RESEARCH ON ENERGY CONSUMPTION BY AN ELECTRIC AUTOMOTIVE VEHICLE

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Summary

In recent years, dynamic development of electric drives in automotive applications has taken place. This has chiefly been driven by ecological considerations, in particular pollutant and noise emissions and the depletion of the natural resources necessary for the production of liquid and gaseous fuels. For the energy characteristics of electric automotive vehicles to be assessed, the energy consumption by such vehicles must be tested in conditions corresponding to the actual operation conditions. In this paper, formal description of energy and economic characteristics of electric automotive vehicles has been proposed. The notions of efficiency of vehicle drive, efficiency of battery charging, efficiency of braking energy recuperation, total efficiency, and distance energy consumption by vehicles without and with braking energy recuperation have been introduced.

Results of testing a Zilent Courant electric passenger car in conditions simulating the urban operation of such a vehicle have been presented. The Zilent Courant car has no braking energy recuperation system. The tests were carried out on a chassis dynamometer according to the procedures defined as UDC (Urban Driving Cycle), FTP 75 (Federal Transient Procedure), and Stop-and-Go test procedure intended to simulate the street jam traffic type. The average distance energy consumption and total vehicle efficiency was determined in the tests. The distance energy consumption was also tested in selected dynamic conditions of vehicle operation: the average values of distance energy consumption at positive and negative vehicle acceleration were determined..

Keywords: electric car, energy consumption.

1. Introduction

The idea of vehicles driven by electric motors is very old. The first electric cars were built as early as 1830s. Prototype electric vehicles were built by e.g. a Scotsman Robert Anderson, a Dutchman Sibrandus Stratingh Groningen, and an American Thomas Davenport [22]. In 1890, mass production of electric cars was started in the United States of America. The largest concentration of cars with electric drive systems could be observed at the beginning of the 20th century: as an example, over 20 000 electric cars were in service in the USA in 1912. After World War I, electric cars were gradually superseded by vehicles with combustion engines, chiefly because of the higher effective power of such engines and better operating properties, e.g. the vastly superior range of vehicles of the latter kind.

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In recent years, electric automotive vehicles have been seen as a remedy for serious environmental problems caused by motorisation, related to such issues as pollutant and noise emissions and the depletion of the natural resources necessary for the production of liquid and gaseous fuels [1, 6, 9, 16].

The assessment of pollutant emissions and energy consumption by electric vehicles in order to compare them with conventional automotive solutions is a complex issue. This is because in the case of electric vehicles, the environmental loading is shifted to the electricity generation stage. A possible method of exploring this problem is the carrying out of the "Wheel-to-Wheel" analysis, i.e. the analysis from the source (of an energy carrier) to the wheel (of a vehicle) [1, 8, 9, 12, 14, 17, 26]. Such an analysis makes it possible to assess the emission of pollutants for the whole cycle of production of energy carriers and their utilisation for the powering of vehicles. Thanks to such an approach, the susceptibility of the total harmful impact of the solutions assigned to the energy carrier processing technology may also be evaluated; actually, this susceptibility is very high and may be decisive to a significant extent for the ecological assessment of the solutions being compared with each other. In the case of electric automotive vehicles, electricity generation is particularly important problem [1, 7–9, 13, 15, 17, 20, 25], because predominantly, at least in Poland, electricity is generated from fossil energy carriers (chiefly coal) with the use of technologies that are far from being environment-friendly. Nevertheless, attention should be drawn to the following important argument for the development of electrically driven vehicles: even if the Wheel-to-Wheel analysis leads to negative results of the assessment of pollutant emissions, such vehicles offer the possibility of "shifting" the pollutant emission sources from the areas of the greatest hazard, i.e. from the central parts of large urban agglomerations, to the locations of power plants [1, 10, 13, 20].

