is motor fuel consumption. It is an important problem as despite considerable reduction of average fuel consumption by motor vehicles (5.8 l/100km on average in EU-27 countries – the lowest in Portugal – 5.1 l/100 km, the highest is Sweden – 6.3 l/100 km [4]), road vehicles in the European Union consume over 260 mega tons of oil equivalent per year. That is why scientists all over the world make more and more frequent attempts at estimating the time for which fuel resources will suffice. It is estimated that oil resources will suffice for about 40 years and the fact that the drivers observe their prices which go up systematically with growing concern is a consequence of that.

Some of the drivers try to look for savings by choosing smaller cars. That is why domination of small and compact models over large and luxurious cars can be observed in the car fleet in recent years [4]. Another popular way to obtain savings is purchasing cars designed to burn gas – in 2011, the percentage of newly registered vehicles with gas installation was 1.0% in EU-27 countries, and only 0.1% in EU-12 countries [4,6]. However, due to the high cost of the installation, the demand for new cars adjusted to burn LPG has been decreasing recently.

A fashionable, although still not that frequent, solution is equipping the vehicle with a different drive system (hybrid vehicles – most often with an electric motor) or replacing an internal combustion engine with an electric engine. According to the data from [4], the number of cars with a hybrid drive system in EU-27 countries was 0,7% in 2011, and the number of cars with an electric motor was 0,07%. This reflects the fact that the drivers consider such solutions as not very cost-effective. Detailed data regarding the number of passenger vehicles registered in EU-27 countries in the years 2008-2011 are presented in table 1.

Table 1. The number of passenger vehicles registered in EU-27 countries depending on the motor type [4] *

Year	Number of registrations	Diesel	Hybrid	Gas	Electric
2008	14 338 100	52,0 %	0,5 %	1,2 %	0,00 %
2009	14 091 605	45,0 %	0,5 %	3,7 %	0,00 %
2010	13 305 479	51,0 %	0,6 %	3,4 %	0,01 %
2011	13 117 185	55,0 %	0,7 %	1,0 %	0,07 %

* the remaining percentage was vehicles equipped with petrol engines

In order to prove that the use of one of the fuel types listed above can be economically justifiable, an energy analysis of a vehicle including the characteristics of its operation was performed. For that purpose, it is necessary to perform an analysis of the forces operating on a vehicle.

Forces operating on a passenger cars

While performing such an analysis, it is necessary to consider the forces operating on the vehicle during its motion. The forces depend on a number of factors, the most important of which include the driving force (F_D), the rolling resistance (F_R) and the aerodynamic resistance (F_A) [8,10]:

(1) $$F = F_D - F_A - F_R$$

Rolling resistance can be estimated on the basis of the following formula:

(2) $$F_R = mgf_{t0}\,(1+Kv^2)$$

where: m – vehicle mass, g – gravitational acceleration, v – vehicle speed, K – additional rolling resistance co-efficient (for asphalt surfaces, the assumed value of this co-efficient is $K = 5 \cdot 10^{-5}\ s^2/m^2$), f_{t0} – rolling resistance co-efficient at low speeds.

The rolling resistance co-efficient for low speeds is most frequently determined by performing the drag racing test. Then, the following formula should be used to calculate its value:

(3) $$F_{t0} = \frac{v_b^2}{2gS_t}$$

where: v_b – the initial speed of the vehicle, S_t – the rolling (drag) route of the car.

For passenger vehicles moving on asphalt surface, the rolling resistance co-efficient for low speeds is assumed to amount to a value between 0,012 and 0,014 [8,10].

(4) $$F_A = \frac{1}{2}\,\rho c_x\, A v_r^2$$

where: ρ – air density (for standard conditions of 0°C and the pressure of 1013 hPa, dry air density is about 1.293 kg/m^3), c_x – air resistance co-efficient in the longitudinal direction – depends on the shape of the vehicle and equals 25% to 45% (usually about 30%) [8], A – the vehicle front surface area, v_r – the speed of the vehicle in relation to the air.

Knowing the forces operating on the vehicle, it is possible to determine the momentary power and the energy needed to cover a given route over the set time.