Extensive literature is available, e.g. [1, 3, 7–17, 20–26], that covers the research on energy consumption and pollutant emissions connected with the operation of electric automotive vehicles. Usually, the analyses are carried out for the conditions of type approval tests. In [12], a comparative analysis of energy consumption and greenhouse gas emissions was carried out for the whole Wheel-to-Wheel cycle, with this cycle being divided into two stages, namely "Wheel-to-Tank," i.e. from the source to the tank of the energy carrier, and "Tank-to Wheel," i.e. from the tank to the driving wheels of the vehicle. The comparisons covered automotive vehicle with a spark-ignition engine, vehicle with a compression-ignition engine, hybrid electric vehicle (HEV [27]) with a no off-vehicle charging system (NOVC), a hybrid electric vehicle with an off-vehicle charging system (OVC), also referred to as plug-in hybrid electric vehicle (PHEV [27]), a pure electric automotive vehicle (battery electric vehicle – BEV [12]), and a vehicle with a fuel cell (fuel cell vehicle – FCV [12]). The best results were obtained for the hybrid vehicles and the fuel cell vehicle. For the battery electric vehicles, the decisive factor in the obtaining of the worse analysis results was the electricity generation phase, which involves energy-consuming processes and is a source of significant greenhouse gas emissions and would be connected with the widespread use of technologies based on the consumption of fossil materials. Many publications contain analytic deliberations about the positive and negative aspects of the manufacturing and operation of electric automotive vehicles and the management of such vehicles when worn-out [1, 7, 13–15, 17, 20, 25, 26].

Contrary to popular opinions, electric vehicles still cannot realistically compete with vehicles driven by combustion engines. At present, rather the vehicles with hybrid propulsion systems, i.e. with electric motors and combustion engines operating together seem to be the most promising solution [9, 10–12, 14, 19]. From the technical point of view, electric storage cells are the weakest link in the present-day electric vehicles [1, 8, 14, 15]. Under no circumstances, can this be considered a surprise because it is generally known that the storage of energy is a particularly difficult problem; so far, the use of liquid fuels is an unequalled solution [12, 14].

This cautious approach to the problem of electric vehicles is by no means inconsistent with the dynamic work on development of electric drives not only in small passenger cars but also in commercial vehicles [1, 9, 25] and single-track vehicles [3, 23, 24].

This study deals with the issue of energy consumption by an electric vehicle in the conditions in which such a vehicle is typically used [21]. In general, electric automotive vehicles are thought of at present as being chiefly intended for use in the traffic conditions prevailing in central urban areas. Therefore, the tests were carried out in accordance with the European UDC (Urban Driving Cycle) and the American FTP 75 (Federal Transient Procedure) type approval test procedures [27] that simulate the urban and suburban traffic conditions. Additionally, tests were carried out to the Stop-and-Go test procedure [2, 5], which represents the traffic jam conditions.

2. Description of energy and economic characteristics of electric vehicles

To describe the energy and economic characteristics of electric automotive vehicles, notions characterising the efficiency and energy consumption are used.

For an electric vehicle without braking energy recuperation, the efficiency system is defined as follows:

- efficiency of vehicle drive

$$\eta_D = \frac{N_R}{N_T} \tag{1}$$

- efficiency of battery charging

$$\eta_{CH} = \frac{N_T}{N_{CH}} \tag{2}$$

- total efficiency

$$\eta_G = \eta_{CH} \cdot \eta_D \tag{3}$$

where:
N_T – electric vehicle drive power;
N_R – resistance-to-motion power;
N_{CH} – battery charging power.

For an electric vehicle with braking energy recuperation, the efficiency system is defined as follows:

- efficiency of vehicle drive

$$\eta_D = \frac{N_R}{N_T - N_U} \tag{4}$$

- efficiency of braking energy recuperation

$$\eta_U = \frac{N_U}{N_B} \tag{5}$$

where:
N_B – braking power;
N_U – braking energy recuperation power.

The distance energy consumption is defined as derivative of the energy consumed relative to the distance travelled by the vehicle. For an electric vehicle without braking energy recuperation, it is:

$$c = \frac{dL_T(s)}{ds} \tag{6}$$

where:
s – distance travelled by the vehicle;
$L_{T(s)}$ – work of the electric vehicle drive as a function of the distance travelled.

For an electric vehicle with braking energy recuperation, the distance energy consumption is:

$$c = \frac{d(L_T(s) - L_U(s))}{ds} \tag{7}$$

where:
$L_{U(s)}$ – braking energy recuperated as a function of the distance travelled.

A schematic diagram of the power flow in the powertrain[2] of an electric vehicle with electricity recuperation has been shown in Fig. 1.

A key role in the recuperation of braking energy is played by the efficiency of braking energy recuperation. During vehicle operation in urban conditions, the phases of acceleration and braking frequently occur; therefore, the braking energy is a significant item in the energy balance. In consequence, the efficiency of braking energy recuperation, which is often quite low, constitutes an important problem [8, 12, 15, 21].

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[2] The term "driving system" is to be understood, consistently with the traditional meaning adopted in automotive sciences, as the system to transmit mechanical energy from the motor to the road wheels of a vehicle ("power transmission system"). The driving system taken together with the motor and the energy storage reservoir is referred to in this paper as "powertrain."

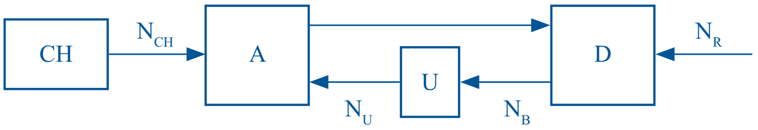

Fig. 1. Schematic diagram of the power flow in the powertrain of an electric vehicle with electricity recuperation

Legend: CH – battery charging system; A – battery; D – vehicle driving system; U – braking energy recuperation system; N_{CH} – battery charging power; N_T – electric vehicle drive power; N_R – resistance-to-motion power; N_B – electric machine braking power; N_U – braking energy recuperation power

3. Empirical tests of the energy consumption by an electric vehicle

Empirical tests of the energy consumption by an electric vehicle were carried out on a chassis dynamometer at the Environmental Protection Centre of the Motor Transport Institute (ITS) [4]. The test specimen was an electric passenger car Zilent Courant, made in the People's Republic of China. According to item 2 of UN ECE Regulation No. 101, this vehicle was a so-called "pure electric vehicle," i.e. a vehicle whose electric motors are exclusively powered from a battery of electric storage cells. The vehicle powertrain had no braking energy recuperation system.

The basic technical specifications of the Zilent car, model Courant, have been given in Table 1.

Table 1. Technical specifications of the Zilent car, model Courant

Description	Data	Unit of measure
Dimensions	3618×1563×1533	mm
Mass of the vehicle in running order	1170	kg
Number of seats	4	
Maximum speed	85	km/h
Economical speed	40	km/h
Maximum gradients negotiated	36% (20°)	
Range at economical speed	over 150 km	
Power rating of the electric motor	8.5 kW	
Total voltage rating of the battery pack	120 V 10 batteries, 12 V / 100 Ah each	
Battery pack type	Lead-acid batteries, maintenance free	
Battery charging system	External supply (220–230 V / (50–60 Hz) 1.5 kW	
Battery charging time	12–14 h	