Sample tests and test analyses

In order to verify the considerations presented in practice, an analysis of energy consumption of a sample vehicle on selected routes of different characteristics was performed. Using a GPS system, momentary speed values of a Ford Focus motor vehicle with the 1596 ccm petrol engine with the capacity of 85 kW (115 KM) and the total mass of about 1300 kg (including the driver) were recorded. An analysis of the drive parameters of the motor vehicle covering two routes – in the city during rush hours (route A – 17,9 km in 41 min) and in mixed area on a non-working day in early morning hours (route B – 13,5 km in 17 min) was performed. Next, a computer program used for the analysis and graphical presentation of the drive was created in the MS Visual Studio C# 2012 environment. The geographic coordinates recorded during the drive are presented on figures 1a and 1b, and the driving speed investigations in time are presented on figures 2a and 2b.

Fig. 1a. City drive route – route A

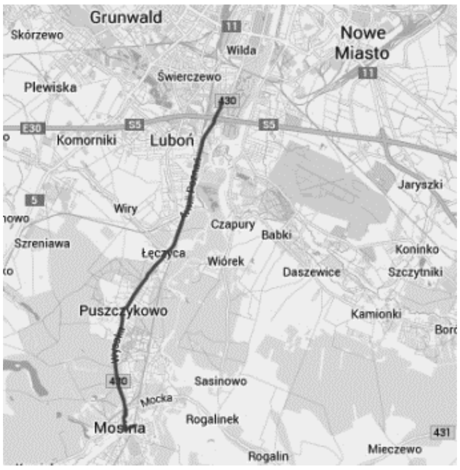

Fig. 1b. Mixed drive route – route B

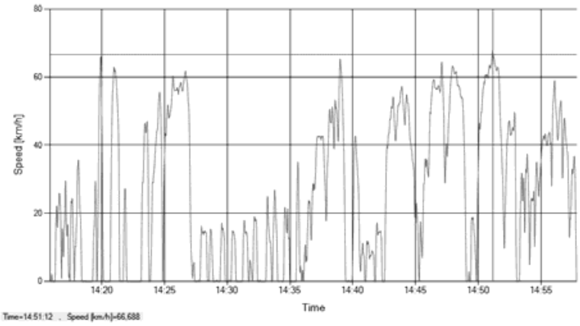

Fig. 2a. Momentary speed during the drive along the city route (A)

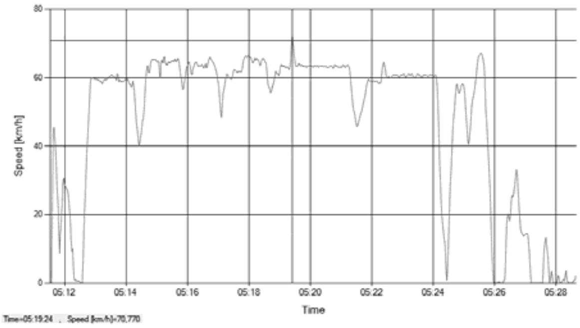

Fig. 2b. Momentary speed during the drive along the mixed route (B)

The motivation behind the selection of the driving route was the intention to show energy recovery capabilities of electric vehicles which, due to the limitations of the current electric energy storage technology, are intended mainly for short distance drives (usually in the city).

Next, an analysis of the energy consumption by the vehicle was performed on the basis of the dependencies described. The following vehicle parameters were assumed during the calculations: rolling resistance co-efficient for low speeds f_{t0} = 0,014, vehicle front surface area A = 2,40 m^2, air resistance co-efficient c_x = 30 %. The energy demand calculation results obtained were assumed as positive values and the recovered energy values were assumed as negative values. The calculated energy levels consumed by the tested vehicle are presented on figures 3 a and b as curve no 1. Additionally, considering motion resistance forces, the energy that could be recovered through electrodynamic braking (fig. 3 a and b, curve no 2) and their sum – that is, the energy that would be consumed by the vehicle if it could recover energy (fig. 3 a and b, curve no 3) were calculated.