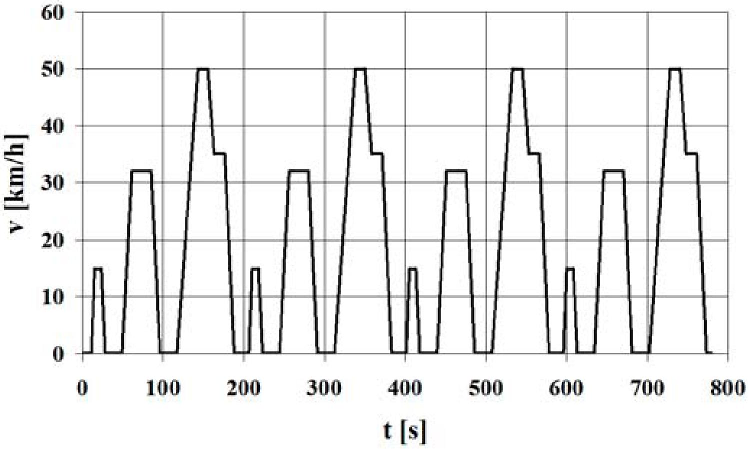

Fig. 2. The UDC test

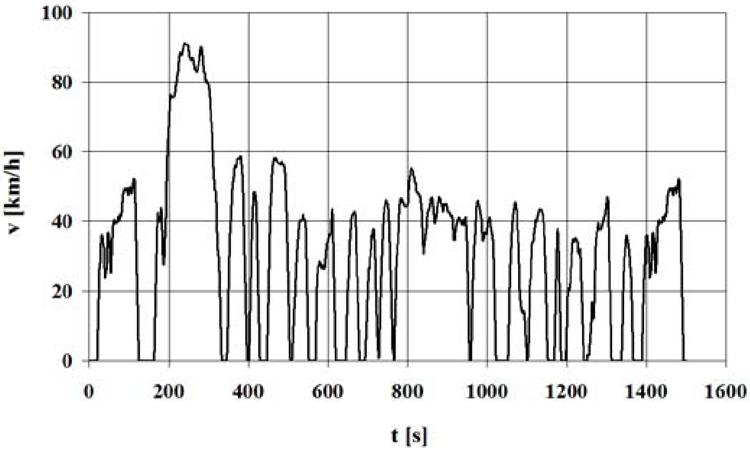

Fig. 3. The FTP-75 test

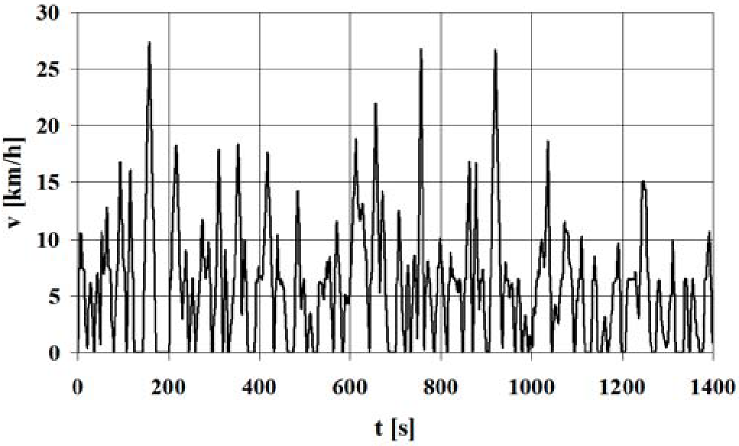

Fig. 4. The Stop-and-Go test

To simulate the urban traffic conditions, two test models were adopted, built in accordance with the European UDC (Urban Driving Cycle) and American FTP 75 (Federal Transient Procedure) type approval tests [27], see Figs. 2 and 3, respectively; they were supplemented with the Stop-and-Go test procedure, which represented the street jam traffic type [2, 5], see Fig. 4.

The tests were carried out on a single-roller chassis dynamometer with controlled load characteristics, manufactured by AVL-Zöllner [4].

The parameters measured during the tests carried out on the chassis dynamometers included:

- vehicle speed measured on the chassis dynamometer roller;
- voltage of the battery pack;
- current in the electric drive wiring of the vehicle.

The characteristic curve of the power absorbed by the chassis dynamometer was identified on the grounds of empirical vehicle coast-down tests [4].

The signals representing the quantities measured were recorded with 1 s sampling time. The signals recorded were preliminarily processed to eliminate gross errors and to reduce the share of high-frequency noise. The gross errors were found by analysing the current variance of the signals. To reduce the share of high-frequency noise in the signals recorded, the signals were subjected to low-pass filtration, with a Golay-Savitzky [18] filter being used, where both-side approximation from two data points on each side to a polynomial of degree 2 was applied.

Results obtained from the Stop-and-Go test have been presented as an example in Figs. 5, 6, and 7.

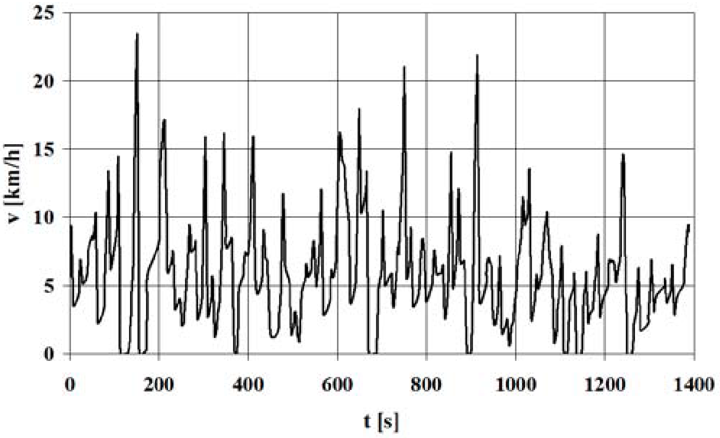

Fig. 5. A realisation of the Stop-and-Go test

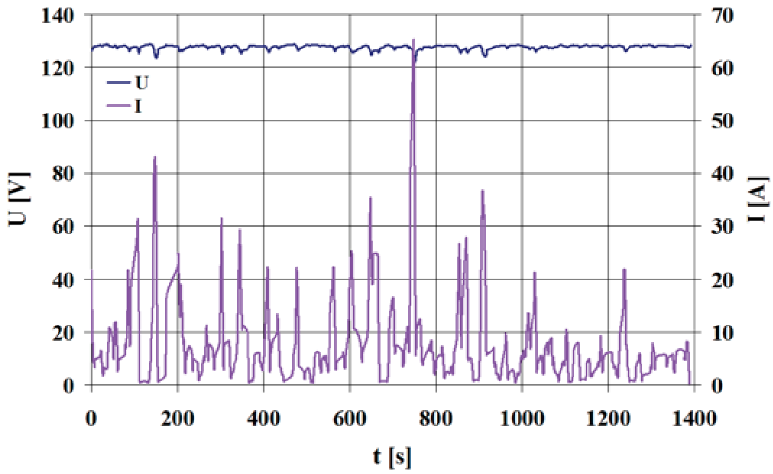

Fig. 6. Current drawn from the battery pack and voltage measured on the battery pack terminals vs. time, at the Stop-and-Go test

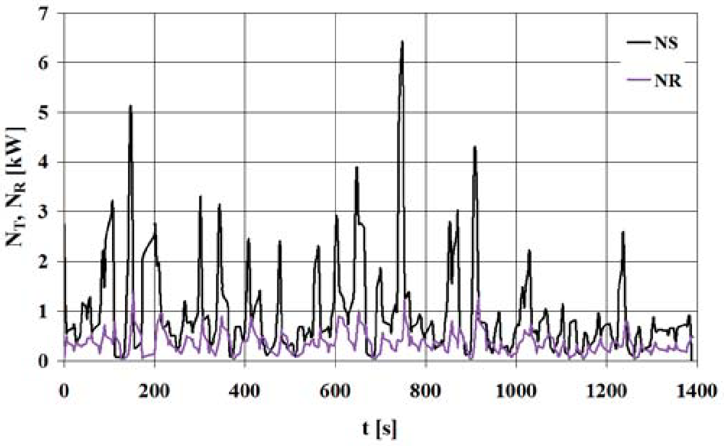

Fig. 7. Electric power of the vehicle powertrain and resistance-to-motion power vs. time, at the Stop and Go test

Based on the experimental tests, the total vehicle efficiency was determined. A problem was encountered with correct adopting of the battery charging efficiency. The battery charging efficiency values that can be found in the literature significantly differ from each other, depending on battery type. As an example, the battery charging efficiency has been specified in publication [8] as 0.86, while significantly lower values, even of the order of 0.6, were recorded for lead-acid batteries in the tests described in report [4]. Finally, the battery charging efficiency value was assumed as 0.65 for the purposes of the analyses presented herein.

The total vehicle efficiency values as recorded at specific tests have been shown together in Fig. 8.

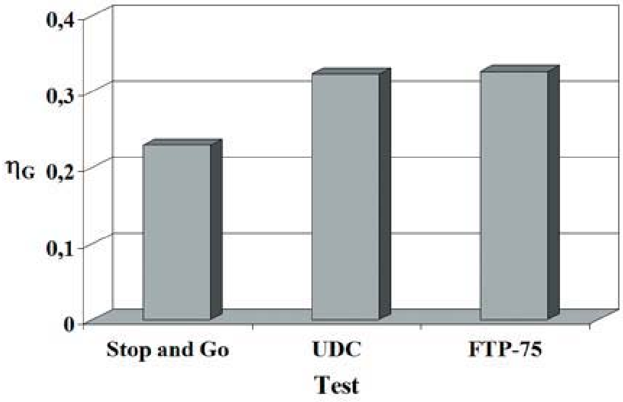

Fig. 8. Total vehicle efficiency as determined from the Stop-and-Go, UDC, and FTP 75 tests

The total vehicle efficiency values recorded at the tests carried out to the type approval procedures are similar to each other. A considerably lower value of the total vehicle efficiency was recorded at the Stop-and-Go test, which is characterised by frequent acceleration and deceleration, with the average vehicle speed being about 5.8 km/h. The specific conditions of this test are likely to cause much higher energy losses. A similar situation can also be observed in the case of automotive vehicles powered with combustion engines [2, 5].