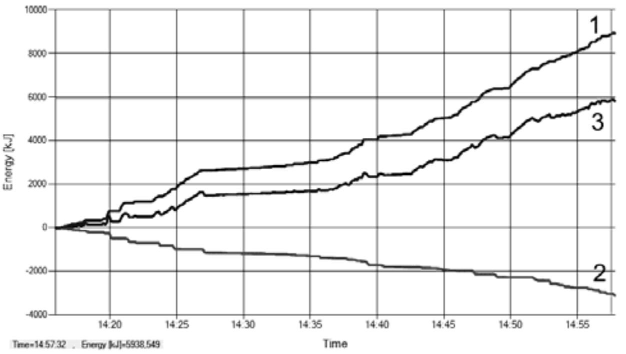

Fig. 3a. Mechanical energy balance during the drive along the city route

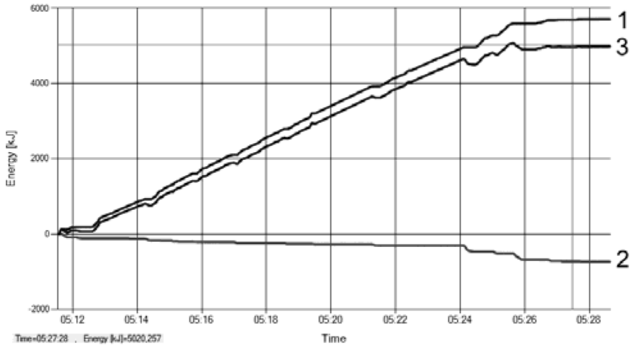

Fig. 3b. Mechanical energy balance during the drive along the mixed route

In order to verify the correctness of the calculations of energy consumption by the vehicle, the demand for E95 petrol during the drive along the routes set assuming average efficiency of the internal combustion engine of 25% [10] and the fuel calorific value of 43 MJ/kg [8,10] at the density of 740 kg/m^3 (at the temperature of about 10 °C) was determined. The results obtained were compared with the values shown by the on-board computer (whose accuracy was previously verified). In the case of the city route, the fuel demand calculated was 1,55 l, and in the case of the mixed route the demand was 1,30 l. Those results were slightly different than the reading of the on-board computer which indicated the value of 1,8 l in the first case and 1,4 l in the second case. The deviations obtained were considered as confirming the accuracy of the energy consumption values calculated as it was found that the differences in the values estimated and the values indicated by the on-board computer most likely result from the approximation of the efficiency of the internal combustion engine and of the drive system which is not constant and depends to a large extent on the current gear and the rotational speed of the engine (determination of the fuel consumption level was not the objective of the task but only a way to verify the correctness of the calculations).

In further considerations regarding the analysis of vehicle energy, the capacity of the electric energy source which would make it possible to cover a 100 km long route was examined in combination with an analysis of the ability of electrical systems to transmit appropriate power in dynamic states – both in the case of energy emission (during vehicle acceleration), as well as in the case of energy recovery (during braking).

Many electric vehicles intended for short distance drives are equipped with a battery module with the voltage of 84 V constructed of seven chains (in total, 42 lead-acid cells). In such a case, using energy storage intended for traction operation (for deep discharge) seems to be sufficient.

In order for the vehicle discussed with the mass assumed to cover the distance of 100 km with the average speed of 45 km/h (as in the case of route B – during the drive in mixed area), it must overcome motion resistance forces (disregarding transmission gear losses as it is often not used in electric vehicles) at the level of 285 N, which translates into the energy level equal to about 7,9 kWh (power in the order of 3,6 kW for 130 minutes). Such a value of electric energy is equivalent to the energy stored in a battery with twenty-hour capacity of 80 Ah (including the Peukert effect).

However, in both cases during the drive positive power (needed to drive the vehicle) during rapid acceleration exceeded the value of a few dozen kW. On such occasions, the batteries used would not be sufficient due to the fact that this would require current input at the level of more than 200-250 A depending on the battery discharge level. This would increase the Peukert effect – accelerating the battery discharge process – and exceed the capacity of the energy sources suggested, that is – it would be harmful to them (considerably shortening their service life), causing their fast destruction and the need for more frequent replacements. A similar situation would occur during rapid braking.