The average distance energy consumption has been presented in Fig. 9.

The average distance energy consumption values were similar to each other at the Stop-and-Go and FTP 75 tests, while this value recorded at the UDC test was visibly lower. This is probably related to the dynamic characteristics of the speed programs followed during the tests carried out. The FTP 75 and Stop-and-Go test programs are more dynamic in

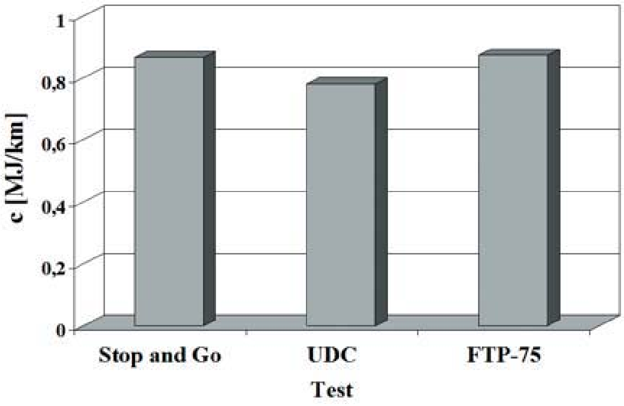

Fig. 9. Average distance energy consumption as determined at the Stop-and-Go, UDC, and FTP 75 tests

comparison to that of the UDC test, which can be seen e.g. in the frequency characteristics: the power spectral density of vehicle speed at the FTP 75 and Stop-and-Go tests exceeds that determined at the UDC test at high frequencies [5]. This is a consequence of the method of setting-up the test programs: the FTP 75 and Stop-and-Go test programs are built in conformity with the criterion of accurate time-domain simulation while the UDC program is synthesised in accordance with the criterion of similarity of point-type characteristics of test conditions and actual vehicle operation conditions.

Tests to determine the average distance energy consumption were also carried out in dynamic states, i.e. at positive and negative acceleration. Results of these analyses have been presented in Figs. 10, 11, and 12.

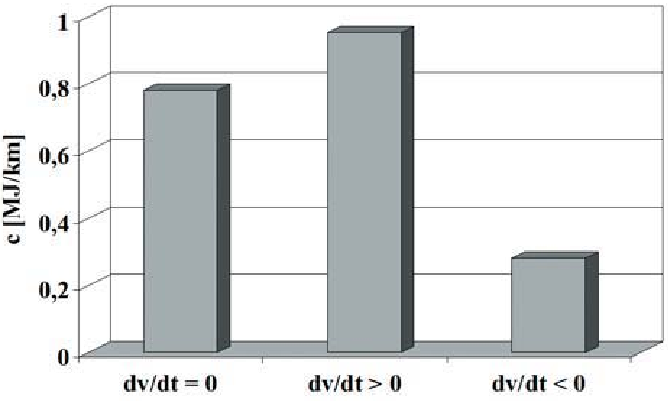

Fig. 10. Average distance energy consumption as determined in the dynamic states of positive and negative acceleration at the UDC test

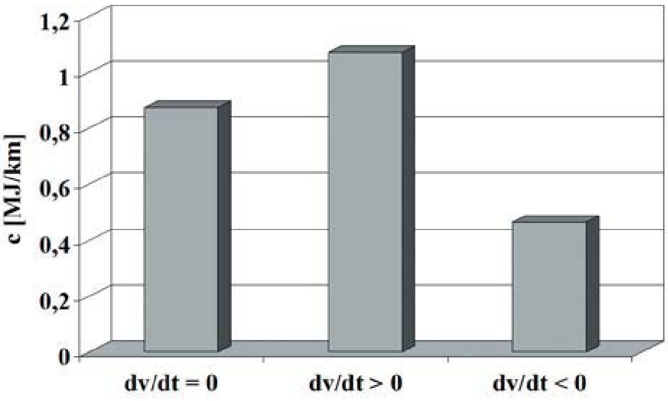

Fig. 11. Average distance energy consumption as determined in the dynamic states of positive and negative acceleration at the FTP 75 test