Considering that battery replacement constitutes a considerable portion of usage costs in the case of electric vehicles, this would be highly uneconomical. That is why it is important to make sure that the battery discharge depth is not too high, providing energy supply. A detailed analysis of momentary current values showed that in the case of the drive with the characteristics presented on figures 1a and 1b, it would be necessary to use batteries with the capacity of at least 120 Ah.

It must, however, be added that using batteries only is disadvantageous even when the amount of energy stored with safe reserve is sufficient to cover the distance set. Firstly, high current values discharge electrochemical energy sources disproportionally faster and, secondly, they lead to faster battery destruction – this applies in particular to popular lead-acid batteries. That is why the designers of electric vehicles decide to use different batteries, e.g. lithium-ion batteries or lithium-polymer batteries. Apart from higher operational voltage (4.2 V/cell), they are characterized by higher energy density (up to 180 Wh/kg) and longer service life (amounting to 2000 cycles) [5].

It is also worth pointing out that in the case of electrochemical energy sources, it is necessary to consider their operation temperature. It is a parameter that considerably influences the efficiency of the battery. That is why additional systems managing battery operation which, apart from analyzing their basic parameters (load, voltage, discharge level and temperature), are equipped with systems that adjust their temperature are present in the solutions of some of the companies designing electric vehicles. They are controlled with the use of different types of optimization methods [2,3,7,9]. Such systems use the Peltier effect (the so-called Peltier cell), which makes it possible both to heat as well as to cool the module. This contributes to relative density increase of the energy stored in the battery [1,5].

Regardless of the type of the electrochemical energy source used, high current values have a negative influence on their operation. That is why it seems important to use additional energy storage – which would make it possible to transmit high current values (in both directions) in dynamic states – such as, for example, supercapacitors. They constitute a type of energy storage which is characterized by considerably greater energy emission capabilities – the power density values of supercapacitors are many times higher than the power density of batteries – and, what is important, they are many times more efficient during charging and discharging, regardless of the temperature [1,5]. Their disadvantage is, however, their low ability to store energy in comparison to the batteries discussed earlier. That is why at the current state of knowledge they cannot be used as the basic energy source in electric vehicles. Their advantages can, however, be utilized when they are used as additional energy buffer, especially in dynamic drive states (rapid acceleration and braking). Thanks to that, high current values which are the most destructive for batteries can be limited.

To sum up, it is also worth discussing the fact that energy demand differences occur in the case of a vehicle with energy recovery capabilities in comparison to a vehicle which makes energy recovery impossible. As it results from the dependencies presented on figure 3, the amount of energy that the vehicle consumed during city drive is about 8.1 MJ, and 5.8 MJ in mixed drive, 2.5 MJ of which could be recovered in the first case and 0.8 MJ – in the second case (the analysis was performed disregarding energy converter losses). The possibility to recover large amounts of energy during city drive results from frequent acceleration and braking and from lower driving speeds (lower motion resistance forces).

Conclusions

On the basis of sample tests performed, it was confirmed that using systems that enable energy recovery makes it possible to obtain considerable economic gains. In the cases under analysis, different with respect to drive characteristics, it was shown that the use of available electric energy storage can make it possible to save energy at the level of a few dozen percent – over 31% in the case of the drive in the city center in dense traffic and about 13% in the case of a drive along a mixed route in a non-working day in early morning hours. Also, the problems connected with energy storage limitations regarding acceptable charge and discharge currents were considered in the present work – it was demonstrated that exclusive use of traditional lead-acid batteries may lead to premature reduction of their ability to store energy and, as a result, to considerable increase of usage costs of electric and hybrid vehicles. Contemporary battery operation management solutions as well as the more and more popular systems using supercapacitor modules to transmit large amounts of energy in dynamic states (rapid acceleration and braking) whose parameters give the hope for efficient and long-term operation (load recovery and emission) during the drive of varying characteristics were also discussed.

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