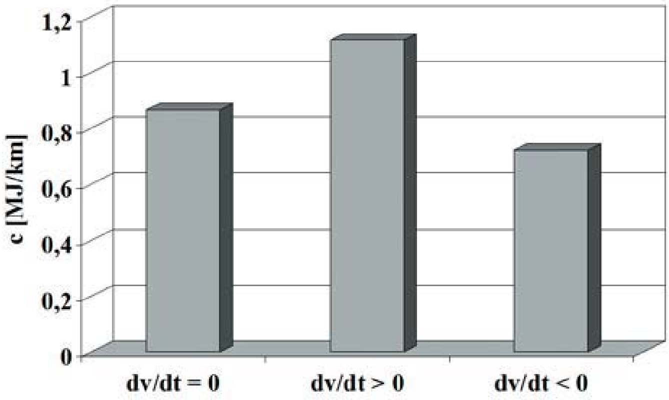

Fig. 12. Average distance energy consumption as determined in the dynamic states of positive and negative acceleration at the Stop-and-Go test

The analysis results are consistent with expectations: the distance energy consumption was higher during the vehicle acceleration phase of each test. The biggest differences between the distance energy consumption values in the dynamic conditions under consideration occurred at the UDC test.

4. Recapitulation

At present, the priorities adopted in the development of electric drives are chiefly based on ecological considerations. Electric vehicles virtually do not emit pollutants at the places where they are used (actually, they obviously cause emission of particulate matter from such sources as tribological pairs in the vehicle, interaction between tyres and road surface, or stirring-up of road dust). Electric vehicles are also characterised by lower intensity of noise emission in comparison with vehicles powered by combustion engines. An important advantage of the use of electric automotive vehicles is the possibility of saving the resources necessary for the production of liquid and gaseous fuels. A wide variety of primary energy carriers may be used to power electric vehicles. The choice is made depending on the electricity generation technology used. At present, at least in Poland, electricity is predominantly generated from coal, but the use of renewable energy as well as nuclear technology is also possible, especially will be in the future, when nuclear fusion energy becomes widely available. Current Wheel-to-Wheel analyses of the harmful environmental impact of electric vehicles are carried out, taking into account the significant environmental loading caused by electricity generation processes. It is difficult, therefore, to make an impartial assessment of the environmental effects of the "electrification" of road transport. The synthetic indicators of the environmental loading, determined in LCA (Life Cycle Assessment) analyses, are heavily dependent not only on the technical and organisational solutions applied (in particular the technologies of processing energy carriers) but also on the LCA analysis method adopted. In addition to this, a significant degree of relativity, as a consequence, a kind of latitude in the carrying out of such analyses give room for manipulation of information in connection with strong pressures of lobbies financially and emotionally involved in the development of various technical solutions comparable with each other, i.e. the classic transport based on the combustion of oil-derivative and the electric transport in this case. For these reasons, the making of comparisons between the values of indicators of the environmental loading caused by motorisation in the case of different technical solutions may turn out to be of little use.

The energy consumption by electric automotive vehicles is determined in most cases in type-approval test conditions. In the work described herein, such tests were supplemented with measurements carried out in the special Stop-and-Go test conditions simulating the street jam traffic type. The test results revealed low susceptibility of the distance energy consumption to the adopted model of vehicle driving; simultaneously, the driving model was found to have considerable impact on the total vehicle efficiency. The susceptibility of the distance energy consumption to the occurrence of dynamic states was confirmed: in all the cases, the distance energy consumption was higher during the vehicle acceleration phase.

The proposed procedure to test the energy consumption on a chassis dynamometer proved to be effective. Nevertheless, it is advisable to verify the test results in the conditions of actual vehicle operation in urban traffic. Tests of this type are now in progress.

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